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**CARDBOARD IN ARCHITECTURAL TECHNOLOGY  
AND STRUCTURAL ENGINEERING :  
A CONCEPTUAL APPROACH TO CARDBOARD BUILDINGS  
IN ARCHITECTURE**

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## Abstract

Corrugated cardboard is increasingly being used in a variety of modern applications, ranging from the printing, packaging and aviation industries to the construction of various indoor elements, including furniture and doors. As a structural building element, corrugated cardboard has many advantages. In addition to being a relatively low cost material, it possesses very strong insulative (thermal and acoustical) properties, is easily recyclable, and can be manufactured using renewable sources. Most importantly though, as a building element, corrugated cardboard possesses a high degree of structural strength and stiffness.

Despite these proven benefits, the growth in popularity of corrugated cardboard as a building material has remained relatively stagnant over the years, due mostly to its perceived limitations. These limitations include its vulnerability to moisture, fire and temperature change, as well as its sensitivity to ultra-violet light and various chemicals. Solutions for many of these issues are currently being addressed and tested by researchers in the field.

In its architectural quest for general acceptance as building material, corrugated cardboard still requires considerable development in order to come into compliance with modern construction paradigms. With this in mind, the fundamental question for this study is therefore:

*Is it feasible to build a house out of corrugated cardboard?*

Suggesting the implementation of a structurally sound corrugated cardboard construction, this thesis, in marked contrast to prior attempts in cardboard architecture, undertakes the goal of examining potential applications of corrugated cardboard within the existing environmental and social contexts and then exploring its relation to modern design guidelines. In particular, the current demands of wall components in relation to architectural space is thoroughly analyzed.

From the onset, corrugated cardboard was selected as a potential building material based on its low cost, load-bearing capabilities, and strong insulative properties. In addition to these advantageous physical characteristics, corrugated cardboard can also greatly increase certain efficiencies in the construction process. Specifically, cardboard blocks can be prefabricated and mass customized, permitting streamlining on the construction site, and thus improved cost savings.

This thesis is primarily guided by the experimental findings of the CATSE collaborative research platform at ETH Zurich. The engineering team, after testing and modeling various cardboard construction prototypes, was able to demonstrate the sufficiency of the material's structural strength and stability.

The findings of the research team also show that prefabricated cardboard-core sandwich composites are particularly well suited for use as wall components. Promising physical and mechanical behaviors were observed when cardboard was utilized as both an exterior and interior wall component. Further investigations revealed cardboard wall's thermal control characteristics, implying a strong potential for overall energy and cost reduction. Moreover, the results demonstrated that impregnation of the material with an inorganic substance secures the material against loss of strength and stiffness when exposed to water and moisture. Guided by these experimental findings, the objectives that form the chapters of this thesis can be summarized as follows:

- *Chapter I* serves as an introduction to the theme and research framework of this thesis. It summarizes the existing research data from the previous attempts to use cardboard as a building material. It further seeks to investigate the background, interrelationships and basic technical comparisons between cardboard and contemporary building demands.

- *Chapter II* examines the societal aspects of cardboard construction within the framework of Switzerland's housing construction industry. In particular, it looks at the current perceptions of using cardboard as a building material in modern residences. This chapter also proposes to develop innovative ways to introduce cardboard construction into the housing market. It does so by analyzing user preferences and market trends in both the housing and construction industries. The end result is a workable solution to gradually introduce cardboard constructed houses as a feasible and flexible alternative for the changing needs of renters and buyers in the housing market.

- *Chapter III* provides an analysis of the environmental aspects underlying the development of corrugated cardboard as a building component. This chapter seeks to make an honest environment assessment using the lifecycle approach (LCA) as a model. The cradle-to-grave cost of corrugated cardboard is calculated by looking at the two main stages of the process: 1) the production stage, and 2) the construction-user stage. For the construction stage, the study evaluates the total environmental impact of manufacturing cardboard wall components. For the environmental cost of the construction phase, the energy costs of various cardboard wall components (constructed with different skin options and thicknesses), in terms of thermal U-value, are compared to the energy costs of other wall materials.

- *Chapter IV* focuses on the structural aspects of cardboard architecture, drawing on the testing and analyses of corrugated cardboard in a sandwich composite for wall components, conducted by the CATSE engineering team. This chapter provides the groundwork for the subsequent

chapter pertaining to the possibilities in the architectonic realm. It further looks at the structural and technical elements of cardboard housing in relation to user sector demands. In doing so, this section draws from and elaborates on prior chapters on the social and environments to set the framework for the architectonic approach.

- *Chapter V* examines the architectonic element underlying the use of cardboard as a wall component within its space-defining function. In this study, nine types of walls, each with varying characteristics, were defined for analysis. The geometric pattern of each wall was modified to control sunlight and its degree of acoustical insulation, as well as to adjust the indoor ambience and spatial qualities. The chapter further looks at other architectonic characteristics of cardboard buildings, including the potential use of cardboard in various other structural elements (i.e. floor slabs).

The concluding chapter describes the developmental criteria for the overall architectural contextualization of contemporary cardboard architecture. An understanding of the structural application potential of corrugated cardboard honeycomb composites as wall components is presented in many perspectives, reflecting its structural performance and environmental benefits within the existing societal context. Concurrently, spatial qualities seeking a distinctive architectural language are specifically suggested for further development in collaboration with the construction sector.

Based on these findings, this study holds that it is feasible to employ corrugated cardboard as the main structural component in contemporary housing. The use of cardboard as an alternative building material not only satisfies a building's structural demands, but also fulfills certain environmental and social demands that make it more potentially more attractive than standard building materials.

## Kurzfassung

Wellkarton gelangt immer öfter in einer Vielzahl von Anwendungen zum Einsatz: Das reicht von Druckerzeugnissen, Verpackungen über die Konstruktion von Türen und Möbeln bis hin zur Luftfahrtindustrie. Als Bauelement hat Wellkarton zahlreiche Vorteile. Karton ist ein sehr günstiges Material mit hervorragender Wärme- und Geräuschkämmung sowie einfacher Wiederverwertbarkeit. Zudem wird das Material aus nachwachsenden Rohstoffen hergestellt. Der entscheidende Grund für den Einsatz von Wellkarton als Baustoff ist jedoch seine hohe statische Belastbarkeit und Verwindungssteifigkeit.

Trotz allen diesen nachgewiesenen Vorteilen stagniert der Einsatz von Wellkarton als Baumaterial seit einigen Jahren, zumeist aufgrund von gewissen unerwünschten Eigenschaften. So ist das Material empfindlich gegenüber Feuchtigkeit, Feuer, Temperaturschwankungen, UV-Strahlen sowie diversen Chemikalien. Zurzeit laufen Untersuchungen mit dem Ziel, Lösungen für diese Probleme zu erarbeiten.

Damit Wellkarton als Baumaterial anerkannt wird, braucht es noch immer erhebliche Entwicklungen, um den Anforderungen des modernen Gebäudebaus zu entsprechen. In diesem Sinne definiert sich die grundlegende Frage dieser Studie wie folgt:

«Ist es möglich, ein Haus aus Wellkarton zu bauen?»

Ganz im Gegensatz zu vorhergehenden Versuchen in der Architektur mit Karton ist es das Ziel dieser Dissertation, das Potential von möglichen Anwendungsgebieten von Wellkarton innerhalb existierender sozio-ökologischer Zusammenhänge sowie dessen Verhältnis zu modernen Designrichtlinien zu untersuchen. Insbesondere werden die vielfältigen Möglichkeiten für Wandelemente im Verhältnis zum architektonischen Raum eingehend analysiert.

Von Beginn an wurde Wellkarton als mögliches Baumaterial in Betracht gezogen, aufgrund seiner tiefen Kosten, hohen Belastbarkeit und seiner hervorragenden Isolationsfähigkeiten. Zudem kann Karton gewisse Bauprozesse massiv effizienter machen. Denn Kartonblöcke lassen sich massgeschneidert vorfertigen und in hohen Stückzahlen produzieren, was eine rationalisierte Arbeitsweise auf der Baustelle zulässt und so Kosten spart.

Die vorliegende Dissertation stützt sich hauptsächlich auf die Ergebnisse des Forschungsprojekts der ETH Zürich «Cardboard in Architectural Technology and Structural Engineering» (CATSE). Nach Tests an verschiedenen Prototypen konnte das Team von Ingenieuren beweisen, dass Wellkarton über hervorragende statische Eigenschaften und Stabilität verfügt.

Die Erkenntnisse des Forschungsteams zeigen, dass sich vorgefertigte Sandwich-Elemente mit Kern aus Wellkarton besonders gut für die Verwendung als Wände eignen. Sowohl als Innen- wie auch als Aussenwandkomponente zeigt Karton vielversprechendes physikalisches und mechanisches Verhalten. In weiteren Untersuchungen wurde deutlich, dass Kartonwände über Wärme regulierende Eigenschaften verfügen, die ein Einsparungspotential für Energieverbrauch und Kosten darstellen.

Darüber hinaus hat sich erwiesen, dass die Imprägnierung des Materials mit einer anorganischen Lösung die Bauteile unempfindlich gegen Feuchtigkeit macht und somit den Verlust von Tragfähigkeit und Steifigkeit verhindert. Zudem verleiht die Imprägnierung dem Karton feuerfeste Eigenschaften.

Basierend auf die Forschungsergebnisse der CATSE kommt diese Studie zum Schluss, dass der Einsatz von Wellkarton als tragendes Bauelement im modernen Hausbau absolut geeignet ist. Die Verwendung von Karton als alternatives Baumaterial erfüllt nicht nur die bautechnischen Anforderungen, sondern auch die gesellschaftlichen und ökologischen Kriterien, was Karton viel attraktiver als Standard-Baumaterialien macht.

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## Chapter VI

### Conclusion: Outcomes and Future Studies

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# Chapter I

## Introduction

"The modern genius is something else again: if we asked a typical modern man to build us a room with a 20 meter opening out of cardboard ...we can fairly be sure that he would ultimately construct the desired room."

Viollet-le-duc, *Entretiens sur l'architecture*

Paper and cardboard, in various forms, have been extensively utilized in a variety of modern day applications, ranging from the packaging and food industries to cable production, aviation, and indoor elements, such as doors and furniture.<sup>1</sup> The main advantages of paper and its byproducts are its relatively low cost, high degree of recyclability, and low environmental impact. In structural terms, paper and cardboard have been shown to have considerable strength, stability and stiffness in comparison with other common building materials.<sup>2</sup> On the other hand, limitations such as its vulnerability to humidity, fire, chemicals, ultra-violet light, and temperature changes are currently being explored by researchers in the paper technology industry.

Despite its proven structural potential, as well as the high degree of flexibility it offers in construction, demolition and disposal, the few existing applications in which cardboard has performed a significant role in building construction have not been developed or thoroughly pursued beyond the prototype level. Moreover, these prior applications were mostly ephemeral in nature and failed to fully utilize cardboard's noted benefits pertaining to *building physics*. A comprehensive overview of prior cardboard applications to date, focusing on their structural and physical shortcomings, is a necessary first step to be able to further explore the promising potential of *cardboard in architecture*.

### **Architectural Background: Cardboard Buildings**

An analysis of former applications of cardboard in architecture must begin with the first attempts during the second world war. The first known building constructed principally out of cardboard

<sup>1</sup> i.e. *Wiggle Chair*, by Frank Lloyd Wright (1972).

<sup>2</sup> V. Sedlak, "Paper Structures," *Proc. 2<sup>nd</sup> International Conference on Space Structures*, University of Surrey (1975) 780-793.



was *The 1944 House*,<sup>1</sup> constructed in the same year, which was followed by a period of slow development in the field. Lack of research and development into cardboard's shortcomings, including its vulnerability to water, fire and other elements, and limited manufacturing and assembly opportunities, were the primary reasons underlying the technology's sluggish development. Following these early trials, several architects, including Buckminster Fuller in the 1950's, and most recently, Japanese architect Shigeru Ban, have steadily influenced the progress of cardboard's use in architecture.

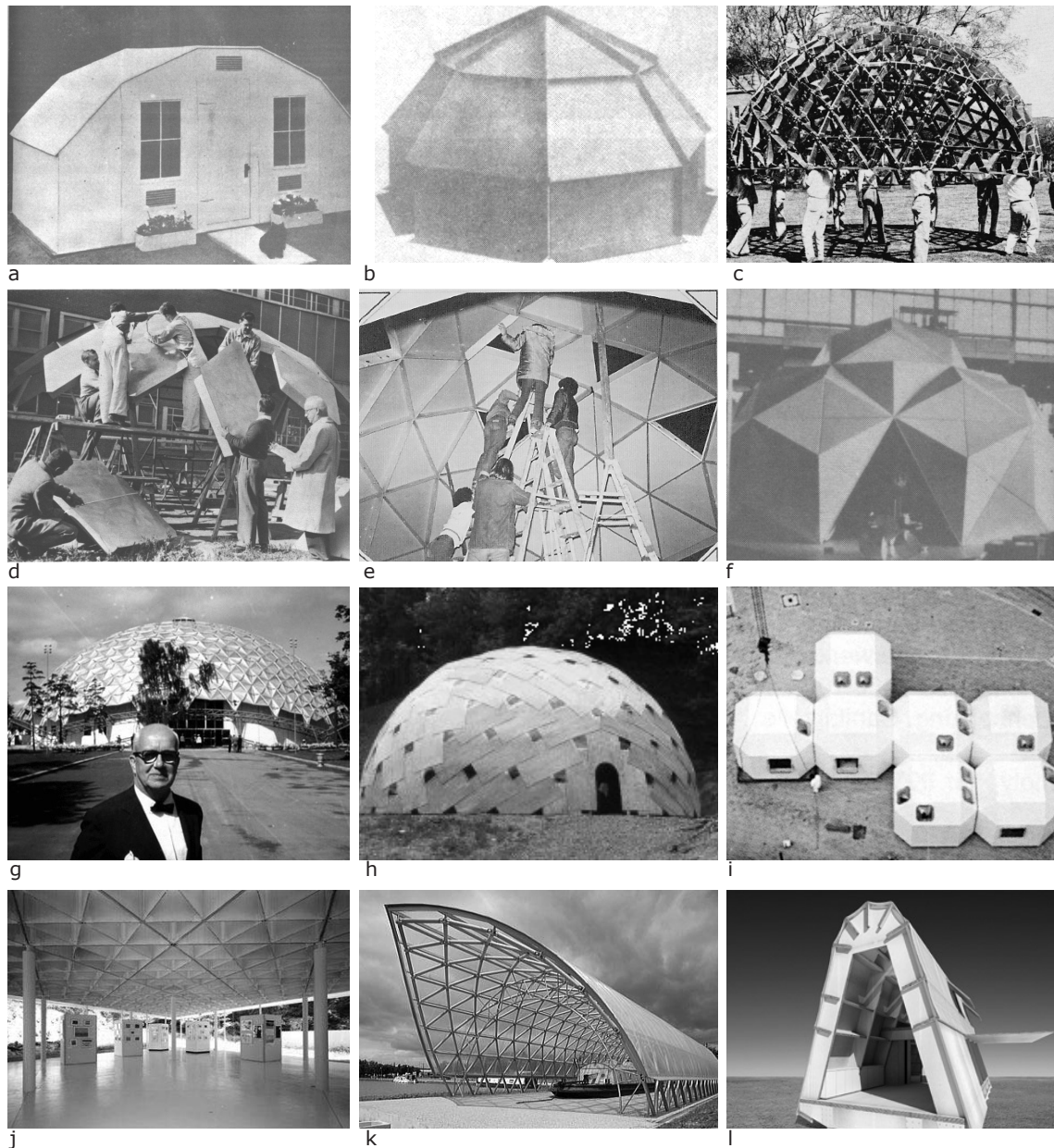


Figure 1.1 - Examples of cardboard buildings.<sup>2</sup>

<sup>1</sup> "Paper House Review," *Architectural Design* (Oct. 1970): 499-505 (The house, known as *1944 House*, was constructed with 1-inch thick corrugated chipboard produced from waste paper. Fifty percent sulphur was added to the content to make the board more rigid. Several layers of fire-proof paints were also applied.

<sup>2</sup> (a) *1944 House*; (b) *Emergency Shelter*, by Container Corporation of America (1954); (c) Paperboard, geodesic dome, coated with polyester resin, by Buckminster Fuller (Tulane University, 1954); (d) *Paper Dome* (McGill University, 1957); (e) *Charas Project*, assisted by Michael Ben Eli (New York City, 1970) (f) *Dome Stéréométrique*, by



Among these pioneers, Fuller, with his innovative vision and experimental application of cardboard components in architecture, has been highly influential in providing the framework for this field of study. He was the first designer who seriously contemplated and worked with cardboard as a building material. His approach was based on a philosophy that combined *environmentally sustainable* building concepts with *economically sustainable* financial terms. He further sought to develop strategies aimed at resolving global problems, drawing on his *more-with-less* philosophy<sup>1</sup>. Pursuant to his acclaimed *Dymaxion*<sup>2</sup> approach, Fuller experimented with several cardboard building projects, utilizing resources and designs that minimized material usage and maximized efficiency. Architects and engineers of the time employed and drew off of Fuller's developments, inspired by his innovative use of cellulose cardboard applications on the construction site, and conducted further theoretical research into his underlying philosophy. Fuller's proposal to the International Union of Architects, "Inventory of World Resources Human Trends and Needs,"<sup>3</sup> in collaboration with John McHale,<sup>4</sup> is one such example.

Fuller's philosophical approach to architecture, as well as his focus on ecologically sustainable building materials and renewable energy sources, combined with his eagerness to challenge traditional building methods, provides the inspiration and contextual foundation for this study.

In the decade following Fuller's groundbreaking work, a small number of architects and engineers continued to experiment with cardboard as a building material. The developmental history of cardboard building projects can be divided into three general periods:

1. The birth of cardboard building prototypes from 1944 through the early 1990's
2. The emergence of Shigeru Ban
3. The development of contemporary prototypes and approaches during the last decade

Research and development into cardboard buildings from the beginning of the 1950's largely failed to generate applications that successfully moved past the prototype stage of development. In these projects, cardboard was used structurally either as the primary element or secondary supporting element and was utilized because of its low cost, ability to be mass manufactured, and its minimal environmental impact. The main challenge faced by architects and engineers during this period was their attempt to maintain the structural strength and stiffness of cardboard when it was confronted with external weather conditions, humidity and fire. As an answer, geodesic domes and other polyhedral macro forms of cardboard were developed and tested,

D.G.Emmerich & Jungmann (Exposition of Wegwerf -Architecture, Paris, 1970); (g) Photograph of Buckminster Fuller in front of geodesic dome constructed as the U.S. pavilion at the American Exchange Exhibit, Moscow (1959); (h) *The New Generation Plydome*, by S. Miller (1994); (i) *Casa-Nova Project*, by 3 H Architects (Olympic Games Munich, 1972); (j) *Nemunoki Children's Art Museum*, by Shiegeru Ban (Shizuoka, 1999); (k) *Centre d'interpretation du Canal Bourgogne*, by Shigeru Ban (Pouilly-en-Auxois, 2005); (l) *The Cardboard House*, by Architects Stutchburry & Pape (Sydney, 2004).

<sup>1</sup> "Libraries Acquire Buckminster Fuller Archive" (Stanford Report, 28 July 1999).

<sup>2</sup> R. Buckminster Fuller and R.W. Marks, *The Dymaxion World of Buckminster Fuller* (New York: Doubleday, 1973) ("Dymaxion" is a word created by Buckminster Fuller, which is a combination of the words dynamic, maximum and Tension, that he describes as meaning "doing more with less," based on the principle that the whole is greater than the sum of the parts).

<sup>3</sup> John McHale, *World Facts and Trends* (New York: MacMillan, 1972) 216 (this study is a proposal of population, renewable resources, poverty, and other environmental factors).

<sup>4</sup> John Baldwin, *Bucky Works: Buckminster Fuller's Ideas for Today* (John Wiley & Sons, 1996) 126-127.

and were soon determined to be the most efficient solution to this dilemma. The most common method used for weatherproofing and sealing these early cardboard building prototypes was the application of substances such as boiled linseed oil, copal varnish, polyurethane paints, resin-based paints, fiberglass and concrete on the outer surface of the structure.<sup>1</sup> Due to the geodesic design of these early applications, construction of opening elements (doors or windows) presented designers with additional issues regarding the effective sealing of joints caused by the various openings. Despite these efforts, the majority of the early prototypes failed testing beyond short-term, small-scale applications.<sup>2</sup> The implementation process into the mass development of cardboard as a commercially-feasible and socially-accepted building element proved to be in need of further development and testing.

Cardboard's progress as a feasible building material was further slowed by the introduction of other new alternative building materials. By the late 1950's, plastic and Formica, a plastic laminate, had developed into popular substitute building materials. By the 1970's, another substitute, polycarbonate, was introduced as an even lower cost, yet durable and waterproof alternative.

After a period of relative disinterest and slow development of cardboard as a building material, in the mid 1990's, Japanese architect Shigeru Ban re-energized the field with his use of paper tubes as a eligible structural element in architectural design. Today, after nearly twenty years of long-term testing, Ban's projects have demonstrated the potential that paper tubes hold as a viable building material. Aspects of his projects, including their relatively low cost, high recyclability, and low environmental impact, as well as their structural strength and stiffness, are the principal reasons underlying his projects' success. Several of his projects have been fully accredited by local and state official authorities worldwide.

Fuller and Ban left a distinct mark on the architectural scene not only with their experimentalism as a designer but also with their will in pursuing cardboard prototypes into full-scale products in the market. Following Ban's work with cardboard and paper tubes, in the last decade, a notable increase in experimental applications of cardboard in architecture has been observed. The late attempts can be differentiated by their usage function (structurally employing cardboard as a either the primary or a secondary supporting element), expected life-spans, form, and geometry.

To date, the most significant example of a modern cardboard application is the *Westborough Primary School* in Westcliff-on-Sea, England, designed by architects Cotterel & Vermeulen in 2001. *The Westborough School* progressed beyond the prototype level, and is foreseen to have an extended lifespan. Another such attempt was *The Cardboard House*, designed by architects

<sup>1</sup> Based on the experience of wood construction weather-proofing solutions.

<sup>2</sup> Paperboard Shelter, Prototype by A. Quarmby (1950s) ; Hexagon and Octagon houses by Keith Critchlow (1960s), Farnham & Guildford Domes (1969); Papp-eder by 3h-Design Buro (1968); "Migrant Worker Shelter" by Sanford Hirshen / Sim Van der Ryn (USA, 1966); Veterinary Research Center House by Architect John Grimshaw, (Uganda, 1970); Fibreglassed 2-Layer Cardboard Dome by Richard & Robin (England, 1972).

Stutchbury & Pape in 2004, in association with the Ian Buchan Fell Housing Research Unit at University of Sydney. Also in 2004, Adriano Pupilli of the University of Sydney, in cooperation with the firm Armacel, constructed a cardboard structure using a composite material.

In recent years, cardboard building research has also found an increased interest in academia. Institutes such as ETH-Zurich, The Architectural Association in the United Kingdom, and TU Delft in the Netherlands (Faculty of Architecture, Building Technology and the chair of Design Constructions) have been conducting experimental and theoretical research into cardboard as a feasible building material.

Contemporary research has focused on several aspects of cardboard applications, ranging from architectural theory to practice. The technical research has focused on both massive and filigree-constructed cardboard building components. These components have been tested in the form of massive *blocks*, and in smaller sizes, such as cardboard *bricks*. Additionally, hybrid combinations with other materials such as air pressure-integrated element experiments in deflated (vacuumed) cardboard facade constructions have also recently piqued the interest of the research community.

### **Comprehensive Look at Cardboard Buildings**

The successful implementation and validation of cardboard building is dependent on the integration of three interconnected areas: *technical* (structural strength and stiffness pertaining to waterproof-fireproof matters), *economical* (manufacturing practicalities, low cost/high profit matters), and *societal* (issues regarding acceptance of paper as a building element, and a potential bias against a new building material and its perceived limitations). These three areas will serve as the foundational framework for this study.

So what does this research project offer? A comprehensive examination of the literature pertaining to the cardboard-paper building field reveals that certain critical aspects have yet to be thoroughly investigated and analyzed. Thus, this research project, entitled Cardboard in Architectural Technology and Structural Engineering (CATSE), aims to differentiate itself from prior studies, and will concentrate on the following areas of cardboard construction and its practical applications: 1) life-span, 2) target group and 3) material usage.

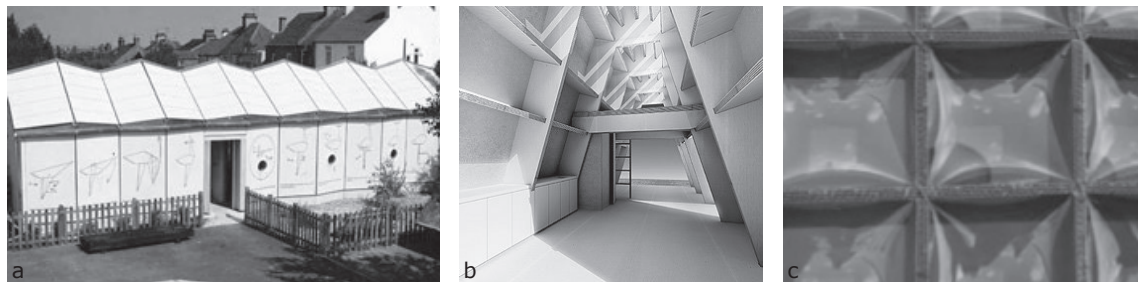


Figure 1.2 - Cardboard building study examples<sup>1</sup>

<sup>1</sup> (a) *Westborough Primary School* (United Kingdom); (b) *The Cardboard House*, by Stutchbury & Pape; (c) *Cardboard House Project*, by Adriano Pupilli; (d) *Deflated Facades* (TU Delft).

- *Lifespan*: Virtually all cardboard building projects to date have failed to progress beyond a single prototype, or were erected only for short term, exhibitional purposes. In contrast, this study will explore a model for constructing cardboard buildings for residential use, with an expected life span of 5-10 years.

- *Target Group*: The vast majority of completed cardboard projects to date were planned to be utilized only by people in emergency conditions or for short-term usage in public spaces. In contrast, this research project will focus on appealing to a broader user target group for use as residential housing in the middle income range.

- *Innovative Material Research and Development*: Differing from earlier attempts, the starting point for this research study is the implementation of *honeycomb-core corrugated cardboard* as the main structural element in construction. Additionally, only ecologically and economically sustainable exterior skin materials will be used to ensure the requisite building strength and stiffness, and to satisfy contemporary building physics demands (i.e. thermal and acoustic insulation).

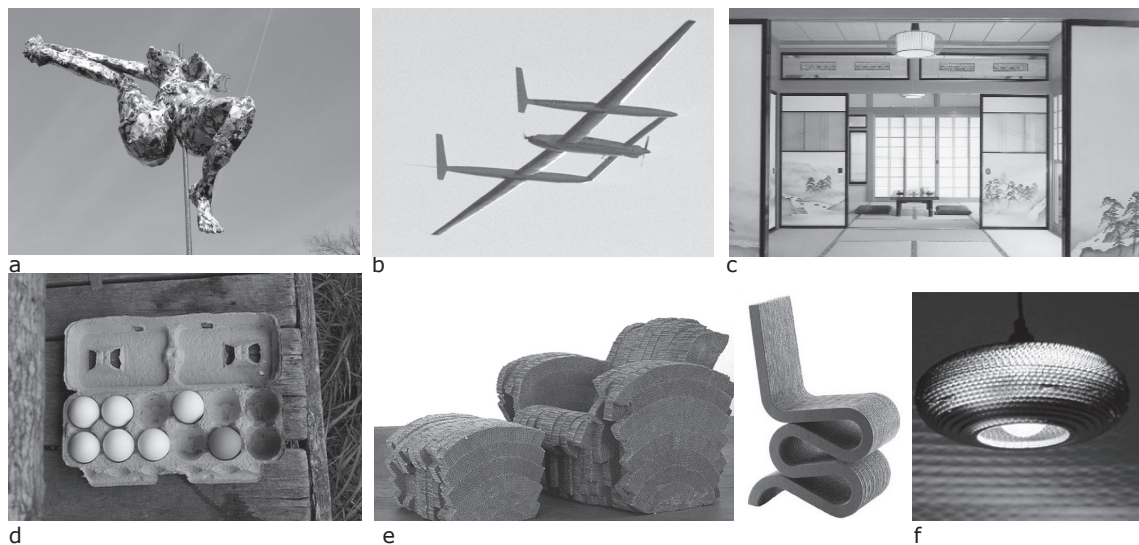


Figure 1.3 - Paper byproducts in art, aviation, dwellings and food packaging <sup>1</sup>

<sup>1</sup> (a) *Papier Mâché Skulpture*, by Claudia Bürgler; (b) *Voyager Aircraft*; (c) Japanese shoji sliding doors (d) egg cartons; (e) Frank O. Gehry's *Wiggle Chair Collection* (1969); (f) *Cardboard Scraplights*, by Graypants.

## **Technical Material Background: Paper and Corrugated Cardboard**

### **1.1 History of Paper and Cardboard's Usage: A Brief Timeline**

Ancient Egyptian and Chinese cultures were the first to utilize paper as a building material in the form of papier mâché. By the 2nd century B.C.E., they had developed papyrus.<sup>1</sup> And by the 9th century A.D., the Japanese were using a paper element in the construction of sliding doors and walls, called *shoji-fusuma*, marking the first time paper was utilized as an interior building component. The concept of using paper for purposes other than writing dates back even further, to the ancient Egyptians, who used layers of paper and adhesive to case mummies. Such non-traditional uses were revived in nineteenth century France, where paper products were used in furniture production, and later as wall covering, marking the first time in history paper served a decorative function. In 1856, corrugated paper was first used by two British entrepreneurs for hat production. The same entrepreneurs later obtained a patent for a similar technology for use in the packaging of fragile items. These new uses eventually led to the introduction of the first continuous corrugation machine in 1895. By World War I, paper products were being used in the production of aircraft and tank components. Using a plaster-made mold for shaping, cellulose reinforced sheets of paper, combined with starch or similar adhesives, it served as a substitute for aluminum sheeting on aircraft wings, after aluminum was discovered to have problems with expansion and shrinking. In the United States, paper and cardboard also began being used as electrical insulation in the 1920's. With the introduction of cellulose fiber laminates into the industry, impregnation experiments began in the 1920's using a solution of phenolic-resin, hydraulic ally pressed under 15MN/m<sup>2</sup>.<sup>2</sup> Following the war, the development of melamine resins led to the increased popularity of paper and cardboard as a building material during the ensuing kitchen revolution of the post-war period.

Today, research into the pulp, paper and corrugated cardboard fields has evolved extensively, and is now represented by worldwide trade associations such as the European Federation of Corrugated Cardboard Manufacturers (FEFCO). Additionally, basic materials research and development into pulp and paper products is being pursued at several academic institutions, some of which now devote entire departments to the field, such as Georgia Institute of Technology's (USA) Institute of Paper Science and Technology and Helsinki University of Technology's Department of Forest Products Technology, Paper and Pulping Technology.

### **1.2 Characteristics of Corrugated Cardboard**

Paper with a density greater than 200 g/cm<sup>3</sup> is generally accepted as cardboard (also referred to as "carton"). *Corrugated* cardboard is a stiff, strong, and light-weight material made up of three liner layers of brown *kraft* paper, a type of paper which is resistant to tearing, splitting and bursting, and is produced by using the kraft process of pulping wood chips. Composed of ply liners and a corrugating flute layer, corrugated cardboard is produced in a variety of Flute sizes (Type A to G/N, thicknesses ranging from 4.8 mm to 0.8 mm). Ply weights between

<sup>1</sup> Therese Weber, *The Language of Paper: A History of 2000 Years* (Bangkok: Orchid Press, 2008).

<sup>2</sup> James Edward Gordon, *The New Science of Strong Materials or Why You Don't Fall Through the Floor* (Princeton: Princeton University Press, 1984) 178-181.

115g/m<sup>2</sup> and 350g/m<sup>2</sup> while corrugating flute weights around 112-180g/m<sup>2</sup>.<sup>1</sup> Today, the vast majority of corrugated cardboard is used by the packaging industry, but it is also used for advertising board, various furniture applications, and the interior core of doors.

Corrugated cardboard can be classified by several different defining characteristics, including: construction (single face, singlewall, doublewall, etc), flute size, burst strength, edge crush strength, flat crush strength, basis weights of its components, surface treatments, impregnation, printing and coatings. In the initial stages of the corrugation process during the production of the paper pulp, paper ply, and flute, cardboard's mechanical and physical properties can be altered and adjusted. The amount and type of additives in the pulp, as well as the type of fibers (primary cellulosic fibers, recycled fibers and other non-cellulose based fibers) are the most important factors during the production of paper. Additional specifications can be adjusted during the coating, forming (combining ply, flutes and layers) and impregnation stages of manufacturing corrugated cardboard, i.e. to reduce water content or enhance optical properties (coloring).

*Mechanical Behavior:* Due to the characteristics of cellulose fibers and the bonds between them, paper has high tension strength, outperforming the strength of its compressive strength in both cross machine direction (CD) and machine direction(MD).<sup>2</sup> As a byproduct of paper, corrugated cardboard is constructed as a sandwich structure that maximizes the bending stiffness of the board.<sup>3</sup>

*Moisture Resistance:* One major limitation of cardboard is that it becomes extremely weak when confronted with humidity or direct water, causing dimensional changes (swelling), distortion and reduced strength (tearing). Several specialized chemicals are widely used in the pulp production process by the packaging industry to strengthen its moisture resistance and durability.<sup>4</sup> Externally, impregnation and coating are also used for moisture protection, as well as for protection against other chemical dangers, such as acids which can damage the cellulose in paper.

*Acoustic Insulation Properties:* Due to its low mass, acoustical qualities are not measurable for a single sheet of paper. However, extensive layering of corrugated cardboard (especially when combined with air vacuum systems) has been shown to provide significant acoustical insulation.<sup>5</sup>

*Thermal Insulation Properties:* Cellulose fibers, the primary material used in cardboard production, are commonly used because of their low thermal conductivity in diverse industries (i.e. automotive, aviation), and are known to have strong insulative properties.

<sup>1</sup> Hannu Paulapuro, ed., *Paper and Board Grades* (Helsinki: Fapet Oy, 2000).

<sup>2</sup> The tensile strength of paper in MD is greater than CD.

<sup>3</sup> Paulapuro.

<sup>4</sup> Phenolic impregnation is commonly used in the packaging industry, i.e. Honicel ([www.honicel.com](http://www.honicel.com)).

<sup>5</sup> The Swiss firm, *The Wall AG* has started to produce building components using air vacuum systems (2009).



**Fire Resistance:** Untreated plain paper has no fire resistant qualities. However, paper boards containing heavy stocks of paper pulp exhibit some fire resistant characteristics, similar to untreated timber. Untreated corrugated cardboard, in contrast, is highly combustible with a tendency to spontaneous combust, seriously jeopardizing the safety of cardboard buildings.

**Biological Attacks:** As with other wood and byproducts, paper and cardboard are sensitive to attacks by rodents, fungi and other bacterial development under certain conditions.

**Toxicity:** Despite the fact that cellulose fiber is derived from a natural resource, under certain conditions recycled paper byproducts can exhibit toxicity as a result of chemicals, bleaching agents, adhesives and inks used during production process.<sup>1</sup>

**Odor:** Paper and cardboard do not release any odors but remain sensitive to foreign odors.

**Testing:** Corrugated cardboard is produced in compliance with international standardized methods. These standards have been approved by institutions such as FEFCO and the International Organization for Standardization (ISO). The mechanical and physical testing of corrugated cardboard is focused primarily on solutions for packaging industry.

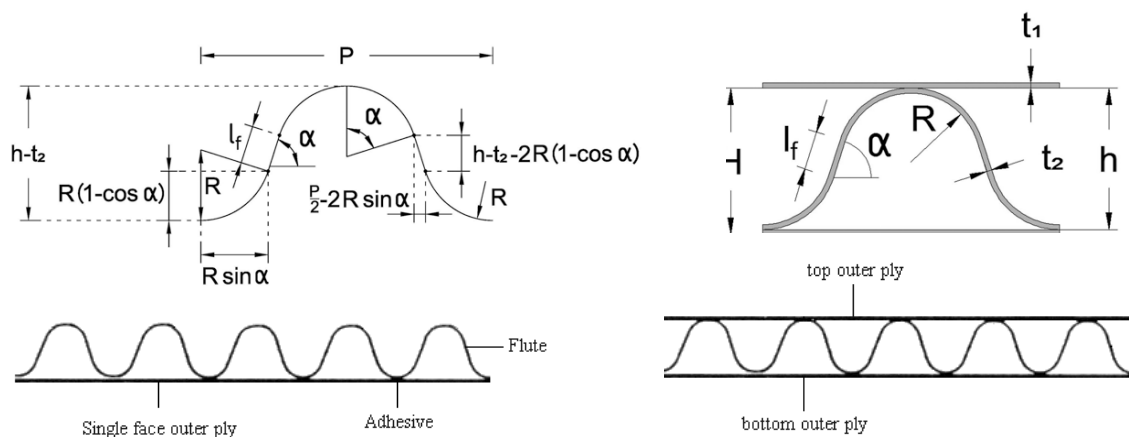


Figure 1.4 - Basics of corrugated cardboard<sup>2</sup>

### Production of Honeycomb Corrugated Cardboard

a) **Production by expansion:** Paper roll is cut and the sheets are then slid-cut and placed on top of each other with a specific geometric layering of adhesives. Then the unexpanded block is sliced into the thickness required. Followed by the expansion of the piece, a honeycomb shaped structure is maintained between the paper layerings. (Figure 1.5) Additional skin on both sides can be applied to form a honeycomb sandwich structure.

<sup>1</sup> Ozaki Asako, "Paper and Cardboard Food Packaging," *Journal of Urban Living and Health Association* 49, no. 3 (2005): 135-143.

<sup>2</sup> (a) Corrugated cardboard geometric basics, by Almut Pohl; (b) corrugated cardboard flute types.

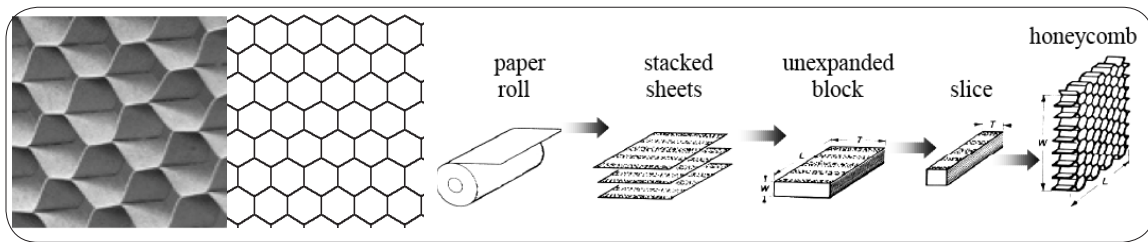


Figure 1.5 - Traditional honeycomb cardboard production by expansion <sup>1</sup>

b) *Production by conventional corrugation machine:* Conventional corrugated cardboard manufacture has two main stages, producing the pulp and the corrugated cardboard. Kraft paper composed of pulped wood chips is converted into corrugated cardboard by first feeding the pulp through massive steam rollers that remove the water and then using the corrugating heavy rollers in the corrugating machine. One roll of cardboard is corrugated and then glued between two other layers (liners) by the same machine. (Figure 1.6) The glue is then cured by passing the cardboard over heated rolls.<sup>2</sup>

Today, corrugated cardboard applications are extensively limited by existing corrugation production machine dimensions. Presently, the maximum production width for corrugated cardboard is approximately 1.20 meters (perpendicular to corrugation direction). A new generation of corrugated cardboard manufacturing machines, which allow a machine corrugation width of 2.40m/3.25 m to panel length of 5.00/6.20 m are being tested in Germany.<sup>3</sup>

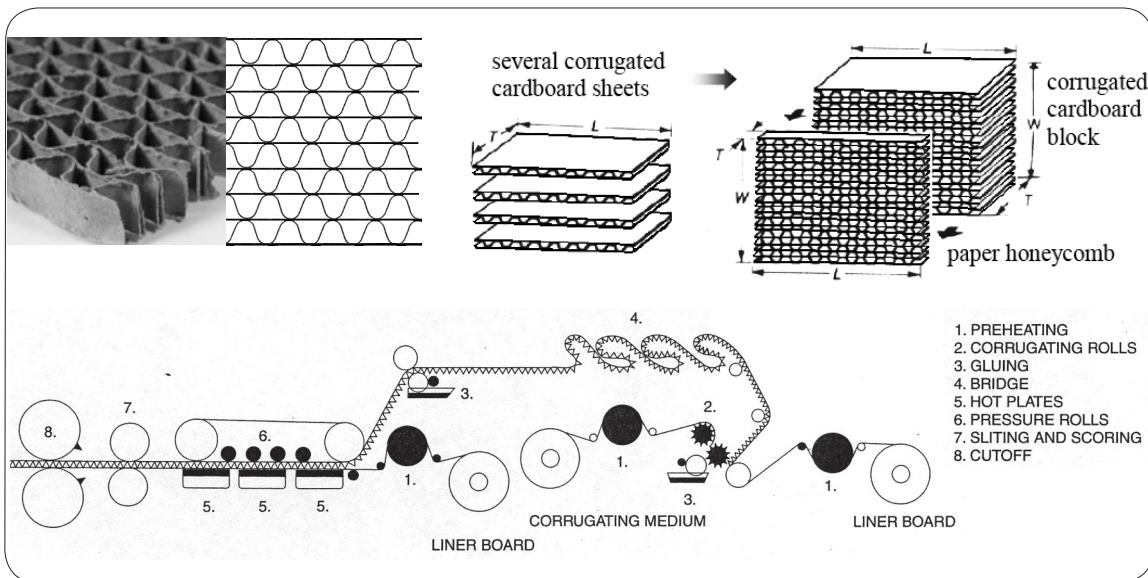


Figure 1.6 - Corrugated cardboard production by conventional corrugation machine <sup>4</sup>

<sup>1</sup> Source: WF Wabenfabrik GMBH (<www.wabenfabrik.de>).

<sup>2</sup> James E. Kline, *Paper And Paperboard: Manufacturing and Converting Fundamentals, 2nd Ed.* (San Francisco: Backbeat Books, 1991).

<sup>3</sup> Firma Spatenstich, Prowell GmbH, based in Germany is capable of producing these dimensions.

<sup>4</sup> Source: Paulapuro 65.



c) *Production by modern fast and continuous systems:* The dimensions, time and cost of conventional corrugated cardboard production has limited the growth of honeycomb corrugated cardboard. Some of the limitations of traditional honeycomb cardboard production have been addressed by recent developments in the field, such as TorHex core and its manufacturing process. Unlike standard methods of production which needs different machines for cutting and corrugating the honeycomb board, the TorHex process generates a lengthwise slitting of the corrugated cardboard and in-line rotation of the strips for fast and efficient production. (Figure 1.7) Similar innovative honeycomb production systems may allow more frequent and efficient usage of honeycomb corrugated cardboard by producing fast and low-cost solutions.

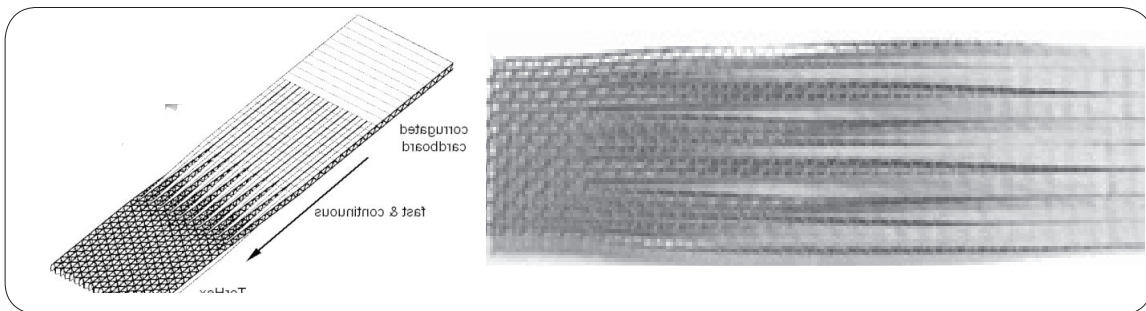


Figure 1.7 - TorHex: an innovative contemporary honeycomb production method <sup>1</sup>

## 2. The Purpose of the Research Study

The research project is undertaken with the goal of investigating the feasibility of using corrugated cardboard, a low cost and environmentally sustainable building material, as the primary structural supporting element in building construction. More specifically, this study will observe the architectural, engineering and strategical feasibility<sup>2</sup> of a two-story cardboard building. The project is based on the hypothesis that the use of solid corrugated cardboard blocks (layers of corrugated cardboard stacked to each other) as the primary structural element in construction of low-rise buildings is a viable low-cost, low-impact alternative to traditional building materials. The study will address and answer some of the problems currently faced in contemporary housing construction, including ecological and economical sustainability issues. Flexibility in architectonic expression will also to be investigated in this study despite the mass production of building components. To cover the various interdisciplinary contexts, this study is positioned as a direct outgrowth of a larger collaborative research project between the departments of architecture and civil engineering at ETH Zurich.

## 3. Organization and Methodology

The objective of this research study is centered around three basic conceptual themes: societal, environmental and constructive. Below, each theme is thoroughly examined as an individual chapter, and then the findings are combined and further elaborated in the concluding chapter.

<sup>1</sup> Torhex is produced by Economic Core Technologies, based in Belgium, which focuses on economic honeycomb cores for lightweight, cost optimal and high quality sandwich panels and parts.

<sup>2</sup> Strategical feasibility by means of an introductory approach for integration of cardboard buildings into Swiss market.

In a broader sense, the research is the culmination of an investigation of the *societal approach* (analysis of the non-technical user and investor-related realms of this study), an investigation of the *environmental approach* (lifecycle approach for cardboard buildings, and a comprehensive overview of all aspects of the production and energy consumption-usage stages for a basic unit wall component) and an investigation of the *technical-constructive approach* (potential benefits and possible directions of the cardboard building market).

For the societal approach, the primary method of investigation was a personal questionnaire, which was broadly distributed to evaluate several of the acceptance issues related to cardboard buildings. The results from the questionnaire, analyzed through the lens of the existing literature provide the framework for positioning the feasibility of cardboard housing in Switzerland.

For the environmental approach, a specialized environmental engineering software (LifeCycle Assessment or LCA), *SimaPro 7*, was used to assess and evaluate of the estimated environmental load of corrugated cardboard in the production and usage stage. For analysis of the usage stage, the environmental load was calculated using the project's U-value and the current Minergie standards.

For the *architectonic-constructive approach*, testing and analyses of corrugated cardboard in a sandwich composite was conducted by the CATSE engineering team is used as a baseline to look at the construction aspects of cardboard architecture in relation to user sector demands. In doing so, the approach draws from and elaborates on prior approaches on the social and environments to set its framework while examining the architectonic element underlying the use of cardboard as a wall component within its space-defining function.

#### **4. Motivational Outline: Why Cardboard Architecture?**

In a kinetically paradoxical relationship, architecture forms lives, as lives form architecture. Whether "capital-a Architecture"<sup>1</sup> or "small-a architecture,"<sup>2</sup> (the anonymous architecture), it articulates the instinct of shelter by defining the space. By doing so, architecture undertakes the role of being the very social instrument that represents changes in living. Architecture in association with the changes in lifestyles and basic household structures (due to changes of socio-political roles, urban living, etc.), along with the developments in construction techniques and materials, underscores this role.

In the current era of convenience and constant change, the needs and trends of today stand for paced consumerism - fast food, fast living, fast communicating, fast traveling.<sup>3</sup> But is a dwelling, a product of architecture, able to answer the ever-changing demands of modern life? Are the socio-anthropological terms of "owning" a dwelling and passing it down to future generations as an asset still an realistic concept? What can cardboard buildings offer to fit into today's changing lifestyle needs? How will the transformation from the mechanical age of speed

<sup>1</sup> From architectural theory.

<sup>2</sup> Sibyl Moholy-Nagy, *Native Genius in Anonymous Architecture* (New York: Horizon Press, 1957).

<sup>3</sup> Michael R. Solomon, Gary Bamossy, Soren Askegaard and Margaret K. Hogg, *Consumer Behaviour: A European Perspective* (Essex: Prentice Hall Europe, 2006).

to the digital age of real-time materialize in the field of architecture?<sup>1</sup> With these questions in mind, the motivational outline identifying cardboard housing as a feasible alternative for the future is discussed below.

### 1) Sustainability as a Contemporary Leading Theme

Today, the architectural scene is increasingly confronted with environmental responsibility issues in construction. These issues, however, have mainly been excused or downplayed by oft-cited financial imperatives and a lack of serious research and development into the economic feasibility of new building materials. Moreover, the resources (both financial and material) used in the construction process are claimed to be largely responsible for many of the negative environmental and economical effects, which may jeopardize the well-being of future generations. The CATSE cardboard housing project begins by addressing this dichotomy and does so by confronting one of the most highly debated issues of the day: the sustainability of a building. The very nature of cardboard as a building element (low-cost, highly recyclable and renewable), provides an excellent starting point for addressing some of these difficult issues that architects, engineers and investors are struggling to understand.

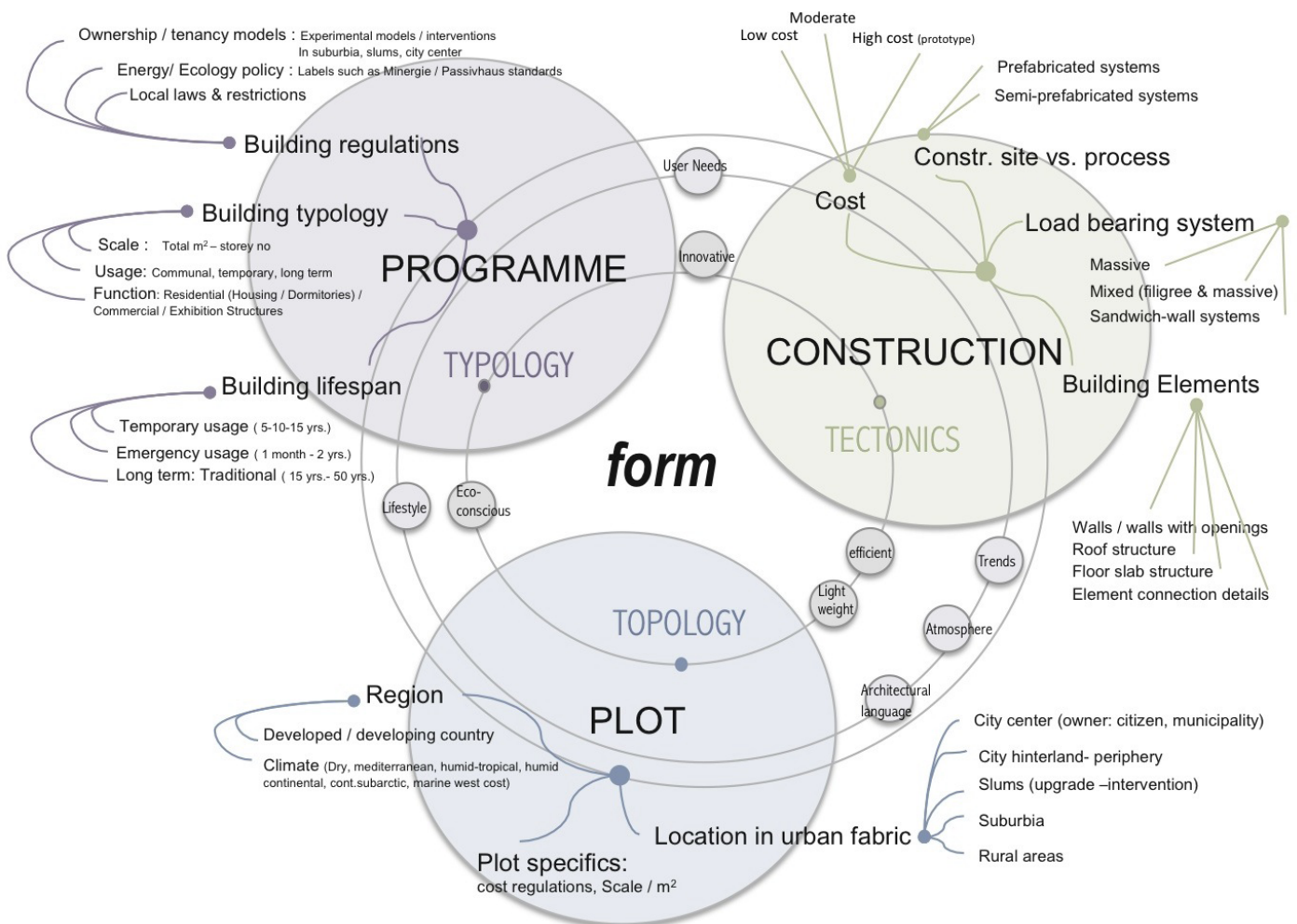


Figure 1.8 - Focal points for cardboard buildings research

<sup>1</sup> Based on quote by Ivan Illich: "We might already be beyond the age of speed, by moving into the age of real-time. The move towards real time is the one way out of the world speed". (Source: *Conference Proc. Doors of Perception IV*, Amsterdam, 1996).

2) Cardboard Manufacturing as an Established Industry

Currently, cardboard is used for seventy percent of the world’s packaging needs, and has evolved into a billion-dollar worldwide industry. The cardboard manufacturing industry in Switzerland and neighboring countries produces carton and carton byproducts mainly for packaging, with a significant number of firms that maintain active research and development departments, some of which are partially supported by academic research studies. The current positioning of cardboard manufacturing industry therefore creates a solid foundation for innovative research into the design and eventual implementation of CATSE Cardboard Housing.

One notable drawback of the existing R&D framework is the industry’s lack of a wide-horized and interdisciplinary study into new uses for its existing products. This study proposes taking the existing research and development framework one step further to provide the industry with the capability to produce cardboard building elements for use in full-scale buildings. To date, cardboard has seldom been used for structural purposes in buildings despite its proven structural integrity and strong insulative properties. This study aims to set a valid starting point for new innovations in the field of building construction; encouraging collaboration between the cardboard industry and academia. It is intended to serve as a guide and impetus to local entities, namely carton manufacturing firms and trade associations, towards expanding the palette of their production capabilities, and creating demand and a new market for cardboard housing.

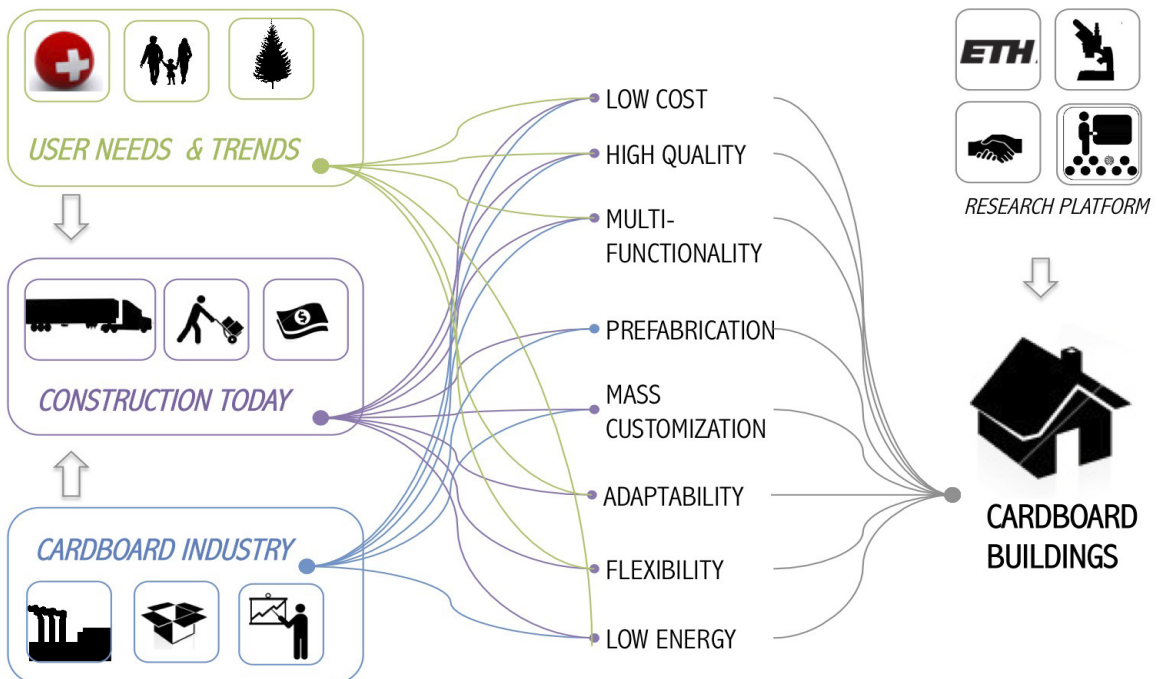


Figure 1.9 - Outline of focal points for cardboard buildings research

### *3) Corrugated Cardboard As a Unique Answer to Today's Demands*

This study is certainly not the first occasion in which the inherent advantages of cardboard have been explored.<sup>1</sup> However, prior studies and projects suggesting cardboard as a viable building material have mainly been geared towards short-term solutions, such as proposing its use in emergency situations (i.e. disasters), or in the context of extremely low-cost housing solutions in developing countries in association with humanitarian aid organizations. This study, in contrast, sets forth to emphasize the technical and psychological complexity of cardboard dwellings, with the goal of establishing the financial and environmental feasibility of cardboard as an alternative building material. Additionally, this study will offer a technical investigation into cardboard as a structural building component, as well as a thorough look at the method and organization of the project's collaborative interdisciplinary research platform. These two aspects can be briefly described as follows:

#### *a) Technical Benefits of Corrugated Cardboard in Construction*

- Efficiencies gained from the multi-functional characteristics of corrugated cardboard: corrugated cardboard building components provide thermal and acoustical insulation, structural strength, and ease of recyclability-dismantling.
- Efficiencies gained in construction site organization: Prefabricated cardboard-based building elements allow for quick, simple, inexpensive manufacturing, and also minimize time spent on the construction site.
- Efficiencies gained by decreasing the number of building materials: Traditionally in construction, the exterior of the building's skin is separated into multiple mono-functional layers, resulting in needless complication and associated costs. Cardboard, in contrast, can alone satisfy all the functions of a building's exterior skin, thereby eliminating the costs of multi-layering.

#### *b) Benefits Resulting from the Interdisciplinary Approach of this Study*

- Interdisciplinary Team: This project was established as an innovative joint research project at the ETH Zurich between the Department of Architecture (D-ARCH) and the Department of Civil, Environmental and Geometric Engineering (D-BAUG).
- Multidisciplinary Research: The CATSE Joint Research Group has served as a platform to promote a multidisciplinary approach. The success in implementing a relatively new building material for permanent load-bearing purposes in construction is highly dependent on the seamless collaboration of several disciplines. In particular, this research study, as part of a larger collaborative research project, includes not only the experimental research and development, but also an analysis of the environmental consequences and social acceptance constraints of cardboard buildings within the Swiss construction market.

<sup>1</sup> See i.e. Andrew Cripps, "Cardboard as a Construction Material: a Case Study," *Building Research & Information* 32, no. 3 (2004): 207-219; Buro Happold, "Constructing a Prototype Cardboard Building: Westborough School, Literature Review," July 2001; M. Eekhout, F. Verheijen and R. Visser, eds., *Cardboard in Architecture: Volume 7 Research in Architectural Engineering Series* (Amsterdam: Delft University Press, 2008).

## 5. Related Work, Review of the State of the Art: A Brief Review

Fields of research related to this study can be classified into two broad categories: *New Material Research and Development* and *Innovative Building Construction Processes*.

a) *New Material Research and Development*: The quest for new materials is dependent on the innovation, the reuse and recycling of existing material,<sup>1</sup> as well as the integration of new paper and byproducts research into existing construction models.<sup>2</sup> Currently, the new material research and development into cardboard is focused on solutions for packaging industry. On the other hand, the integration of these new products into the market has been slow to take hold as a result of a lack of coordination in the communication of its benefits. Organizations such as *Material Connexion* play an important role, acting as global platform for material solutions and innovations for strategic material selections, a potential tool to bring cardboard to light for solutions more than simple packaging.

Recently, experimental work on paper tube and cardboard mechanical behavior has been pursued at TU Delft's Department of Product Engineering and Faculty of Architecture, including projects on the construction of buildings with a deflateable façade construction. Additionally, the *Cardboard School Project* (UK) by the architectural firm Cottrell & Vermeulen constitutes the most fully integrated cardboard building to date.

b) *Innovative Building Construction Processes*: At the building construction level, this research will focus on the theoretical and experimental work in mass customization and off-site construction. Significant early development of these processes was accomplished by the American architectural firm Kieran & Timberlake<sup>3</sup> and Martin Bechthold, who conducted theoretical work on digital robotic prefabrication in architecture.<sup>4</sup> On a purely experimental level, Ludger Hovestadt's team at ETH Zurich is currently experimenting with the digital processing of cardboard, focusing on software that would allow for a greater efficiencies in the automated production process. His work has revealed the advantages and limitations of CAAD rapid cutting, folding and origami in the context of cardboard. Also at ETH Zurich, Fabio Gramazio and Matthias Kohler are advancing digital fabrication techniques used in build non-standardized architectural components.

Additionally, Rene Snell's *Winding Machine Project* is an example of the use of cardboard in innovative building construction processes. Using a continuous roll of corrugated cardboard and a winding machine, Snell was able to produce relatively stable blocks of space. However, the project has yet to advance beyond its basic, temporary level to answer additional construction demands.

<sup>1</sup> i.e. *The Strawbale House and Office* (UK, 2001).

<sup>2</sup> i.e. Paper tube projects of Shiegeru Ban

<sup>3</sup> James Timberlake and Stephen Kieran, *Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction* (New York: McGraw-Hill Professional, 2004).

<sup>4</sup> "Digital Design and manufacturing by M. Bechthold, Harvard University, Cambridge, 2001



Beyond its technical aspects, this research will also draw on several sociological and sustainability studies that have been conducted in the field of innovative construction and dwellings. Theoretical research highlighting socio-anthropological studies and consumer behavior with respect to architecture and buildings will prove to be highly relevant to this study. The work of ETH Wohnforum<sup>1</sup> will serve as a starting point for the social realms of this study.

Lastly, following the technical, theoretical, and social analyses, the research will undertake a review of several innovative building construction processes that may play an essential role in evaluating the integration potential of a new product like cardboard buildings. The work of Wolfgang Wallbaum at the Sustainable Building Department at ETH Zurich will be the direction to evaluate the energy cost aspects of cardboard buildings.

## 6. Research Question

The baseline for future innovations in construction research and practice requires a focus on innovative multi-functional building materials and implementation of new construction processes (prefabricated and/or digitized) in order to respond to the changing market pressures which demand a delicate balancing between a project's environment impact and its cost. As an answer to these demands, a stock-flow approach focusing on re-materialization and recycling are becoming increasingly integrated into these processes. This study is therefore based on these interconnected aspects, investigating the potential of corrugated cardboard to serve as a multifunctional, structural, eco-conscious and low cost building component. Simply put, the research question is stated as: "is it possible to build a house out of (corrugated) cardboard?"



Figure 1.10 - Related works and projects<sup>2</sup>

<sup>1</sup> The ETH Wohnforum (Center for Research on Architecture, Society & the Built Environment) is an interdisciplinary research center within the Faculty of Architecture, focused on architecture, society and the built environment.

<sup>2</sup> (a) *Cardboard Dome*, by Tom Pawlofsky (2008); (b) *9 Stock Orchard Street Strawbale House*, by Wigglesworth Office (Islington, 2001); (c) *Westborough Cardboard School interior*, by Cottrell & Vermeulen (UK, 2001); (d) *Strawbale*

### **Selected Terms and Definitions**

The following is a brief list of selected terms and phrases that are frequently referred to throughout this study. The definitions provided below are not intended for general design and construction application. Instead, they are intended only to provide a general understanding of these terms as they relate specifically to building design and performance within the framework of this study.

- *Cardboard building/cardboard housing*: A general term for a building whose structural massive system consists of corrugated cardboard building components.

- *Corrugated cardboard structural building component - cardboard based prefabricated sandwich panels*: The corrugated cardboard honeycomb core sandwich composite element, or combination of these elements, placed in an exterior wall system or assembly that is intended to effectively resist both living (wind) and dead loads acting on a building or structure through the efficient and effective distribution of those loads to the underlying structural fundament.

- *Thermal Control*: The act of controlling or regulating heat loss and heat gain across an exterior wall system or assembly.

### **7. Further Research**

Further research for this study will include an analysis of the following disciplines and their interrelationship:

a) *Urban scale effect*: The measures related to cardboard buildings on the wider environment scale, and their potential as a tool for control in urban planning (of urban sprawl-growth-land) need to be further investigated with urban planning experts.

b) *Legal inquiries regarding the implementation of cardboard housing with a shorter lifespan*: legal issues related to the definition and application of cardboard houses regarding: i) renewal of construction; ii) possible long/short-term leases and ownership; iii) official recognition by building law and regulation of constructive and energy standards.

c) *Manufacturing and onsite assembly*: The development of manufacturing and handling requirements, on-site and factory assembly line coordination, constructive flexibility for expansion (adequate structure and floor loading capacity to receive heavier equipment), modular structural systems and portioning systems to permit horizontal modifications, and expansion-reconstruction possibilities of cardboard components need to be further investigated and coordinated with industry partners.

d) *Prototype Building*: As the deployment of the conceived theoretical work, a multi-functional platform to test the project's feasibility and illustrate other aspects of cardboard components

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House; (e) *Expo Building*, by Shigeru Ban (1999); (f) Brick digital wall production, by Gramazio & Köhler, ETH Zurich.



within a system is the next logical step for this study. On a strategic level, the prototype is planned to be a tool to inform the the public about the cardboard in architecture. The structure will be composed of cardboard-based prefabricated sandwich panels, structured as load-bearing and non-load bearing (interior and exterior) wall elements, incorporated with low cost and eco-conscious materials for optimum mechanical behavior and building physics requirements.



# Chapter II

## Societal Approach

### The Perception of Cardboard Buildings

" Say, it's only a paper moon  
sailing over a cardboard sea. "

E.Y. Harburg, Lyrics from *Take a Chance*, Motion Picture (1933)

#### 1. Background: Trends and Innovation in the Swiss Construction Sector

The construction industry constitutes a considerable part of the Swiss economy, contributing 6-10 percent to the country's gross domestic product, and employing nearly 400,000 people (approximately ten percent of the Swiss workforce).<sup>1</sup> The sector is driven by a relatively heterogeneous demand, in which housing construction makes up 41 percent of the market, while industrial buildings account for 30 percent, and civil infrastructure projects make up a 29 percent share.<sup>2</sup> As a nation with high median income, Switzerland is home to the highest consumption prices in Western Europe.<sup>3</sup> The most recent consumption trends and developments have centered around alignment with current European Union issues, transformation of the retail business sector after the global economical crisis, and a noticeable increase in demand for eco-friendly products. Additionally, reports indicate that Swiss consumers have a strong demand for innovative products. According to a market analysis by Euromonitor:

*"Switzerland's high income economy affects the domestic market and reflects administrative hurdles, marketplace rigidities and inefficiencies, and a lack of competition ... However, increasing price awareness among consumers, deregulation, growing competition, globalization and technological progress are leading to price adjustments. So while the prices are declining, manufacturers actively took steps to stem this decline by launching new and innovative products onto the market. Convenience and innovation became essential for Swiss consumers and, indeed, frequently decide the success or failure of a new launch."*<sup>4</sup>

2001). <sup>1</sup> Patrick Vock, *An Anatomy of the Swiss Construction Cluster* (Center for Science and Technology Studies, Jun.

<sup>2</sup> *Wiederbeschaffungswert Bauwerk* (Wuest & Partner, 1999) 8.

<sup>3</sup> Excluding agricultural products and automobiles.

<sup>4</sup> *Household Care in Switzerland Report* (Euromonitor, Jul. 2008).

The increase in diversity of and number of innovative products in the Swiss construction sector may have dramatic consequences within the economy for its workforce. With this basic understanding of the Swiss construction sector, the strategic positioning for cardboard buildings is undertaken within this chapter.

### ***Innovation in the Construction Sector***

In general, no substantial or comprehensive research and development activity has occurred in Switzerland's construction sector in recent years. However, there has been some minor research and development performed in the private sector and by the country's specialized technical schools, ETH-Zurich and ETH-Lausanne. While one report indicates that 42 percent of the construction sector applies innovative methods, suppliers to the industry have demonstrated the same innovative spirit in recent years.<sup>1</sup> The country's innovative energy has been focused primarily on specialized fields such as construction chemicals, which stems from the overall innovativeness of the chemical industry, where ninety percent of firms conduct internationally recognized innovative activity.<sup>2</sup>

Focusing on the broken link between academia and industry in the field of construction innovation, this study is structured as an attempt to promote research and development in the nation's carton manufacturing firms, and suggests an extension of their product palette from its existing monofunctional cardboard packaging into multifunctional cardboard building components.

Finally, it is important to stress the rising public recognition and demand for "sustainability," which coincides with innovation in the Swiss construction industry and this research project's main objectives. The sector's vast potential for ecological improvements depends on two basic facts: 1) fifty percent of construction investment is applied toward new buildings, and 2) sixty percent of total Swiss energy consumption is for construction and operation of buildings. Therefore, there has been an increase in public and private attempts to incorporate certain ecological requirements in construction activities by innovation-focused platforms such as the Swiss Governmental Commission on Technology and Innovation, which is a vital funding mechanism for applied research and development, particularly for industry-university partnerships that support sustainable products.

### ***Innovation and Patents in Switzerland***

A study by the European Patent Office shows that the Swiss construction sector was responsible for only six percent of all patents that were granted to Swiss applicants, a number that is dwarfed when compared to the sector's significant share of the overall economy.<sup>3</sup> A possible explanation for this fact is the low rate of cooperation between the sector and the country's

<sup>1</sup> S. Arvanitis, et al., *Innovationstätigkeit in der Schweizer Industrie* (Swiss Federal Office of Economics, 1998).

<sup>2</sup> Vock 12.

<sup>3</sup> U. Schmoch, A. Jungmittag and R. Rangnow, *Innovation Standpoint: Switzerland (in original language: Innovationsstandort Schweiz), a study for Swiss Federal Office for Professional Education and Technology* (Fraunhofer Institute for System techniques and Innovation-Research, Feb. 2000).

technical universities, which often possess the time and resources to fully engage in long-term innovative projects. In his comprehensive examination of the construction sector, Peter Vock points out the link of innovative and dynamic firms to the university in Switzerland, emphasizing the role and importance of the country's universities.<sup>1</sup> These facts show a clear need for more innovative cooperation within Swiss construction sector, as well as collaborative platforms between industry and the university. This academic study aims to increase the share of innovative products in construction practice.

### 1.1 Home Ownership in Switzerland

According to the yearly real estate report published by Credit Suisse,<sup>2</sup> the typical Swiss building, whether commercial, industrial or residential is built as a long-term investment. In Switzerland, buildings are constructed with brick walls, and a concrete basement made of high quality building insulation and roofing materials. Construction standards are high because the average Swiss home-owner, who tends to "stay put," expects a high degree of quality.<sup>3</sup> An increasing percentage of Swiss home buyers and renters are demanding higher performing, more comfortable and healthier buildings.<sup>4</sup> This innovative study on cardboard buildings looks to these high demands as a foundation for the product. However, it suggests a new limited life-span, a concept to which many Swiss customers may require time to adopt.

One of the main predictors of home ownership in Switzerland is location, which often drives cost and availability of residences in the country's 27 cantons. The highest rates of home ownership occur in the rural cantons of Valais, Appenzell, Innerhoden and Jura, where over fifty percent of residents own a home, a fact due primarily to those areas' affordable land and lower purchase prices. On the other hand, in the canton of Zurich, the overall home ownership rate was a mere 7.1 percent in 2006.<sup>5</sup> Overall, only about one third (34.6%) of Switzerland's seven million citizens owned a home in 2000. This is partly attributable to the country's high home prices and lenders' regulation which often require owners to make a twenty percent down payment in order to qualify for a loan. These figures indicate a highly liquid market for rental properties, which are clustered primarily in the country's major cities. With this understanding, cardboard housing's limited lifespan model will allow tenants to restructure their living situation periodically.

Due to the high costs of ownership in Switzerland, renting is often the only remaining alternative for the majority of the country's citizens. Studies show that most citizens cannot afford to purchase a home until close to retirement age.<sup>6</sup> Since most Swiss attain home ownership only in later stages of life (mostly by inheritance from relatives) when they are not particularly mobile, many prefer to settle down and accordingly choose home renovation over relocation.

<sup>1</sup> Vock 12.

<sup>2</sup> *The Swiss Real Estate Market: Facts and Trends* (Credit Suisse, 2005-2009).

<sup>3</sup> *Back on Firm Ground: The Construction Sector in Switzerland* (Trade and Investment Canada, 2001) 2.

<sup>4</sup> *Sustainable Solar Housing: Marketable Housing for a Better Environment* (International Energy Association, 2005).

<sup>5</sup> *Immo-Monitoring* (Wuest & Partner, 2006).

<sup>6</sup> *The Swiss Real Estate Market: Facts and Trends* (Credit Suisse, Feb. 2005), 21.

On the other hand, low interest rates, stabilized mortgage rates (approximately four percent per year), an increase in restorations of existing buildings, and an increase in consumer buying power are likely to cause a notable jump in home ownership rates in the near future.<sup>1</sup> Several other options have been proposed to promote home ownership in Switzerland, including:

- Political initiatives such as "Home-Ownership for All,"<sup>2</sup> which draws support from Swiss citizens' growing demand for feasible options for home ownership.

- Pension Fund Financing: In the last five years, the Swiss Government has made it possible for individuals to withdraw money from pension funds accounts to finance home purchases in Switzerland.

- Bank Loans: Several regional banks have begun offering a wide range of new home financing options. For example, the Kantonal Bank of Lucerne now offers two types of loans, including "The Family Loan" with a fixed interest rate, and "The Environmental Loan," which supports the purchase of environmentally-sound housing.

### 1.2 Tenants in Switzerland

Tenants, who in 2000 constituted 65.4 percent of all Swiss residents, pay considerably higher monthly rents compared to tenants in neighboring European countries. The rental market conditions, caused primarily by political initiatives, which have caused rents to remain in line with mortgage rates, have remained relatively stable and predictable for the last decade.<sup>3</sup> On the other hand, recent discussions show a desire to displace this mechanism with an inflation-coupled index which would allow more market-driven adaptations of prices in the Swiss construction market.<sup>4</sup>

Despite the country's relatively high rents, there nonetheless continues to be a high rate of relocation among Swiss residential tenants, as the market is quite liquid, and reliable public transportation allows residents to commute easily throughout a wide portion of the country.



Figure 2.1 - Architectural products reflecting user needs vs. experimental approaches.<sup>5</sup>

<sup>1</sup> "Market Highlights & Prospects", The International Market Research Reports (The Government of Canada and Industry Canada, 2006) <http://strategic.ic.gc.ca>, 6.

<sup>2</sup> Translated from the German "Wohneigentum für Alle".

<sup>3</sup> Vock 16.

<sup>4</sup> Vock 16.

<sup>5</sup> From left to right: A Mongolian Yurt; *Red House*, by Philip Webb; *Villa Savoye*, by Le Corbusier; *Curtain House*, by Shigeru Ban; *Kitagata Apartment Building*, by Kazuyo Sejima.

### 1.3 An Introduction to Cardboard Housing as a Product

Buildings in architectural anthropology serve a variety of purposes. These purposes range from shelters and works of arts to an experimental playground for the architect or just another product in the marketplace (Figure 2.1).

Identification of the market forces' interaction and its influence on the positioning of an innovative product and development, such as in a building system, is necessary to effectively position cardboard housing in the market. Andrew Grove, a housing market researcher, has suggested the following six primary market actors to be thoroughly analyzed for concrete positioning; customers, suppliers, existing competitors, potential competitors, substitutes and complementary industries.<sup>1</sup> Based on the analysis of these actors, this study aims to position cardboard housing in Switzerland as a viable alternative to traditional residential construction options. The lifecycle of cardboard housing in the Swiss housing market and the application of strategic planning tools such as S.W.O.T. (Strengths, Weaknesses, Opportunities, Threats) and P.E.S.T. (Political, Economic, Sociological, Technological) analysis are used in combination with a comprehensive questionnaire to position cardboard housing in relation to Swiss market demands.

<b>INTERNAL</b>	<p><b>Strengths:</b> Internal factors about the organisation and the product-definition of the project's strengths and competitive advantages</p> <ol style="list-style-type: none"> <li>1-Research by ETHZ with high credibility &amp; reputation in Switzerland</li> <li>2- Unique, innovative, high quality, low cost product in the construction sector following             <ul style="list-style-type: none"> <li>- latest product demands in housing</li> <li>- intellectual demands suggesting sustainable future / new lifestyle</li> <li>- user facts and statistics: such as high mobility in residence, Switzerland</li> </ul> </li> </ol>	<p><b>Weaknesses:</b> Internal factors about the organisation and the product- choice of activities to reduce the weaknesses</p> <ol style="list-style-type: none"> <li>1-Lack of experimental and market research data available</li> <li>2-Possible high construction costs in the prototype stage</li> <li>3-Prejudice against short lifetime of cardboard buildings</li> <li>4-Prejudice against short-term ownership concept</li> <li>5-Approval from the authorities needs to be first received to be marketed with the Minergie© standard.</li> </ol>
<b>EXTERNAL</b>	<p><b>Opportunities:</b> External-market attributes and factors which affect positively the project and the end product's possibilities in the market</p> <ol style="list-style-type: none"> <li>1- Rise of construction of Minergie© / eco-houses in Switzerland</li> <li>2- Rise of awareness of environmental issues among public/media</li> <li>3-Minergie standard turning into a regulation and investment tool</li> <li>4- Extinction and therefore high cost of fossil fuels; electricity and energy</li> <li>5-Growing interest of Banks &amp; Cantonal offices in environmental thinking(lower interest rates, tax reductions for eco-house decisions)</li> </ol>	<p><b>Threats:</b> External factors which affect the project and the end product's possibilities in the market – definition of activities to defeat the threats, negative developments or attribute of the market or other external actors or factors.</p> <ol style="list-style-type: none"> <li>1- High initial costs; users overseeing the long-term advantages of a new product</li> <li>2- Extra-cautious Investors: investing on product in construction sector takes long years.</li> </ol>

Figure 2.2 - SWOT Analysis for the CATSE Cardboard Housing Project.

<sup>1</sup> Andrew S. Grove, *Only the Paranoid Survive: How to Exploit the Crisis Points that Challenge Every Company and Career* (New York: Doubleday, 1996).



### 1.3.1 SWOT Analysis for CATSE Cardboard Buildings Study

SWOT analysis is a strategic planning tool used to evaluate the internal strengths, weaknesses, and external market-based opportunities and threats involved in a project or in a business venture that help to evaluate a project’s viability. The SWOT analysis illustrated in the figure above shows how these factors are applied to the CATSE Cardboard Housing research project (Figure 2.2).

### 1.3.2 PEST Analysis for CATSE Project Cardboard Buildings Study

PEST analysis is another valuable strategic tool that can be employed to define the political, economic, social and technological factors that directly or indirectly influence the competitive arena of a new business idea (Figure 2.3). In today’s Swiss housing market, the factors that are relevant to eco-housing and CATSE Cardboard housing are highly dependent on Switzerland’s energy demands and planning for future challenges caused by building regulations.<sup>1</sup> But it is also unrealistic to presume that neither regulations to enforce sticter standards, nor a single supplier for cardboard housing could significantly affect the outlook of CATSE Cardboard Housing in the near future. This concept is illustrated in Figure 2.4.

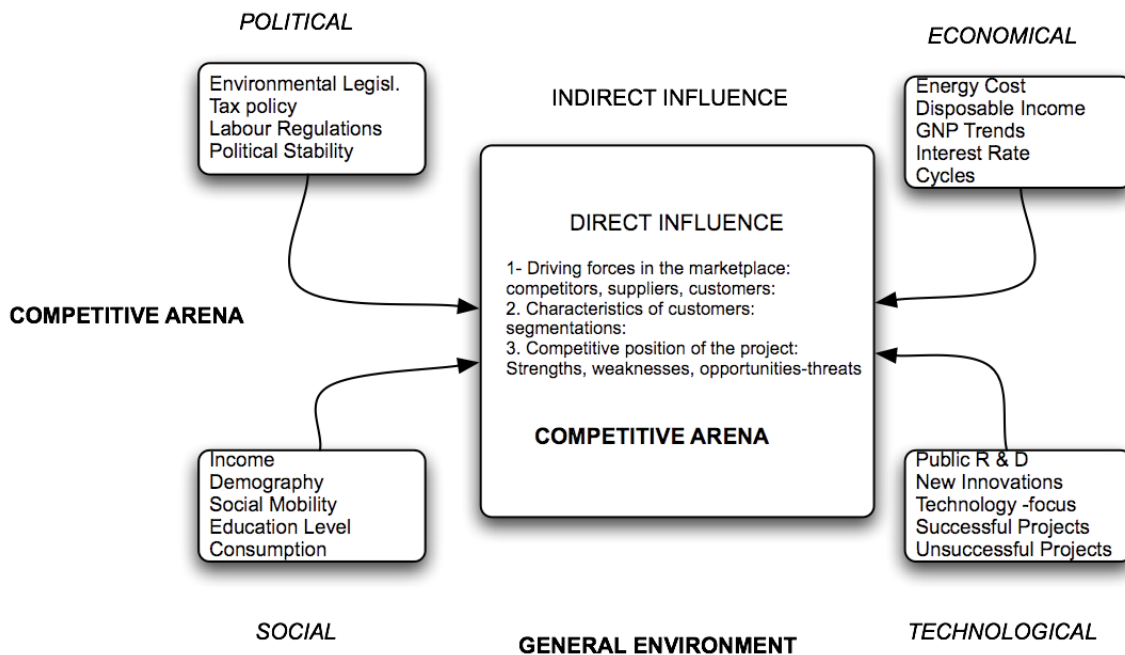


Figure 2.3 - PEST factors and influence on the competitive arena for a general product.

<sup>1</sup> Sustainable Solar Housing (International Energy Agency Solar Heating and Cooling Programme, Apr. 2005) <[www.iea-shc.org/task28/](http://www.iea-shc.org/task28/)>.

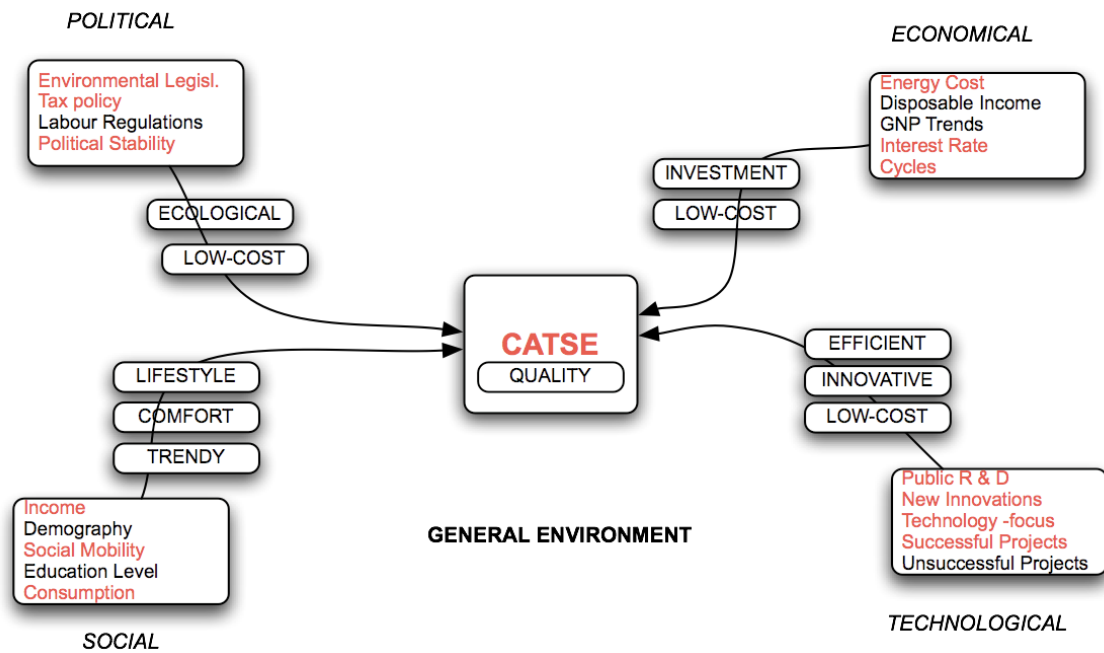


Figure 2.4 - PEST Analysis Diagram for CATSE cardboard housing.

### 1.3.3 Product Lifecycle for CATSE Cardboard Buildings Study

The product development cycle has five stages: introduction, growth, maturity, decline and withdrawal. Ideally, the consequences of each phase provide an individual development strategy to divert the specific need of the target user group and to implement the technical feedback mechanism, while securing growth of market share of the product (Figure 2.5).

As a product in the introduction stage, CATSE cardboard housing requires a comprehensive definition and communication of the innovative service and product it offers, along with the lifestyle it suggests. The introduction phase also necessitates a substantial initial investment to cover prototype construction as well as the initial implementation costs of introducing the product to the mainstream construction market. Research also suggests that it is there are proven advantages to being the first viable company in a particular market, and often deliver significant benefits like greater market share earned by gaining the trust and name recognition of users.

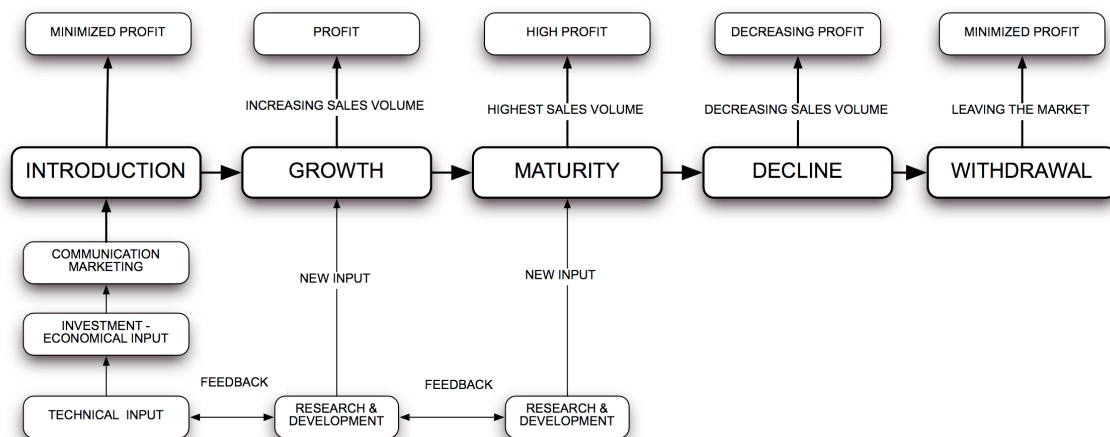


Figure 2.5 - Product lifecycle, input and outputs.

### 1.4 Organization of the Societal Approach for the Perception of Cardboard Housing

Based on the concept of “eco-conscious cardboard housing” as the desired end-product, this chapter will discuss the implementation of cardboard housing in Switzerland at the user and product levels as well as its governance on pre-conditioned ownership (reconstruction in ten to fifteen year intervals). The link between user group identification and the implementation process of contemporary new dwellings in the Swiss construction sector must be defined to generate an introductory acceptance strategy for cardboard housing (Figure 2.6). How user choice orients itself under the influence of current facts and trends in the Swiss real estate market is a critical question that this study aims to answer. A survey study within this chapter is conducted as the main tool to evaluate and understand the current state of cardboard material and its associations in housing, as well as the potential of positioning CATSE cardboard housing in the existing product market. As a result, the proposed societal approach outlines cardboard housing as having the potential in the low-cost and eco-friendly housing niche in the mature Swiss construction sector. Accordingly, the study will pursue the related customer identification of target groups and the potential investors who define the bases of strategy to enter the Swiss real-estate market.

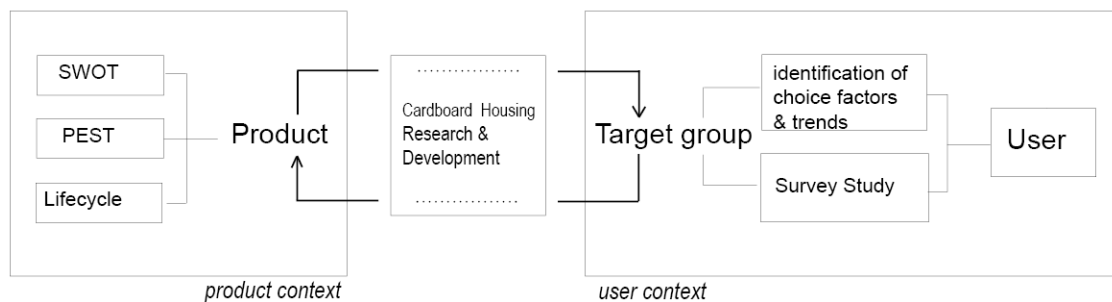
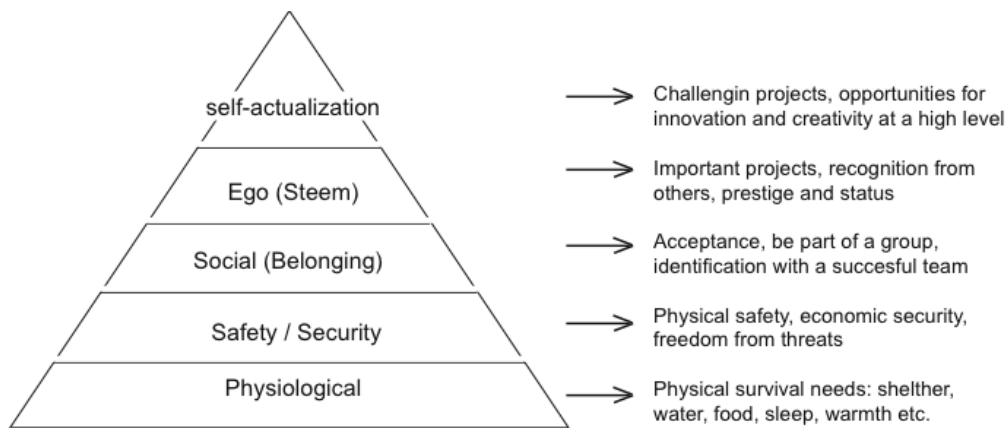


Figure 2.6 - Chapter structure: “Cardboard Housing” - User vs. Product level.

## 2. Factors Affecting the Choice of Cardboard Housing in Switzerland

The dwelling as a product represents the most private social space associated with the first step of the late psychologist Abraham Maslow’s hierarchy of needs diagram: physiological need: shelter (Figure 2.7). The safety instinct and shelter choice are both connected to physiological, sociological and psychological identifications. Correspondingly, defining the target user group for a dwelling - “home” as a product, is much more complex than most other commercial products. The decision to invest in a new home, albeit one built using an untested building material, is based on the structural, economic and opportunity factors in the larger social context, as well as on the cost, quality and the trends on the basic personal choice level. This subchapter will analyze the factors related to the choice of a dwelling to underscore the current preferences for the implementation of cardboard housing.

Figure 2.7 - Maslow's Hierarchy Triangle.<sup>1</sup>

## 2.1 Factors Affecting Product Acceptance in Housing

According to recent housing studies, the demand for residential construction is strongly influenced by changes in structural factors (i.e. age, family structure, lifestyle), cyclical/economic factors (i.e. income distribution), and opportunity factors.<sup>2</sup>

- *Structural Factors* (demographic changes, birth rate, immigration rate): Switzerland's rapidly changing demographics will likely influence the implementation of CATSE cardboard housing. First, the country's aging populace may provide a challenge toward widespread acceptance of new built cardboard housing. However, the country's net immigration increase (43,000 people in 2003) will likely counter this trend and lead to a slight decrease in the overall average age of the population. Accordingly, with its target user at the lower segment of the age spectrum, CATSE cardboard housing's altering lifecycle (renewal according to the changing life needs) has a realistic opportunity to capture a niche market share among eco-conscious first-time home buyers in Switzerland.

- *Cyclical/Economic Factors* (income, interest rate trends): Switzerland has a relatively stable economy, and its citizens earn comparatively high incomes. However, the correspondingly high home prices often serve as a impassible hurdle to home ownership. The country's economic cycles and interest/mortgage rates affect consumer behavior, particularly when purchasing non-movable assets such as dwellings. For CATSE cardboard housing, subsidies or more advantageous bank loans could be provided in the short term to help propel market growth.

- *Opportunity Factors*: Demand for residential property is also heavily influenced by various advantageous circumstances that fall under the generic "opportunity" heading. The major parameters which affect the "opportunity factor" are the rental or mortgage cost of a residence, the price of other goods and the relative prices between these two categories. Additionally the movements in the relative prices between locations and forms of accommodation (single family house, owner occupied apartments, etc.) affect the opportunity factor in demand.

<sup>1</sup> Abraham H. Maslow, "A Theory of Human Motivation," *Psychological Review* 50 (1943): 370-396.

<sup>2</sup> *The Swiss Real Estate Market: Facts and Trends* (Credit Suisse, Feb. 2005).

In the context of the Swiss housing market, preference for dwellings is based on diversification of lifestyles, moral concepts and, accordingly, the household structure. The consequences of these preferences are observed in the trend in favor of increased comfort and living space. The average Swiss now resides in a 44 m<sup>2</sup> living space, compared to 1980 when the average was 34 square meters.<sup>1</sup> This increase in average living space is thought to be the result of two separate trends: 1) increased mobility of the populace, and 2) increase in the amount of time spent in one's resulting from more study and work-at-home opportunities.<sup>2</sup>

In terms of building stock, Switzerland has an surplus of older buildings that were built from 1960-1980. Currently, most investors now find it more cost efficient to renovate these older buildings than to invest in new single-family residential projects.<sup>3</sup> Nevertheless, there still remains a liquid supply of residential buildings. Added to this supply is an increasing sense of eco-consciousness - the change in demographics and lifestyle preferences demand not only economical, but also ecologically sustainable means. The CATSE cardboard building project finds itself at the intersection of ecological and economical sustainability. This new demand will be fulfilled not only by using eco-friendly building materials and construction techniques, but also through thoughtful location choice, such as outer suburban areas, which tend to be more reasonably priced, or in less developed urban areas in collaboration with governmental entities. Among many other factors, the acceptance of CATSE cardboard housing in the real estate sector will be determined by three main themes: cost, trends, and quality.

## 2.2 Cost

For the average Swiss household, housing and energy accounts for 17 percent of monthly expenditures, the largest such expense. Thus, it is understandable that the Swiss remain very cautious about their investments and the consequences of such on monthly housing and energy expenditures. Figure 2.8 highlights the extent of costs related to residential property and demonstrates how household income is apportioned for various expenses. Today, given Switzerland's rapidly changing demographics, taken together with its economic stability, and relatively low interest rates, there is a now the ideal climate for a considerable acceleration in demand for new housing.

In addition to the factors listed above, tax rates also play a particularly important role in the choice of a dwelling in the country. There is a strong negative correlation between tax levels and the cost of housing: the higher the tax, the lower the rents and lower the price of real estate. For the announcement and implementation process for the proposed CATSE cardboard housing, aiming to lower construction costs, these existing tax rates will pose a certain stresses with the real-value of rent-cost indices.

<sup>1</sup> J.E. Van Wezemael and Joris Ernest, *Investieren im Bestand: Eine Handlungstheoretische Analyse der Erhalts- und Entwicklungsstrategien von Wohnbau-Investoren in der Schweiz* (St. Gallen, Switzerland: Ostschweizerischen Geographischen Gesellschaft, 2005) 129.

<sup>2</sup> Margrit Hugentobler, *Demographischer Wandel: Herausforderung für den Wohnungsmarkt* (ETH Tagung des Novatlantis Bauforums, 20 Jun. 2006), Zurich, 15.

<sup>3</sup> Hugentobler 28.

On the other hand, governments can use their taxing power to positively guide its citizens' consumption behavior, i.e. to promote the purchase of eco-conscious homes. In Switzerland today, energy efficiency is promoted by framework conditions (temporary restricted promotion programs, taxes, export promotion, production cooperation, and pooling of demand) for the citizens and also as a means of supporting the companies which have provided investment capital, in order to initiate innovative eco-projects.<sup>1</sup> Currently, the government is looking to improve the effectiveness of additional subsidies and tax incentives.<sup>2</sup> Correspondingly, this project is well-positioned to take full advantage of the present eco-conscious political culture.

Finally, entering the construction market with an unfamiliar product poses certain risks for investors, requiring attention to be placed on the proposed intervention of CATSE cardboard housing into the Swiss real-estate market. But what are the constraints and investment risks for Swiss investors? Due to the cost dynamics of cardboard housing projects, investors are burdened with the responsibility to supply the market, based on their *assumptions* regarding demand of the residents, rather than the *known and direct* demands of the residents. Releasing a new technology-based product is extremely costly and risky for large-scale investors, especially in the traditionally conservative Swiss real-estate market. For early investors, initial costs are a relatively high barrier since new technologies have a higher cost in the early stages of the products lifecycle. However, experience indicates a ten to twenty percent decrease with every doubling of the application.<sup>3</sup>

### 2.3 Trends

Social trends are patterns of human social behavior, analyzing the repeating origins, organizations, relationships, and the development motives in a society. They define a certain amount of inclined tendency on a specific choice, behavior or position on a particular framework. The current trends in Swiss construction sector are discussed below in order to position the cardboard housing in the existing housing market. However, this subchapter is merely a brief introduction to trends in the Swiss housing industry, offering a glimpse into themes in which CATSE cardboard housing as a system might be positively influenced during its implementation. The trends which affect the development and influence fast commercialization of CATSE cardboard housing will be discussed under the following titles: The eco-consciousness, mobility and transportation realms in Switzerland. The main underlying factor of all these trends is the Swiss citizenry's strong opinions on issues of global climate change. These opinions have led to the wide popularity and effectiveness of the country's public transportation facilities.

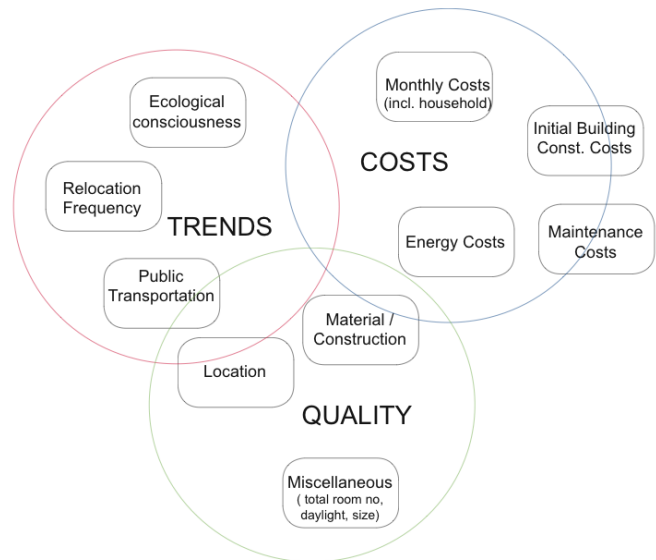
<sup>1</sup> Martin Jakob, "Marginal Costs and Co-Benefits of Energy Efficiency Investments in the Residential Buildings Sector," *Energy Policy* 34, no. 2 (Jan. 2006): 184.

<sup>2</sup> A. Lien and R. Hastings, *IEA SHC 28 ECBCS 38: Sustainable Solar Housing - Marketable Housing for a Better Environment* (EMPA-ZEN, Sep. 2001).

<sup>3</sup> Jakob 184.

<b>Expenditure among private households</b>		<b>TE 2.5.2</b>	
In % of consumer expenditure			
	<b>2003</b>	<b>2004</b>	
Food and non-alcoholic beverages	8.1	8.0	
Alcoholic beverages and tobacco	1.1	1.3	
Clothing and footwear	2.9	2.8	
Housing and energy	17.6	17.0	
Furniture and fittings, daily expenses	2.8	3.1	
Healthcare	4.3	4.4	
Transport	7.6	7.4	
Telecommunications	2.0	2.1	
Entertainment, recreation and cultural pastimes	6.3	6.7	
Schooling and education	(0.6)	(0.5)	
Restaurants and holiday accommodation	6.1	6.3	
Other goods and services	2.2	2.3	

Figure 2.8 - Expenditures among private households.<sup>1</sup>



### 2.3.1 Eco-consciousness in Switzerland

Starting in the 1980's, Switzerland population has demonstrated a growing awareness of eco-consciousness in the public and political arenas. According to reports and the state's strict policies<sup>2</sup> - through additional taxes, fees, fines, subsidies or promotions - the household consumption patterns have begun to shift. Important steps in this transformation have included: obligatory state garbage bag system, introduced in 1992 for waste reduction, a usage option of *ökostrom* in several Swiss cities (Bern, Winthertur and Zurich), a solar power exchange allowing customers to buy renewable energy, and the increasing popularity of eco-labels like Minergie.<sup>3,4,5,6</sup>

The United Nations Framework Convention on Climate Change's (UNFCCC) 2001 study summarized the political framework that led to environmental changes taken by Switzerland as follows:

*"The principles and instruments of Swiss environmental policy are formulated in the Federal Law on the Protection of the Environment, adopted in 1985 and revised in 1995. Accordingly, the new CO<sub>2</sub> legislation provides an accepted framework for policy on climate change, focusing on transparent targets based on the Swiss commitments under the Kyoto Protocol."*<sup>7</sup>

### Environmental Standards in Modern Swiss Construction

The definition of construction standards and their regulation, including their legal implementation and control, have notable effects on several levels concerning sustainability from energy and material consumption to cost-reduction promoting economic sustainability. According to one analysis by Martin Jakob:

<sup>1</sup> Source: Swiss Federal Office of Statistics (2004).  
<sup>2</sup> Swiss Federal Office for Environment.  
<sup>3</sup> *The Swiss Real Estate Market: Facts and Trends* (Credit Suisse, Feb. 2005).  
<sup>4</sup> *Third National Communication of Switzerland 2001* (Swiss Agency of Environment, Forestry and Landscape, Jul. 2001): 34.  
<sup>5</sup> *EWZ Geschäftsbericht* (Stadt Zurich): 19.  
<sup>6</sup> Elisabeth Rosenthal, "Thinking Twice About the Garbage," *International Herald Tribune* (23 Apr. 2005).  
<sup>7</sup> *Third National Communication of Switzerland 2001* (Swiss Agency of Environment, Forestry and Landscape, Jul. 2001): 28-30.



"[I]t helps to reduce the specific energy requirements of new buildings with each tightening of standards, it informs about construction practices and identical construction components (i.e. windows, improved insulation materials, rationalized installation) and it also causes a reduction of the energy requirements of the existing building stock ... Above all, the standards promote new technological solutions and techno-economic progress through learning and economy of large scale effects resulting in further cost reductions for producers and installation businesses, thereby creating new markets. A regular tightening of the construction standards according to technological developments is therefore requisite.<sup>1</sup>

The residential buildings in Switzerland hold an important share of the end-use energy consumption, which is leading the notion and definition of eco-standards in the country, and greenhouse gas emissions. It follows then that the building sector possesses tremendous potential to substantially lower the country's CO<sub>2</sub> emissions by building new residences that require less energy to maintain. Accordingly, the present regulations<sup>2</sup> related to space heating requirement of new buildings are becoming increasingly strict. Additionally, energy efficiency programs like Energy 2000 have been initiated for both new and renovated buildings, and provide further incentive to lower emissions.<sup>3, 4, 5</sup>

One of the most influential contributions to the Energy 2000 initiative has been the promotion of the Minergie environmental label for the Swiss building sector.<sup>6</sup> Apart from the primary benefits of reduced energy demand and costs for homeowners and tenants, there are also secondary benefits of the standards, which providing higher living comfort, such as improved indoor air quality, improved external noise protection and improved thermal comfort (Figure 2.9). Martin Jakob summarizes the extent of the label as follows:

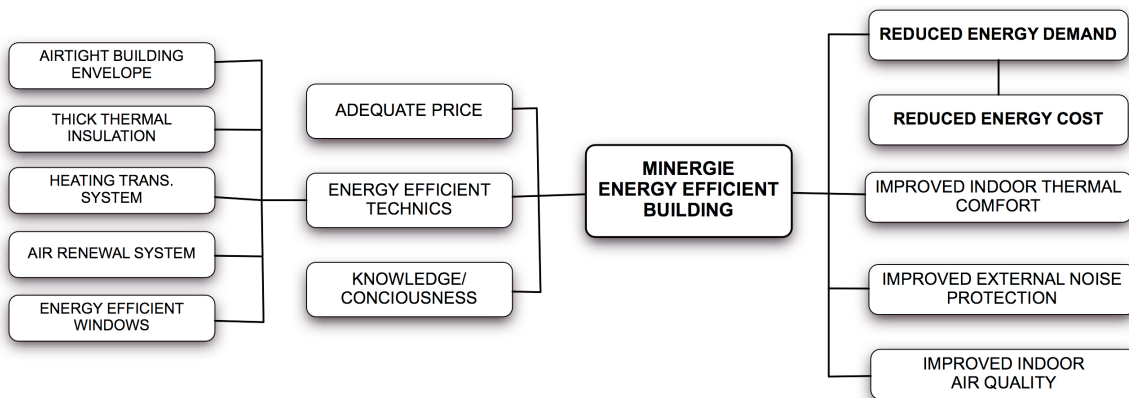


Figure 2.9 - Minergie Standard: Building Benefits<sup>7</sup>

<sup>1</sup> Jakob 186.

<sup>2</sup> SIA 380/1: corresponding to EU Standard SNEN832.

<sup>3</sup> *Third National Communication of Switzerland 2001* (Swiss Agency of Environment, Forestry and Landscape, Jul. 2001) 42.

<sup>4</sup> Silvia Banfi, Medhi Farsi, Massimo Fillippini and Martin Jakob, "Willingness to Pay for Energy Saving Measures in Residential Buildings," *Energy Economics* 30, no. 2 (March 2008).

<sup>5</sup> Jakob 175.

<sup>6</sup> *Third National Communication of Switzerland 2001* (Swiss Agency of Environment, Forestry and Landscape, Jul. 2001) 34.

<sup>7</sup> Banfi et al. 504-505.

*"Minergie is a quality label for buildings that combines high comfort of living and low energy demand which has to be reached within a limited cost surplus of at the most 10% of the construction price. Controlled air exchange is a requirement, which is mostly met with a housing or "comfort" ventilation system. By Minergie, houses have an energy consumption which is 70% to 85% lower than the consumption of traditional houses built prior the 1970's or 50% lower of the standard of today's new buildings. <sup>1</sup>*

### **Reflections on Eco-consciousness in the Swiss Construction Sector**

1. Standards and labels such as Minergie, or the German *Passivhaus* label play an important role in the integration of the sector's changing needs and understanding of sustainability. The labels give new impulses for environmentally friendly building owners, and architects, and thus have an innovation-stimulating effect, serve as benchmarks, and result in market transparency. Moreover, they also serve as experimentation field for the next tightening of the construction standards and requirements. <sup>2</sup> However, there is a certain resistance when the standards were first introduced. For example, the biggest barriers for the Minergie standards standing in the way of widespread acceptance are socio-demographic barriers and lack of knowledge about energy efficiency. <sup>3</sup>

2. The niche in today's Swiss market for eco-houses offers a focus on "high performance," which is primarily accomplished by reducing heat loss through compact building form, thick insulation and ventilation heat recovery, despite high initial costs. <sup>4</sup> Only ten percent of the energy used will be accumulated for new buildings in the next fifty years. This will inevitably lead to a political focus on existing buildings and an extremely slow renewal for the eco-supportive changes to begin to take effect among Switzerland's building stock. <sup>5</sup> In order to meaningfully reduce the energy consumption of the overall housing stock and to aid in the process of implementation, the use and better communication of promising new technologies and materials in construction is required.

3. The shorter renewal cycles for technical vehicles and installations in cardboard buildings poses a major impediment to satisfying energy efficient measures. Adaptation of these two areas will be costly and will likely take between fifty and one hundred years to accomplish these up-to-date energy efficient measures. <sup>6</sup> The proposed CATSE cardboard housing system within this study offers a solution to this dilemma by suggesting a shorter life span and ease in demolition and reconstruction. The typical CATSE house would undergo complete renewal, including infrastructure installations every 10-15 years of usage time. The infrastructure as a whole as well as the standards for thermal insulation and energy usage are redefined by re-

<sup>1</sup> Banfi et al. 504-505.

<sup>2</sup> Jakob 186.

<sup>3</sup> S. Banfi and Martin Jakob, *Energieeffizienz und Komfort: Wie viel sind Mieterinnen und EigentümerInnen zu zahlen bereit?* (Tagung Novatlantis Baufroum) 506-507.

<sup>4</sup> *Business Opportunities in Sustainable Housing A Marketing Guide Based on Houses in 10 Countries*, International Energy Agency, Solar Heating and Cooling Programme (2006).

<sup>5</sup> *Smarter Living, Generating a New Understanding for Natural Resources as the Key to Sustainable Development*, (The 2000 Watt Society) 11.

<sup>6</sup> *Smarter Living, Generating a New Understanding for Natural Resources as the Key to Sustainable Development*, (The 2000 Watt Society): 8.

installing the system performance in cardboard housing systems, and transformed according to the changing needs of users and the existing climate.

4. On the macro level, with regard to the housing unit, other factors affecting energy efficiency measures are regarded as case-specific parameters. The research contained in the recent CEPE report *Willingness to Pay for Energy Saving Measures in Residential Buildings*, argues that the utility of living in energy efficient apartments or houses is a function of the price, the house's energy efficiency characteristics, the characteristics of the building's location, household characteristics and a random component that captures the influence of unobserved factors. Household characteristics include income, education, environmental consciousness, as well as site-specific characteristics of the household's actual residence.<sup>1</sup> These criteria are used as a starting point for the formulation of the architectural language and space in CATSE cardboard buildings.

As price is a leading factor in the choice of energy efficient measures, currently both the users and investors seek to gradually build the understanding of the relationship between the costs and the eco-supportive decisions. Research by Borsani and Salvi<sup>2</sup> in 2003 demonstrated that new single family houses certified with the Minergie label in Switzerland yielded higher selling prices by nearly 9 percent.<sup>3</sup> This demonstrates that the standard for environmentally conscious construction remains affordable, but yet more expensive than traditional construction. CATSE cardboard housing, on the other hand, addresses the demand for low-cost housing by reducing energy loss and delivering the same high performance as conventional construction systems, as well as additional architectural freedom and improved living quality.

5. On a more architectonic level, the building skin (walls, windows, doors, roof, and floor surfaces), building configuration (open spaces and built form, building orientation, building shape, surface area to volume ratio), and surroundings govern the energy consumption in every building as well as cardboard housing system proposed. CATSE cardboard housing, as a new product in the real-estate market, aims to fulfill the need for lower energy consumption by using technical as well as architectural concepts. The key themes to be considered in the evolving design are planning aspects (i.e. improved window orientation, use of shading), local limitations, architectural expression, reliability and simplicity in energy efficiency (highly insulated, airtight building envelope, minimized thermal bridges, energy efficient windows, efficient ventilation with heat recovery, efficient appliances, solar cells, improved insulation of ground floor and basement walls, improved wall, roof and ground floor), all in relationship with cost dynamics.

<sup>1</sup> Banfi et al. 506-507.

<sup>2</sup> C. Borsani and M. Salvi, *Analysebericht zum MINERGIE-Standard* (Internal Memorandum, 5 Aug. 2003).

<sup>3</sup> Jakob 182.

### 2.3.2 Ease in Public Transportation: Policies and User Behavior

Modernization of the Swiss railway infrastructure and related railway reforms have resulted in

high rate of regular users. In particular, the system has efficiently connected the suburban areas to the peri-urban areas of the country's more populated cities. As reachability and the quality of the service are high, environmentally conscious Swiss citizens have embraced the country's public transportation system as a low cost alternative to individual means of transportation. The United Nations Framework Convention on Climate Change's (UNFCCC) 2001 study noted that:

*"[s]ince 1972, Switzerland has developed an integrated approach to transportation, focusing on better co-ordination between transport modes, and emphasizing environmental problems.<sup>1</sup>*

Figures 2.10 and 2.11 illustrate the results of an EPFL study<sup>2</sup> on the usage rate of public transportation and other means of transportation in Switzerland. These figures demonstrate the focus around the population centers and peri-urban agglomeration. CATSE Cardboard Housing is positioned for initial implementation in the outskirts of the population due to high cost of real estate in Switzerland's city centers. The country's efficient public transportation infrastructure and its general acceptance by the masses will prove to be critical in the proposed integration of cardboard housing in the suburban areas.

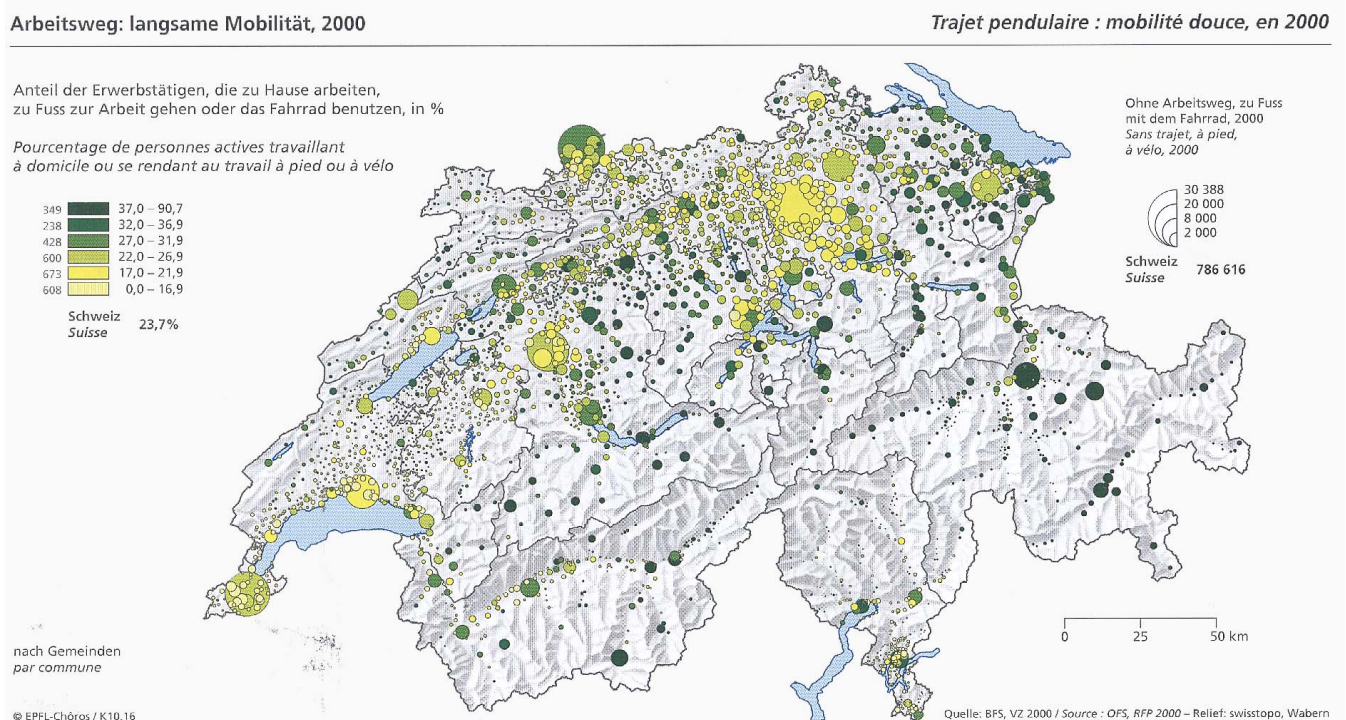


Figure 2.10 - The ratio of people who have short distance from home to work: Percentage of working respondents who either work at home, walk or ride a bicycle to work, 2000.<sup>3</sup>

<sup>1</sup> Third National Communication of Switzerland 2001 (Swiss Agency of Environment, Forestry and Landscape, Jul. 2001): 29.

<sup>2</sup> Swiss Federal Institute of Technology in Lausanne.

<sup>3</sup> Martin Schuler, Pierre Dessemontet, Christophe Jemelin, Alain Jarne, Natacha Pasche, Werner Haug, *Atlas des Räumlichen Wandels der Schweiz* (Zurich: Verlag NZZ, 2006) 278.



### 2.3.3 Mobility in the Swiss Real Estate Market

Changes in household structure and lifestyle, together with a relatively liquid rental stock are both indicators that Swiss residents are highly mobile and do not spend their lifetimes in the houses in which they were born, unlike their ancestors in beginning of the previous century.

Whether a homeowner or a tenant, they do occasionally change their living environments according to their changing needs and social arrangements. This “frequent relocation rate” is illustrated in this study through the social acceptance study conducted on 200 Swiss residents for CATSE cardboard housing, as seen in Figure 2.12.

On a national scale, according to the Swiss Federal Office of Statistics (BFS), for the period of 1995-2000, more than two million of the country’s seven million residents relocated at least once. The following statistics provide further insight into the Swiss housing market:

- More than 45 percent of residents relocated within the same municipality
- Four out of five relocators were 55 or younger
- Residents in the 25-39 age category show a preference for municipalities in the suburbs
- When Swiss residents start families, home ownership becomes a principle demand.

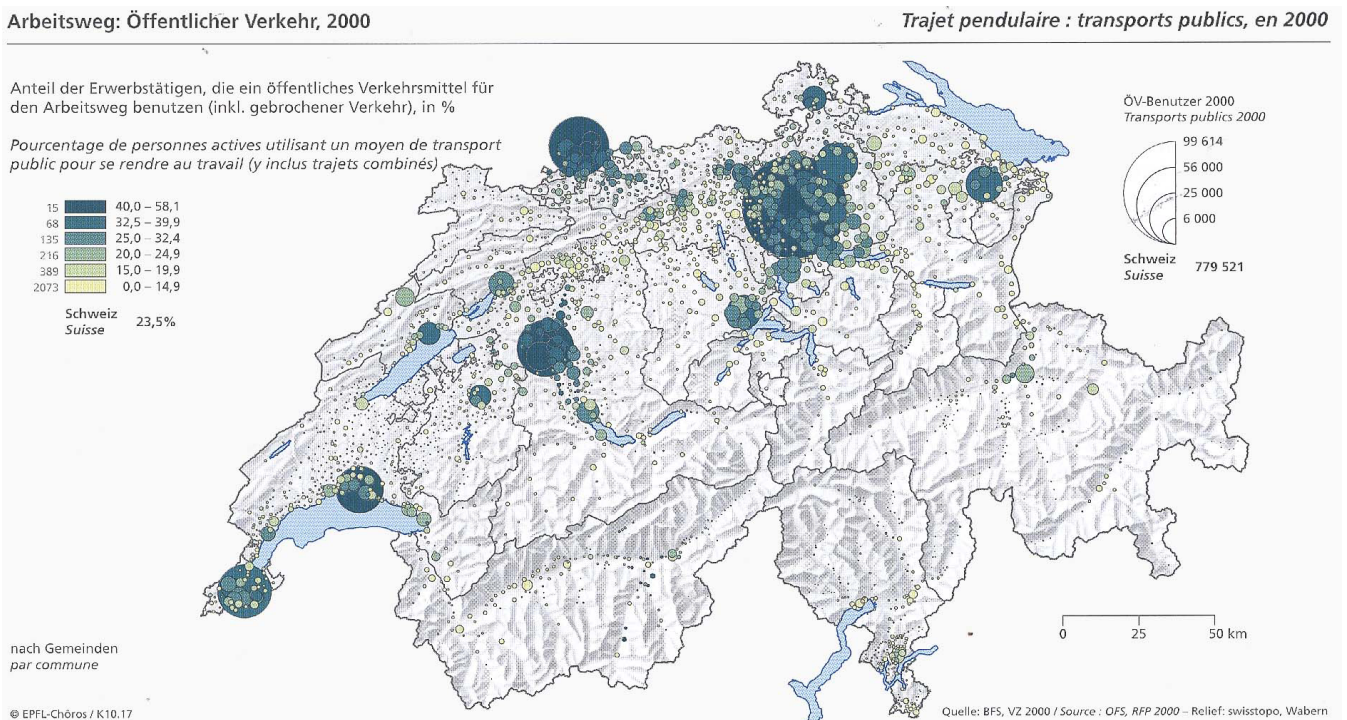


Figure 2.11 - Percentage of respondents who use public transportation from home to reach work (Switzerland, 2000)<sup>1</sup>

<sup>1</sup> Schuler et al. 278.

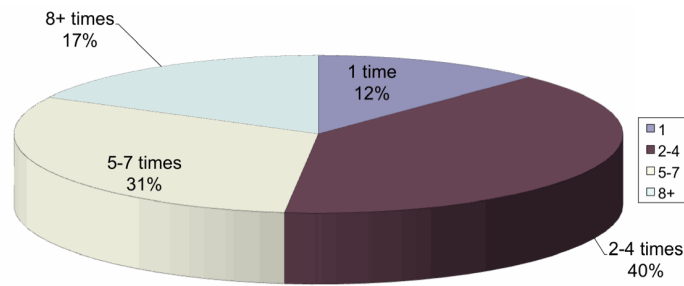


Figure 2.12 - Respondent's frequency of relocation.

As residents age, they tend to prefer owner-occupied apartments. Additional studies have revealed the fact that their desire to change location decreases with age, due primarily to physical limitations. In sum, these trends showing a high rate of relocation among younger residents place CATSE cardboard housing in a beneficial position to capture a significant portion of the population. The proposed renewal period of ten to fifteen years can be marketed as an opportunity for the residents to adjust their living environments (size/function of spaces) based on their changing lifestyle and needs, while remaining at the same location (Figure 2.13).

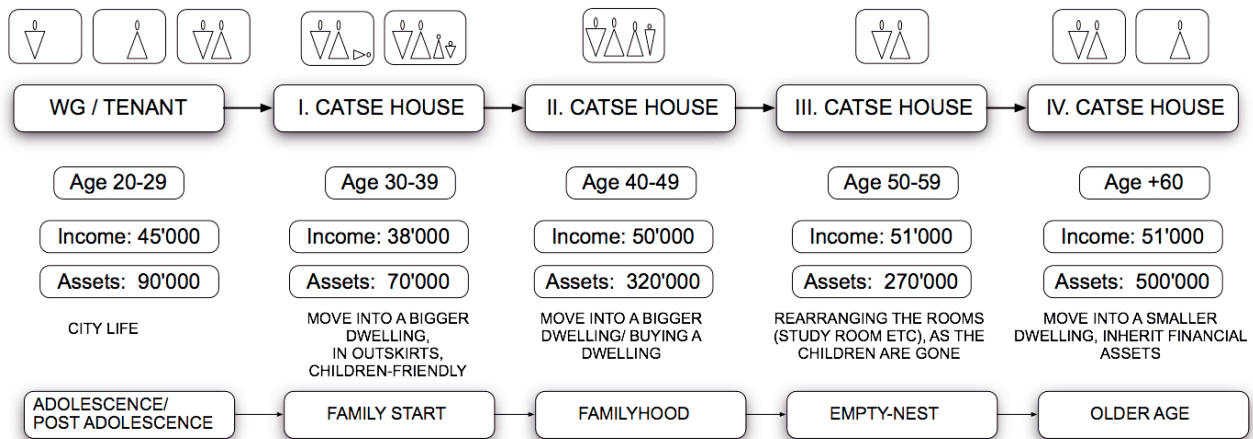


Figure 2.13 - Life-long relocation with CATSE Housing.<sup>1</sup>

## 2.4 Quality: A Swiss Tradition

One's perception of a dwelling's quality is assessed by several different factors, including human comfort, safety and amenities. Studies pertaining to quality in housing have focused on the following specific parameters:

- *Space*: size of dwellings, size of rooms, private circulation spaces, common interior spaces, internal layout, storage spaces, and private outdoor space
- *Accessibility*: external access, size of circulation spaces, doorways, size of rooms, size and use of equipment, other mobility, consideration for people with sensory impairments, provisions for future adaptation
- *Internal Services and Hygiene*: power and lighting sockets, telecommunications, TV

<sup>1</sup> Margrit Hugentobler and Andreas Huber, *Lebensphasen, Wohnungsnachfrage und Finanzielle Situation* (Tagung des Novatlantis Bauforums, Zurich, 20 Jun. 2006).

aerial sockets and radio reception, provision for/of kitchen appliances, provision of sanitary equipment, refuse storage and collection

- *Internal Environment and Health*: heating system, water supply and hot water system, energy efficiency, ventilation, air quality, daylight and sunlight, acoustic performance

- *Safety*: safety of stairways and at other changes of level, safety of windows and glazing, kitchen safety, safety of heat-producing appliances

- *Neighborhood*: density, vehicular and pedestrian circulation, car parking, common open areas, privacy, security, other neighborhood quality topics

- *Architectural expression*

- *Technical Aspects of Construction Materials and Structure*<sup>1</sup>

This subchapter will offer a brief summary of the areas in which CATSE cardboard housing has a particular quality advantage in the context of innovative housing in Switzerland, where the majority of residents are highly concerned with issues of quality.

### 2.4.1 Location as a Parameter for Quality

The oft-repeated phrase “location, location, location” expresses the long-experienced importance of neighborhood and location choice in real estate properties. Numerous housing studies on consumer behavior indicate that location as one of the top three priorities for potential homebuyers.<sup>2</sup> The perception of location as an important fact in home selection is further supported by the data collected in the social acceptance survey conducted within this study.

In general, the trend observed in rent versus location is that many residents now choose to live closer to the city center to save on travel costs and commute time, despite the fact that it is typically more expensive to live closer to the city center. However, in Switzerland, the strength

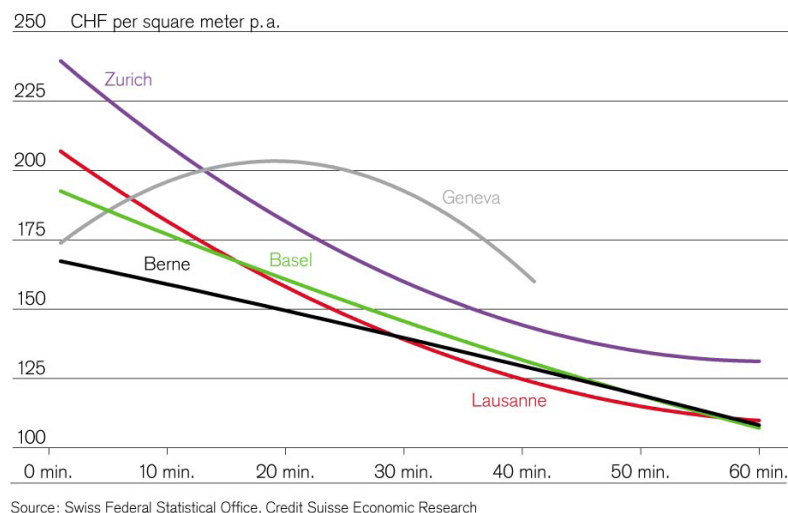


Figure 2.14 - Age distribution according to municipalities.<sup>3</sup>

<sup>1</sup> *Comparative Study of the Control and Promotion of Quality in Housing in Europe* (UK Communities and Local Government Organization, 1999).

<sup>2</sup> After location, cost and property size are the next two highest priorities for potential home buyers.

<sup>3</sup> Schuler et al. 111.



of this trend is significantly weaker as a result of the country's vast public transportation system. Nevertheless, rents still fall in line with the distance from the city center, especially in population centers such as Zurich, Basel, Bern and Lausanne (Figure 2.14). Additionally, statistical studies have shown that a significant percentage of low income young couples move to suburban areas once they have their first child.

On the other hand, a counter trend is simultaneously observed in Switzerland's periphery-*mania*, with a resurgence in the appeal of densely populated metropolitan areas, which has resulted in resulting in a boom of apartment blocks supply. A large portion of these new apartment buildings have been built in the major centers of Geneva, Zurich and Basel. Zurich alone has accounted for 35 percent of all recently approved apartment units.<sup>1</sup>

With regard to the implementation of cardboard housing, it is essential to identify and analyze the two parameters that are directly related: location and price. The main limiting factors for the cost in relationship to the location choice for cardboard housing is the ten to fifteen year renewal interval and the two-story height restriction.

Initially, placement of cardboard houses in the suburban environment will be accomplished to avoid the high cost of real estate in the city centers. Several housing studies provide support for this decision, asserting sustainable interventions in suburbia as ideal practical laboratories. Additionally, placing the cardboard buildings in the periphery as an initial strategy for the implementation will allow for more rapid and effective development since suburban areas often have less stringent building requirements<sup>2</sup> (Figures 2.15 and 2.16).

In case of governmental ownerships, experimental cardboard housing has potential in being located in city centers, despite the high price vs. square meter ratio. On macro level, even at the start of the implementation process, cardboard buildings with short life-span can be a tool for urban sprawl control with limited time vs. usage matrices. The bigger scale applications of cardboard housing in control and diversion of urban planning by authorities, offering customized ownerships (both time limitations and usage-function limitations) is to be further examined.

<sup>1</sup> *The Swiss Real Estate Market: Facts and Trends* (Credit Suisse, Feb. 2005).

<sup>2</sup> *Smarter Living, Generating a New Understanding for Natural Resources as the Key to Sustainable Development*, (The 2000 Watt Society) 12.

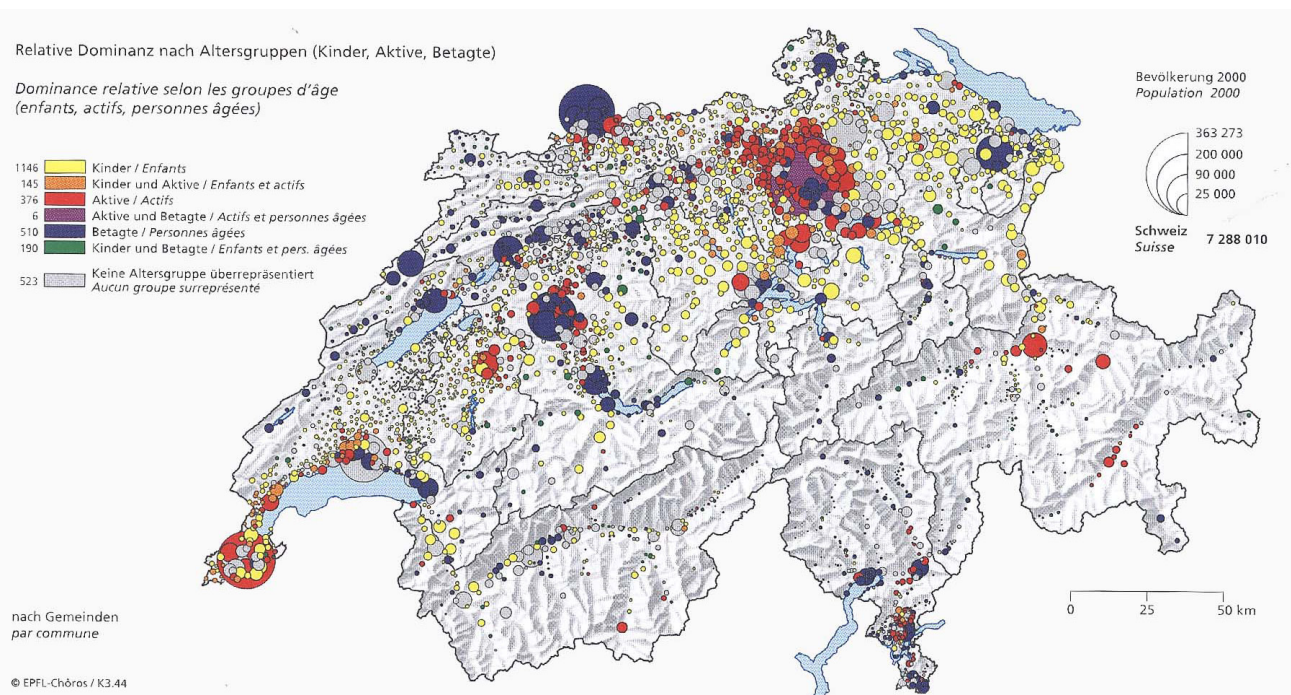


Figure 2.15 - Distribution of age groups according to municipalities<sup>1</sup>

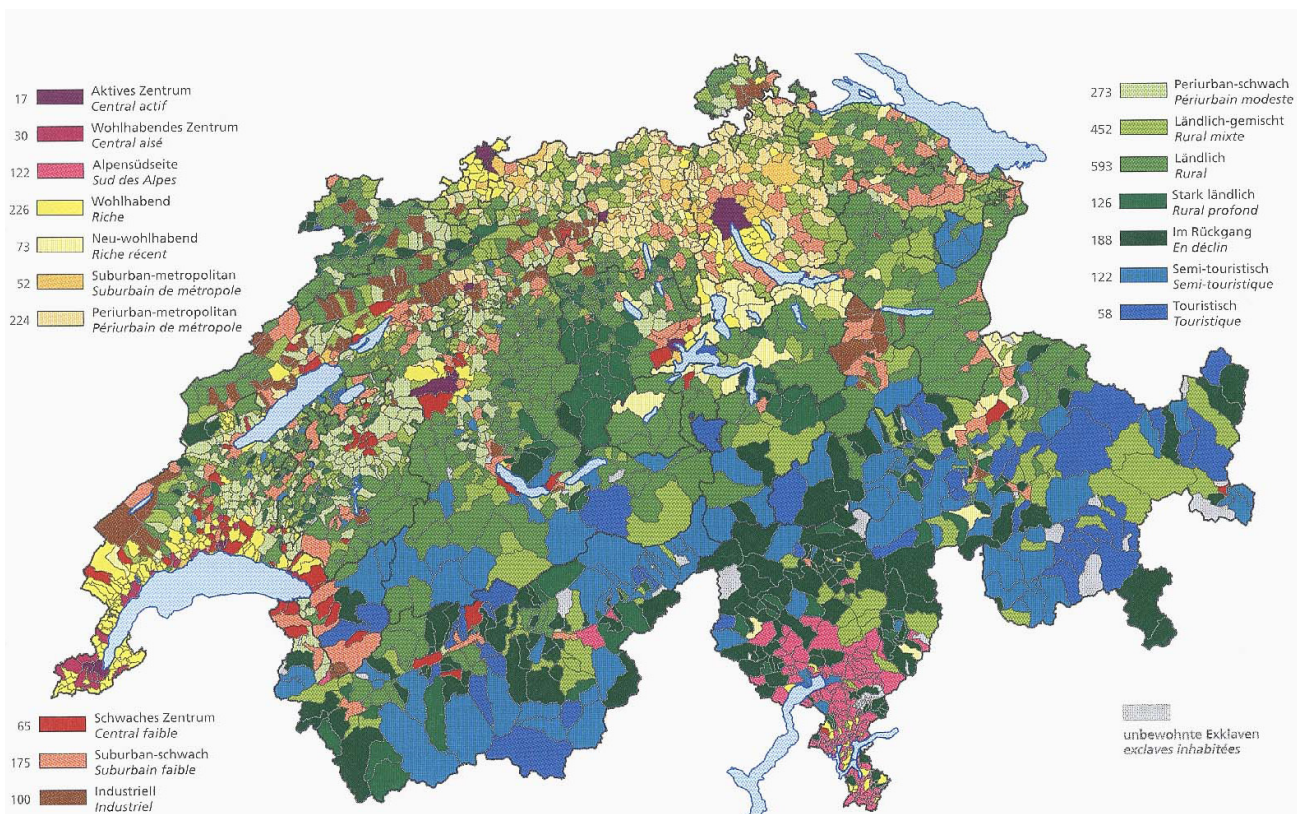


Figure 2.16 - Distribution of spatial characteristics.<sup>2</sup>

<sup>1</sup> Schuler et al. 381.

<sup>2</sup> Schuler et al. 385

#### **2.4.2 Materials and Construction Type: An Increasing Awareness**

In terms of choice of materials and construction style used for housing, along with their financial prosperity, Switzerland's citizens, as mentioned above, generally pay more concern the environmental impact of their housing choices. In many situations, their financial prosperity allows them to afford some of the high initial costs associated with installing environmentally friendly solutions. Recent consumer behavior studies in the real estate market indicate a significant increase in the number of wood constructions and other eco-conscious housing built in Switzerland. In addition to wood construction, the following construction types are used to categorize the Swiss housing construction market:

1. Wood Construction: Timber remains an important material in the construction of new homes. In 2005, the number of wood constructions for new single-family homes increased substantially.<sup>1</sup>

2. Minergie Houses: According to Wuest & Partner's recent publication *Immo-Monitoring 2006*, homes that employ the Minergie technology have shown the greatest increase in recent years. Minergie buildings use ecologically and economically sound materials designed based on a "minimum energy" concept. In general, new homes that are constructed using Minergie technology have high initial costs means higher initial building costs than traditionally constructed homes. However, owners experience a substantial decrease in lifetime energy costs.<sup>2</sup> The CATSE project intends to gain approval to use the Minergie label by using simple technologies that are energy efficient.

3. Beton: According to Wuest & Partner's recent report, usage of beton as the main construction supporting system material continued to be the most used material in Switzerland. However, usage of masonry, in housing constructions has steadily decreased its market share but still maintains a leading position in the building construction market.<sup>3</sup>

4. Facades: Wood cladding and curtain walls also continue to hold a significant share of the in Swiss home construction market. Although plastered facades lost some of its market share in 2005, they still hold a fifty percent market share. They are mostly used in renovation and new building construction. In recent years, the popularity of curtain wall facade cladding with materials such as eternit or wood by-products has increased substantially. Accordingly, the number of wood construction increasing in number is predicted to further aid the popularity of cladding systems. Additionally, glass-metal, masonry and exposed masonry continued to hold a seven percent share of the Swiss housing construction and renovation market.

<sup>1</sup> *Immo-Monitoring 2006* (Wuest & Partner, 2006) 82.

<sup>2</sup> *Immo-Monitoring 2006* (Wuest & Partner, 2006) 81.

<sup>3</sup> *Immo-Monitoring 2006* (Wuest & Partner, 2006) 82.

### 2.4.3 Other Preferences Affecting Housing Selection

The last category that helps shape the quality trends in the housing market are miscellaneous other consumer preferences, which focus on the physical capacity of the house. These preferences range within planning and design of the building described in themes such as total room number, property size or daylight exposure, and personal choice of building material. Within this study, a survey is conducted to better understand the some of these priorities. A more complete analysis into consumer behavior in cardboard housing market in relation to complex and changing lifestyle choices, the interrelationships between diverse expectations, and socio-cultural backgrounds of the users are issues that go beyond the scope of this study. This study merely aims to provide a brief introduction into these areas.

### 3. Social Acceptance of Cardboard Housing: A Demonstration Study for Users

Today, there remains a strong cultural bias against cardboard as a legitimate building material, as many consider it to be a mere byproduct of simple paper. The majority of people continue to associate cardboard with the packaging industry, which often uses a lower grade product. Because of these long held beliefs, the characteristics and full capabilities of the material are not well known among the general public.

In order to find a solution to the problem of widespread societal acceptance of cardboard as a building material and cardboard housing in general, a statistical survey 200 Swiss residents was been conducted within the framework of this study. The survey attempts to identify trends, collective consumer behavior, and respondents' acceptance of cardboard as a building material, as well as their expectations relating to a new home. The following subchapter identifies and explores several questions and doubts raised by respondents to guide the strategy for successful implementation of cardboard housing in Switzerland (Figure 2.17).

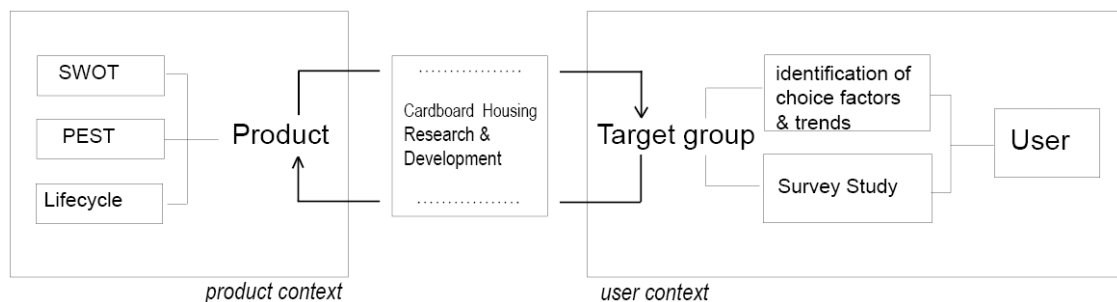


Figure 2.17 - Chapter structure: "Cardboard Housing" on user vs. product level.

### 3.1 Introduction: Social Acceptance as a Theme

The two primary categories that have brought attention to user acceptance have been the unconventional short lifespan of cardboard buildings and the acceptance of cardboard as a building material. To address these concerns, the following questions were posed:



*1. Demographic changes, new commercial opportunities, social lifecycle/needs/demands/realms and other basic lifestyle changes confirm the obsolescence of a single dwelling throughout the lifetime of a user. The traditional way of seeing dwellings as an investment - a lifetime inheritance object is therefore altering itself. How strong are these trends to support the buildings constructed from cardboard, which has an estimated life-span of 5, 10 or 15 years?*

*2. What could be the user profile within the Swiss market structure for this new concept of cardboard construction? What are the social and cultural impacts and issues that have to be identified to address its benefits to the society? Since architecture itself is a social instrument in cultural terms, what other macro dimensions of social psychology are related to the acceptance factor of an innovative building system with cardboard?*

*3. Finally, how, in reaction, could a strategy concerning the architectural language be formulated by articulating cardboard's potential and characteristics? How to effectively influence the perception and to persuade the public to be convinced of CATSE Cardboard housing?*

The act of perceiving a product and acceptance of what it represents and offers involves the study of human behavioral science. Apart from the physiological comfort level, even sometimes contradictively trespassing it, the societal comfort acts a leading role in acceptance in wider sense of a product.

For spaces, the science of environmental psychology investigates societal the acceptance theme using inter-independent tools such as context and spatial characteristics, in collaboration with the reflections of physiological comfort factors (noise/acoustics, temperature, lighting, air-quality). Accordingly, an architectural product: a dwelling to be claimed as "pleasant" (positive perceiving) and accepted whether materially (purchased/rented) or spiritually (admired) is a complex issue. The parameters for choice as described in prior subchapters are "price," based on economic constraints, "location in the city," based on basic daily practical and social reasons, but also other physiological comfort related factors like total room number, "infrastructure," "daylight" or plainly the dwelling's positioning in the society among new trends, affecting the attractiveness or acceptance value of the house.

Concurrently, the role and perception of differentiation between the user and the designer, in the process of implementing new products like cardboard housing is quite challenging. Throughout history, implementation of new styles or usage of new materials in architecture has not taken place in a parallel timeline of acceptance between the architects and the users. In other words, as discussed thoroughly in the what lay people may consider architecturally pleasant or popular may, for various reasons, not coincide with the opinion of architects.<sup>1,2</sup>

<sup>1</sup> Banfi and Jakob.

<sup>2</sup> K. Devlin and J.K. Nasar, "The Beauty and the Beast: Some Preliminary Comparisons of 'High' Versus 'Popular' Residential Architecture and Public Versus Architect Judgments," *Journal of Environmental Psychology* 9, no. 4 (Dec. 1989): 333-344.

### 3.1.1 The Semantics of Architecture

The semantics of architecture, a catch-phrase well known in the field of examining the meaning of the architecture and the buildings associated in people's minds, has three basic concerns:

- 1) the relations of the physical presence of the buildings to the definitions denoted by them.
- 2) the relationship between the physical presence of the buildings with the interpreters - the users and designers.
- 3) in symbolic logic, the formal relations of buildings to one another in a complex environment.

As the physiological presence of the building is presented by the building material itself, the building material seems to have the most primary role in the perception and acceptance of a building. However, human perception does not only rely on what is seen visually, but also employs an elaborate evaluation system based on prior experiences and knowledge to contextually interpret the situation as a whole. The relationship between perceiving and accepting a design product, therefore does not only depend solely on the material itself as a visual presence but also based on the context and associations, and the user's interpretation. Using paper as an example of this concept, people tend to have positive associations with paper's use as wallpaper, but negative connotations when the same material is used as bedding for a homeless person. From this, the questions related to context are: what determines the like, indulgence or form, space and perception of a building? What is the role of the material? How would a cardboard dwelling need to be presented in order to be accepted by the user, designers and investors in the construction market?

The following survey, therefore, using these questions as a starting point, seeks to reveal some preliminary factors related to the user's associations of cardboard in order to build a framework to describe the architectural language of cardboard buildings.

### 3.1.2 Actors in the Implementation and Acceptance of a New Building Product

The key actors in the equation for a successful implementation of a cardboard housing project are the user, designer, investor and the legislature. To gain full acceptance of cardboard material for building systems requires a thorough understanding of these roles.

*Users:* The dwelling as a product where the user spends at least one third of his/her time is also a representation of private social space, highly connected to one's instinct for comfort and safety. This is certainly the reason a dwelling-home as a product is linked with many sociological and psychological identifications underlying the basic definition of a residence. The decision of where to live is much more complex process than a typical decision about, say, which toothbrush to purchase at the store. Consequently, a user's decision to invest in a new home, a dwelling with a new building system or material is an enigmatic task based on the culture, environmental and human psychology. Such a new product can only gain the user's trust over time, by observing and experiencing the product in the market or through other media.

*Designers:* For designers and architects, the effective communication of the capabilities and characteristics of the new system must be ensured. Material and system choice is highly dependent on the project and client, but also on the known strengths and the weaknesses of the material, the trends and tendencies of the architectural scene, and economic factors. In most cases, architects believe that the challenge to use a novel material/system is dependent on the material's flexibility in design. In the case of CATSE cardboard housing, the system offers not only sound structural performance, but also provides an economically and ecologically sustainability alternative.

*Contractors and Construction Companies:* Prior to accepting a new material and building system, contractors and construction companies focus on the efficiency of the new product, evaluating as a whole the financial, managerial and manufacturing aspects. Maintenance, infrastructure and risk management questions must also be clearly addressed and answered before these actors will enter the market.

As it applies to most of the new building system in the sector, the biggest drawback for the users, architects and contractors is the period immediately after implementation during which time the product proves has yet to prove itself within the system. Therefore, often times new technologies are applied to public buildings sponsored by the state or large, economically stable organizations.<sup>1</sup> The survey conducted as a part of this study acts as a starting point for positioning users' opinions related to cardboard housing. This same method will be applied to designers, and contractors in the future.

### **3.2 Social Acceptance Survey Study for Cardboard and Cardboard Buildings**

The primary goal of the survey is to provide a pathway for this research - a conceptual approach to cardboard housing and the social acceptance issues of cardboard as a building material. By creating an information resource, the aim of this study is to build an understanding of the material and the formulating of an architectural strategy in the next stages of the research.

#### **3.2.1 The Structure of the Survey**

The goal of the survey was to reach as many respondents in short period of time for purposes of evaluating general social acceptance without overwhelming or confusing respondents with an extended series of complicated questions. The entire survey was thus contained to a single page of six simple questions. The respondents' identity has been kept anonymous and were asked only to state their nationality, age, occupation and education level to define the profile of the potential user. An introduction letter with a brief explanation of the research objective was distributed together with the questionnaire. The survey was distributed personally as well as digitally via electronic mail. A recognizable logo of the university, *ETH Zurich*, was placed on the top of the survey form.

<sup>1</sup> Vock 12.



Two hundred survey respondents were chosen at random to obtain a reasonable sample size and degree of diversity for the study. From December 10-14, 2006, approximately 150 individuals were contacted electronically and personally with the option of forwarding the survey to a friend or acquaintance.

### 3.2.2 Characteristics of the Survey Respondents

The characteristics of survey respondents have been divided into categories based on age group, gender, educational level and nationality.

**Age:** In Figure 2.18 below, information regarding respondents' age is presented. Age statistics were collected to determinable the relationship between age and the perceptions of cardboard as a building material, the frequency of relocation, the personal preferences for a new house, and reactions about cardboard architecture. Assuming that preferences would differ among age groups, the overall result of the survey would accordingly affect the product's implementation strategy. The majority of the respondents fell within the 24-34 age category, which coincidentally the proposed target age group for the end product.

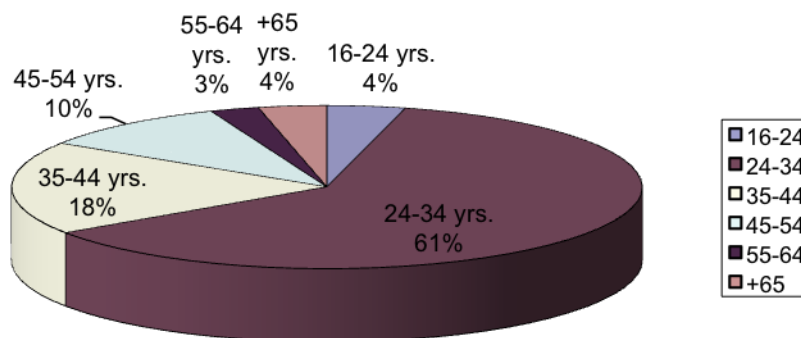


Figure 2.18 - Age of Survey Respondents.

**Gender:** Men represented sixty percent of all survey respondents, while women made up forty percent, as shown below in Figure 2.19. The gender disparity is essential to determine the relationship between age groups profile and primary preferences related to a new home in the second survey question. This highlighted the difference in preference for a new house based on gender.

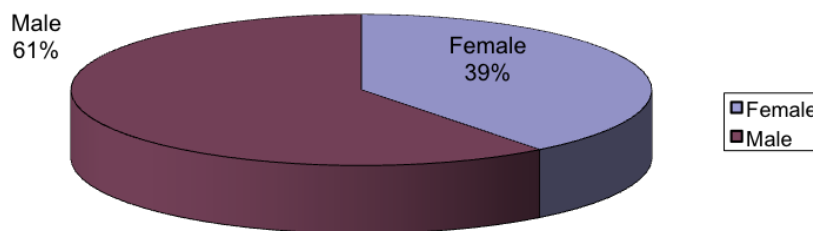


Figure 2.19 - Gender ratio among the Respondents.

*Education Level:* The respondents' education level is presented in Figure 2.20. The education level of the survey respondents is higher than that of the general population, with 48 percent of respondents reporting having obtained a graduate degree (Masters or PhD). However, the the survey results indicated that there was no disparity in a respondent's association of cardboard as a building material based on their level of education.

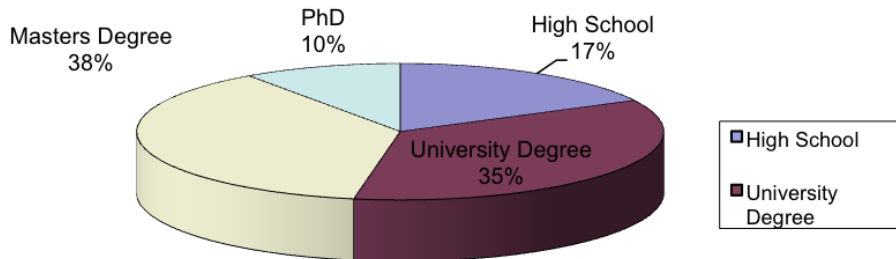


Figure 2.20 - Education level of Respondents.

*Nationality:* Although the survey was intended to demonstrate Swiss-born residents' social acceptance level for cardboard as a building material, due to the high rate of the foreign-born residents in Switzerland, Swiss Nationals composed only 63 percent of all respondents, as shown in Figure 2.21. The rate of respondents from neighboring countries such as France, Germany, Italy represented fifteen percent of total respondents. The remaining 22 percent were born in various foreign countries, including Turkey, United States, Greece, Japan, and New Zealand. The results demonstrate that a respondent's nationality was not a significant indicator of preference for cardboard as a building material.

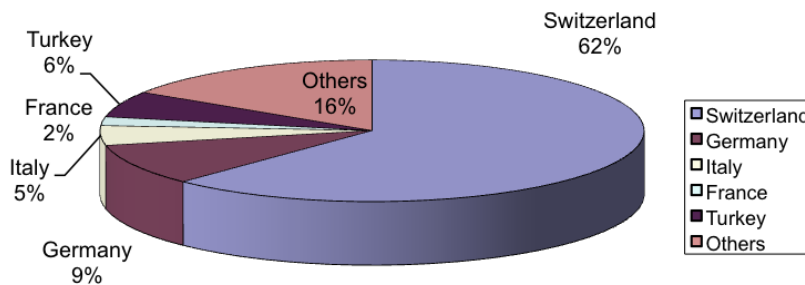


Figure 2.21 - Nationality distribution of the Respondents.

### 3.2.3 Survey Questions and Evaluations

The survey, "Social Acceptance in Cardboard Housing," aimed to cover aspects that are related to user preferences about a new dwellings and the perception of cardboard as a material and as an end-product: the building.

#### 3.2.3.1 Question 1: Frequency of Relocation

The survey begins with a reference question regarding the relocation frequency of users of dwelling as indicated in "Immo-Monitoring" market research study by the firm Wuest & Partner in Switzerland.<sup>1</sup> The survey questions the relatively high rate of relocation shown in the report.

<sup>1</sup> Immo-Monitoring 2006 (Wuest & Partner, 2006).

Out of 200 respondents, 88 percent revealed that they had relocated at least once to a new residence within their lifetime. Seventeen percent of respondents reported relocating more than eight times, while thirty percent reported relocating between five and seven times, and 40 percent reported moving between two to four times during their lifetime.

The survey results support the earlier finding by Wuest and Partner that Swiss residents have a relatively high rate of relocation. Figure 2.22 presents this frequency as a percentage of relocation based on the respondents' age.

The results indicate that there is a linear increasing relationship between a respondent's age and the number of times they have relocated. The results show a slight increase in the number of respondents who report having relocated at least five times, increasing with age. The 55-64 age group had the highest rate number of respondents who have relocated between five and seven times, demonstrating a high rate of mobility. The only notable exception in the survey was among respondents age 65 and over. However, there were a low number of respondents in this category, so the results may not be representative of the population. Moreover, there is a noticeably unevenly distribution among each age group, and there appears to be a nonlinear relationship between the frequency of relocation and the age of the respondents. Thus, the greater number of relocations reported by older respondents does not necessarily imply a higher degree of mobility or likelihood of future relocation.

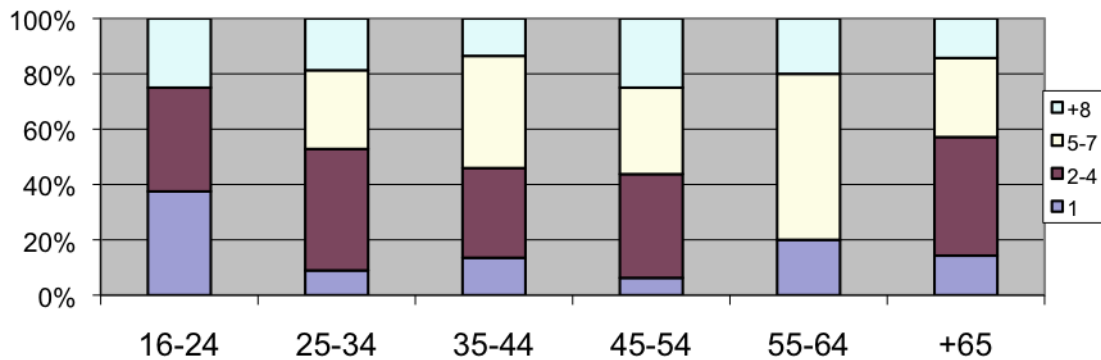


Figure 2.22 - Rate of relocation based on Respondent's age.

### 3.2.3.2 Question 2: Consumer Preferences in New Dwellings

The second question was formulated to investigate the priorities that users look for in a new dwelling and to determine the relationship between the user and diverse<sup>1</sup> variables. Represented with corresponding shares in Figure 2.23, responses included; location, price, plan/design, daylight, total no of room, style, material quality, parking facilities, balconies/lifts, room dimensions, typology, infrastructure, security, investment potential and age.

<sup>1</sup> Third National Communication of Switzerland 2001 (Swiss Agency of Environment, Forestry and Landscape, Jul. 2001).

The respondents were also asked to choose the most favorable three variable among the list or, in the alternative, to input their own choice. Out of 200 respondents, location (29%) was the most important variable identified, with price as a close second (22%), followed by plan/design (8%). Figure 2.23. illustrates the variables that respondents reported to be most crucial in the selection of a residence. Figure 2.24. provides further analysis of the survey results by setting forth the number of respondents who selected each variable.

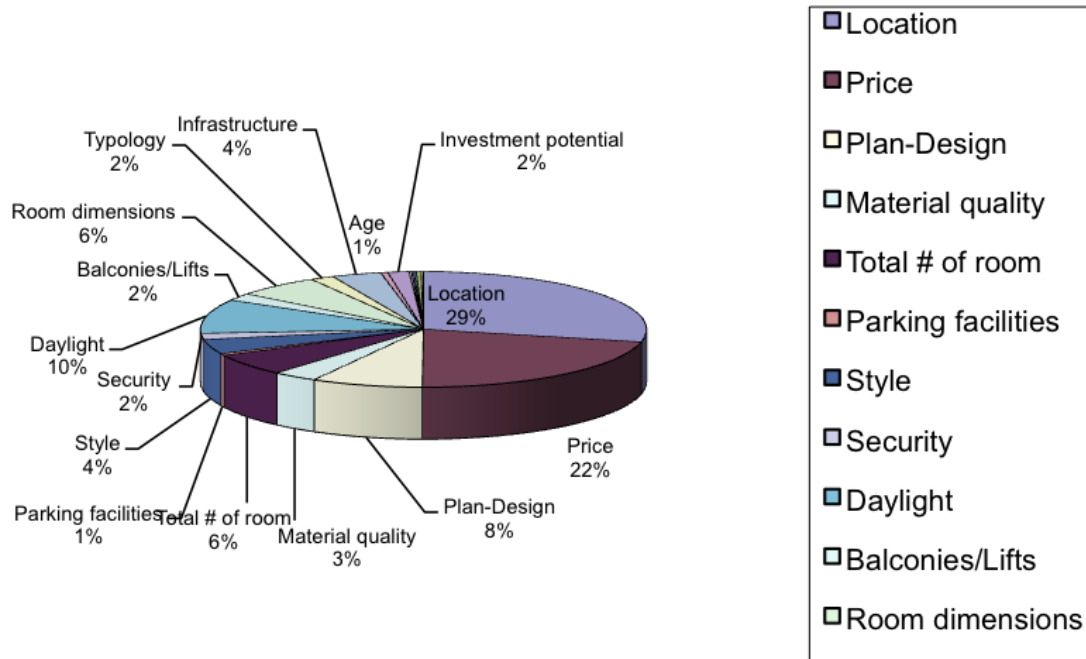


Figure 2.23 - Preference criteria for a new home.

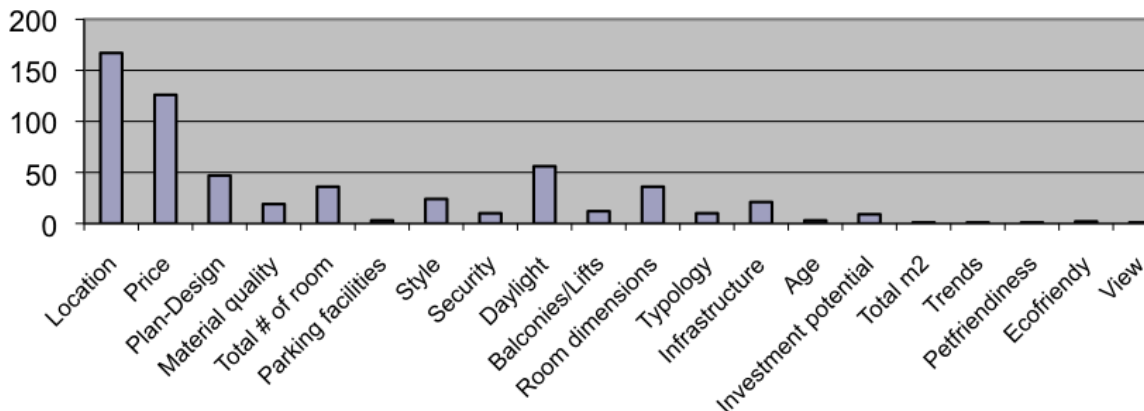


Figure 2.24 - Numerical graph indicating number of respondents and their preferences.

When respondents' preferences are examined in terms of their relevance in cardboard buildings, the responses can be further categorized into two subsets, namely "CATSE-related" and "general." As shown in Figure 2.25, price, plan/design, room dimensions, infrastructure, material quality, security, material quality, typology, investment potential, and age have been categorized as CATSE-related. Additionally, the respondent-inputted variables "pet friendliness," "eco friendliness," and "trendiness" have also been labeled as CATSE-related for purposes of Figure 2.25.

Analysis Question 2 : Preference categories on a new dwelling

Independent Categories	Location, Total Room Number, Parking Facilities, Typology, Balconies / lifts, Daylight
Categories effecting the Cardboard Dwelling	Price, Plan/Design, Material Quality, Room dimensions, Infrastructure, Style, Security, Investment potential, Age of the building

Figure 2.25 - Preference categories in a new dwelling.

Figure 2.26 indicates the critical variables directly related to the prospective CATSE cardboard buildings. These points indicate the priority in the examination and investigation of the design process of CATSE building.

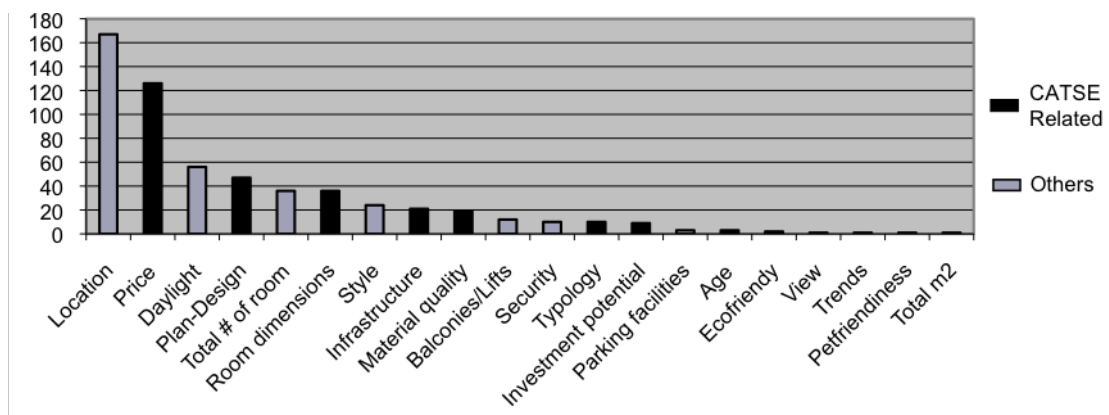


Figure 2.26 - Preference categories in a new building in relation with this research.

3.2.3.3 Question 3: Negative Experiences With New Dwellings

The third question of the survey asked respondents whether they have had any negative experiences moving into a new residence. The purpose of the question was to determine the reasons people have disappointing experiences with new homes. Based on the responses to this question, the problems that respondents were unhappy about have been classified to constitute the facility managing approaches for CATSE cardboard housing. Figure 2.27 lists respondents' most frequently cited "disappointing" characteristics of a new residence. The most commonly selected problem was "infrastructure and other structural problems," cited by 26 percent of respondents. The next most frequently noted complaint was "sound insulation," which 21 percent of respondents cited, followed by 18 percent who have had problems with "neighbors or neighborhood." As all these complaints have some connection to the choice of the material cardboard, these survey responses imply that the target user group has realistic expectations about the potential of cardboard housing and some its limitations.

The list of disappointment categories is summarized and formulated according to the direction of the response. The participants who cited "inadequate space" as a complaint were mainly suffering from a lack of adequate storage space and poor floor design. Those who cited "sound insulation" problems were often disturbed by noises from the urban environment or as a result of thin separating walls. The complaint of "energy issues" incorporated general energy

loss and inadequate insulation, as well as the negative effects of “encapsulation” when a building envelope becomes so enclosed that the users feel uncomfortable. Complaint regarding “infrastructure” included a building’s weak infrastructure and foundation, problems caused by low material or building quality and decay caused by pests, insects, fungi, and mold.

**3.2.3.4 Question 4: Associations with Cardboard as a Building Material**

The survey’s next aim was to determine how and with what respondents associate cardboard. The hypothesis was that people generally associate cardboard with its uses in the packaging industry. The survey found that 26 percent of respondents associate cardboard with its capacity in the storage and packing industries. Also, it was predicted that people held rather negative connotations about the capabilities of the material. These negative associations were clearly stated under option “Characteristics (-),” which was selected by twelve percent of all respondents, who described the material as “a cheap/no quality,” “non-stable,” “messy when wet,” “ugly,” “low durability outdoors,” “weak,” and “combustible.” The distribution of association themes are illustrated in Figure 2.28.

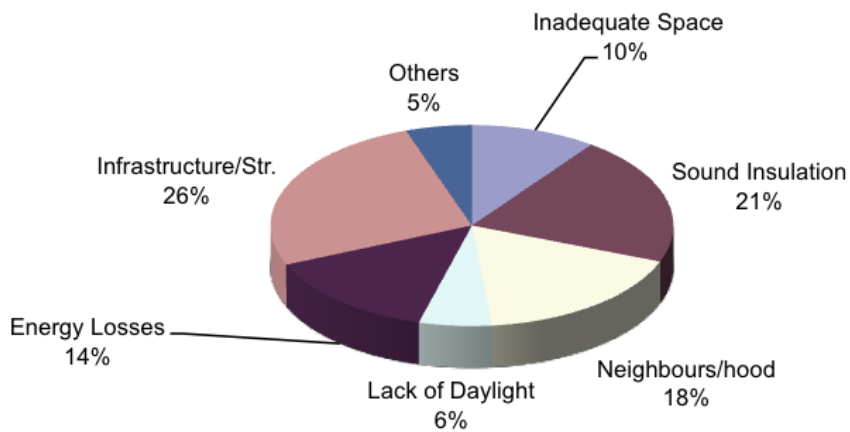


Figure 2.27 - Disappointment categorization of the respondents in a new house.

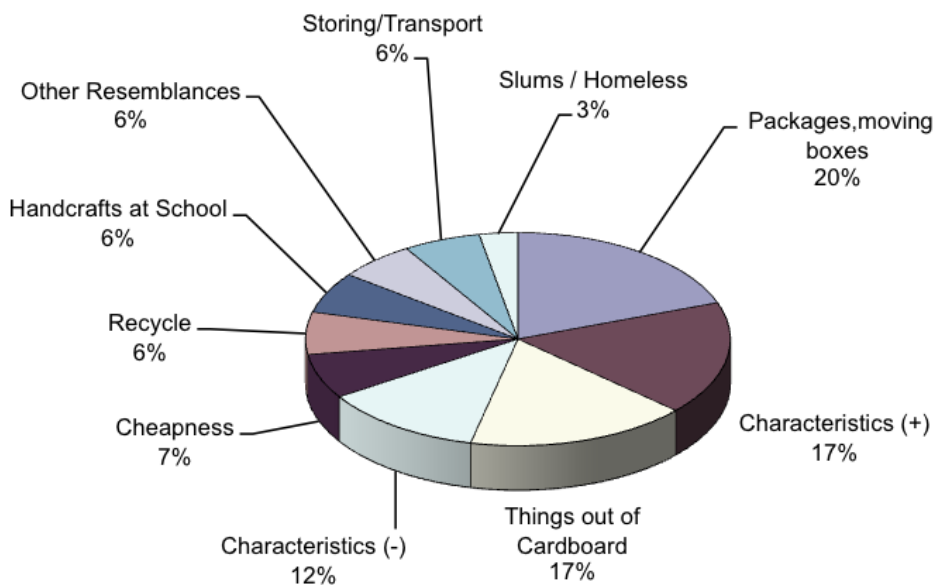


Figure 2.28 - Respondent’s associations of cardboard.

The percentage of common associations with cardboard are illustrated in Figure 2.28. They are summarized and formulated under titles according to participants' responses. The response "Packages and Moving Boxes" (106 respondents) relates to associations respondents have with moving boxes and other packaging for diverse products. The response "Things out of Cardboard" (92 respondents) includes respondents who associate cardboard with a diverse palette of products, such as egg cartons, furniture, paravane, shoeboxes, toys, and architectural models. The response "Cheap" (37 respondents) includes both the positive and negative connotations of the word, which can relate to both a products quality and its affordability. The response "Recycle" (35 respondents) relates to the associations of cardboard with recycling process. The "Positive Characteristics" category relates to respondents who have characterized cardboard by using adjectives such as "universal," "modular," "disposable," "quick to install," "good insulation," "strong," "stable," "useful," "creative," "ecological," "foldable," "light," "efficient," and "flexible." The "Negative Characteristics" theme included respondents who described cardboard with terms such as "flimsy," "temporary," "not stable," "strange smell," "glue," "useless when wet," "humidity," "buckling," "noise," "weak," "ugly," "flammable," and "to touch uncomfortable." The response "Handcrafts" represents the associations people have with cardboard as being used in school, such as playing with cardboard and doing handcrafts in kindergarten.

The fact that the share of respondents who selected positive characteristics of cardboard (17%) was greater than those who focused on negative characteristics (11%) is evidence that most survey respondents associate cardboard with positive things. However, the survey also revealed that very few respondents had knowledge of the diverse fields in which cardboard is employed, and often times only associated cardboard with its uses in the packaging and storage industries. With regard to its potential uses in the field of architecture and construction, the results indicate that 8 percent of respondents associate cardboard with homeless people and slums. Accordingly, using cardboard in its raw form without any additional skin material in the facades/walls appears to be faulty strategy.

### **3.2.3.5 Question 5: Associations with Cardboard Buildings**

The next question of the survey attempted to assess respondent's views on cardboard houses, asking respondents to identify perceived negative aspects they held about cardboard houses. Figure 2.29 provides an illustration of the most commonly identified negative associations that respondents had about cardboard buildings. Through this graph, the the study hoped to achieve a better understanding towards forming a way to gain social acceptance of the CATSE building system.

A near-majority of respondents (47%) focused on the perceived structural problems that may occur in a cardboard building. Forty-nine percent of the respondents expressed concern about the structural integrity, especially under diverse weather conditions or point stresses, potential problems with joints, compatibility issues with other materials, sealing, friction problems, wind threat, overall security.



A cardboard building’s perceived inability to adequately deal with “Water/Humidity” was also cited by a majority of respondents (50%). Many listed worries about its ability to provide protection against rain, moisture, humidity and seasonal complexities posed by Switzerland’s quickly changing weather patterns.

The “Energy Issues” response addresses concerns about cardboard housing’s perceived problems with insulation and heating. The survey results revealed that the vast majority of the population is unaware of cardboard’s relatively high insulative value.

Under the response of “health/comfort”, respondents expressed concerns over the toxicity of the adhesive material used in corrugated cardboard. Concerns over mold, insects and rodents also fall under this category, as well as concerns over indoor air quality, and other harmful chemicals that may be released when living inside a cardboard building.

Questions regarding the “durability” of cardboard houses were also raised by several of the survey’s respondents. This response includes concerns related to the expected lifetime of the material, its maintenance and disposal. This category also reaches questions from an investor’s point of view related to the investment value, methods of quality control, and length of investment. Several respondents also raised concerns about cleanliness and daily maintenance, issues which must be addressed.

Concerns over “sound insulation” in cardboard houses involve the belief that a cardboard wall would be unable to block outside noise from entering the building. Under the response “architectural expression/design” the survey aimed to gain a sense of the perceived aesthetic deficiencies of a cardboard house. Since most respondents expressed that they found cardboard to be “cheap-looking” and “ugly,” the implementation of the CATSE systems would involve concealing the cardboard material from the exterior of the building.

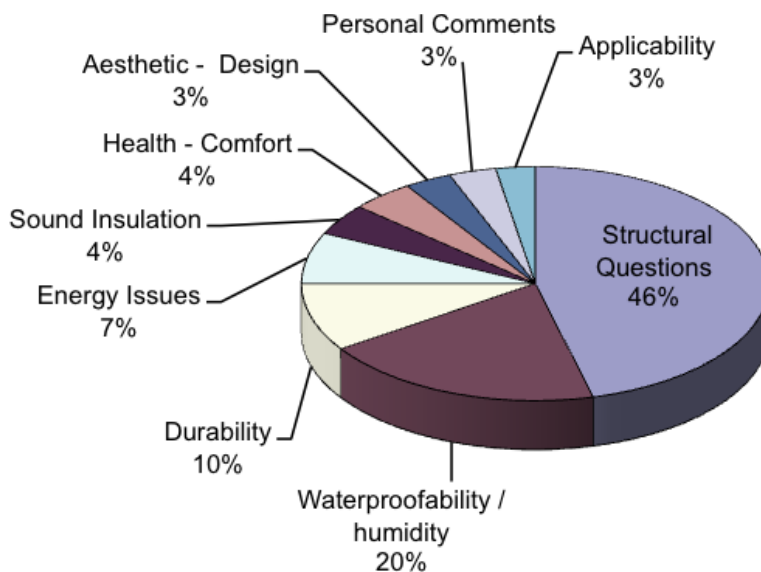


Figure 2.29 - Respondent’s associations with Cardboard Building

Finally, the “Personal Feelings/Comments” response permitted respondents to express any other thoughts or concerns about cardboard houses. Some participants candidly noted that cardboard buildings are difficult to imagine, and that cardboard building would have to overcome a tremendous amount of prejudice and lack of trust at the onset. Some respondents further expressed that the stigma attached to the cardboard as a material for homeless would prevent the material from gaining widespread acceptance as an alternative building material. These responses constitute legitimate concerns that must be addressed and communicated prior to the successful implementation of cardboard buildings.

### **3.2.3.6 Question 6: Increasing the Acceptance Rate of Cardboard Buildings**

The final question of the survey asked respondents what other factors would persuade them to accept cardboard as a feasible building material. The responses to this question are displayed below in Figure 2.30. Thirty-two percent of respondents stated that they further “scientific test results from the university and the state that prove that Cardboard Housing is structurally stable, waterproof, fireproof and secure” would help to convince them of the legitimacy of cardboard housing.<sup>1</sup> Besides scientific testing, 22 percent of participants noted that they would be more likely to accept cardboard housing if they were able to experience the finished product at an exhibition or fair. Twenty-seven percent of respondents stated that hearing about positive experiences with cardboard houses from friends or colleagues would cause them to have more confidence in the product. Similarly, ten percent said that positive reports from the news media would help to persuade them to accept cardboard housing, while only two percent claimed that commercial advertisements would be effective in doing the same.

Seven percent of respondents described their own impressions under the “Others” category. This section is divided into three major comment groups. The first group of respondents said that only a full-scale cardboard building that was tested for 3, 5, 30, or 100 years would persuade them to fully accept the feasibility of a cardboard house. The second group of respondents stated that they would be urged to accept cardboard house if they were permitted to personally experience a full-scale cardboard house for one week or longer. The final group of respondents listed a variety of additional measures, such as testing insulation of the building with electro-magnetic fields, or preparing a price/value study for investors.

Persuading factors cited in the final question were also analyzed with respect to the age group of the respondents. Figure 2.32 illustrates the distribution of responses based on respondents’ age. As the graph indicates, through nearly every age group, a high rate of respondents stated that they would be convinced of cardboard housing feasibility with further scientific test results and experiencing the product in exhibitions and fairs. Similarly, preference for mouth-to-mouth publicity was not influenced by age. Only respondents in the higher age brackets responded that commercial advertisements would convince them of cardboard housing’s legitimacy. The 45-64 age group had the highest percentage of respondents who claimed that media reports

<sup>1</sup> The term “cardboard architecture” has been used in order to convey a general feeling of a well-established building technology, complete with architectural quality in design.

would help to persuade them.

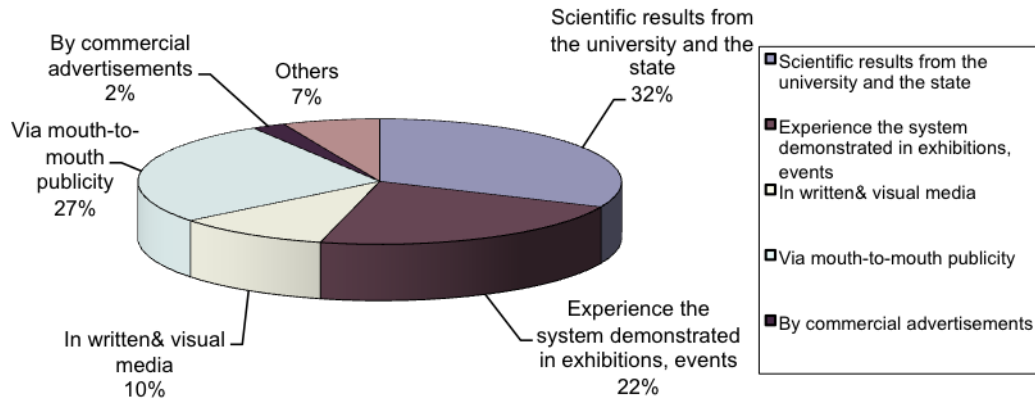


Figure 2.30 - Persuading factors for cardboard housing.

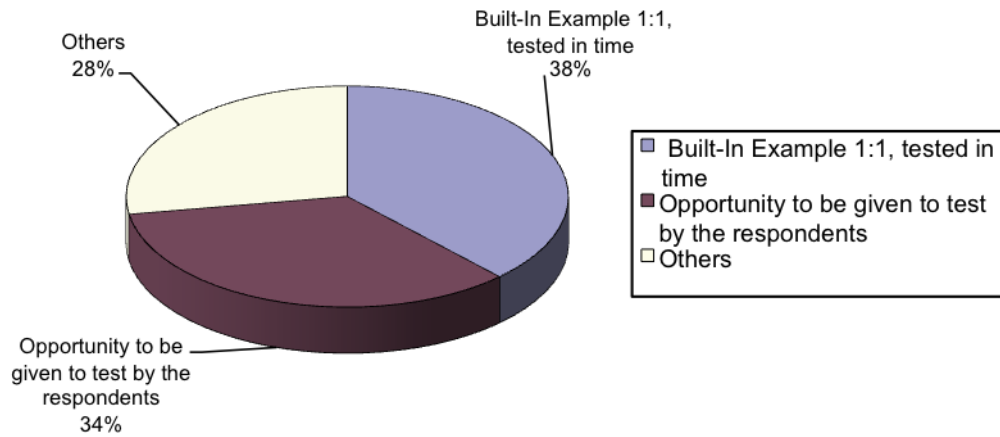


Figure 2.31 - Distribution of personal comments on persuading factors

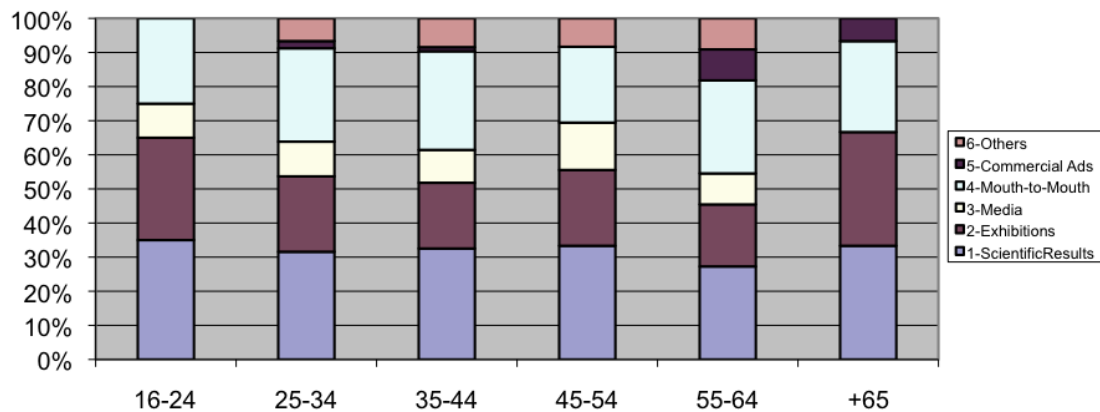


Figure 2.32 - Techniques for communicating the dependability of cardboard buildings.

### 3.3 Survey Findings and Conclusions

The survey helped to answer two basic questions: the acceptance of cardboard housing among the general public, and the characteristics and preferences of Swiss residents. It further revealed several facts regarding the direct link between the users and their opinion about cardboard as a building material. The results confirmed the following hypothesis as set forth below:

- *Although respondents frequently use cardboard in their daily lives, they have a negative opinion of cardboard's appearance. Thus concealing cardboard building components with various skins is a necessary strategy.*
- *The public is largely unaware of the structural and other material properties of cardboard- a fact which stresses the need to effectively communicate its advantages and potential uses as a structural component in modern buildings.*
- *There is no distinguishable disparity between age groups, level of education, or their associations or knowledge about cardboard. This result suggests that a general strategy can be applied to all groups.*
- *Swiss residents have a relatively high rate of relocation, due primarily to changing environmental and demographic factors.*
- *Cardboard housing systems need to fulfill the preference criteria of the user for new housing, as well as be able to alter their negative associations related to cardboard-building by communicating the capabilities and the product. Thus, CATSE building systems need to become highly visible in the media and at exhibitions and fairs where a high volume of people will be exposed to the new building material.*
- *LCA studies on the ecological sustainability and economic viability of the system must be effectively presented in various contexts, and compared to traditional buildings.*
- *Strategies that have been successfully applied to other new technology systems in Switzerland need to be analyzed to formulate a coherent marketing strategy for CATSE cardboard dwellings.*

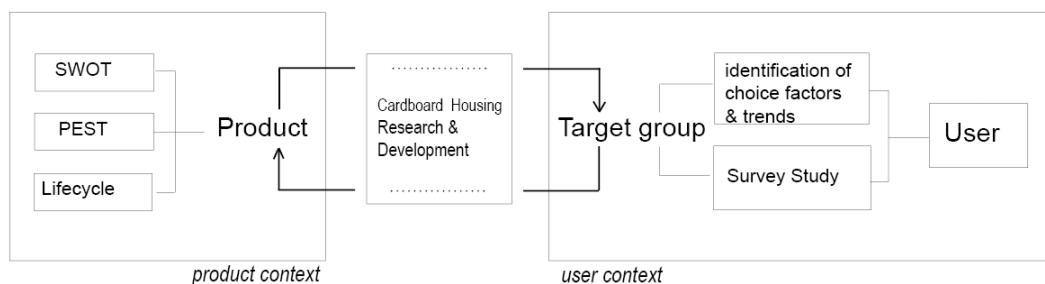



Figure 2.33 - Chapter structure: Cardboard Housing- User vs. Product level.



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## SURVEY ON SOCIAL ACCEPTANCE OF CARDBOARD IN HOUSING

WE ARE WORKING ON A PROJECT WHICH USES CARDBOARD IN HOUSING AS THE MAIN STRUCTURAL ELEMENT. THE MATERIAL ITSELF, IS ALREADY PROVED TO BE LOW-COST, ECOLOGICALLY AND ECONOMICALLY SUSTAINABLE, WITH HIGH HEAT INSULATION VALUES. THE RESEARCH GOAL IS TO FURTHER DEVELOP IT TO BE WATERPROOF, FIREPROOF & SECURE IN COLLABORATION WITH THE INSTITUTE OF STRUCTURAL ENGINEERING, ETHZ. THIS SURVEY IS THE SEARCH ON USER NEEDS AND PERCEPTION OF CARDBOARD. WE ARE GRATEFUL FOR YOUR COLLABORATION.

**Nationality:** .....

**Gender:**     Male     Female

**Age Group:**     16-24     25-34     35-44     45-54     55-64     65+

**Education Level:**     High School Degree     University Degree     Masters Degree     PhD Degree

**Occupation:**     Education     Finance     Legal     Media     Health     Service Provider     Government

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**QUESTION 1:**  
 HOW MANY TIMES UNTIL NOW HAVE YOU MOVED INTO A NEW HOUSE?  
 1     2-4     5-7     8+

**QUESTION 2:**  
 WHICH ARE THE MOST IMPORTANT THREE „MUST HAVE“ YOU WOULD LOOK FOR WHEN IN SEARCH FOR A NEW HOUSE?  
 Location     Price     Plan/ Design     Material Quality     Total Room number     Parking Facilities  
 Style     Security     Daylight     Balconies / lifts     Room dimensions (m<sup>2</sup>)     Type (ex: apartment/villa/etc.)  
 Infrastructure     Age     Investment potential for the future     .....     .....

**QUESTION 3:**  
 WHAT HAS BEEN THE BIGGEST DISAPPOINTMENT YOU EXPERIENCED ABOUT A NEW HOUSE YOU MOVED IN?

**QUESTION 4:**  
 WHICH THREE THINGS COME TO YOUR MIND WHEN GIVEN THE WORD „CARDBOARD“ (WELLKARTON)?  
 1-  
 2-  
 3-

**QUESTION 5:**  
 WHAT DO YOU CONSIDER AS THE MOST PROBLEMATIC THREE THINGS ABOUT A HOUSE PRIMARILY BUILT OUT OF CARDBOARD?  
 1-  
 2-  
 3-

**QUESTION 6:**  
 HOW DO YOU THINK YOU'D BE CONVINCED ABOUT CARDBOARD ARCHITECTURE ? (MAX. THREE)  
 By scientific test results from the university and the state that prove that Cardboard housing is structurally stabile, waterproof, fireproof and secure.  
 By experiencing the building system of CATSE demonstrated in exhibitions, fairs, events and other happenings  
 By means of written and visual media as in forms of articles, news etc.  
 By a colleague or another related person's personal experience (mouth-to-mouth publicity)  
 By commercial advertisements of the product  
 Others .....

Figure 2.34 - The survey form.

#### 4. Positioning of Actors for Implementation of Cardboard Housing

Defining the target group for cardboard housing is an essential aspect in implementing a development strategy for an innovative product. The first step is analyzing the general environment - political, economic, social and technological forces - that influence the market and the competitive arena (suppliers, competitors, substitutes, customers). Concurrently, an implementation strategy must be formulated and the target group defined for the offered service/product lifecycle in a specified niche of the market.<sup>1</sup>

Understanding Swiss residents and their general living habits is key to evaluating the parallels between the needs of the society and the innovative cardboard housing system. Statistically, in Switzerland, a family household continues to be the predominant living arrangement. Almost one-third of the population resides in a two adult household - 48 percent with children, 24 percent without. Only six percent of residents live in a single parent household. Among 35-49 year-olds, the traditional family structure (a married couple with one or more children) continues to make up the largest share of living arrangements with 58 percent of the population. A mere two percent of Swiss live in a household where an unmarried couple resides with children. Even among childless adults, a minority live alone - 28 percent of 21-34 year-olds and 37 percent of 35-49 year-olds live in a single person household.<sup>2</sup> Figure 2.35 provides a comprehensive picture of the household distribution in Switzerland.

To effectively market cardboard housing as an eco-conscious product, another key in defining the target group is evaluating the potential of selling low cost, environmentally friendly housing to Swiss residents. The present deficit in eco-buildings among Switzerland's residential building stock may be explained by consumer's general lack of knowledge and exposure to the personal benefits of such housing. This has prompted Swiss officials to invest in an informational campaign and adopt policies that provide direct subsidies to buyers of eco-friendly homes.<sup>3</sup> A recent study by Banfi, Farsi, Filippini and Jakob regarding home buyers and tenants and their reaction to more energy efficient buildings provides a more optimistic outlook for energy efficient homes. Their study demonstrates the following pattern: persons that choose new buildings prefer a high standard of living and consequently their willingness to pay for energy efficient measures may accordingly be higher.

Another analysis of the market for newly constructed Swiss homes by the construction firm Anliker AG confirms this demand and concludes there is a clear niche for economically, environmentally and functionally efficient housing, especially for younger families.<sup>4</sup> Anliker notes that families within this group demand practical, economical flats with an appealing architecture and healthy environment for children.

<sup>1</sup> *Business Opportunities in Sustainable Housing A Marketing Guide Based on Houses in 10 Countries*, International Energy Agency, Solar Heating and Cooling Programme (2006).

<sup>2</sup> *Statistical Yearbook of Switzerland - Statistical Data in a Nutshell* (Swiss Federal Statistical Office, 2007).

<sup>3</sup> Banfi et al. 1.

<sup>4</sup> *Business Opportunities in Sustainable Housing: A Marketing Guide Based on Houses in 10 Countries*, International Energy Agency, Solar Heating and Cooling Programme (2006).

Based on research by Margrit Hugentobler and Andreas Huber,<sup>1</sup> the renewal sequence for CATSE cardboard housing in a lifetime of a family is set forth below in Figure 2.37. The built-in renewal period for CATSE housing may prove to be a distinct advantage for young families whose needs and desires change on a regular basis. It is predicted that a young couple would initially move into CATSE housing as a tenant. After approximately ten years, having acquired a higher degree of financial stability, the couple may then choose alter their living situation based on these changed circumstances and the needs of the family.

	Housing units Total	% of singlefamily houses	No. of people per room	No. of people per household	% of homeowners
<b>Total</b>	<b>3 027 829</b>		<b>23.5</b>	<b>2.3</b>	<b>34.6</b>
Single-person households	1 072 342		10.9	0.34	19.7
Family households	1 895 226		30.9	0.68	43.5
Couples without children	833 309		28.5	0.50	42.9
Couples with children	884 009		35.1	0.84	46.8
Single-parent households	156 211		19.4	0.64	26.1
Single person with parent(s)	21 697		36.2	0.49	54.2
Non-family households	60 261		15.4	0.59	21.2
including relatives	15 858		22.6	0.56	36.0
including no relatives	44 403		12.9	0.59	16.0

Figure 2.35 - Housing conditions according to average household age. Source: "Statistical Yearbook CH" (2007).

However, given the optimum usage of the foreseen structure above, it is highly unlikely to immediately implement an innovative flexibility-oriented system into the real-estate market. In order to gain acceptance among users and investors, a developmental strategy must be created. The identification of the structure of Swiss household and living habits, together with the demand for the type of service cardboard housing is intended to provide, creates the basic framework of the developmental strategy. It places the following three target groups into the lifecycle of cardboard housing: innovators, tenants and buyers. The definition of these strategically oriented target groups, as well as the role of the investors in the lifecycle of CATSE cardboard housing are sought within the framework of this subchapter.

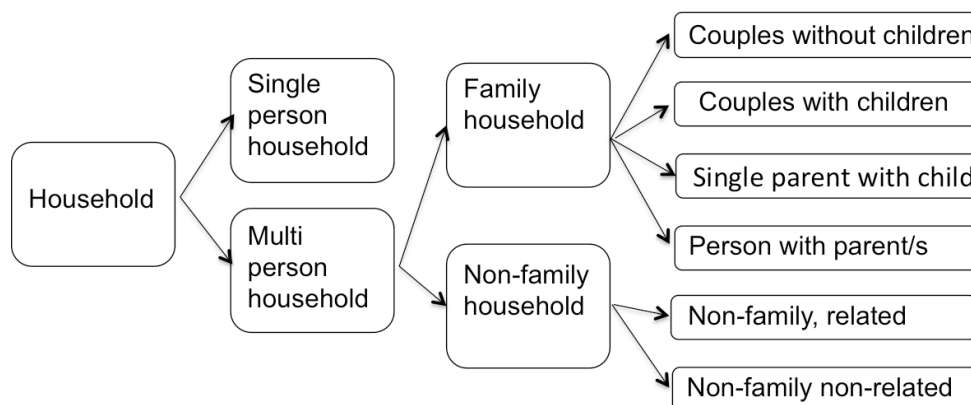


Figure 2.36 - Household Typology in Switzerland.<sup>2</sup>

<sup>1</sup> Hugentobler and Huber (noting Swiss residents' shifting dwelling demands).

<sup>2</sup> Swiss Federal Office of Statistics (2000).



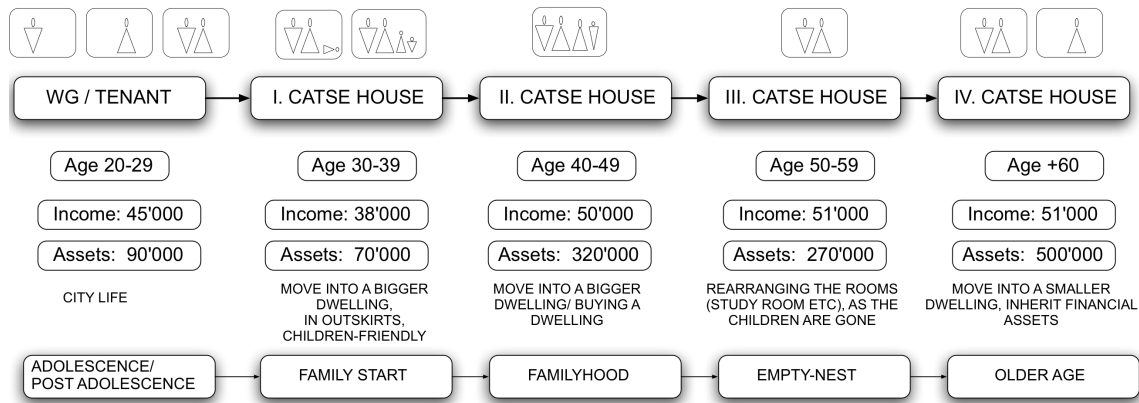


Figure 2.37 - Relocation with CATSE Housing.<sup>1</sup>

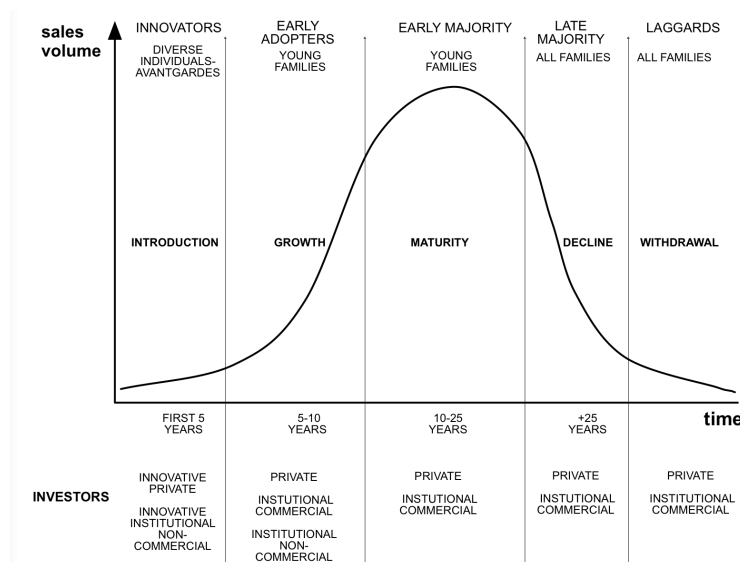


Figure 2.38 - CATSE cardboard housing product lifecycle.

#### 4.1 Positioning the Innovators in the Cardboard Housing Market

The focus for the introduction stage will be on increasing the market interest for cardboard housing and widespread communication of the product to wider masses (Figure 2.38). In this stage, potential homebuyers who are interested in CATSE cardboard houses will be divided into two categories: 1) those who have a special interest in the product, and 2) those who are so-called “innovators” or “avantgardes,” who are willing to try a new and untested product without price sensitivity. Once this group has tested out the product and provided a sufficient amount of feedback, the followers will enter the market. The innovators are expected to be concerned primarily with environmental factors - the trendsetters of the society who have the financial means and are more likely to take risks on innovative and creative products without the need for assurance. Therefore the marketing and communication plan for this group will focus on the underlying philosophy of CATSE cardboard housing. A strong emphasis will be placed on the product’s innovative technology, attractive architectural expression, flexibility, and energy efficiency.

<sup>1</sup> Hugentobler and Huber.

In terms of communicating the purchase price, during the initial years it is estimated that the average selling price to be on par with those for conventional housing, but will drop following this initial phase. Thus, the early buyers in the introduction phase are assumed to be less price sensitive.<sup>1</sup> The price category for this stage is foreseen to be in the middle to high range (considering the initial costs of the introduction phase). However, relatively to other eco-housing options, its price will be on the lower end of the spectrum.

#### 4.2 Positioning the Tenants for Cardboard Housing

As discussed earlier, due to the high purchase price of housing in Switzerland, along with the increasing rate of relocation among its citizens and the country's dependable public network, 65 percent of all Swiss residents are tenants. Particularly in the population centers, the home prices are extremely high and almost entire out of reach for the average resident (see Figure 2.39). Accordingly, following the first group of innovators discussed above, the development strategy of cardboard housing foresees the second target group as young families in urban areas who will be drawn into the market as renters. It is estimated that this group will begin entering the cardboard housing market 5-10 years after the product's introduction.

In Switzerland's mature economic landscape, residents are typically more concerned with the initial cost of housing than operational costs, and thus it is crucial to maintain prices at a reasonable level for this target group. It is assumed that on average the second group in the growth phase is relatively price sensitive.<sup>2</sup>

The most critical characteristics of young families is their concern are the financial limitations and the environmental consciousness. In many instances, they look to the avant garde group for direction. On average, they live in less costly residences outside of the city center, with a less chaotic and family friendly environment. They rely heavily on public transportation to commute to work. Additionally, they hold a steady job with a consistent income, but have yet to accumulate substantial savings.<sup>3,4,5</sup>

The strategic role of this target group is to serve as the vehicle to communicate the philosophy of cardboard housing. They are the group that is best situated to voice the benefits of the system and appeal to the next target group in timeline: home buyers. In this stage, sales volume will gradually increase as tenants begin transitioning into homeowners.

<sup>1</sup> *Business Opportunities in Sustainable Housing: A Marketing Guide Based on Houses in 10 Countries*, International Energy Agency, Solar Heating and Cooling Programme (2006).

<sup>2</sup> *Business Opportunities in Sustainable Housing: A Marketing Guide Based on Houses in 10 Countries*, International Energy Agency, Solar Heating and Cooling Programme (2006).

<sup>3</sup> Van Wezemaal and Ernest 116.

<sup>4</sup> Robert E. Leu, Stefan Burri, Tom Priester, *Lebensqualität und Armut in der Schweiz* (Bern: Paul Haupt, 1997).

<sup>5</sup> With the birth of its first child, the majority of couples elect to decrease their working hours, which often times places an increased burden on the couple's budget.

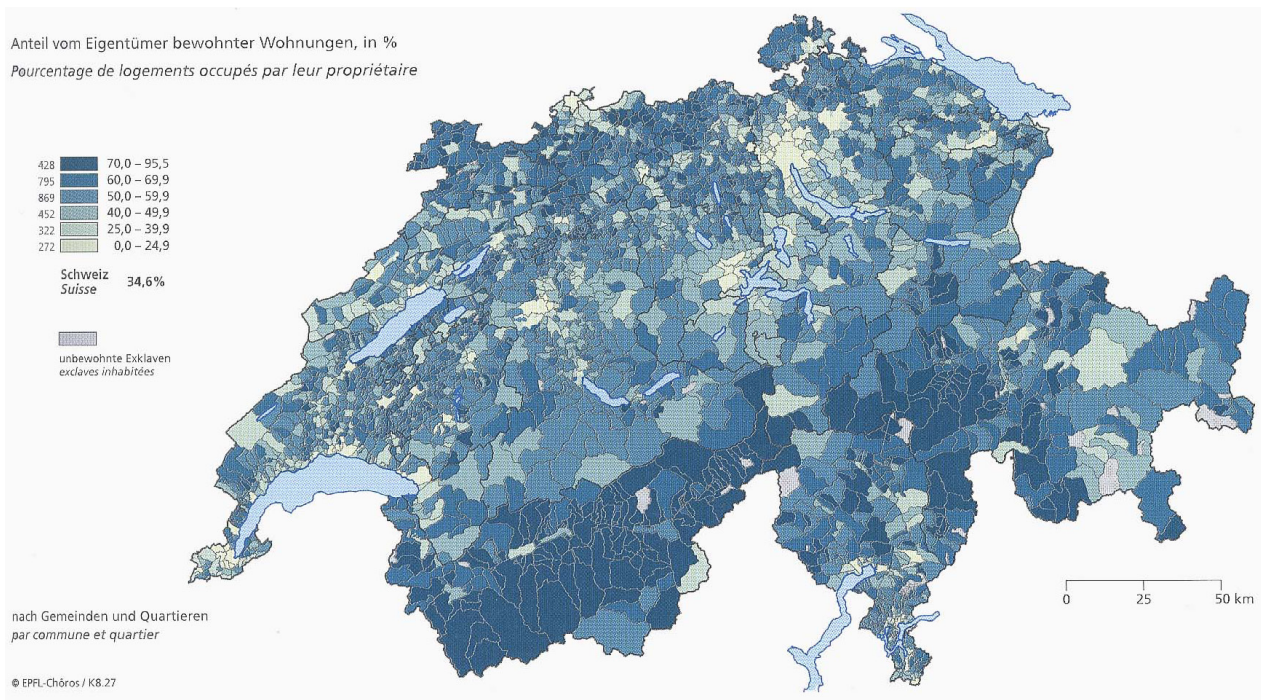


Figure 2.39 - Low rate of homeownership in Switzerland's population centers.<sup>1</sup>

### 4.3 Positioning the Buyers for Cardboard Housing

Eight to ten years after the implementation of CATSE cardboard housing, it is foreseen that institutional and profit-oriented commercial stakeholders and private buyers will enter the target market. These entities engage themselves with a new product only once it has established itself within a market.

In this *maturity* stage of cardboard housing, the characteristics of the target group are expanded. In general, these users are financially stable, environmentally-conscious young couples, single-investors, and established families from every age bracket. They will influence the system not only financially but also by exerting additional pressure on investors to implement further large-scale cardboard housing projects to satisfy growing demand.

The communication strategy for this group will highlight the possibility of renewal of a house coinciding with the changing needs of the user every ten to fifteen years without being forced to change location. The main appeal to this group will focus on their ecological and economic sustainability.<sup>2</sup> However, the product must satisfy their expectations for location, quality, and price.

In terms of location, cardboard houses will be situated in either suburban setting or in the city centers through the implementation of customized semi-ownerships, in coordination with governmental entities and commercial institutional investors, as a tool to control the land for

<sup>1</sup> Schuler, et al. 237.

<sup>2</sup> *Business Opportunities in Sustainable Housing: A Marketing Guide Based on Houses in 10 Countries*, International Energy Agency, Solar Heating and Cooling Programme (2006).

further planning investments.

In terms of the renewal process, due to the product's high use of offsite prefabrication, it is predicted that a cardboard house can be renewed with only minimal disruption to the owner. Owners will be bonded legally on the decomposition, reconstruction and maintenance rights of the system.

Finally, the price category for this stage is foreseen to be lower relative to other eco-housing and conventional housing options. On average, the price of an eco-house is 7-10 percent higher to cover the additional costs. With that in mind, and knowing that young family will make up a large portion of buyers in the maturity phase, those looking to purchase a cardboard house will still be price sensitive.<sup>1</sup> In Switzerland, the 50-59 age group has the highest average incomes, whereas those in the 60-69 age group have more assets on average than any other age group. As people age, they generally become more conservative and less likely to try a new product, particularly non-movable assets.<sup>2,3</sup>

#### **4.4 Positioning the Investors for Cardboard Housing**

In Switzerland, demand for residential property is being answered by a supply that is very fragmented. The supply is strongly influenced and directed by banks, institutional investors and private financiers. Annually, various sources attempt to describe the status of housing stock according to diverse investor groups and locations, as shown in Figures 2.40 and 2.41.

Current investment possibilities and needs in Switzerland necessitate a definition of the quality development in housing for the needs and the current challenges of the clients. In a recent study, Margrit Hugentobler<sup>4</sup> argues that there is a moving market for rented dwellings, therefore shifting availability of short and long term rented dwellings and optimizing the utilization of the housing space and flexibility. Therefore a flexible planning and usage of the dwelling for building or renovation is a necessity in the current housing market.<sup>5</sup> Investors focus on convenient housing in the city centers and affordable housing for young families in suburban areas. Additionally, given the aging population of the country, there is a growing demand for customized housing for the elderly.

To categorize the interest groups for investors, a typology for investors based on institutionalization (institutions vs. non-institutional investors), commerciality (commercial vs. non-commercial investors) and real estate investment (real estate investors vs. other stakeholders) is presented in a recent study by Joris Van Wezemaal.<sup>6</sup> Van Wezemaal defines

<sup>1</sup> Price setting for cardboard housing purchase will take into consideration the existing cost of 4 and 5 room apartments, the standard apartment size in Switzerland. In Zurich the average selling price of a 4-room apartment is 1,334,000 CHF (\$1,256,000) For a 5-room apartment, the average selling price is 1,588,000 CHF (\$1,467,000). Source: *Immo-Monitoring 2006* (Wuest and Partner, 2006) 76.

<sup>2</sup> Van Wezemaal and Ernest 116.

<sup>3</sup> Leu et al.

<sup>4</sup> Hugentobler and Huber 29-32.

<sup>5</sup> Hugentobler and Huber 29-32.

<sup>6</sup> Van Wezemaal and Ernest.

stakeholder groups: 1) institutional and commercial stakeholders; 2) institutional and non-commercial stakeholders; and 3) non-institutional and commercial stakeholders. Using this typology, the following classifications are made: 1) Institutional and Non-commercial Investors; 2) Commercial and Institutional Investors; and 3) Private Investors (non-institutional, commercial).

*Institutional and Non-Commercial Investors:* This non-profit group of investors would likely support CATSE cardboard housing since they are known to encourage the development of economically and environmentally sustainable housing. The dilemma facing this group of investors is the amount of capital at their disposal, as many have limited investment budgets. However, associations with these investors may prove to be beneficial in the decision making and approval processes. Examples of Institutional and Non-commercial investors are the Federal and Cantonal Finance and Energy Departments, Building Cooperatives, and non-profit foundations, such as Novalantis.

The underlying principle here is that the non-commercial and institutional investors are more like to pursue broader social goals and offer core product housing in mixed residential areas. Ronald Stulz, the managing director of Novatlantis, an initiative on sustainability at the ETH has openly stated his group's support for eco-conscious projects in Switzerland, noting that:

*"Pilot and demonstration projects are a means of showing investors what has been achieved in practical terms. Supporting this process is one of the main functions of Novatlantis."*<sup>1</sup>

Building and Housing in terms of ownership	Building	in %	Housing	in %
Single Persons	1 295 190	88,6	2 617 011	73,3
Housing Cooperatives	21 034	1,4	119 779	3,4
Other Coops(no memberships)	5 078	0,3	42 166	1,2
Property Funds	4 752	0,3	58 306	1,6
Other Real Estate Comp.	15 817	1,1	110 695	3,1
Building Associations	4 826	0,3	21 329	0,6
Insurance Companies	11 924	0,8	118 584	3,3
Personal Provisions	18 996	1,3	181 743	5,1
Other Charities	7 870	0,5	44 365	1,2
Associations / Unions	5 225	0,4	15 141	0,4
Other Companies	5 078	0,3	42 166	1,2
Local Municipality-Canton	32 108	2,2	84 088	2,4
Other Property Ownership	1 129	0,1	5 953	0,2
<b>Total</b>	<b>1 462 167</b>	<b>100,0</b>	<b>3 569 181</b>	<b>100,0</b>

Figure 2.40 - Property ownership statistics in Switzerland, 2000 (Gebäude und Wohnungen nach Eigentümertyp, BFS).<sup>2</sup>

<sup>1</sup> *Smarter Living, Generating a New Understanding for Natural Resources as the Key to Sustainable Development*, (The 2000 Watt Society) 11.

<sup>2</sup> Hans-Rudolf Schulz, Peter Würmli, Peter Farago and Beat Brunner, *Wohnen 2000: Detailauswertung der Gebäude- und Wohnungserhebung*, Swiss Federal Statistical Office/Federal Office of Housing, 2005).



**Commercial and Institutional Investors:** This profit investor group would likely remain distant from any innovative technology or material choice, including CATSE cardboard housing during the first 5-10 years following implementation. However, they would likely make investments once the product has proven itself with the first group. Examples of commercial investors include pension funds, insurance companies, and private real-estate investment companies.

Commercial entities seek to improve their rate of return by making reliable investment. Thus, an institutional entity would be interested in a new innovative project offer only after it shows accepted by the mainstream and becomes a strong candidate for a strong investment return. Commercial investors rely on the stable, medium-sized projects secure their investment portfolios. To underscore the framework in which a commercial investor works, it is helpful to look at an example from the investment firm Swiss Prime Site AG. Its website sets forth that its investment criteria include quality of location, income, potential for value, economic development potential, transport connections, architectural concept, renovation standards, rentability and actual rental situation, solvency and composition of tenants and use flexibility of the building.

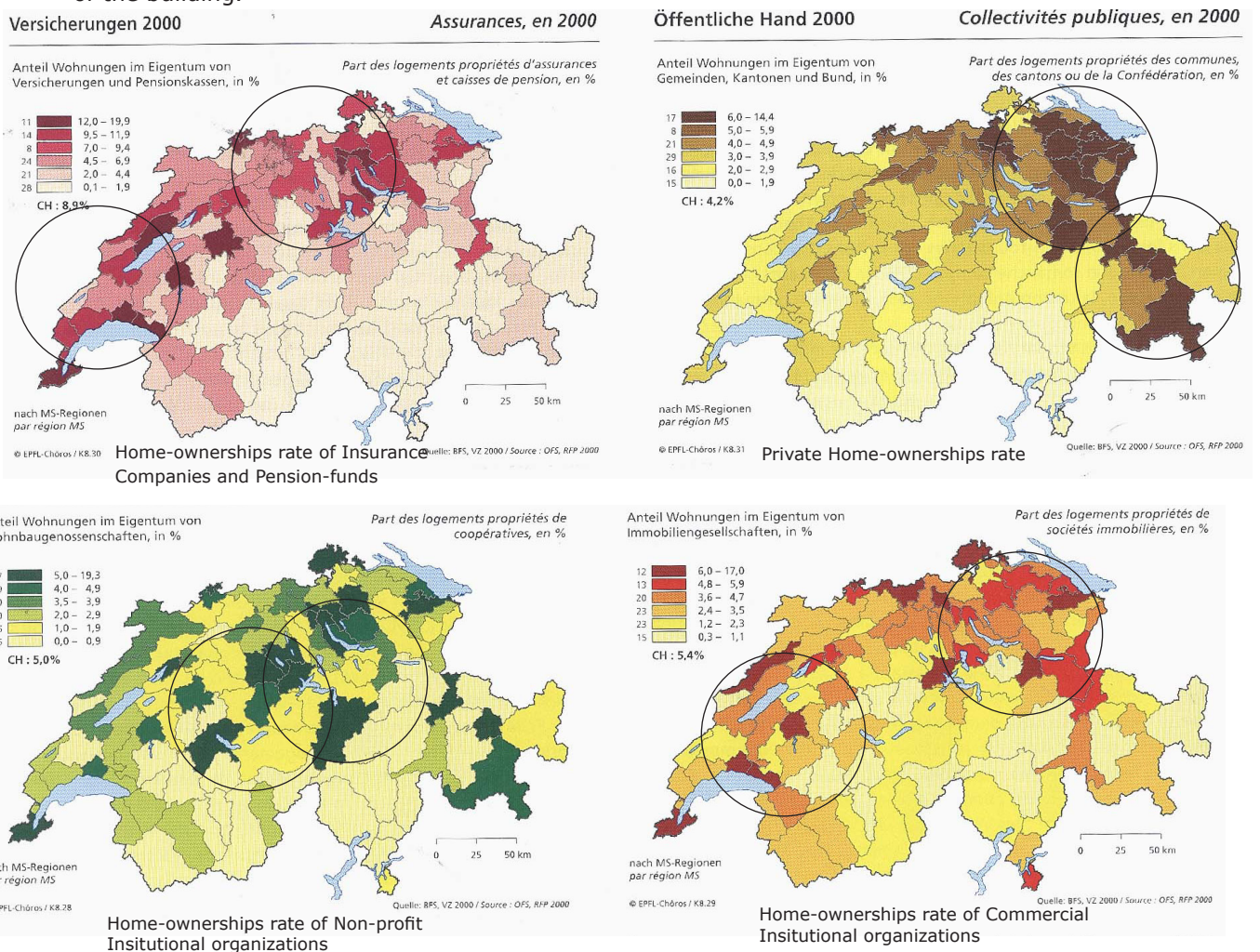


Figure 2.41 - Comparative investor analysis, according to the geographical areas agglomeration.<sup>1</sup>

<sup>1</sup> Schuler et al. 238.

*Private Investors (non-institutional, commercial)*: The profit investor group, composed of individual investors similarly tend to avoid most risky projects involving innovative technology or material choice, including CATSE Cardboard Housing. This group represent the largest percentage share of ownership, although they do not have the same official/legal joint perspective as the others. Effectively communicating the future of cardboard housing is essential to gaining the financial support of this group.

#### 4.4.1 Eco-Housing and Investors in Europe and Switzerland

Investors as a whole often seem indifferent or at least unconcerned with environmental issues until their is a sufficient demand from clients or legal regulations. The reasons for this phenomenon are more likely caused by a lack of understanding rather than a lack of moral concern. Another reason may be linked to their inability to understand the extent of the energy shortage, and uncertainty about how to measure its future impact.<sup>1</sup> However, there have also been numerous positive developments from this investor class, such as the development of Minergie standards in Switzerland, backed with the support of the state or private foundations. Some of the current themes that socially responsible investors want to communicate to the wider population and apply to their business models are “social impact assessment” and “socially responsible investment” approaches, which are defined as follows:

*Social Impact Assessment (SIA)*: A study whose aim is to foresee and measure the effects of a public or private policy, program or project on surrounding populations;<sup>2</sup>

*Socially Responsible Investment (SRI)*: Socially responsible investing takes into account social responsibility, environmentally sustainability criteria and conventional financial criteria.<sup>3</sup>

**Minergie Standard**: Minergie, as mentioned above, is a Swiss quality label for new and refurbished buildings that indicates that a building conforms to high standards of comfort, economic efficiency and energy consumption.<sup>4</sup> The Swiss Minergie standard has earned an increasing market share of about thirty percent of all new construction.<sup>5</sup> The Federal and cantonal authorities support renovations and new investments in housing that conforms to the standards of the Minergie label, and owners receive subsidies from the cantons and lower interest rates from banks for houses constructed or renovated according to the energy efficiency standards of Minergie. Although energy efficient buildings are heavily promoted, a relatively small number of houses are built according to this standard (five to ten percent of new single family houses and less than five percent of new apartment buildings), and only a minimal number of renovations follow the Minergie guidelines.<sup>6</sup>

<sup>1</sup> Asa Skillius and Ulrika Wennberg, *Continuity, Credibility and comparability: Key Challenges for Corporate Environmental Performance Measurement and Communication* (European Environment Agency, Feb. 1998).

<sup>2</sup> “Glossary of CSR / Sustainability Terms and Concepts,” Interpraxis, <<http://www.interpraxis.com/glossary.htm>>. 30 Mar. 2009

<sup>3</sup> “Glossary of CSR / Sustainability Terms and Concepts,” 30 Mar. 2009

<sup>4</sup> *Third National Communication of Switzerland 2001* (Swiss Agency of Environment, Forestry and Landscape, Jul. 2001) 34.

<sup>5</sup> *Business Opportunities in Sustainable Housing: A Marketing Guide Based on Houses in 10 Countries*, International Energy Agency, Solar Heating and Cooling Programme (2006) 20.

<sup>6</sup> Banfi et al. 2.



In a recent study, Banfi and Jakob<sup>1</sup> examined the interest for better living comfort with higher energy efficiency through lower energy costs and stronger environmental protection. They found that the majority of people desire energy efficient changes in the building sector, but the market has not acted yet to provide a sufficient supply. They argue that this shortage is due to barriers caused by a lack of communication between the investors and users.

For investors, in order to define policy actions that help to spur further interest in energy efficient housing, it is important to investigate factors that influence the investment decision of the home owners and their willingness to pay for improvements in energy efficiency.<sup>2</sup> One problem is that for investors in energy efficient buildings who need to ensure sufficient demand, there is only a limited number of published economic studies analyzing consumers' willingness to pay for energy saving measures in residential buildings.<sup>3</sup> Most investors simply know that most potential homeowners are aware of energy loss due to poor insulation and the associated costs.

The obstacles facing investors are thus incomplete information about costs and benefits of energy efficient houses, and a lack of awareness about shifting consumer demands. Other commonly cited arguments explaining the deficit in eco-housing investment are inadequate tenancy laws, budgetary constraints, and insufficient knowledge regarding cost and benefits. Also, investors, homeowners and interest groups often refer to the poor profitability of energy efficiency measures. However, several other examples demonstrate that the emphasis placed on the extremely low cost of energy and environmentally related improvements.

To energize investment, promoters of energy efficient housing must not focus exclusively on cost issues, but also on the increased living comfort, operational simplicity, sound insulation, and lower occurrences of respiratory illnesses that energy efficient houses offer.<sup>4</sup>

#### **4.4.2 Eco-Conscious Investors for Cardboard Housing**

A current and comprehensive economic assessment of energy efficiency measures with comparative present and future cost and benefit analyses is a necessary starting point in the development plan for CATSE cardboard housing.<sup>5</sup>

Moreover, promoters must undertake the risks that investors face when deciding whether to invest in a cardboard housing project:

a) *Unknown Cost Structure:* As discussed before, the cost dynamics for an investor is frequently an issue when implementing new technologies, new materials and building concepts or processes. These are partly based on a lack of knowledge, including, with regard to CATSE,

<sup>1</sup> Banfi and Jakob.

<sup>2</sup> Banfi et al. 2.

<sup>3</sup> Banfi et al. 1.

<sup>4</sup> Jakob 173.

<sup>5</sup> Jakob 173.

serial production and other economies of scale, which could substantially lower the costs of the projects. A comprehensive economic assessment should therefore account for these economies of scale. Indeed, the literature reports on technological learning in different fields and using policies as an instrument could make use of it by stimulating the learning and experience process to attain economic viability more quickly.<sup>1</sup>

Investors mainly interested in CATSE will benefit from the efficient construction process, and the economical point of the project however the management aspects such as availability of the knowledge, material and the availability of technical personnel in construction are missing. Also maintenance and infrastructure questions must be clearly declared for the acceptance of a new system among the contractors and construction companies.

*b) Shortened Lifetime of Cardboard Houses:* Investors may also have some apprehension about the short lifecycle of cardboard buildings. Most are likely to believe that potential buyers would see this as a major drawback. This potential drawback must be reframed as an advantage, by communicating to investors that most Swiss residents remodel their homes on at least one occasions. In fact, 33 percent of all construction activity in the private sector, and 55 percent in the public sector can be attributed to upgrading Switzerland's aging buildings.<sup>2</sup> Investments in new building are often times being replaced with transformations, renovations and maintenance of existing buildings, which should represent approximately half of all building construction expenditures.<sup>3</sup>

Since these high rates of renewal-refurbishing practices already play a prominent role in amount of construction performed per year in Switzerland, and reports confirm a high rate of relocation, a system that requires reconstruction every 10-15 years may prove to be viewed as an advantage.

#### *Opportunities for Cardboard Building Investors*

According to Swiss real estate studies, sustainable housing is still considered to be in its initial phase. As this market enters into a growth phase, existing construction companies will redefine their positions according to the "commonized" phenomenon accepted by majority.<sup>4</sup> Therefore, we can expect the focus of the investors to be on conceptually well analyzed and cost-efficient projects, to demonstrate product differentiation from their competitors by defining the position of the company and the product range in the marketplaces.

Above all, more political pressure to encourage investment in energy efficient building will be canalized to obtain strict measures from the federal and provincial governments in the near future. Regulations prescribing significantly higher insulation standards are expected to be

<sup>1</sup> Jakob 173.

<sup>2</sup> *Back on Firm Ground: The Construction Sector in Switzerland* (Trade and Investment Canada, 2001) 1.

<sup>3</sup> *Market Highlights and Prospects* (Industry Canada/Government of Canada, 2005) 2.

<sup>4</sup> *Business Opportunities in Sustainable Housing: A Marketing Guide Based on Houses in 10 Countries*, International Energy Agency, Solar Heating and Cooling Programme (2006).

very effective and to play a key role in triggering other technologies whose acceptance and economic application depends on an optimized building envelope.<sup>1</sup> Investment will certainly be spurred if these types of measures are adopted.

In conclusion, the model for CATSE cardboard houses looks to initially attract interest from governmental and private entities in the introductory phase, and will eventually seek investments and support from institutional and commercial investors as the product earns the trust of the market (Figure 2.42).

**5. Development Strategy for Implementation of Cardboard Buildings in Housing**

CATSE cardboard buildings is an academic interdisciplinary research project, with a particular interest in housing, and a goal of developing cardboard as a feasible building material. It will focus on the potential of introducing cardboard houses into the Swiss real estate market. Despite the constraints of scarcity regarding innovative initiatives, a systematic definition of the needs of the market and of the intended user, and a development strategy for cardboard housing must be formulated. The implementation requires a strategy to guide the commercialization transition. This subchapter works to describe this stage prior to the introduction of commercialization illustrated in Figure 2.42. Examination of the implementation process of similar innovative building systems highlights two significant themes in communicating the product: 1) the project research team and management, and 2) the first demo project and execution.

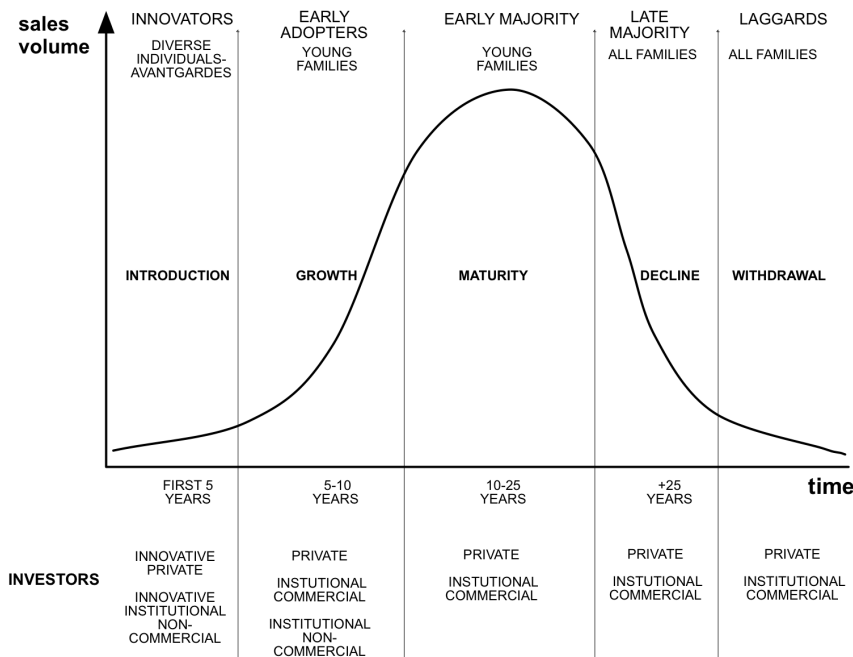


Figure 2.42 - Lifecycle of cardboard housing as a product vs. sales volume.

*i. The Project Team:* Because it concerns a rather small number of innovative and eco-friendly residential buildings in the market, the engagement of technically and ecologically motivated actors who are able to push the project forward is vital.

<sup>1</sup> Lien and Hastings.

ii. *The Demo Project:* Prior examples of energy-efficient houses have demonstrated the need to develop pilot projects to help overcome the market barriers for innovative building concepts.<sup>1</sup> Therefore, under the current market conditions, building a full scale cardboard house model will provide additional peace of mind for investors and individual owners who are concerned about being the first to enter the market. Such a pilot project would also benefit the project by providing analysis and feedback for theoretical research, and by gaining crucial experience in the design and construction phases of the project.

A diagram organizing the initial implementation phase for CATSE Cardboard Housing Project, followed by the commercialization phase, is divided into four stages and shown in Figure 2.43 below.

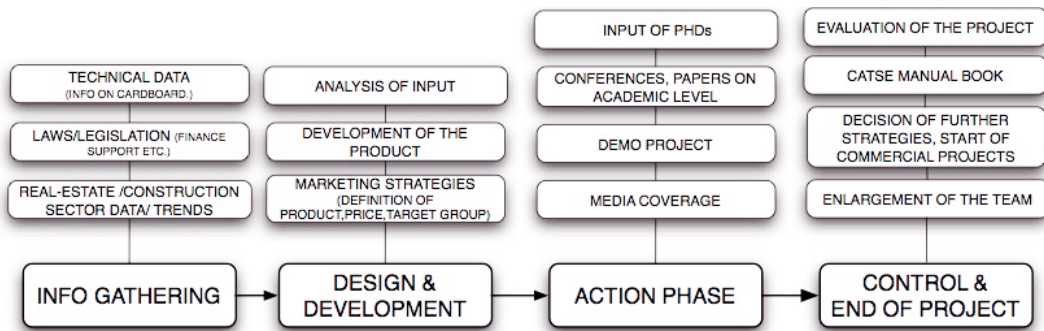


Figure 2.43 - Phase diagram of CATSE Cardboard Housing Project.

### 5.1 The Information Gathering Phase

This initial phase includes the harvesting of background information and relationships between market actors. A new product requires the integration and cooperation of all actors - contractors, subcontractors, specialists and potential home buyers.<sup>2</sup> Thus, information must be collected about the market, competitors, suppliers, users and combine it to create a comprehensive analysis. Information gathered during this stage must be further processed, systematized and analyzed to be used in the design and development stage of the project (Figure 2.44).

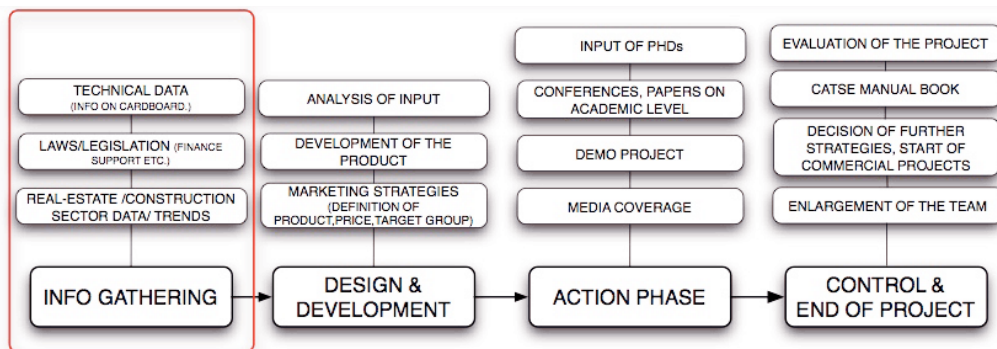


Figure 2.44 - Phase I.

<sup>1</sup> Lien and Hastings.

<sup>2</sup> *Business Opportunities in Sustainable Housing: A Marketing Guide Based on Houses in 10 Countries*, International Energy Agency, Solar Heating and Cooling Programme (2006).

### 5.2 Design and Development Phase:

The design and development phase of cardboard housing requires the utilization of the technical, financial and social input from prior stages to define the process of developing an ecologically and economically efficient cardboard housing system. This phase will result in the creation of a CATSE cardboard housing handbook. It will include a complete evaluation of the idea and technical study framed by the academic studies. This phase will also mark the beginning of the development of a marketing strategy for the communication of the plan with the media and public (Figure 2.45).

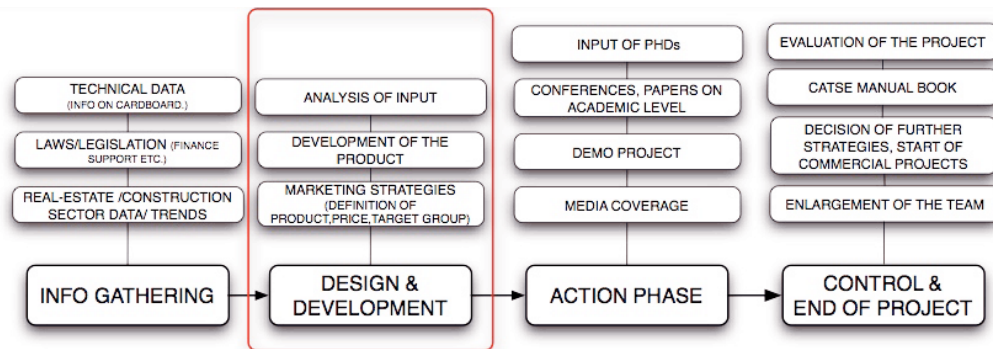


Figure 2.45 - Phase II.

### 5.3 Action Phase: Construction and Demonstration

The Action Phase will mark a significant milestone of the planning stages of CATSE cardboard housing. It will entail the completion of the theoretical and experimental studies, followed by the design and construction of a full-scale demo project with Minergie Standard approval. The demo and theoretical work on the academic level will be presented in papers and at conferences and design fairs (Figure 2.46).

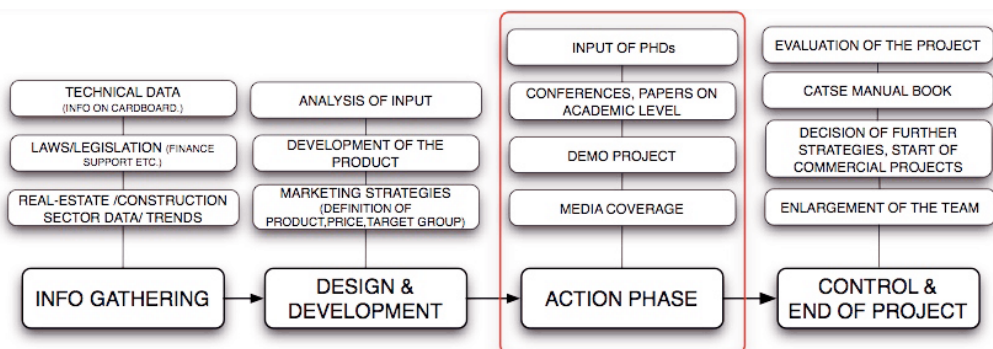


Figure 2.46 - Phase III.

### 5.4 Measurement and Evaluation Phase

This last phase of the introductory scheme focuses on a complete evaluation of the preliminary aspects of the project prior to full-scale commercial implementation. Following the testing and reviewing of the demo project, a complete CATSE cardboard housing technical manual containing the design and construction guidelines will be created and published with performance and operation data.

Additionally, a feedback mechanism will be put in place. The criteria will include the assessments on the technical, economic (affordability among the various target groups), ecological (energy usage and operation costs) and societal aspects of the project. Also, generation of a genuine architectural language to define cardboard buildings will be investigated in this stage. Flexible and apatable design with multifunctional properties of cardboard within the construction system will be presented for adoption by design professionals.

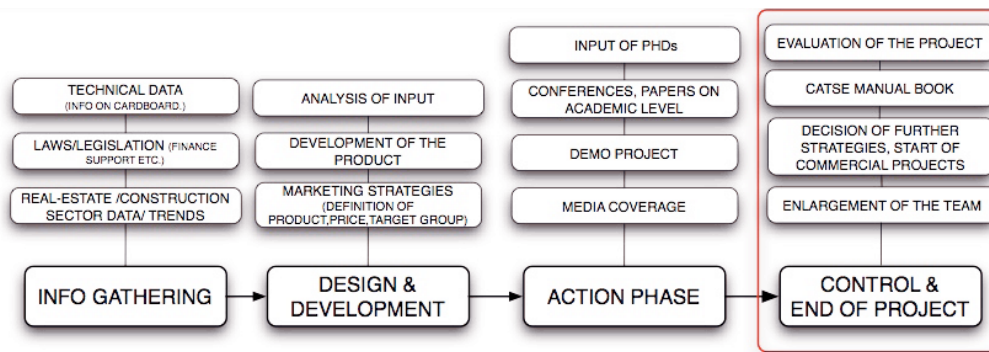


Figure 2.47 - Phase IV.

### 5.5 Task Scheme as a Development Strategy Tool

The task scheme for this project focuses on four elements: 1) the user; 2) architectural thinking; 3) constructive demands; and 4) building. These elements are illustrated in Figure 2.48. The figure is used within the research study as a tool among the research team to communicate the variation of themes in cardboard housing and the interrelationships between these demands.

*Architectural thinking* examines cardboard buildings within the boundaries of adaptable, prefabricated and social housing through the definition of “interchangeable housing concept.” This definition requires a low-cost, eco-friendly, modern building with practical solutions.

The *user* thematic entails a broad spectrum of questions based on user needs, trends affecting and user typology, and positioning of the choice for dwelling and ownership issues.

The *building* thematic examines questions regarding physical needs of a cardboard building, ranging from its location with a city to its potential building typology, as well as its spatial transformation and flexibility.

Finally, the question “*how*” examines the focal point regarding the technical questions that arise during the construction phase. The constraints are categorized based on structural strength and stability of cardboard buildings against moisture, humidity, condensation, fire protection, as well as thermal and acoustic quality and control, spatial qualities and cost issues.



## **6. Conclusion: Implementation and Perception of Cardboard Buildings**

The hypothesis, as set forth above, is that CATSE cardboard houses as a system is representative of modern society's shift in the way it lives. Therefore, this chapter has aimed to compare current Swiss housing needs and trends to the proposed system of renewable, ecologically and economically sustainable, innovative cardboard construction. The focus has been to generate an understanding of the housing market for cardboard housing. Within the overall structure of this study, this chapter's role is to present the base for the technical chapters on environmental and constructive concepts.

In particular, the potential of cardboard housing, influenced by shifting market forces are examined. The potential is illustrated through the needs of the most influential stakeholders and by classifying current housing preferences factors. Accordingly, a survey of the target group and the development of a implementation strategy based on the short lifecycle of the CATSE Cardboard housing were performed. The survey "Social Acceptance of Cardboard in Housing" helped provide an understanding of the user's perception of cardboard buildings. The outcomes of the survey lend support to the initial hypotheses regarding cardboard buildings:

1) There is a high relocation rate in Switzerland. A majority of respondents noted that location, price, daylight, plan-design, total number of rooms and material quality are the most important factors when purchasing a new home.

2) The most commonly-cited complaints about a new home are sound insulation problems, neighbors, inadequate planning, energy loss, lack of daylight, and other infrastructure problems. There will, in turn, become an essential focus in the CATSE cardboard housing project design process.

3) People associate the material cardboard with a wide array of both positive and negative qualities, such as its use in the packaging industry, handcrafts, recycling, its low cost, and its use as housing and bedding by homeless individuals. With regard to cardboard buildings, respondents raised several concerns about the structural stability of cardboard based on questions about its durability, waterproof nature, heat and sound insulation, and health and comfort.

The chapter is concluded with suggestions for the management of the implementation phase, aiming to reconcile the the high housing standards demanded by Swiss residents and the potential supply of cardboard housing into the market.

There are three interrelated lines that directed the analysis on the users and the general framework of the construction sector to formulate the development strategy of the CATSE cardboard housing. These three lines are: (i) positioning of CATSE cardboard housing and users, (ii) positioning of Swiss construction sector and cardboard housing, (iii) positioning of the trend of eco-housing and cardboard housing.





*i) Positioning of CATSE Cardboard Housing and Users*

- Swiss residents typically are highly conscious of quality in housing, and have recently become increasingly environmentally conscious. The recent increase in wood construction can be attributed to this new eco-conscious thinking.
- Corrugated cardboard, a low cost wood byproduct that is already heavily used in the packaging industry will satisfy the ecological and economic demands of cardboard housing.
- The Swiss currently have a relatively rate of refurbishment, renovation and renewal of existing residential buildings. Thus, any psychological inhibitions that prospective buyers may have about the short lifecycle of cardboard houses does not represent a major barrier to the successful implementation of the product.

In the introduction phase, the most difficult challenge will be communicating the benefits of cardboard buildings to prospective homebuyers. The new type of living arrangement suggested by cardboard housing and its regarding its parallels with the users' changing spatial needs will be emphasized. For the Innovators user group, one of the most critical communication points is the underlying philosophy of the project. Following the innovators, tenants, and finally a group of buyers are foreseen to enter the cardboard housing market. In terms of investors, institutional-commercial entities are expected to work with cardboard housing on the maturity of implementation. Nevertheless, innovative private and non-commercial institutions like governmental entities are foreseen to find cardboard housing as a environmentally low impact and low cost alternative in which to invest starting from the introduction phase (Figure 2.50).

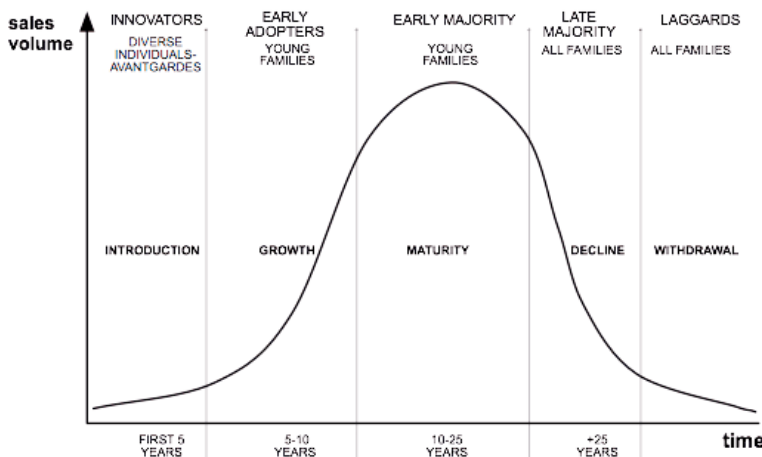


Figure 2.49 - CATSE Product Lifecycle.

Stakeholder		Interest / Stake high, medium, low	Power / Influence high, medium, low	Expected Reaction 😊 😐 😞
Architects		MEDIUM	MEDIUM	😊
Investors	Private Inv. (non-institutional, commercial)	LOW	HIGH	😊
	Institutional & Non-commercial Inv. - State / Canton Finance Dep. - Baugenossenschaften - Foundations	HIGH	LOW	😊
	Commercial & Institutional Inv. - Pension Fonds, - Insurance Companies - ImmobilienFonds,	LOW	MEDIUM	😊
Users	Innovators	HIGH	MEDIUM	😊
	Young Families (tenants)	MEDIUM	MEDIUM	😊
	Young Families (buyers)	LOW	HIGH	😊

Figure 2.50 - Stakeholder Analysis.

*ii) Positioning of the Swiss Construction Industry*

The Swiss construction sector has regained market stability after several years of crisis in the 1990's. Recently, there has a notable increase in single-family home ownership in rural areas of the countries. Several of the population centers have also experienced construction

booms for apartment complexes. Based on these facts, the CATSE cardboard housing project intends to set a foundation by suggesting a new system of eco-conscious and low-cost prefabricated construction. Due to land costs and the constraint that cardboard buildings can only be constructed with two floors, they will first be placed in suburban environments and then eventually be introduced to the urban landscape on a smaller scale in cooperation with local authorities and commercial investors.

It should also be expected that an innovative concepts' mass approval will inevitably take years or even decades to gain stability. Accordingly, the success of CATSE cardboard housing will depend on the mutual learning process of service providers (construction sector, architects, investors, engineers) and users<sup>1</sup> (see Figures 2.49 and 2.50).

### *iii) The Trend of Innovative Eco-Housing and its Impact on Cardboard Housing*

The resources, both financial and material, used in the construction process are often claimed to be responsible for several negative impacts to the environment. Sustainability as a motivating factor has recently attracted an increasing interest to the Swiss eco-housing market. However, until very recently, the indifference of the sector's indifference was excused by economic justifications and lack of research and development into innovative building materials. As such, the following points must be emphasized during the implementation of cardboard housing:

- The innovative concepts and technologies in the building sector are strongly influenced by technical, legal, sociological, psychological, ecological, and economical constraints where "continuity, comparability and credibility" shape the key challenges.<sup>2</sup>
- Under the influence of global developments, public awareness and policy decisions, the Swiss housing industry is realizing that sustainability will be inevitably an important factor in future developments.<sup>3</sup> Urgency in the need for innovative eco-products or process technologies in construction is expected to increase both the market's supply and demand, the acceptance and and implementation of these products.

There is also a need for increased public awareness and a better understanding of sustainability in housing, especially for the main players involved in planning decisions (planning officers, local communities, investors and lobbying groups).<sup>4</sup> It is therefore foreseen as a challenge to communicate cardboard housing to the general public with the goal of overcoming the existing psychological barrier.

Finally, this examination of the societal perception of cardboard buildings helped to gain an understanding of the advantages and challenges stemming from user needs, and financial and market conditions that will permit a better formulation of the implementation conditions for cardboard buildings. Using this as a foundation, the creation of an unconventional, functional

<sup>1</sup> Lien and Hastings.

<sup>2</sup> Skillius and Wennberg.

<sup>3</sup> *Business Opportunities in Sustainable Housing: A Marketing Guide Based on Houses in 10 Countries*, International Energy Agency, Solar Heating and Cooling Programme (2006).

<sup>4</sup> Lien and Hastings.

and flexible construction system that utilizes the full potential of cardboard as a construction material with a genuine architectural language are forwarded in the research of technical aspects regarding the environmental, constructive and finally architectonic approach for cardboard buildings.

In sum, both the environmental approach and the constructive approach regarding the technical constraints and opportunities of cardboard housing are strongly influenced by the findings regarding the construction sector framework in Switzerland.

# Chapter III

## Environmental Approach Development of a Low-Impact Building Component

" Buildings, too, are children of Earth and Sun "  
-Frank Lloyd Wright

### 1. Introduction

The public's awareness of the environmental impact of the energy and materials used in building has increased dramatically in recent years. Construction professionals and property owners must now assume more responsibility for the environmental costs of the buildings that they build and own. Some government agencies have started to adopt certain control mechanisms like optimizing a building's energy and resource requirements and diverting more into the use of "eco-materials."<sup>1</sup> Due to changing market conditions, the key is to balance this proposed ecological sustainability with economic sustainability. Economic sustainability demands that investment and use costs be optimized to lead to the efficiency of the building in terms of capital and service for the highest level of durability and reusability (Figure 3.1.).<sup>2</sup>

Today, case studies on both regional and national scales have been conducted to evaluate the extent to which energy and resources are being used in the production, use and disposal of buildings. The results of these studies show that building construction and operation amounts to a significant portion of world's carbon emissions. For instance, in the United Kingdom, researchers found that the manufacture and transport of building materials accounted for as much as ten percent of the country's total carbon emissions.<sup>3</sup>

<sup>1</sup> H.W. Kua and S.E. Lee, "Demonstration Intelligent Building - A Methodology for the Promotion of Total Sustainability in the Built Environment," *Building & Environment* 37, no. 3 (Mar. 2002): 232.

<sup>2</sup> N. Howard and P. Kapoor, "Software for Assessing the Environmental Impact of Buildings ('Envest')," *Environmental Expert* (1 Jan. 2000): 2.

<sup>3</sup> Howard and Kapoor 67.

### 1.1. Sustainability in Today's Buildings

Innovative eco-implementations in modern buildings, whether as a material, product or system, have gained increasing relevance in today's climate of energy efficiency and durability. In practice, identifying the construction materials and methods in the early stages of the design process is often beneficial. This is often the first step in the creation of an efficient overall system when accompanied with the social, environmental and economic values required for the project. Only then, achieving targets such as a high level of lifetime energy efficiency, lower operating costs, and long-term flexibility and marketability can become a reality for the future of sustainable buildings.<sup>1</sup>

Full implementation of sustainability into building systems and building materials have historically, however, experienced delays in adoption despite assessments of resulting negative environmental impacts. Nevertheless, ecological sustainability issues have remained at the forefront of several non-governmental organizations, including the U.N. Development Program, the U.N. Earth Summit, United Nations Conference on Human Settlements, World Sustainable Building Conference, International Council for Research and Innovation in Building and Construction, as well as several governmental agencies and academic institutions.

The lack of information flow to the general public is generally considered the primary reason for this slow adoption, as well as a failure to communicate the issues of economic and socio-cultural sustainability. Economic sustainability focuses on long-term resource productivity and low-use costs, whereas ecological sustainability focuses on protection of eco-system and its resources. Socio-cultural sustainability focuses on issues of user health and comfort, and preservation of social and cultural values within a community.

Ecological and economic sustainability, supported by socio-cultural sustainability, creates "total sustainability" - a holistic approach to the problem (Figure 3.2).<sup>2</sup> Total sustainability constitutes an approach where the optimized solution addresses both the economic (long-term resource productivity and low-use cost) and ecological sustainability (utilization of renewable energy and energy conservation techniques).<sup>3</sup> This approach encourages innovations, invention and development into new materials and techniques in accordance with the fragile relationship between the building stock's needs. As explained by Kohler:

*"... the object of sustainability is not to improve qualitatively the building stock, but to improve without growth by reducing material through put and improve functional quality and durability. Therefore we should develop technics.... for new buildings, create long term adaptable, repairable structures..."<sup>4</sup>*

<sup>1</sup> Zhen Chen, Derek Clements-Croome, Ju Hong, Heng Li, and Qian Xu, "A Multicriteria Lifespan Energy Efficient Approach to Intelligent Building assessment," *Energy and Buildings* 38, no. 5 (May 2006): 394.

<sup>2</sup> Kua and Lee 232.

<sup>3</sup> Kua and Lee 233.

<sup>4</sup> N. Kohler, "The Relevance of the Green Building Challenge: An Observer's Perspective," *Building Research and Information* 27, no. 4/5 (1999): 309-20.



This study proposes a conceptual approach in accordance with the total sustainability approach by introducing an innovative use of cardboard as a legitimate building material to generate the acceptance and development in the contemporary construction sector.

**1.2. Environmental Impact Assessment for Buildings**

How exactly is it possible to articulate total sustainability through a building’s performance? The key in answering this questions is understanding the needs of the user and the needs of the building before implementation. Total building performance on the user vs. building level requires coordination of the intervoven needs of the user with flexible spatial building solutions, as Kua and Lee (2002) have noted in their research on the subject:

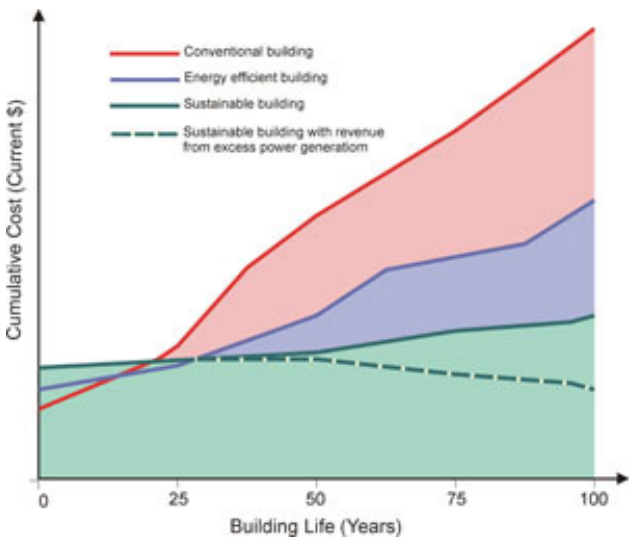


Figure 3. 1 - Sustainability vs. costs.<sup>1</sup>

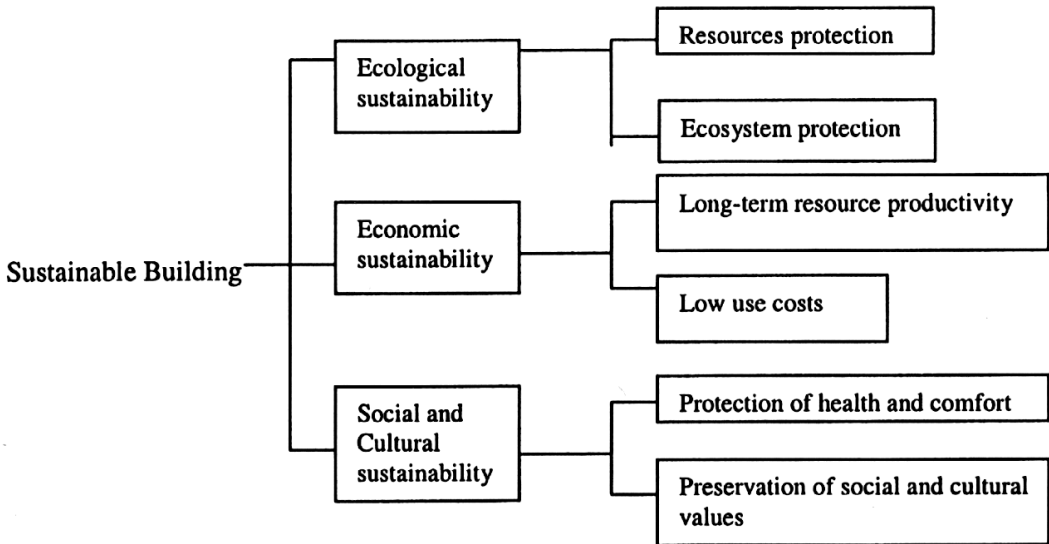


Figure 3. 2 - The three dimensions of sustainable building. <sup>2</sup>

<sup>1</sup> The Swiss Real Estate Market: Facts and Trends (Credit Suisse, 2005-2009).  
<sup>2</sup> C. Kaniut and H. Kohler, "Lifecycle Assessment - A Supporting Tool for Vehicle Design?" *Proceedings of the IFIP WG5.3 International Conference on Life-Cycle Modeling for Innovative Products and Processes* (1996): 444-458

*"...user satisfaction by fulfilling user's psychological, sociological and physiological needs, which are affected by basic performance criteria like space, temperature, air quality, acoustics, lighting and view and building integrity. Organizational flexibility (of space) and technological adaptability are critical to ensure that designs are compatible to rapid changes in working and living modes and formats. In short, these buildings provide environmental performance at a level that consistently and reliably ensures health, comfort and security while supporting high standards in productivity with continuing organizational and technological upgrade...<sup>1</sup>*

Correspondingly, to achieve understanding of sustainability on the user level, strengthening the public's concern and knowledge of environmental issues is essential. Effectively communicating the individual's often underestimated role in the environment's wellbeing is critical in creating a base of users that grasp the potential of sustainability.

At the construction industry level, a recently applicable common net of regulations and building codes both in the construction process and construction management fields are the main causes for the rise in sustainable building investments. Today, these building regulations and demands have slowly prompted a search for criteria, approaches and practices which lead to more environmentally sound building design, construction and operation in the future. On the other hand, as the number of eco-investments increase, confusion as to the definition and terms have occurred. Development of more comprehensive and reliable data as well as internationally approved assessment tools for evaluating alternative design options in terms of their overall environmental consequences are presently being discussed.<sup>2</sup> Currently, several building assessment approaches are being evaluated in order to have a standard method to guide tomorrow's new and existing building design.<sup>3</sup>

### **Lifecycle Assessment (LCA) Method: Background and Drawbacks**

Until recently, only two or three comprehensive data sources, created during the 1970's/ early 1980's were being used for the evaluation of the environmental impact of buildings. The slow progress is the result of a complex structure of specialized personnel<sup>4</sup> and funding problems in the field. Over the past decade, more building performance simulation algorithms and predictions are being developed as a result of an increase in computing power and the maturing of the building simulation field. Until now, the process has been driven primarily by research efforts (academic and governmental) and commercial entities. Both sectors have benefitted from advances in computation such as new programming paradigms and the

<sup>1</sup> Kua and Lee 239.

<sup>2</sup> R.J. Cole and P.C. Kernan, "Lifecycle Energy Use in Office Buildings," *Building and Environment* 31, no. 4 (1996): 307-317.

R.G. Stein, D. Serber and B. Hannon, "Energy Use for Building Construction," *R.G. Stein and Associates. U.S. Department of Energy, EDRA Report* (3rd Ed.), Center for Advanced Computation, University of Illinois (1976).

G. Baird and S.A. Chan, "Energy Cost of Houses and Light Construction Buildings," *New Zealand Energy Research and Development Committee, Report No. 76* (1983).

<sup>3</sup> Chen, et al 393.

<sup>4</sup> Ali M. Malkawi, "Developments in Environmental Performance Simulation," *Automation in Construction* 13, no. 4 (July 2004): 437-445 (Specialized personnel which targets the design, engineering, construction, operation and management of buildings, drawing its resources from many diverse disciplines including physics, mathematics, material science and human behavior)

increased power of computing and the internet.<sup>1</sup> Accordingly, rapid growth in the integration of eco-performance and quality simulations in the building industry have been observed.<sup>2,3</sup> The building industry, including architects, is slowly becoming aware of the need for better integration of these tools into the lifecycle of the building.<sup>4,5,6,7</sup>

Among the various tools available, LCA has become a leading analytical tool for assessing the environmental impacts of a product or a building from cradle to grave. It is a methodology for assessing the environmental performance of a service, process, product, or a building over its entire lifecycle. LCA takes into consideration that the lives of buildings are often complex, including successive stages in design, construction and operation relevant to their structural and service systems.<sup>8</sup> The ISO14000 standard describes the lifecycle analysis and assessment of buildings as a "quantitative approach to assess load magnitude in both natural and built environments in different patterns attributable to various influential factors at each stage of building system."<sup>9</sup>

Though some deficiencies still exist, LCA-based methods, compared with scoring-type methods, such as BEES, ATHENA, LCA id, Green Guide for Housing Specification, and ECOPT-ECOPRO ECOREAL, have an unmatched depth of coverage of environmental impacts associated with design and building materials.<sup>10,11</sup> Based on the LCA approach, specialized building environmental and economical performance simulating platforms have been developed, including SimaPro and OGIP software.

## 2. CATSE Cardboard Housing and Environmental Performance

The environmental performance of cardboard building will depend significantly on the cooperation of the cardboard manufacturing industry. Today, LCA method-based studies provide comprehensive information about the impact of the cardboard industry on the environment. As well as the environmentally focused studies, the LCA approach is used for several other performance simulating applications focusing on identification of product improvement – support, decision making, selection of performance indicators, and marketing.<sup>12</sup>

LCA operates in four stages; 1) setting the goal 2) Lifecycle Inventory Analysis (LCI), 3) impact analysis, and 4) evaluation. Based on the European Database for Corrugated Board lifecycle studies conducted by FEFCO, the list of general aims for an LCA study on cardboard for use in

<sup>1</sup> Malkawi 437.

<sup>2</sup> Chen, et al 398.

<sup>3</sup> John Seddon, *The Case Against ISO 9000* (Ireland: Oak Tree Press 2001).

<sup>4</sup> Malkawi 437-443.

<sup>5</sup> Cole and Kernan 307-317.

<sup>6</sup> Stein, et al.

<sup>7</sup> Baird and Chan.

<sup>8</sup> Chen, et al 397.

<sup>9</sup> "ANSI/ISO 14040-1997: Environmental Management - Lifecycle Assessment - Principles and Framework," *International Organization for Standardization* (2003).

<sup>10</sup> Z. Zhang, X. Wu, X. Yang and Y. Zhu, "BEPAS: A Lifecycle Building Environment Performance Assessment Model," *Building and Environment* 41, no. 5 (May 2006): 669.

<sup>11</sup> I. Reijnders and A. van Roekel, "Comprehensiveness and Adequacy of Tools for the Environmental Improvement of Buildings," *Journal of Cleaner Production* 7, no. 3 (Mar. 1999): 221-225.

<sup>12</sup> "Lifecycle Analysis - Assessment," *European Federation of Corrugated Board Manufacturers (FEFCO) Official Website*, Jun. 2006 <[www.fefco.org/index.php?id=172](http://www.fefco.org/index.php?id=172)>.

residential buildings can be summarized as follows:

- a) to integrate environmental concerns into decision making and to open a basis for cardboard products and process improvements as a building material and construction system;
- b) to compare the impact of possible industry applications of “cardboard in construction” to articulate the potential to bigger masses; and
- c) to prove the environmental low impact of corrugated cardboard as a viable building material.<sup>1</sup>

Since 1994, three European associations have been working together to provide the corrugated cardboard industry and customers up-to-date information concerning the impact of the industry on the environment. FEFCO, together with the Groupement Ondulé (GO - the European Association of Makers of Corrugated Base Papers) and the European Container Board Organisation (ECO) have taken a leading role in providing the European Union Commission with current industry views on the LCA approach. Several research projects regarding the environmental impacts of paper and cardboard have been supported by the industry and the EU, including ECOTARGET, which examined the pulp and paper industry in nine European countries.<sup>2</sup> As a result of this work, the European Database for Corrugated Board Lifecycle Studies and an LCA software tool for corrugated board were developed for analyzing the impact of cardboard on the environment.

Additionally, several academic collaborations, particularly in the fields of Chemistry, Environmental Science, Manufacturing Engineering and Management, have begun conducting lifecycle assessment on paper and cardboard, looking to integrate recyclability and manufacturing efficiency. These efforts have also played a significant role in the development of innovative implementations of paper grades and products with specialized characteristics.<sup>3</sup>

### **2.1. Objectives of the Environmental Impact Approach for Cardboard Buildings**

The broad objectives of an environmental approach for cardboard housing, using the LCA method, are as follows:

- a) analyze the existing environmental impact associated with the entire lifecycle of cardboard packaging, with a focus on the production stage of the basic component;
- b) identify and analyze other materials to be used in cardboard housing as wall components;
- c) compare a sample of cardboard wall segments with traditional building materials used for wall construction;
- d) compare cardboard wall composites with respect to their energy consumption in operation of the building; in particular the thermal energy loss.

<sup>1</sup> *European Database for Corrugated Board: Lifecycle Studies* (FEFCO, 2003): 3.

<sup>2</sup> *European Database for Corrugated Board: Lifecycle Studies* (FEFCO, 2003): 7.

<sup>3</sup> The Technical University of Denmark, Massachusetts Institute of Technology, Technical University of Catalonia, National University of Singapore, National Taiwan University, and the Asian Institute of Technology (Thailand) are all currently producing studies in this field.

## **2.2. Method for Environmental Impact Approach for Cardboard Buildings**

A building's environmental impact is typically not considered a primary factor during the developmental process in new construction. The priority is instead given to technical properties and cost, where the choice of input materials constitute an essential part of the overall efficiency. For construction of a new end-product such as cardboard housing, there must be a strong focus on optimizing structural and mechanical behavior (compressive strength, elasticity, shear, torsion), satisfying the building's physics characteristics, and defining the availability and manufacturing opportunities, as well as the economic and miscellaneous user factors in the market. A building's predicted environmental impact is often only among secondary concerns in a complex series of decisions in the development phase of a new product.

Part of the reason for this lack of priority can also be accounted for by a lack of knowledge held by actors in the construction sector. Environmental impact assessment is a complicated field, which requires a concrete understanding of other scientific principles. But even as the science and limitations of environmental impact assessment are still maturing, the focus within the environmental field continues to rapidly change. Even as global warming and climate change crowd today's headlines, there is a likelihood that these concerns will become secondary to worldwide cumulative energy demand.

The chapter aims to utilize preliminary environmental impact assessments for cardboard wall elements, and use the findings to select the optimal components and materials. This method will examine the composite wall element during the production stage and operation stage of the building.

The main objective in this stage is to demonstrate the environmental impact of cardboard and guide the parameters for the selection process of the additional materials, such as facings and adhesives). The environmental impact assessments of the production stage of cardboard wall composites were conducted using the SimaPro software, a commonly used program. To identify the environmental impact during the operation stage of a cardboard building, this study examined the buildings energy consumption based on its U-value. A building's U-value represents its energy loss during the operation stage.

As a further study, other software such as OGIP are suggested to be used in the analysis of the prototype building to confirm the results obtained in this chapter. OGIP tends to produce a more comparative, cradle-to-grave approach, specialized for the Swiss housing market.

### ***Lifecycle of a Cardboard Building***

The lifecycle of a building spans from the extraction of the materials and the composition of components until the final demolition of the building into its initial components and input materials. The lifecycle of a cardboard building goes through resource extraction, manufacturing, onsite construction, operation and maintenance, recycling, reuse and disposal.

Within this study, these phases are simplified into three stages: 1) production/construction; 2) use/operation; and 3) destruction/dismantling/recycling. The focus is to be on the environmental impact of production and operation of a cardboard building.<sup>1</sup> Two additional assumptions define the approach for this chapter:

a) The environmental impact of a building is greatly affected by the length of its useful life and for its individual elements; and

b) Buildings are embodied by a variety of building materials and components, facilitated with various building service equipment. Environmental impact assesment of a building therefore requires and extensive coverage of these areas. However, to generate a preliminary environmental approach for cardboard buildings within this study, only 1m<sup>2</sup> wall components with different thicknesses have been selected as the basic unit to illustrate the environmental impact in production and operation stages.

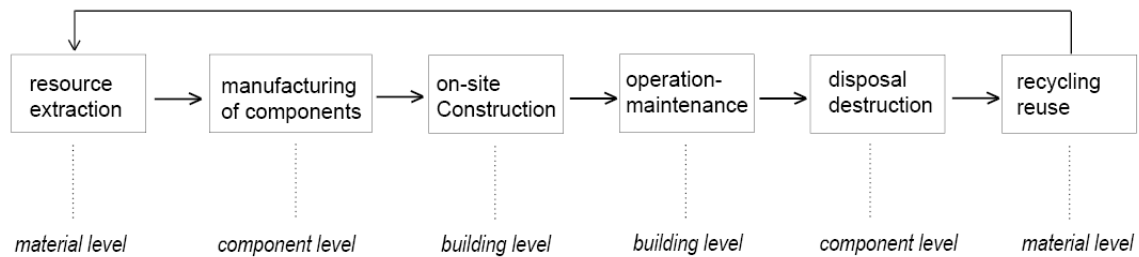


Figure 3.3 - Lifecycle of a building.

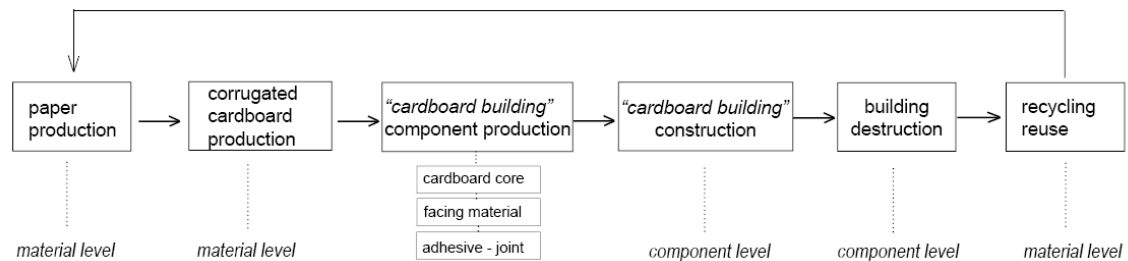


Figure 3.4 - Manufacturing lifecycle of a cardboard building.

**i. Environmental Impact During the Production Stage**

Environmental-impact-integrated production and recycling planning already plays a significant role in competitive positioning in many fields, and is gradually beginning to play a role in the construction sector. Due to increasing disposal costs for industrial byproducts and waste as well as stronger emission standards, companies are now required in advance to set up and control production technologies that drastically reduce emissions and waste byproducts. Planning problems in the recycling of industrial byproducts, dismantling and recycling of products at the end of their life time also needs to be investigated further starting in this first phase of design.<sup>2</sup>

<sup>1</sup> Zhang, et al. 670

<sup>2</sup> T. Spengler, H. Püchert, T. Penkuhn and O. Rentz, "Environmental Integrated Production and Recycling



The production stage of cardboard buildings has two main divisions: 1) the extraction of resources and 2) the preparation stage. In this study, the basic wall unit consists of corrugated cardboard core, facings, adhesives and a connection. The facings will be composed of a wood-based material (plywood, wood sheeting, or mdf), metal based skins (steel-aluminum), transparent (fiber-reinforced plastic or glass) or gypsum fiber-based panels.

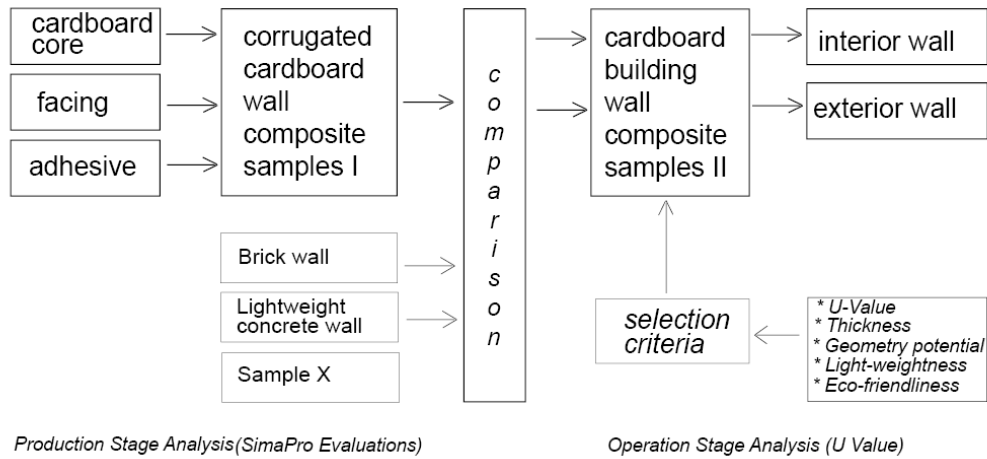


Figure 3.5 -Role of the Environmental impact assessment in the decision making process of cardboard wall composites.

**ii. Operation Stage**

The environmental impacts during the operation phase are caused primarily from the building’s consumption of energy, electricity and water. A great number of pollutants are generated and a large volume of natural resources are consumed in the production of electricity, heating-cooling and water.

The methodology used in this impact analysis study is based on the calculation of the average annual consumption of electricity, water and fossil fuels; information that can be obtained from the design documents or facility managers. Multiplying this annual average consumption by the expected lifespan of a cardboard house (10-15 years) will provide an estimate of the total consumption over the building’s lifetime. The total volume of the discharged pollutants and consumed natural resources can also be calculated. To control the consumption of the energy and water during the operation phase of the building lifecycle is the key to reducing the building’s environmental impact. Pollutants, including carbon dioxide, sulfur dioxide, ash and cinder, are often attributable to increase in global warming, acidification, and solid waste. Thus adjusting current energy supply structure and developing clean energy can greatly help to reduce the environmental impacts of buildings. In this study, a building’s U-value, its degree of thermal energy insulation, is used as a method for evaluating the environmental impact of a cardboard building during operation.<sup>1</sup> As a further study, it’s recommended to conduct an electro-smog analysis, which will look at the building’s artificially-generated electrical, magnetic and electromagnetic fields. Cardboard houses with thick walls and fiber-based cardboard material are predicted to decrease electro-smog.

Management,” *European Journal of Operational Research* 97, no. 2 (Mar. 1997): 308.  
<sup>1</sup> Zhang, et al. 670, 674.

### **iii. Destruction, Dismantling and Recycling**

The minimization and recycling of byproducts and industrial waste from buildings is becoming an essential element for planning and control of a building's lifecycle. This is because the environmental impacts are significantly increased by decreasing availability of natural resources. Today, environmental costs during the entire lifecycle of buildings already plays an important role in the calculation of total production costs. The developed planning models for this purpose can be classified into strategic and tactical planning tools. These tools have been applied to two themes: 1) dismantling and recycling, and 2) the location and allocation of recycling applications that produce waste byproducts.<sup>1</sup>

Today, reuse options for contemporary buildings today are often limited to road construction or soundproof barriers as end stations for brick, concrete and stone. These uses represent a down-cycling and therefore do not provide sufficient economic justification.<sup>2</sup> With the long history in extensive recycling and reuse in packaging and reading materials, paper and paper byproducts like cardboard potentially represent a less complicated and more environmentally sound alternative for the destruction stage of the cardboard buildings. Moreover, cardboard could also potentially compete with traditional materials on economical bases in this respect.

On the other hand, maintenance remains a concern during the life of a cardboard building. Many modern building materials and components have rather short maintenance intervals. With regard to handling these environmental impacts, two alternatives have arisen: prolonging the lifetime of a building and choosing materials that use less energy. Since cardboard buildings have a relatively short life span, the second option, using energy efficient materials, will provide the best results when attempting to decrease the building's environmental impact. Therefore, using recyclable materials, avoiding materials that contaminate the environment, and avoiding construction designs that are difficult to disassemble are three of the main priorities for cardboard buildings. Accordingly, in order to promote considerable reduction of energy use and increase the likelihood of re-use, a great deal of attention must be paid to the standardization and flexibility of design.

Recycling of a cardboard building during the disposal stage must focus on optimal recycling techniques for the transformation of dismantled materials and building components into reusable materials. Political decision makers and environmental legislation in the near future is expected to focus increasingly on selective dismantling and recycling of buildings, favoring eco-conscious materials like cardboard. A cardboard building's reusability and recyclability provide a serious marketing advantage, particularly in an age when a greater portion of the population is now concern with environmental issues. Application models can include new environmental control instruments, such as waste duties, recycling quotas or taxes on primary raw materials.<sup>3</sup>

<sup>1</sup> Spengler, et al. 308-309.

<sup>2</sup> Spengler, et al. 310.

<sup>3</sup> Spengler, et al. 309-311.

### **3. Analysis I: Production Stage**

The primary objective of this subchapter is to demonstrate the environmental impact of a basic unit wall component, composed of corrugated cardboard and other materials, such as facings and adhesives. This phase is positioned as a decision-making tool to identify the parameters for these additional materials and their compatibility with environmental guidelines. The study further seeks to develop a catalogue of environmental sustainability criteria to serve as the basis for the upcoming chapters on the architectonic and constructive approaches.

As a technical modeling tool, SimaPro software was used to evaluate the environmental impact during the production stage of a building. By measuring and comparing the building performance with other existing systems and building materials in the sector, a comparative search was created. The SimaPro model calculates the environmental impact of a building by focusing on six categories: global warming, acidification potential, eutrophication, photochemical ozone, energy use, and solid waste generation.

The basic unit wall component is a composite in nature, consisting of a cardboard core, two facings as the skin, and adhesive to connect the three layers with one another in this stage. Corrugated cardboard, the primary element in a cardboard house, is manufactured from a natural renewable source. Renewable sources are regenerated by natural processes, such as oil, vegetation, animal life, air, water. If not used prudently, the overuse of renewable resources can result in irreversible degradation.<sup>1</sup>

#### **3.1. Introduction: The Cardboard Manufacturing Process**

The packaging industry often promotes cardboard as a low-cost, low-impact, and highly recyclable alternative to plastic, polymer-based packaging. Several research platforms are supported to investigate and communicate these advantages by cardboard packaging industry and its associations such as FEFCO. Particularly within the European Union, environmental impacts on the manufacturing process of corrugated cardboard are strictly regulated by governmental entities.

Over the last 10-15 years, the cardboard industry has developed significantly in terms of quality, productivity, protection of the environment and palette of products. Customized features focusing in packaging have been applied for various demands such as improved structural strength, quality printability, and toxicology-protected usage for transporting frozen food and fresh vegetables and fruits, while still maintaining cardboard's cost and environmental advantages.

Today, the lifecycle for cardboard production is mostly limited to packaging as an endproduct. The existing configuration of cardboard package manufacturing will nevertheless guide the production process for cardboard buildings. Figure 3.4 displays the complexity of stages for

<sup>1</sup> A. Ongmongkolkul, *Lifecycle Assessment of Paperboard Packaging Produced in Medium Sized Factories in Thailand*," Master's Thesis, Asian Institute of Technology (2001): 19.

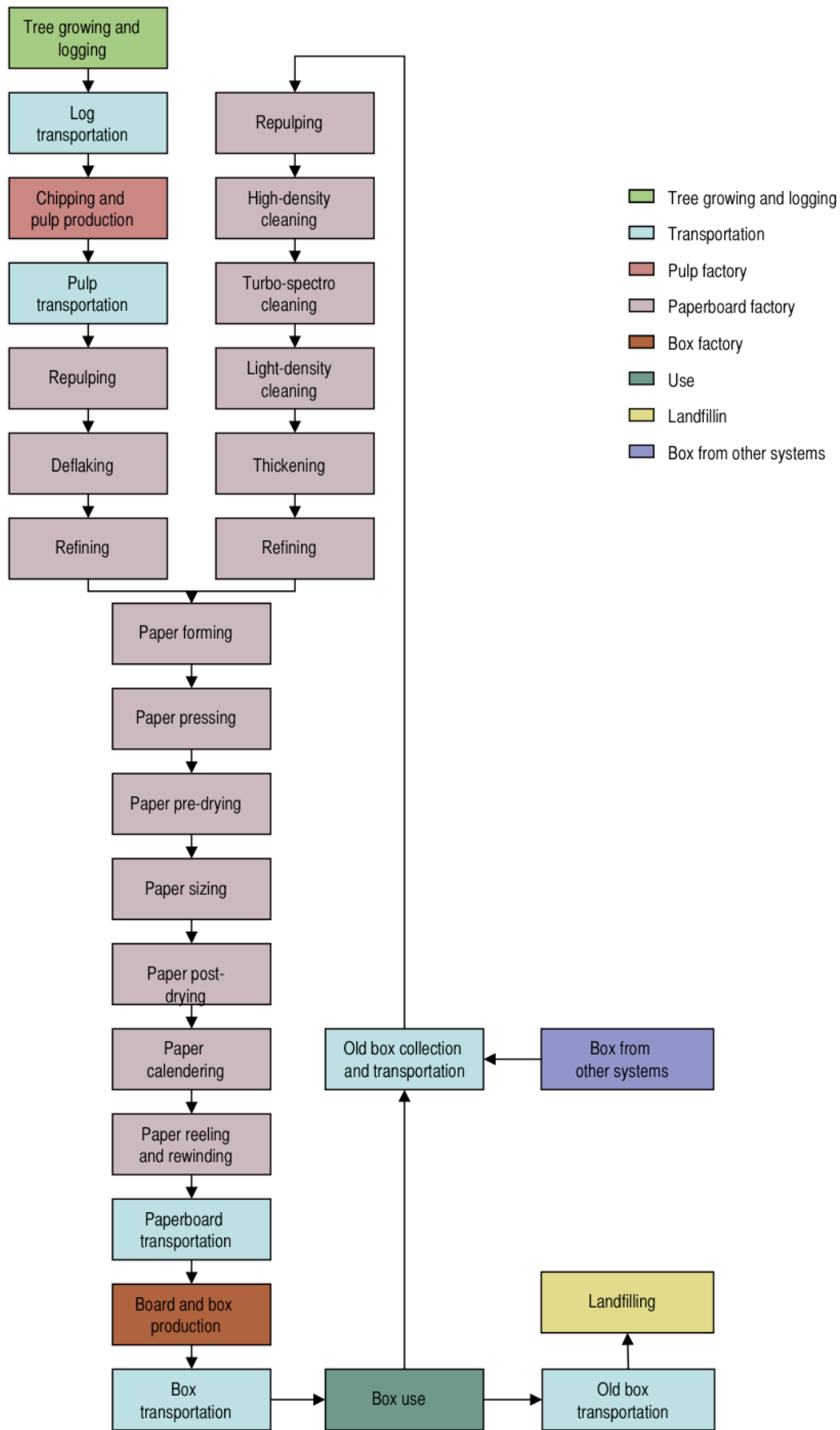


Figure 3.6 - Production line for cardboard packaging.

cardboard packaging material, while the overview of the cardboard industry in Figure 3.5 demonstrates the complexity of the environmental inputs and outputs for cardboard production.

### **Composition**

Cardboard is composed of several different layers of fibers. It can be produced from new fibers such as cellulose (sulphate or sulphite, bleached or non-bleached), wood pulp, recycled fibers or combinations thereof, with the addition of auxiliary materials such as aluminum sulphate, kaolin, starch and synthetic latex).<sup>1,2</sup> *Corrugated* cardboard is composed of linerboards and a corrugating medium. The linerboard is typically a two-ply cardboard commonly used as the outer plies of corrugated board. The linerboard must possess are a high level of stiffness and burst resistance, as well as a clean appearance and printable surface. The corrugating medium is produced from light-weight paperboard, used for the inner plies of corrugated cardboard.

### ***i) Environmental Impact of Cardboard Production***

An environmental impact assesment of cardboard in packaging industry, from the input of virgin materials to the output, focuses on several areas. The approach of the impact assessment is guided by the following goals:

- a) identifying and quantifying data of each unit processes throughout the lifecycle of corrugated cardboard, from raw material to end product;
- b) using the environmental impact performance results to reduce negative environmental impacts such as solid waste generation and emissions into the air, water and soil.

The major environmental impacts and resource consumption of cardboard in production are categorized into three main scales: global, regional and local. Each stage in the cardboard manufacturing process generates emissions that affect all three scales in an interrelated manner. They contribute to the environmental burdens through global warming, acidification, eutrophication, oxygen depletion and photochemical ozone formation (smog). Ongmongkolkul describes these impacts as follows:

- *High water consumption / pollution: Not only are large amounts of water needed for the paper making process, the water becomes highly contaminated as a result of the processing. It then causes serious water pollution as the released water has high BOD and SS levels that serious endanger aquatic organisms.*
- *High energy consumption: energy cost contributes approx. 16-40% of the production cost of cardboard*
- *Air pollution: Chemical recovery, combustion, bleaching procedures in cardboard production endangers the quality of air by emissions like BOD,COD, SS, Nitrogen, phosphorus; toxic*

<sup>1</sup> *SimaPro 7: Database Manual: The BUWAL 250 Library* (PRe Consultants, June 2004): 13.

<sup>2</sup> *SimaPro 7: Database Manual: The BUWAL 250 Library* (PRe Consultants, June 2004): 13.

pollutants such as AOX.

- Global warming: even with a low estimated land filling rate of 20%, methane emissions from anaerobic degrading of the paperboard appears to constitute a major potential source of global warming and smog formation in the box's lifecycle.

- Acidification: Contributions to acidification are to a large extent due to transportation, paper forming and virgin pulp productions as a result of SO<sub>x</sub> and NO<sub>x</sub> emissions from the engines, heat and power plants.

- Eutrophication: The main source of eutrophication and oxygen depletion are the cleaning steps in recycling processes of cardboard factory as well as thickening and paper pressing in papermaking processes, due to wash-out of organic matter and nutrients from pulp. N-Based sizing additives shall be avoided.

- Smog: Other sources of smog formation are drying processes in paperboard factory as a result of coal based steam production.

- Electricity consumption by cardboard factories can also play a significant role in cardboard's total impact. Global warming, smog formation and acidification could be reduced with cleaner production at the factories. <sup>1</sup>

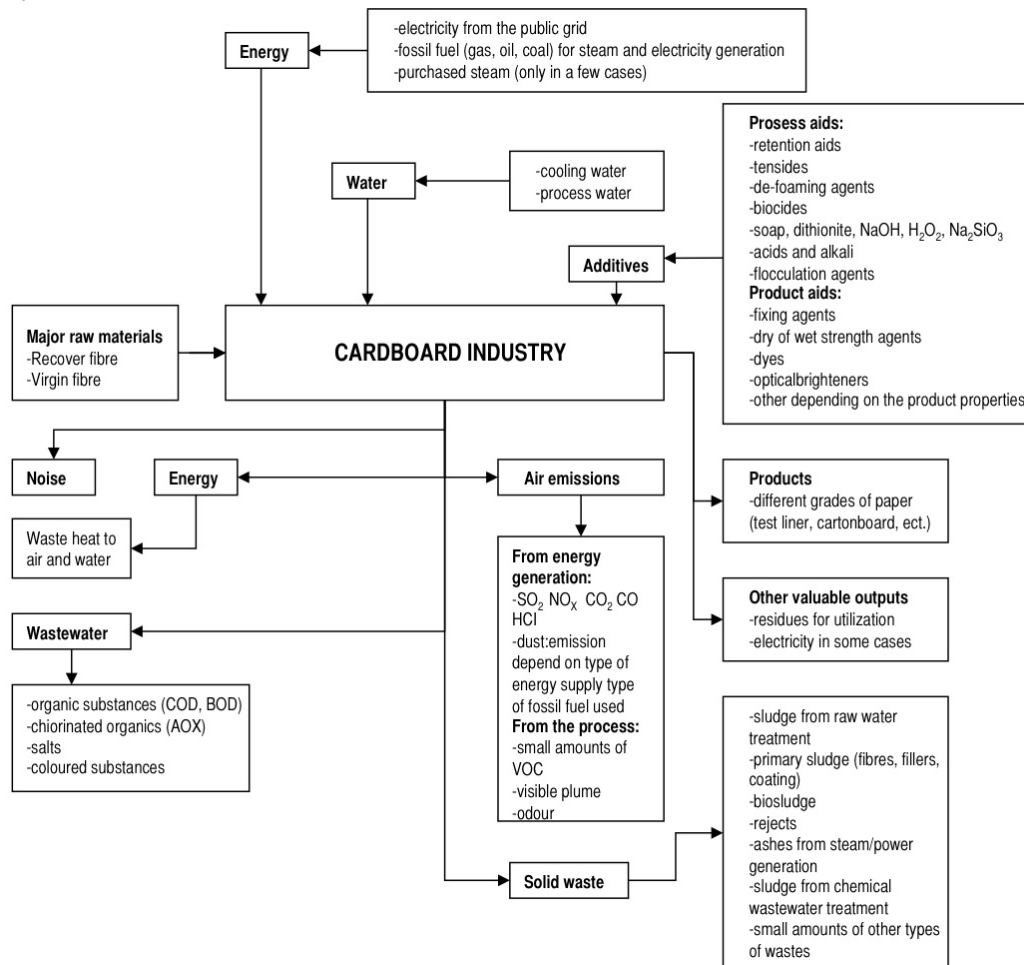


Figure 3.7 - Overview of input and outputs within the paperboard industry. <sup>2</sup>

<sup>1</sup> Ongmongkolkul 15.

<sup>2</sup> Source: European Commission (2000).



**ii) Environmental Impact of Cardboard as a Building Component**

The lifecycle of a cardboard building from cradle to grave proceeds through the following stages: 1) production of paper; 2) production of corrugated cardboard; 3) prefabrication of cardboard construction element (stacking layers of cardboard with facings); 4) construction of the building on-site; and 5) following usage, deconstruction into basics to be recycled/reused (Figure 3.8).

The positioning and optimization of the production line stages, starting from paper pulp production to the prefabricated cardboard building wall component, requires attention to cost and quality manufacturing and engineering solutions. Within this study, the production line stages for a cardboard composite building component are defined as follows:

1. *Pulp Production*: This stage consists of tree growing/cutting, debarking and chipping, digesting, washing, chemical recovery, screening and bleaching.
2. *Stock Preparation*: This second stage consists of repulping, cleaning, dewatering and refining. This is the process of preparing the pulp for the paper machine.
3. *Paper Production*: This third stage consists of forming, pressing, drying, sizing, calendaring, reeling, and rewiring. During this stage, a high amount of energy is consumed, and produces various forms pollution.
4. *Cardboard Manufacturing*: In this stage, the paper is converted into corrugated cardboard. Depending on the format, single-faced, single-walled corrugated cardboards, double/triple corrugated cardboards are formed by gluing a flat sheet of linerboard to a sheet of corrugated material that has passed through facers to form it into series of arches. The aim of this structure is to take advantage of the corrugated material for added strength and rigidity.<sup>1</sup>
5. *Cardboard Construction Element Production*: The prefabrication of the construction element is one of the focuses of this research project. Cardboard core based composite building elements are prefabricated in this stage by combining different layers of corrugated cardboard core with facings and joint elements. Some additional layers or additives in the pulp may be used to customize the building component composite and to secure structural strength and stiffness under humidity and to ensure sufficient thermal and acoustic performance. The additives used in the pulp and cardboard core must comply with both ecologically and economically

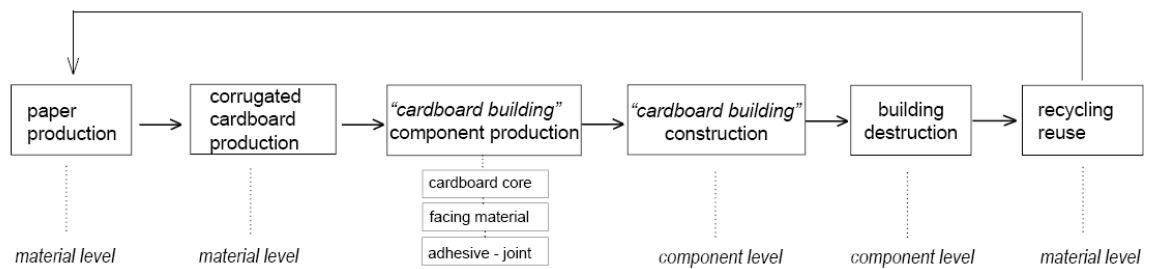


Figure 3.8 - Manufacturing lifecycle of a cardboard building.

<sup>1</sup> Ongmongkolkul 15.

sound measures. Prefabrication of the wall construction element is completed off-site in the factory under controlled working conditions because of the vulnerability of the cardboard core cardboard. The stage includes finishing, packaging for protection from external damages, and transportation of the elements to the construction site.

Understanding the production stages and the environmental impacts of cardboard packaging process will guide the bases of cardboard building component production in terms of both manufacturing engineering and reducing the overall ecological impact (Figure 3.9).

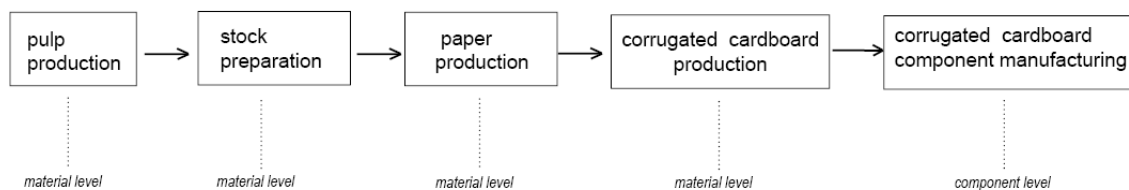


Figure 3.9 - Production line of prefabricated cardboard composite components.

### 3.2. Method and Boundaries for SimaPro Calculations

The life-cycle assessment approach (LCA) and SimaPro software are the tools used in this study to evaluate the environmental impact of the cardboard production process. LCA is used as an approach to quantify the resources that are consumed during the entire lifetime of a product, as well as its emissions. This is done by drawing information from the Swiss Centre for Life Cycle Inventories' EcoInvent database.<sup>1</sup> Within this study, a series of analyses are performed on a functional unit of 1 m<sup>2</sup> wall samples of varying thicknesses. The first environmental impact analysis investigated cardboard core with various facings, including steel, aluminium plywood and glass fiber reinforced plastic, based on two different thicknesses. The second series of analyses involved comparison of two adhesives, epoxy resin and polyurethane. Lastly, a sample of cardboard sandwich panel composites (corrugated cardboard core, facing and adhesive) were compared with traditional building materials, including a brick wall and a concrete block wall. Parameters, such as structural, mechanical, building physics properties, availability, and budgetary limits constrained the breadth of choice of some of the sample composites. The analysis and results are used as a low-cost, low-impact decision-making tool in the categorization of sample cardboard wall composites.

The parameters for this study using SimaPro program in the environmental performance analysis are set forth below:

1) One of the major parameters to start a LCA environmental assessment and run SimaPro models is the transportation. This title refers to the transportation of the raw materials from the extraction to the construction site, which is acclaimed to be responsible of a major amount of environmental high impact. The calculations in this study have accepted the hypothesis that the materials needed for production of cardboard buildings are easily available within the

<sup>1</sup> The Swiss Centre for Life Cycle Inventories (EcoInvent Centre) has created harmonized, quality-assured life-cycle assessment data for the past five years, which makes this task significantly simpler.

borders of the Switzerland. Therefore when using the SimaPro model, minimum transportation based environmental impacts are chosen to be added to the overall calculation.

2) In order to perform an accurate assessment of these impacts, the LCA approach includes the material’s entire lifecycle (usage, end of life, disposal and recycle) in its calculation. However, in this study, due to time constraints and the lack of a prototype, the environmental impact assessment investigates only the production stage of the project. Thus, the system boundaries are set to the production of the materials and exclude the use, end of life/disposal, and recycling stages. The calculations assume a twenty year lifespan.

3) Comparison of the data between the configured cardboard building composite samples and conventional wall samples on a functional unit of 1 m<sup>2</sup> was based on the samples’ availability, ecological impact, price and weight. However, the comparisons made with the conventional materials were made based on the material in its raw state, and exclude any specification with any additional insulation material. Therefore, the resulting comparison of prices and insulation values therefore can only be used as preliminary data. Further study are necessary for a more precise determination, in which the calculations involving traditional building material are made once insulation and plaster have been added.

**SimaPro Environmental Impact Analysis Categories and Boundaries**

The SimaPro program generates an analysis according to four environmental impact classifications (Global Warming Potential, Cumulative Energy Demand, Eco-Indicators and Eco-Points) and models that result in “characterization, weighting or single score” graphs. For the characterization graphs, within each environmental impact category, the emissions are calculated in the same unit and then summarized. The weighting graphs demonstrate the severity of the impact categories relative to one another, as defined by the software. For the single score graphs, the relative importance of the effect is given by multiplication with the weighting factor. Both the weighting and single score modeling methods involve some degree of subjectivity.

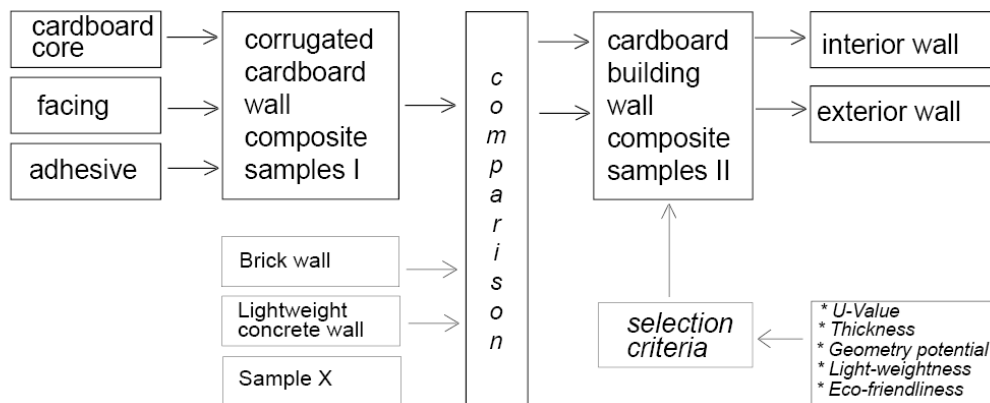


Figure 3.10 - Environmental impact assessment process for the production and operation stages.

These impact assessment types are important steps to interpret the environmental impacts within LCA. US Environmental Protection Agency defines the concept of Global Warming Potential as:

“The concept of a global warming potential (GWP) was developed to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas. The definition of a GWP for a particular greenhouse gas is the ratio of heat trapped by one unit mass of the greenhouse gas to that of one unit mass of CO<sub>2</sub> over a specified time period.”<sup>1</sup>

Association of German Engineers (Verein Deutscher Ingenieure) describes Cumulative Energy Demand as the entire demand, valued as primary energy, which arises in connection with the production, use and disposal of an economic good.<sup>2</sup>

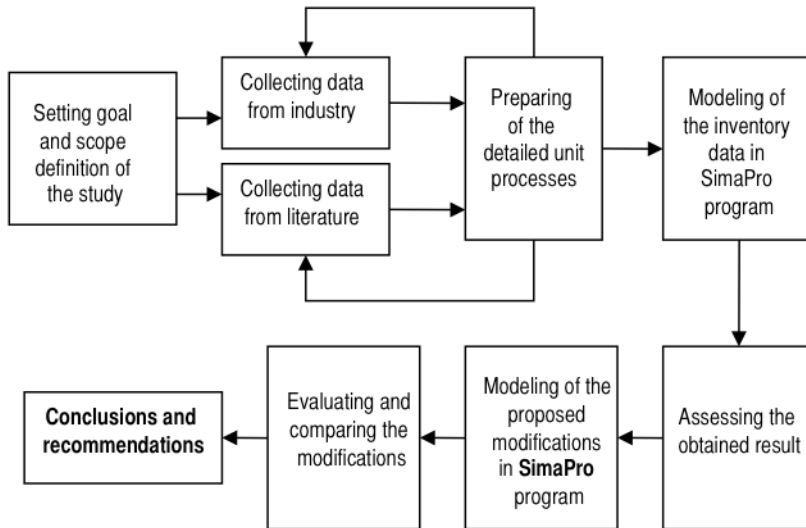


Figure 3.11 - Algorithmic structure of Simapro software environmental assessment.

*Functional Unit: 1m <sup>2</sup>	Simapro Chosen item	Thickness of facing Per layer (mm)	Density- kg/m <sup>3</sup>	Weight (kg) used for m <sup>2</sup>	Price per 1m <sup>2</sup> (.CHF) per ply	Thermal conductivity (W/mK)
Facing	Steel, converter, at plant/RER U	0.5 mm	8000 kg/m <sup>3</sup>	4 kg	10.72.- <small>*CHF268/100kg</small>	52 W/mK (41-58 W/mK)
		1 mm	8000 kg/m <sup>3</sup>	8 kg	19.76.- <small>*CHF247/100kg</small>	
	Aluminium alloy, AlMg3, at plant/RER U	1 mm	273 kg/m <sup>3</sup>	2.73 kg	25.30.- <small>*onlinemetals.com 23.13\$</small>	201 W/mK
		3 mm	273 kg/m <sup>3</sup>	8.19 kg		
	Plywood, outdoor use, at plant/RER U	5 mm	800 kg/m <sup>3</sup>	4 kg	11.90.- <small>or o hne stick 22.00- *haas-holz.ch/douglas.html</small>	0.13 W/mK (0.11-0.22 W/mK)
		10 mm	800 kg/m <sup>3</sup>	8 kg		
Glass fibre reinforced plastic, polyamide, injection moulding	3 mm	800 kg/m <sup>3</sup>	2.4 kg	123.00.- <small>112.5\$, (for 1.2mx1.2m)</small>	0.4 W/mK	
	6 mm	800 kg/m <sup>3</sup>	4.8 kg	177.00. <small>*162\$mparts.com/Catalog/Box_Building/frp.as 38x38"</small>		
Glue	Polyurethan-PUR- 2-Komponenten kleber „Collano VM5480“- 0.023 ?			1.3 kg	2.00.- <small>*1.8\$ PU Sol tempstroy.com/materials/price.shtml</small>	
	Epoxy resin A (or I)			1.3 kg	63.00.- <small>* www.darfrog.co.uk/</small>	
Cardboard core	Corrugated board, recycling fibre, single wall, at plant/RER U. Paper tesliner: 115g/m <sup>2</sup> . Total weight(single wall+%20glue weight: 345gr/m <sup>2</sup> x 22 layers	100 mm		7.59 kg	15.60.-/m <sup>2</sup> x 2 = 31.20.- CHF	0.09 W/mC (corrug. Perp.to the plane) 0.05 W/mC (corrug. Parallel to the plane)

Figure 3.12 - List of material properties used in Simapro from the integrated Eco-Invert database.

<sup>1</sup> «High Global Warming Potential (GWP) Gases», US Environmental Protection Agency, [www.epa.gov/highgwp/scientific.html](http://www.epa.gov/highgwp/scientific.html), 2009.

<sup>2</sup> W. Klöpffer, «In defense of the cumulative energy demand», Earth and Environmental Science Journal, Volume 2, Number 2 / June, 1997, Page 61.

### 3.3. Analysis I: Production

The goal in this analysis was to interpret the environmental impacts of diverse skin materials. The graphs introduce the SimaPro outcomes regarding four facings, compared to each other in terms of impacts and thickness, to form a sandwich wall component. The facings selected for analysis were steel plates (0.5 mm - 1.00 mm thick), aluminum plates (1 mm - 3 mm thick), plywood (5 mm - 10 mm thick), and glass fiber-reinforced plastic (3 mm - 6 mm thick) (Figure 3.12). Below, the graphs based on the SimaPro analysis of the four facings demonstrate the environmental impact of each material.

#### 3.3.1. Environmental Impact Analysis for Sample Facings

##### Cumulative Energy Demand Analysis

The Cumulative Energy Demand calculates the total (primary) energy used through a material's life based on lower heating value, which is the industry standard. Graphs of cumulative energy demand during the production phase of four facing materials with two different thicknesses are illustrated below. The analysis shows that steel facing has the most significant environmental impact, followed by glass fiber reinforced plastics (Figure 3.13).

Sets of facings selected from the SimaPro inventory: steel converter, low alloyed, at plant/ RER / U (0.5-1.00 mm thick), aluminum allow, AlMg<sub>3</sub>, at plant/ RER / U (1.0 -3.0 mm thick), plywood outdoor use (5-10.00 mm thick), glass fiber reinforced plastic, polyamide, injection molding, at plant/ RER/U (3.00-6.00 mm thick).

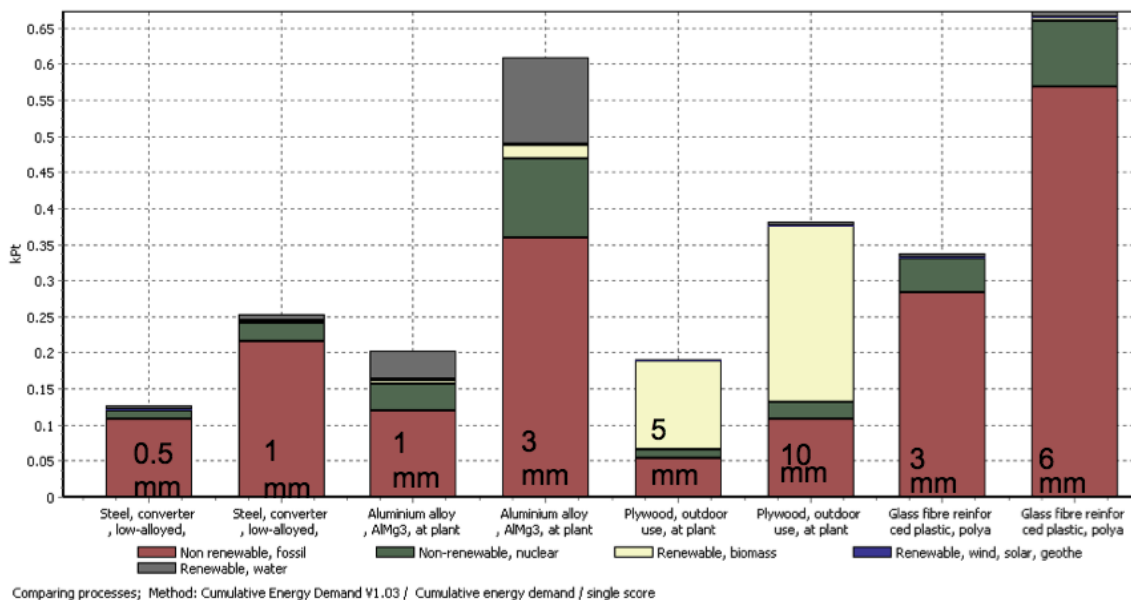


Figure 3.13 - Cumulative energy demand for various facings samples.

**Global Warming Potential Analysis**

The Global Warming Potential category is often utilized in various debates regarding CO<sub>2</sub> emissions. These values are defined as “Intergovernmental Panel on Climate Change (IPCC) characterization factors” for direct global warming potential of airborne emissions. Initially, the software analyses the impact of the materials under three different time frames: 20, 100 and 500 years. The aluminum alloy and the glass fiber-reinforced plastic facings showed the greatest airborne emissions in this impact category; referring that these samples indicate the highest global warming potential (Figure 3.14).

Sets of facings selected from the SimaPro inventory for this method: steel converter, low alloyed, at plant/ RER / U (0.5-2.00mm), aluminum alloy, AlMg<sub>3</sub>, at plant/ RER / U (1.00-3.00mm), plywood outdoor use (5.00- 10.00mm), glass fiber reinforced plastic, polyamide, injection molding, at plant/ RER / U (3.00-6.00mm). Method of calculation: characterization.

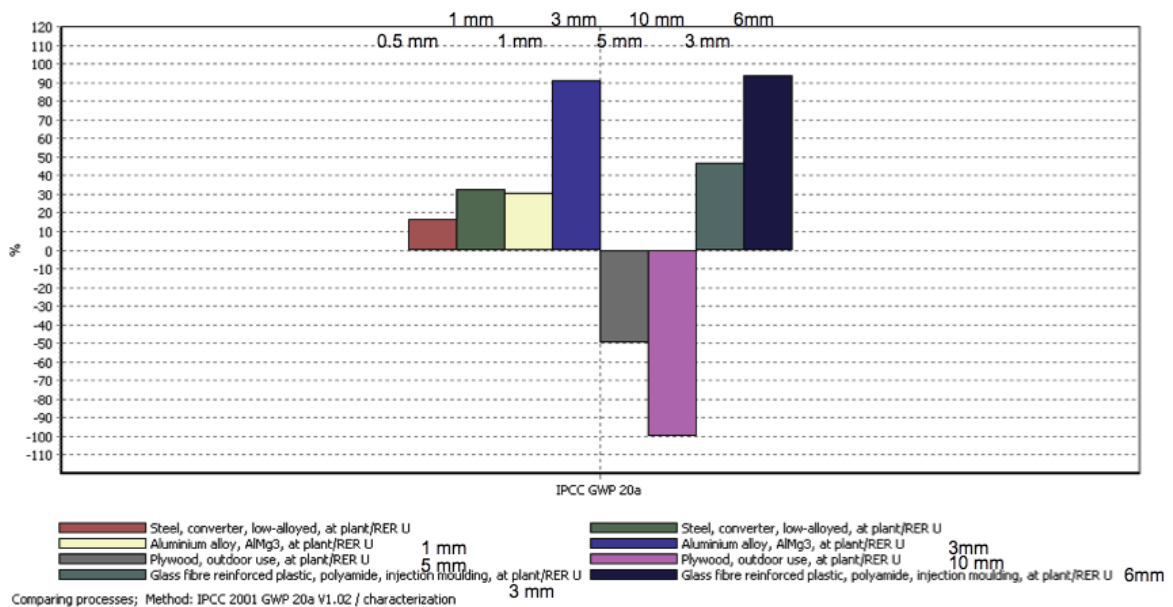


Figure 3.14 - Global Warming Potential for various facing samples.

**Eco-Indicators Analysis**

The “Eco-Indicators” analysis focuses on three main categories: the material’s effect on human health, ecosystem and natural resources. It is a complex calculation that entails a variety of environmental harms including radiation, smog, carcinogens, acidification and eco-toxicity. For this analysis, plywood facings showed the greatest number of types of environmental impacts as well as the overall environmental impact in this category (Figure 3.15).

Sets of facings selected from the SimaPro inventory: steel converter, low alloyed, at plant/ RER / U (0.5-1.00mm), aluminum alloy, AlMg<sub>3</sub>, at plant/ RER / U (1.00-3.00mm), plywood outdoor use (5.00- 10.00mm), glass fiber reinforced plastic, polyamide, injection molding, at plant/ RER / U (3.00-6.00mm).



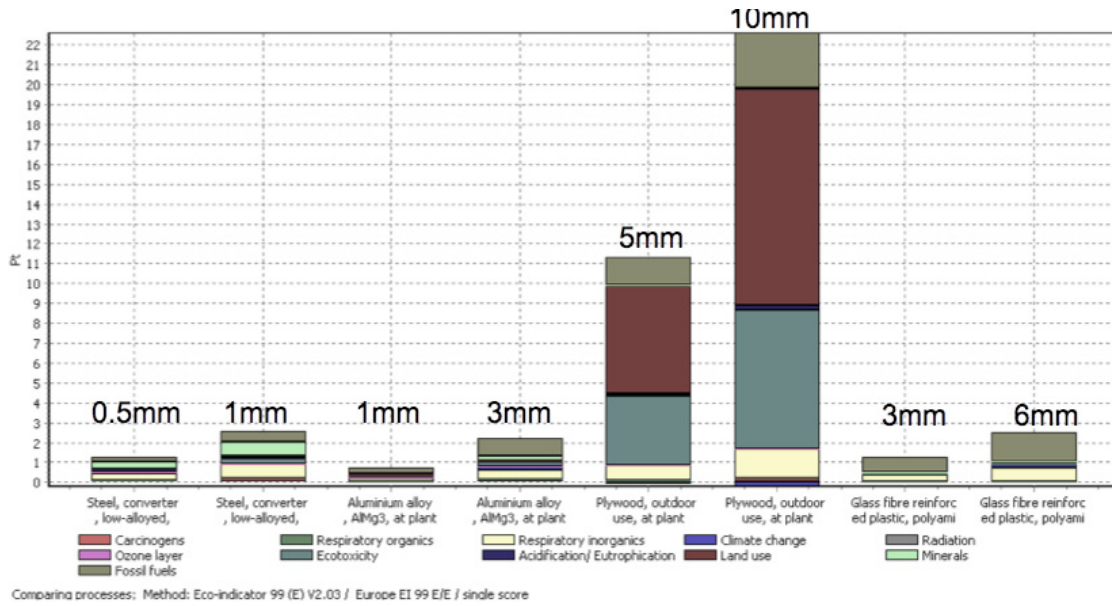


Figure 3.15 - Eco-Indicators for various facing samples.

**Eco-Points Analysis**

The Eco-Points method of analysis was developed in Switzerland and based on national government policy objectives. It shows how far a material is from a reference value, usually the legal boundaries of the country, in this case Switzerland. Under this method, plywood facings led to the highest emissions scores in the “single score” category, followed by aluminum alloy, glass fiber-reinforced plastic, and steel facings (Figure 3.16).

Sets of facings selected from the SimaPro inventory: steel converter, low alloyed, at plant/ RER / U (0.5-1.00mm), aluminum allow, AlMg<sub>3</sub>, at plant/ RER / U (1.00-3.00mm), plywood outdoor use (5.00- 10.00mm), glass fiber reinforced plastic, polyamide, injection molding, at plant/ RER / U (3.00- 6.00mm). Method of calculation: “single score”.

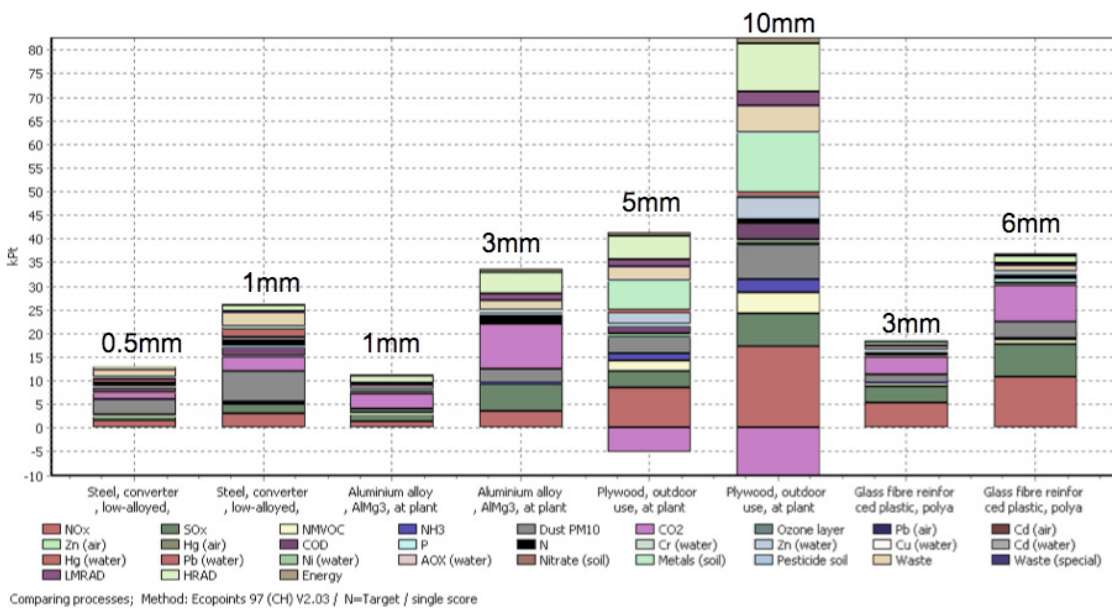


Figure 3.16 - Facing material environmental impact analysis in eco-points impact category.



### 3.3.2. Environmental Impact Analysis for Adhesives

Corrugated cardboard core sandwich wall components are composed of cardboard core, two facing materials and the framing material that allows it to join with other components. The assembly has two main directions: the assembly of corrugated cardboard core block and the wall component using other materials. Several diverse bonding methods including thermal joining, mechanical fastening, and adhesive bonding will be used. The assembly process necessarily requires the choice of right adhesives, considering several parameters including their environmental impact.

In this research, Polyurethane-PUR-Komponentenkleber (Collano VM5480) was used as the primary adhesive at the mechanical behavior experiments by the engineering team. Focused on environmental impact, polyurethane type adhesive, used for the experiments are compared with a similarly functioning adhesive epoxy resin. Epoxy resin A and Polyurethane flexible foam were selected as the set of adhesives from the SimaPro software inventory to run the calculations below.

#### Cumulative Energy Demand

This analysis was used to determine the total energy consumed during the production phase for the two adhesive options for the 1m<sup>2</sup> surface. The single score graphs shows that Epoxy Resin (%100) has a higher environmental impact in terms of cumulative energy demand than the polyurethane adhesive (%65) (Figure 3.17).

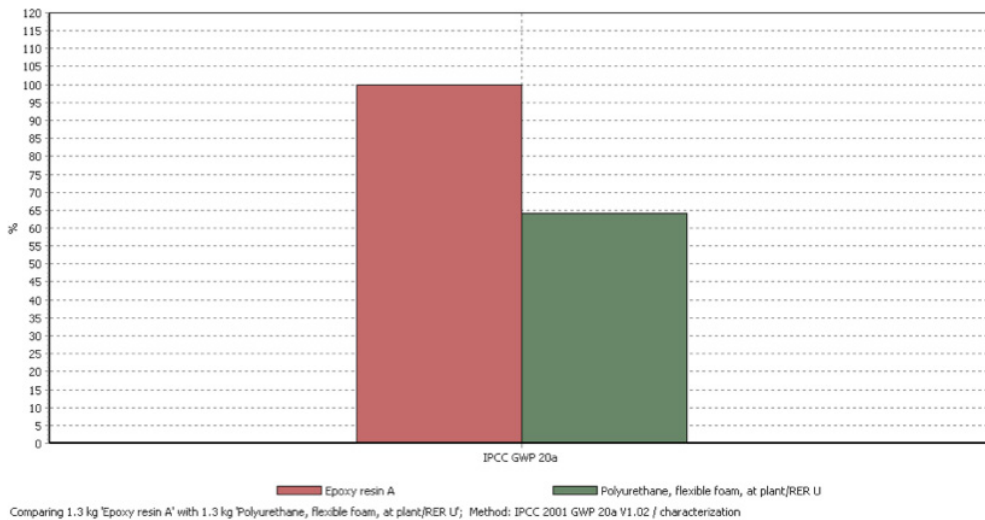


Figure 3.17 - Cumulative Energy Demand for adhesive samples.

#### Global Warming Potential

As displayed in Figure 3.18, the characterization graph for Global Warming Potential, using a 20 year time frame, the predicted global warming impact of Epoxy Resin A is measurably higher than Polyurethane. This analysis assumes that equal amounts of each adhesive are used to construct a 1m<sup>2</sup> surface. Non-renewable fossil fuels are observed to add the most to the global warming potential of both samples, followed by non-renewable nuclear fuels used to manufacture both adhesive types (Figure 3.18).

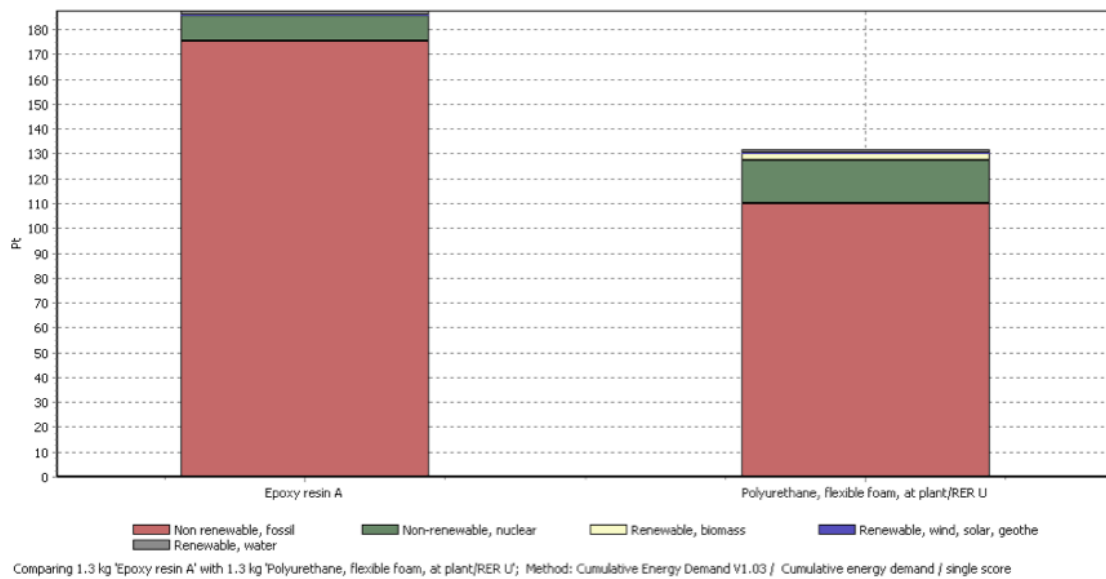


Figure 3.18 - Global Warming Potential for adhesive samples.

### Eco-Indicators

The Eco-Indicators analysis, which examined the two adhesives' consumption of fossil fuels, impact on climate change and respiratory inorganics issues, indicated that Epoxy Resin A has a substantially greater impact than Polyurethane. The eco-indicator results close to twice figures of fossil fuel consumption of epoxy resin, compared to the polyurethan sample chosen.

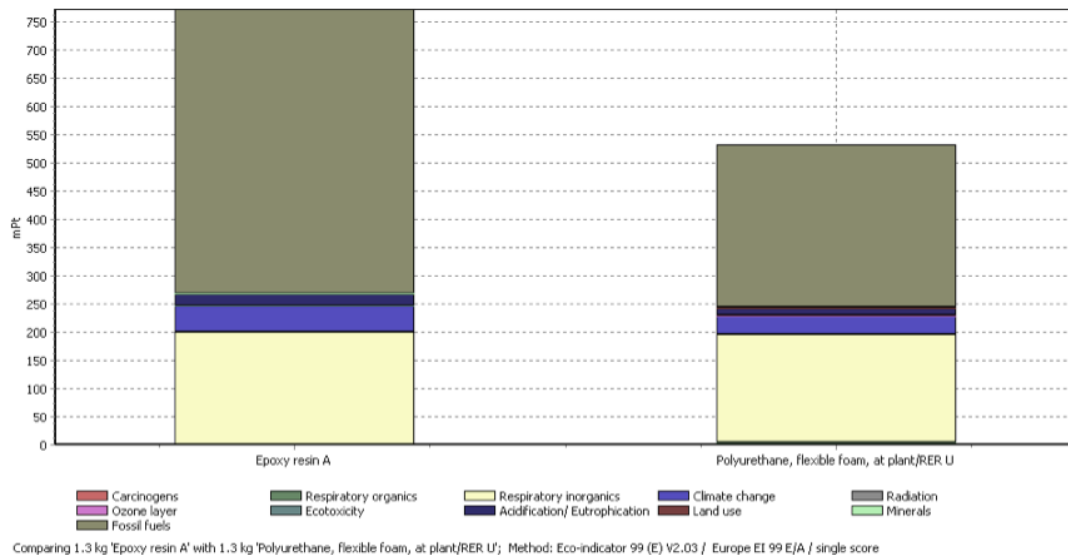


Figure 3.19 - Eco-Indicators analysis for adhesive samples.

### Eco-Points

The Eco-Points analysis indicated that epoxy resin A produces more harmful emissions into the environment compared to polyurethane. However, most of the categories within the Eco-Points analysis showed such a small amount of emissions so as to render the results not significant. Only the amount of carbon dioxide emitted by epoxy resin was significant enough to take into consideration.

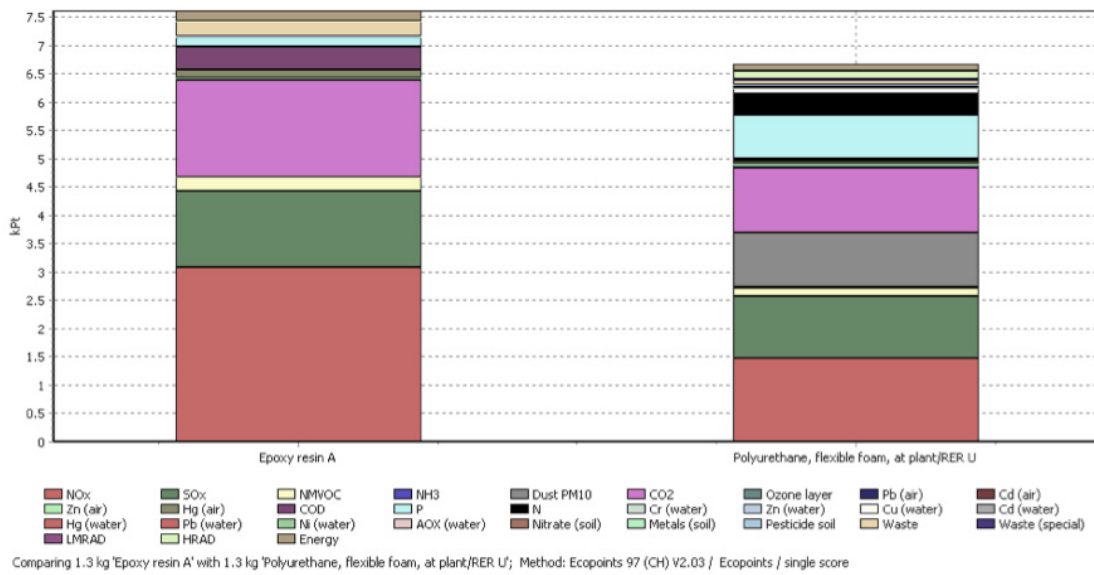


Figure 3.20 - Eco-Points analysis for adhesive sample.

### 3.3.3. Environmental Impact Analysis for Composites

The 1m<sup>2</sup> functional wall unit is configured with facing material on both sides of a 100 mm thick cardboard core, affixed with an adhesive. The composites were chosen based on the results of the SimaPro impact analyses discussed above. Then the cardboard core sandwich wall segments were compared to other traditional building materials. The outer-most skin layer (paint, exterior insulation) of the wall components was not factored into the comparison.

The functional unit of 1m<sup>2</sup> wall, composed of cardboard core (100 mm thickness) with steel plates (0.5 mm thickness), aluminum plates (1 mm), plywood (5 mm), and glass fiber reinforced plastic (3 mm) facings with polyurethane as the adhesive are being compared with a brick and a concrete wall using SimaPro7. The total thicknesses achieved, the used weight and the prices (where applicable) for the functional unit, and also material properties such as gross density and thermal conductivity are shown in Figure 3.21 and 3.22 describing the tested samples.

*Functional Unit: 1m <sup>2</sup>	Simapro Chosen item	Thickness of each layer (mm)	Cardboard core Thickness
Composite Facing (2 facings+2 glues layers+ cardboard core)	Steel, converter, at plant/RER U	0.5 mm	100 mm
	Aluminium alloy, AlMg3, at plant/RER U	1 mm	100 mm
	Plywood, outdoor use, at plant/RER U	5 mm	100 mm
	Glass fibre reinforced plastic, polyamide, injection moulding	3 mm	100 mm
Brick wall Swissmodul	Brick, at plant RER U, (einsteinmauer) 1100 kg/m <sup>3</sup> , 0.44 W/mK (290mm x 200mm x 190 mm, 10.4 kg) uninsulated	200 mm	
Lightweight Concrete Wall	Leightweight concrete block, expanded clay, at plant/ CH U, 500kg/m <sup>3</sup> density, 0.19 W/mK uninsulated	200 mm	

Figure 3.21 - Cardboard composite samples vs. traditional samples.

Functional Unit: 1m <sup>2</sup>	Simapro Chosen item	Thickness of each layer (mm)	Cardboard core Thickness	Total Weight Kg	Total thickness (glue layers each taken 0.25mm)	U-WERT (W/m K)=1/R R=d/1+ 14 d2/ 2+ d3/ 3	Total Price -CHF
Composite Facing (2 facings+2 glues layers+ cardboard core)	Steel, converter, at plant/RER U	0.5 mm	100 mm	18.19 kg	100+0.5x2+0.5= 101.5 mm	1/((0.005/52)x2+0.1/0.09)= 0.9	10.72x2+2.00x2+15.60= 41.04.-CHF
	Aluminium alloy, AlMg3, at plant/RER U	1 mm	100 mm	15.65 kg	100+1x2+0.5= 102.5 mm	1/((0.0012/0.1)x2+0.1/0.09)= 0.9	35.30x2+2.00x2+15.60= 70.20.-CHF
	Plywood, outdoor use, at plant/RER U	5 mm	100 mm	18.19 kg	100+5x2+0.5= 110.5 mm	1/((0.005/0.13)x2+0.1/0.09)= 0.85	11.90+2.00x2+15.60= 43.40.-CHF
	Glass fibre reinforced plastic, polyamide, injection moulding	3 mm	100 mm	14.99 kg	100+3x2+0.5= 106.5mm	1/((0.003/0.4)x2+0.1/0.09)= 0.79	123.00x2+2.00x2+15.60= 265.60.-CHF
Brick wall Swissmodul	Brick, at plant RER U, (einsteinmauer) 1100 kg/m3, 0.44 W/mK (290mm x 200mm x 190 mm, 10.4 kg) uninsulated	200 mm		156 kg	200 mm	1/ (0.2/0.44) = 2.20	90.-CHF
	Lightweight concrete block, expanded clay, at plant/ CH U, 500kg/m3 density, 0.19 W/mK uninsulated	200 mm		100 kg	200 mm	1/ (0.2/0.19) = 0.95	85.-CHF* *gasbeton

Figure 3.22. Comparison of Cardboard composite samples vs. conventional samples (per 1m<sup>2</sup>)

### Global Warming Potential (GWP)

A comparison in terms of GWP is made in this analysis among the different wall samples and their thicknesses, between the samples discussed within this study (formed by cardboard core and diverse facing materials) and two conventional wall segments (Brick wall module and lightweight concrete wall segment). As seen in figure below, GFRP sandwich wall demonstrated the highest amount of global warming potential, followed by aluminium facing, cardboard core sandwich wall, and then concrete wall. Plywood facing cardboard core sandwich wall demonstrated the lowest potential impact. Additionally, it has been observed that the global warming potential is determined more by the facing material within a cardboard core wall block.

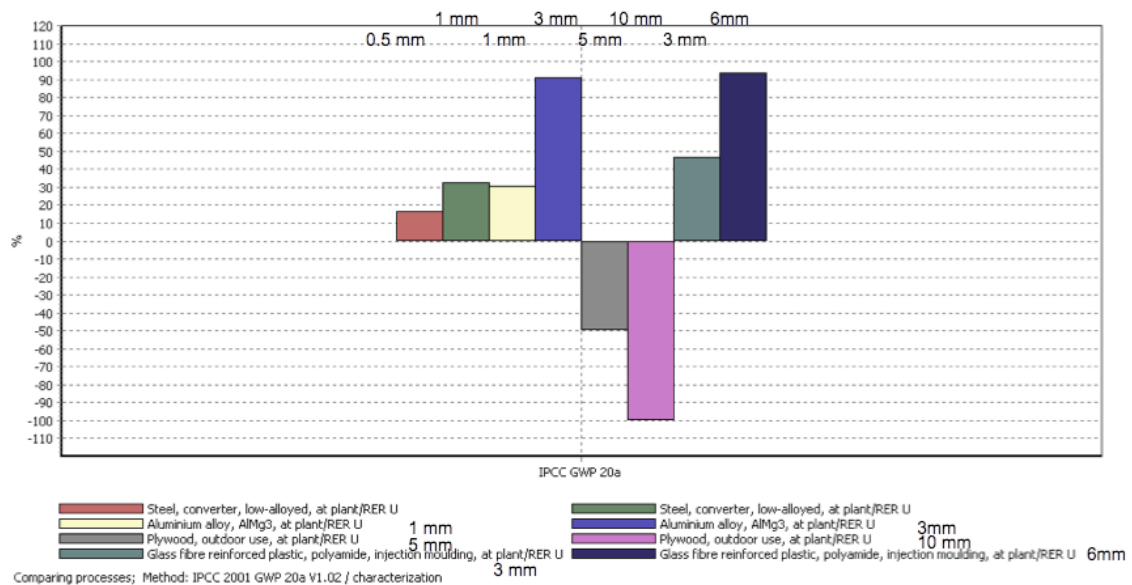


Figure 3.23 - Global Warming Potential for the selected sandwich composites.

### Cumulative Energy Demand

As seen in the figure below, GFRP facing-cardboard core sandwich wall followed by the sample with aluminium facings demonstrated the highest impact on the environment on especially regarding the non-renewable fossil resources, which is considered to have the most significance. Among all the fuel categories that influence cumulative energy demand, the samples showed

high consumption of non-renewable fuels, followed by non-renewable nuclear fuel, used for their manufacturing. Especially manufacturing of cardboard core samples with aluminium, GFRP and steel facing samples indicated consuming most of non-renewable nuclear fuels.

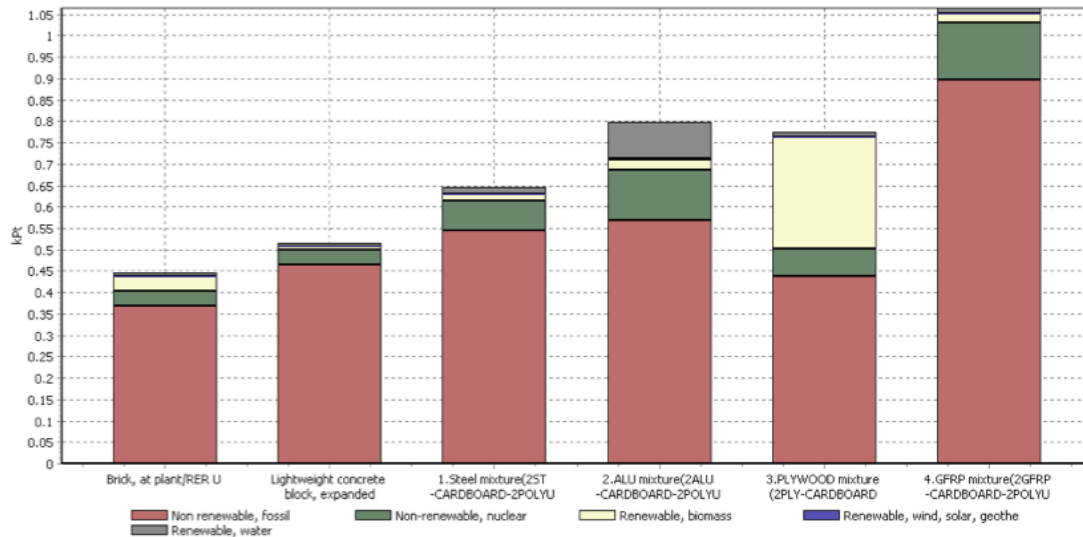


Figure 3.24 - Cumulative energy demand amongst selected sandwich composites.

**Eco points**

As seen in the figure below, cardboard core sandwich wall with GFRP, followed by steel facings and aluminum facings with cardboard core samples have the major impact on the release of the majority of the listed substances according to the Eco-Points Analysis (Figure 3.25).

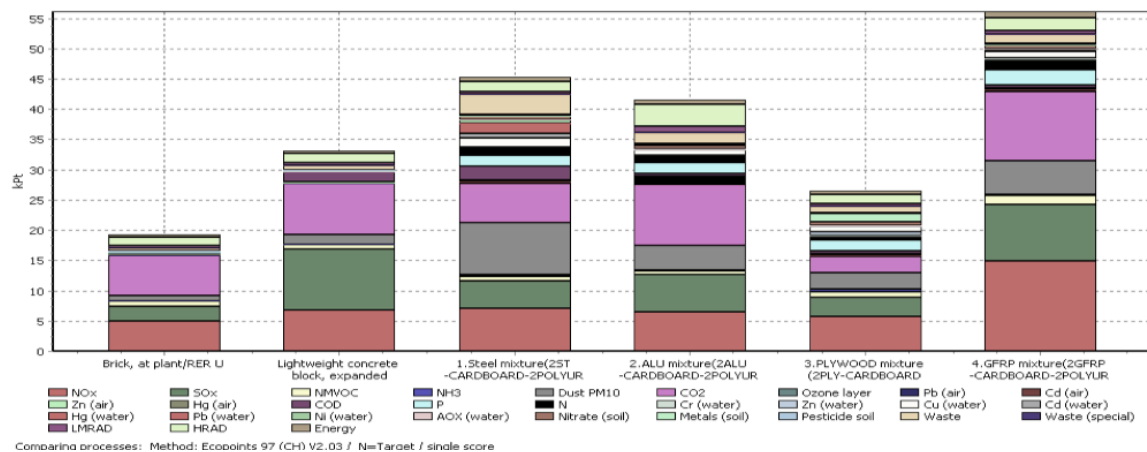


Figure 3.25 - Eco-Points analysis for the selected sandwich composites.

**Eco-Indicators**

In the Eco-Indicators analysis, the cardboard core sandwich wall with the Glass Fiber Reinforced Plastic and steel facing composite scored the highest impact with the total number of categories as well as the environmental impact. The cardboard core sandwich walls with plywood and aluminum facings also demonstrated relatively high scores on the Eco-Indicators scale, particularly when compared to the conventional wall samples. The brick wall, on the

other hand, performed surprisingly well, and indicated the lowest environmental impact of all the materials. However, this result may be skewed by the fact that it was tested without any additional insulating material or plaster, which would significantly increase its level of impact. The biggest impact was analyzed to be referring fossil fuels, respiratory inorganics and climate change categories.

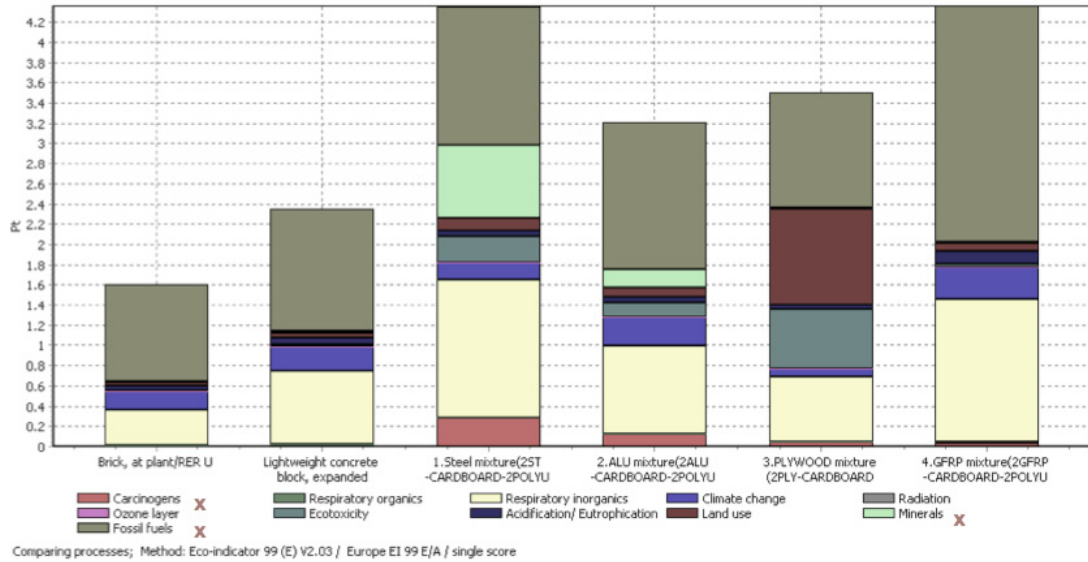


Figure 3.26 - Eco-Indicators analysis for selected sandwich composites.

### 3.4. Conclusion: Cardboard Composite Wall Component in Production Stage

The environmental impact assessment study for the production stage of cardboard building components was conducted using the LCA approach by modeling the analyses of SimaPro environmental engineering software. The SimaPro model calculated the environmental impacts with four types of analyses: Global Warming Potential, Eco-Indicator, Cumulative Energy Demand, and Eco-Points. These analyses took into consideration six impact categories: global warming, acidification potential, eutrophication, photochemical ozone, energy use and solid waste generation.

The analysis of the production stage for the cardboard building component was based on a comparison between the selected cardboard building composite samples and traditional wall components, on a functional unit of 1m<sup>2</sup>. The choice of core-facing configurations for the wall samples was based on their availability, ecological impact, price and weight.

The tests compared the cardboard core sandwich walls affixed with various facings. The results of the the Eco-Points and Eco-Indicator analyses showed that the wall components equipped with the steel and glass fiber reinforced plastic had the highest environmental impact. For the Global Warming Potential and Cumulative Energy Demand analyses, the cardboard core wall equipped with an aluminum alloy facing showed the highest impact, followed by the cardboard core wall with the GFRP facing.

For the two adhesives tested, Polyurethane demonstrated a lower overall impact than the Epoxy Resin A. Polyurethane chosen from the SimaPro inventory for the environmental impact analysis was similar to the polyurethane adhesive used during the experiments.

Finally, last environmental impact analysis compared the cardboard core sandwich walls affixed with various facings and two conventional wall segments, used in the sector. In the comparisons of cardboard core sandwich walls with conventional brick or concrete walls, there's a clear gain of cardboard core sandwich walls in weight, prices and U-values.

The potential advantages of cardboard core sandwich samples concerning the weight, prices and thermal insulation value might compensate for some of the high ecological impacts produced by cardboard core walls with metal facings. The one fact that is clear from these analyses is that the glass fiber reinforced plastic seems, although possibly more visually appealing than the other facing options, offers neither environmental nor economic benefits.

#### **4. Analysis II: Usage Stage**

Energy loss during operation, the usage stage, is generally considered to have the most significance in terms of a building's environmental impact. Heating, cooling, ventilation and lighting of regular buildings often consume up to forty percent of a nation's primary energy demands. Thus, combining energy consumption during the usage stage and material input during construction stage represents the total environmental impact of the sector. Because this accounts for such a large portion of a country's environmental impact, there is significant potential for energy and natural resource savings.<sup>1</sup> This study will focus on a building's thermal energy loss during the usage stage of a cardboard building.

##### **4.1. Introduction**

The cardboard building concept within this study was not pursued to the prototype stage, which could have provided more insight into its total energy consumption. Under these circumstances, a possible starting point for investigating the behavior of cardboard is to analyze the properties of wood, a recyclable material which has several characteristics in common with cardboard. Recent studies on wood construction have established that it has a reduced environmental effect in comparison with other building materials. Several recent studies have suggested that increasing the emphasis and use of wood and its byproducts as a building material could have significant implications for global energy requirements and global CO<sub>2</sub> emissions.<sup>2,3</sup>

Despite the recent improvement in the understanding of environmental concerns, there continues to be a general belief that a building's energy consumption is limited to the energy it uses during the operation stage. The likely reason for this misconception is that operational

<sup>1</sup> Kua and Lee 232.

<sup>2</sup> A. Buchanon and B. Levine, "Wood-Based Building Materials and Atmospheric Carbon Emissions," *Environmental Science and Policy* 2, no. 6 (Dec. 1999): 427-437.

<sup>3</sup> C. Thormark, "The Effect of Material Choice on the Total Energy Need and Recycling Potential of a Building," *Building and Environment* 41, no. 8 (Aug. 2006): 1019.



energy consumption accounts for the approximately 85-95 percent of a dwelling's energy use during a fifty year period.<sup>1</sup> This approach, however, is an act of "environmental load shifting", and therefore underestimates the responsibility of the user during the production stage, and instead focusing almost entirely on the energy consumed during operation. This project intends to emphasize to users their responsibility for energy consumption during every phase of a building's life, including construction, operation, and recycling. To that end, CATSE cardboard housing will introduce a system that is composed of low-impact cardboard and promote a dismantling and reconstruction process that is customized to each user's needs.

In order to comprehend the relationship between a building and the energy it consumes during its lifespan, it is necessary to systemize the four types of energy that are used<sup>2</sup>:

- a. Energy to initially produce the building and materials*
- b. The recurring embodied energy*
- c. Energy to operate the building*
- d. Energy to demolish and dispose of the building at the end of its effective life*

#### **a. Initial Embodied Energy**

The embodied initial energy of a building is the energy used to acquire raw materials and manufacture, transport and install materials in the construction of a building. It does not include the energy associated with maintaining, repairing and replacing materials and components over the lifetime of the building.<sup>3</sup>

As initial embodied energy concerns energy consumed by all of the procedures associated with the production of a building, from the acquisition of natural resources to product delivery, including mining, manufacturing of materials and equipment, transport and administrative functions<sup>4,5</sup>, the choice of building structure, envelope and material predominantly influence the overall consumption. The initial embodied energy consumption during the production phase for cardboard housing is analyzed in the prior subchapter.

#### **b. Recurring Energy**

The recurring embodied energy in buildings represents the non-renewable energy consumed to maintain, repair, restore, refurbish and replace materials, components or systems during the life of the building. The building structure typically lasts the full life of the building without need for replacement or repair. The only significant building elements that require recurring embodied energy are the building services and its interior finishes.

<sup>1</sup> Cole and Kernan 314.

<sup>2</sup> Cole and Kernan 307.

<sup>3</sup> Cole and Kernan 308.

<sup>4</sup> CSIRO Sustainable Built Environment Online Brochures: Embodied Energy, CSIRO Manufacturing & Infrastructure Technology (Commonwealth Scientific and Industrial Research Organisation, 2002).

<sup>5</sup> Chen, et al. 399.

In the case of CATSE cardboard buildings, maintenance and replacement are planned to occur more frequently compared to traditional building. Because the expected lifespan of a cardboard building is ten to fifteen years, precise planning and organization of the maintenance and replacement is critical. The energy costs for cardboard buildings are thus divided into two categories: 1) maintenance-related energy incurred during a completed lifecycle, and 2) replacement-related energy incurred during the incomplete lifecycle of a product due to the expiration of the building. However, the recurring energy assessment for cardboard buildings is outside the scope this project's preliminary study.

### **c. Operating Energy**

Operating energy is the energy required to operate the building. This includes the energy required to condition and light the interior spaces and to power equipment and other services. The amount of operating energy varies considerably with building use patterns, climate and season, as well as the efficiency of the building and its systems.<sup>1, 2</sup>

Energy used during operation of a building is invariably the largest component of a building's lifecycle energy use. On a national scale, energy consumed for building operations accounts for a significant portion of a country's total energy consumption. One Canadian study found that, the energy consumed by a typical building for heating, cooling, lighting and ventilation amounts to eighty to ninety percent of the total energy consumption.<sup>3,4</sup> Additionally, the same study found that this energy accounts for approximately thirty percent of Canada's national energy use. In other countries with different industrial bases and transportation networks, heating, cooling, lighting and power in buildings can account for up to fifty percent of a nation's energy use.<sup>5</sup>

On the building scale, the embodied energy of the building services represents the second most significant component of total building embodied energy, representing approximately 20-25% of a building's total initial embodied energy.<sup>6</sup> This portion of energy consumption, however, can be decreased considerably by making regular improvements, such as insulation upgrades of the building envelope and other technical solutions. This study will focus on a preliminary evaluation of the thermal energy loss during the operation of a cardboard building.

### **d. Demolition Energy**

Up until recently, the energy required for a building's demolition and transport and disposal of waste was considered insignificant and therefore disregarded. Current demolition practice involves application of serious amounts of energy and disposal of large of waste into landfills. The main difficulty in assessing the amount of energy consumed during demolition is accurately predicting these costs fifty years in the future.

<sup>1</sup> Cole and Kernan 313-314.

<sup>2</sup> N. Howard and H. Sutcliffe, "Precious Joules," *Building* (18 Mar. 1994): 48-50.

<sup>3</sup> Test case buildings for a typical building life of fifty years, respectively chosen from Toronto and Vancouver.

<sup>4</sup> Thormark 1019.

<sup>5</sup> N. Howard and H. Sutcliffe 49

<sup>6</sup> Cole and Kernan 310.

In the case of cardboard building construction, the time period for demolition and recycling is more predictable due to its shorter lifespan. Moreover, disposal is made simpler by cardboard's high recyclability rate.<sup>1</sup> Also, the dismantling process is similarly painless due to the simplicity of materials. In the near future, when salvaging material from buildings becomes a more critical cost saving measure, this ease of destruction and disposal will pose a serious advantageous for cardboard buildings.<sup>2,3</sup>

#### 4.2. Method and Boundaries

The system boundaries regarding the environmental analysis of the operation stage in this study are the building's thermal conductivity (U-value), using Minergie standards as a guideline for its ecological impact.

Consistent with this study's analysis of the production phase, a functional unit of a 1 m<sup>2</sup> is used for analysis of the operation stage. Parameters such as total U-value, thickness, weight and price are used to identify sandwich wall composites with diverse characteristics and qualities. Steel, gypsum board<sup>4</sup>, and glass fiber reinforced plastic facings were selected for the study's comparison.

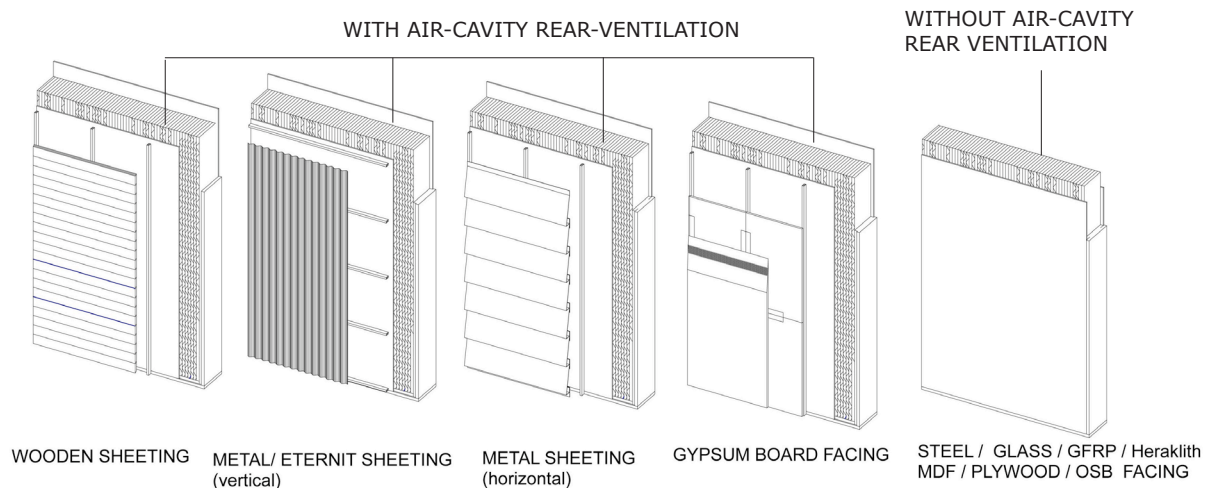


Figure 3.27 - Sample composite walls with cardboard core.

#### 4.3. Analysis

The negative environmental effects caused by a cardboard composite wall component during a building's usage stage were analyzed, based on its thermal energy loss. The analysis conducted in this research study involves the identification of the façade materials for the cardboard core composite and the illustration of graphs comparing these samples and characteristics.

<sup>1</sup> Excluding hazardous wastes within the disposal.

<sup>2</sup> Cole and Kernan 312.

<sup>3</sup> Kalin, Z.: "The State of Demolition Waste Recycling in Canada," *University of Western Ontario, Centre for Studies in Construction* 1993.

<sup>4</sup> "Fermacell" is selected as the sample gypsum board product within this study.

The analysis compared ten composite samples of gypsum board, steel and GFRP facings, with parameters such as total weight per 1 m<sup>2</sup>, U-value (W/m<sup>2</sup>K), thickness (cm) and provisional price (CHF).

These samples were analyzed under three different wall thicknesses: 30 cm, 45 cm and 60 cm. Four of the cardboard core samples were impregnated and applied with an inorganic substance. The impregnation was necessary to secure the material against loss of strength and stiffness caused by moisture, and for protection against fire. The cardboard core samples were also divided on the basis of their direction of corrugation, which was either parallel or perpendicular to the facing. The direction of the corrugation affects the cardboard core's thermal conductivity characteristics. This can also lead to some degree of increased complexity in the impregnation process.

#### **4.3.1. Sample A: Cardboard Core Composite with Gypsum Board Facing**

Gypsum board facing is one example of a panel type facing material. Found in a standardized format in the market, it also has the possibility of being divided into smaller pieces. The size of the *Fermacell* (Powerpanel H20)<sup>1</sup> gypsum board panels selected for this study was 260 cm/300 cm x 125 mm. As a progressive panel type facing material, the gypsum board industry is well-established. The basic properties of gypsum board, specialized as facings within a cardboard core composite are as follows:

- Composed of cement and cellulose-fibers
- Panels are fire resistance
- Strong accoustic insulation properties
- Water-resistant
- Suitable for use in air-ventilated facade applications
- Conventional paint and plaster can be affixed to it
- Depending on the thickness and type, gypsum board can provide additional thermal insulation
- Recommended by the Institute for Biological Research (IBR)

The negative characteristics of this facing material are its limitations in the application process. Onsite application for cardboard buildings is relatively complex, while offsite application and completion of the wall component is likely to be inefficient and costly considering the workload and the limitation of the size of the panels. Use of gypsum board facing needs particular attention to ensure airtight applications.

<sup>1</sup> "Fermacell Dry Lining Systems," *Xella International Group GmbH*, <<http://www.xella.ch>>. 23 Feb. 2009s

#### **4.3.2. Sample B: Cardboard Core Composite with Glass Fiber-Reinforced Plastic (GFRP) Facing**

The GFRP facing provides a new development in wall composites that are both translucent and load-bearing, and possess the same porous properties of corrugated cardboard. To form GFRP, plastic and glass fibers are combined at high temperatures during a liquid thermoset phase and molded into either standardized panels or other form-active applications.<sup>1</sup> The following is a list of some of GFRP's characteristics, when used as facings for cardboard core composites:

- Translucency: able to transfer light between the exterior and a building's interior
- Capable of serving as a screen for the electricity cables, when spread through the corrugated core channels
- The application process with thermoset properties cannot be melted or reshaped
- Suitable for form-active organic surfaces
- Flexible and malleable when applied in a liquid state

However, despite these positive characteristics, GFRP remains relatively expensive. Further, it is quite dense at 800 kg/m<sup>3</sup>, and too heavy for manual transportation on a construction site. It is also limited to air ventilation channeled facades and connected to its primary function as a translucent wall.

#### **4.3.3. Sample C: Cardboard Core Composite with Steel Plate Facing**

Steel plate facings for use with cardboard core composite have advantages related to similar applications in the conventional sandwich panel industry. Composed of steel plates and core insulating materials such as polystyrene, this facing type is commonly used today in the construction of industrial buildings. The main advantages of steel plate facings, used for cardboard core composites are as follows:

- CAD/CAM advanced manufacturing systems are well-suited for steel, allowing flexibility in dimensions and form. Accordingly, it is suitable for form-active panels, either with CAM or façade applications composed of hand-worked smaller pieces.
- Can be used to create air-tight sandwich box systems that are completely water resistant
- Suitable for curtain wall systems or air ventilation channeled façade systems
- Fire resistant when combined with fire-retardant paint systems
- Highly durable
- Reusable and recyclable

Despite steel's advantages as a building material, it continues to have a rather negative public image based on its perceived environmental impact. Also, when used without a skin or facing, steel is visually unappealing to the conventional buyer. If used as a facing for cardboard housing,

<sup>1</sup> Engin M. Reisa and Sami H. Rizkallab, "Material Characteristics of 3-D FRP Sandwich Panels," *Construction and Building Materials* 22, no. 6 (Jun. 2008): 1009-1018.

it can mislead building's massive structure in exchange with steel frame construction. Doing so may also tend to contradict the project's aim of promoting cardboard-based construction.

#### 4.4. Conclusions

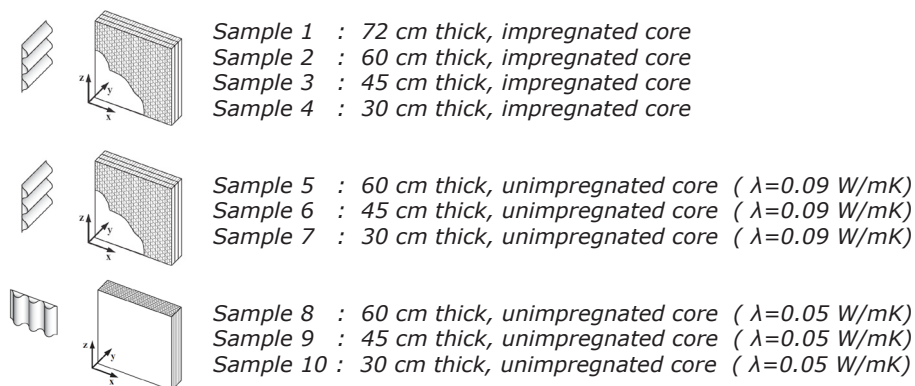
As illustrated in Figure 3.28, the U-Value comparison between the composite samples and the Minergie walls (Minergie external walls: 0.2 W/m<sup>2</sup>K, windows: 0.7 W/m<sup>2</sup>K) shows that an unimpregnated-plain 30 cm thick cardboard core sample (corrugation direction enabling 0.05 W/mK) results in the lowest U-value of the group (0.08 W/m<sup>2</sup>K). This value is just one-third of the minimally required U-value for Minergie standard walls. The cardboard core composite Fermacell gypsum board facing resulted in a slightly higher U-value, followed by the GFRP and steel facings.

Figure 3.29 below provides a total weight per 1 m<sup>2</sup> comparison between the various composite wall samples. The heavier wall units pose a major onsite impediment for builders. The graph also demonstrates that impregnating the material significantly increases the total weight of the composite. In terms of the effect of facings on the total weight of the composite, the GFRP facing added the least amount of weight, followed by the steel and Fermacell facings.

Figure 3.30, which shows a provisional price comparison between the composite samples per 1m<sup>2</sup> functional unit wall, confirms the significant price disparity between the GFRP facing and the other facings. The calculations do not include any further manufacturing costs in forming the composite with the cardboard core, the two facings and the joint material.

Figure 3.31 illustrates a comparison graph of the total thickness among the various composite samples of the functional unit wall. The results merely demonstrate that the selection of facing type does not substantially affect the total thickness of the composite.

The results can be used as a preliminary guide for understanding the price difference between the impregnated and unimpregnated cardboard core samples when only material costs are considered. However, these figures will eventually need to be adjusted to include the manufacturing costs of impregnating the cardboard. Figure 3.28 also indicates that the steel facing composite has the lowest provisional price.



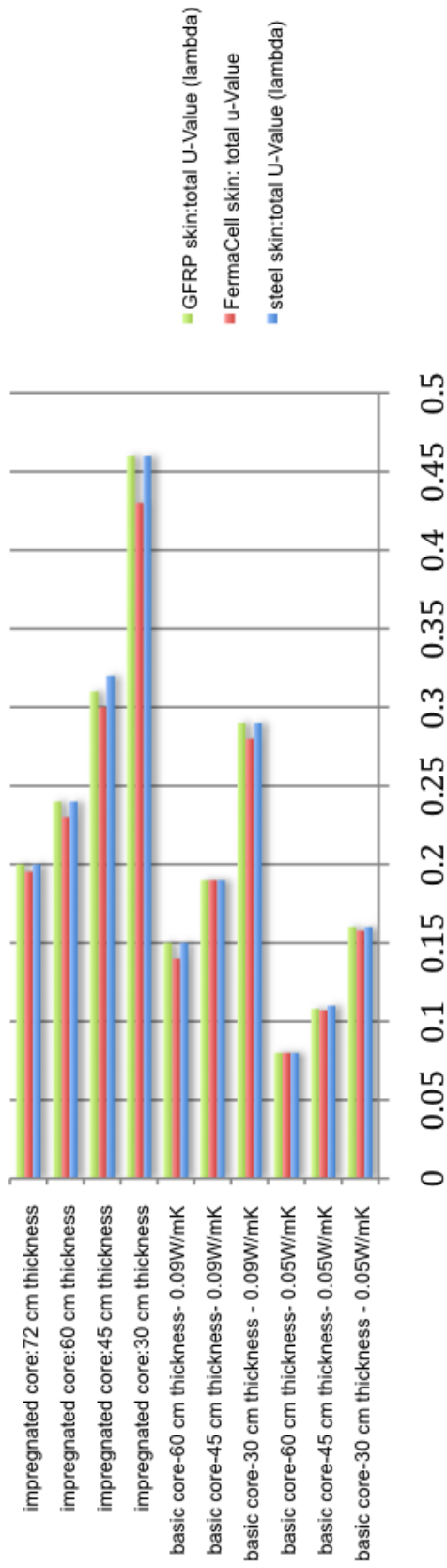


Figure 3.28 - U-Value comparison between the composite samples and Minergie U-value standards.

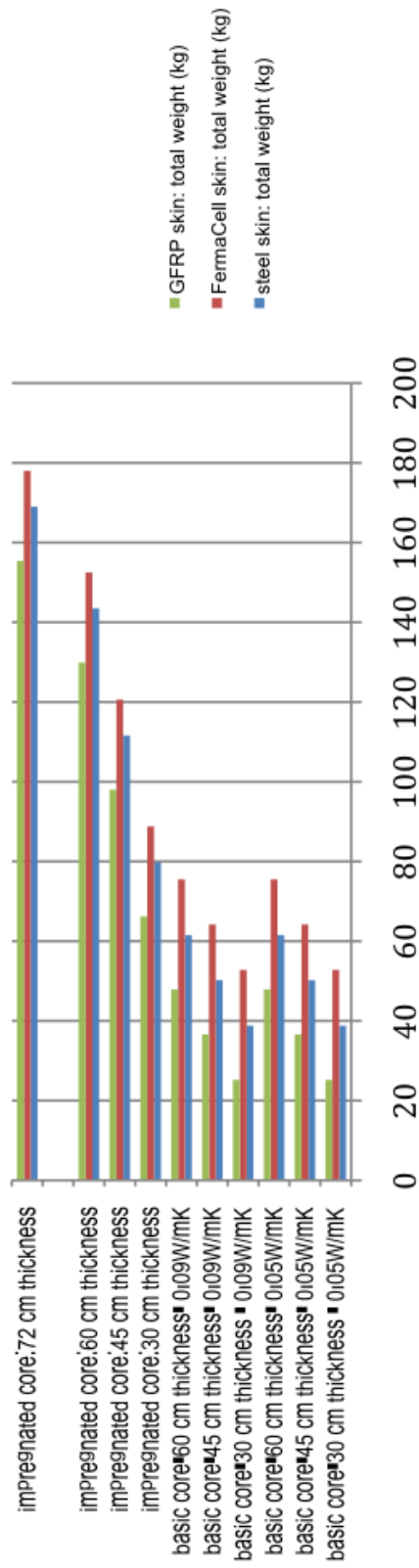


Figure 3.29 - Total Weight per 1 m² comparison between the composite samples.



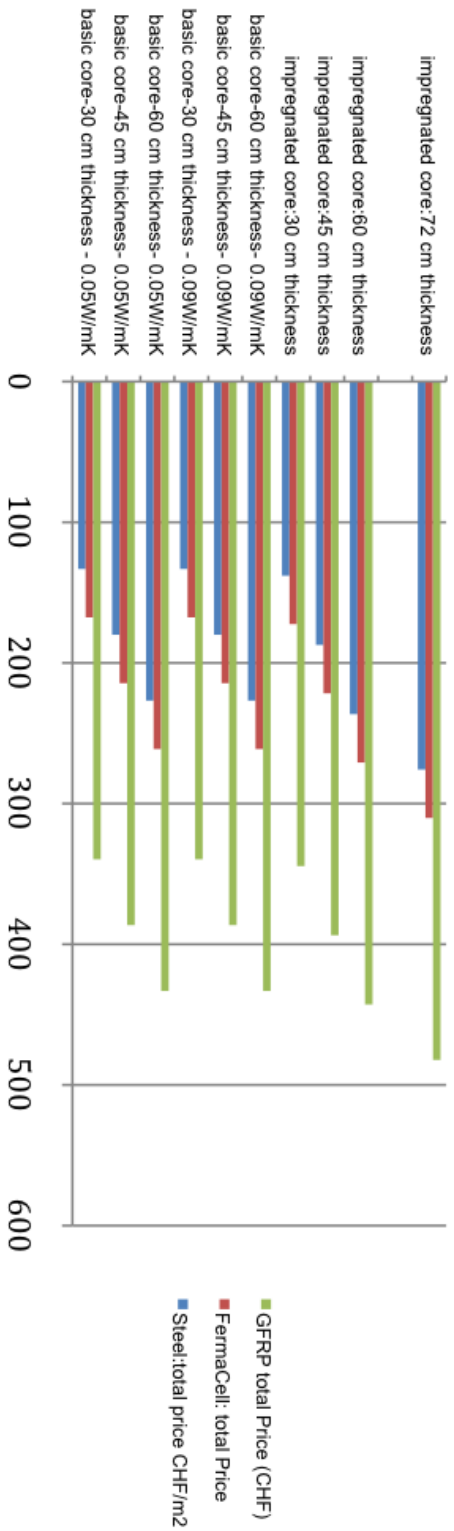


Figure 3.30 - Provisionary price comparison between the composite samples per 1m² functional unit wall.

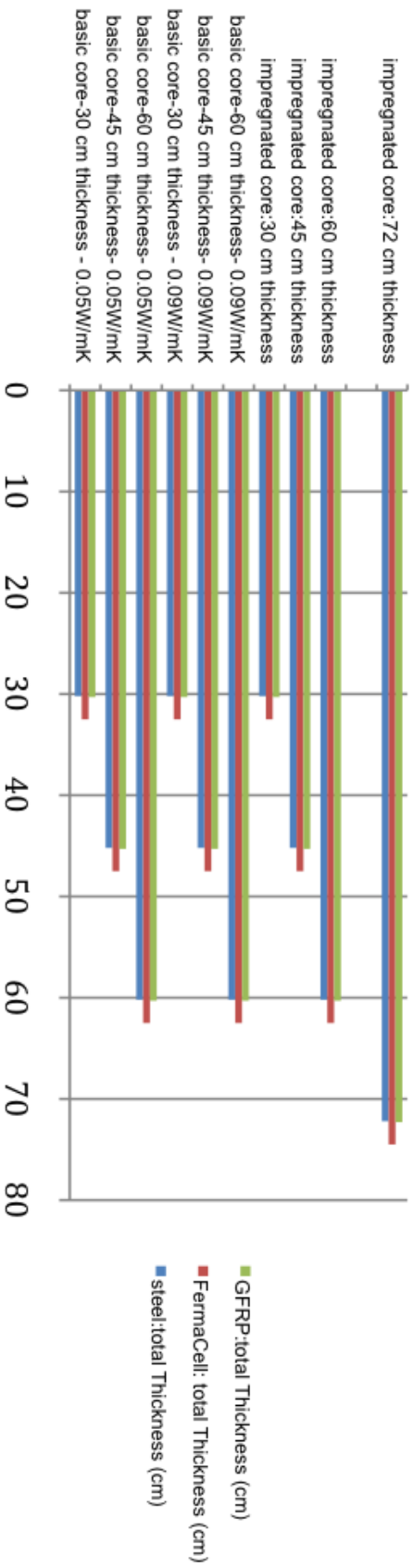


Figure 3.31 - Total thickness comparison between the composite samples of the functional unit wall.

	CORE	FACING TYPE	FUNCTION	U-VALUE	WEIGHT	PRICE
TYPE 1	30 cm thickness  Impregnated	GFRP Facing (3 mm)  Glass Fiber+ Plastic	Opening Structural wall Facades Dividing Walls	0.46 W/m <sup>2</sup> K  *minergie window:	66 kg/m <sup>2</sup>	345.- CHF*
TYPE 2	72 cm thickness  Impregnated	FermaCell Facing(1.25 mm)  Cellulose + Gypsum fiber	Structural wall Facades Curtain walls	0.19 W/m <sup>2</sup> K  *minergie wall: 0.2 w/m2K	178 kg/m <sup>2</sup>	310.- CHF*
TYPE 3	45cm thickness  Unimpregnated core ( 0.09-0.05 W/mK )	FermaCell Facing(1.25 mm)  Cellulose+ Gypsum fiber Density: 1000 kg/m <sup>3</sup>	Structural wall Facades Curtain walls	0.19 -0.11 W/m <sup>2</sup> K	64 kg/m <sup>2</sup>	215.- CHF*
TYPE 4	45cm thickness  Unimpregnated core (0.05 W/mK )	Steel Facing (1mm)  Density: 8000 kg/m <sup>3</sup>	Structural wall Facades Curtain walls	0.12 W/m <sup>2</sup> K  *minergie wall: 0.2 w/m2K	50 kg/m <sup>2</sup>	180.- CHF*
TYPE 5	30 cm thickness  Unimpregnated core : ( 0.05 W/mK )	Steel Facing (1 mm)  Density: 8000 kg/m <sup>3</sup>	Structural wall Facades Curtain walls	0.16 W/m <sup>2</sup> K  *minergie wall: 0.2 w/m2K	39 kg/m <sup>2</sup>	133.- CHF*

Figure 3.32 - Properties of selected composite samples (est.).

The table in Figure 3.32 provides a comparison of five selected sample composites. Below is a brief description of the selected composites:

**4.4.1. Translucent Cardboard Wall (GFRP):** Depending on the direction of the cardboard’s corrugations, when configured as in Figure 3.33(a) below, the porous side of the cardboard block with an translucent facing can be used as a light-transmitting, structural exterior wall, curtain wall or façade element. This configuration satisfies the Minergie U-value standard of 0.7 w/m<sup>2</sup>K. Another advantage of a translucent cardboard wall is that it can serve as a substitute for a glass wall, which is significantly heavier and more brittle than cardboard. The GFRP composite wall would provide the translucent outer facing of the cardboard structure. Because of its flexibility on the construction site, the GFRP-cardboard composite can also be used for interior dividing walls. GFRP facing also has the potential of being applied to more form active walls (with CAM cardboard core) by using the thermo-set material and coating the form-active wall element.

Translucency of the composite in a cardboard building can be used to perform the following functions:

i) Transmission of exterior light (natural sunlight) into the building’s interior: Increased natural light is a common user preference that adds quality to the interior space, as shown in this

study's *Social Acceptance Survey*. Translucent cardboard walls also permit energy gain in the winter through a controlled and insulating wall structure. Several attempts to increase a building's natural interior light through the use of translucent, load-bearing walls have been made.<sup>1</sup>

ii) Transmission of artificial light from a building's interior to its exterior (Figure 3.33(c): Allianz Arena Project). iii) Media Facades: Configured as shown in Figure 3.33(a), using the direct connection between a building's interior and its exterior through the cardboard's corrugation direction, a translucent cardboard wall can be transformed into a media wall. This changes the facade into a communicating, holistic product with the help of light and facade engineers. Media facades are gaining popularity and relevance in the today's digital age.

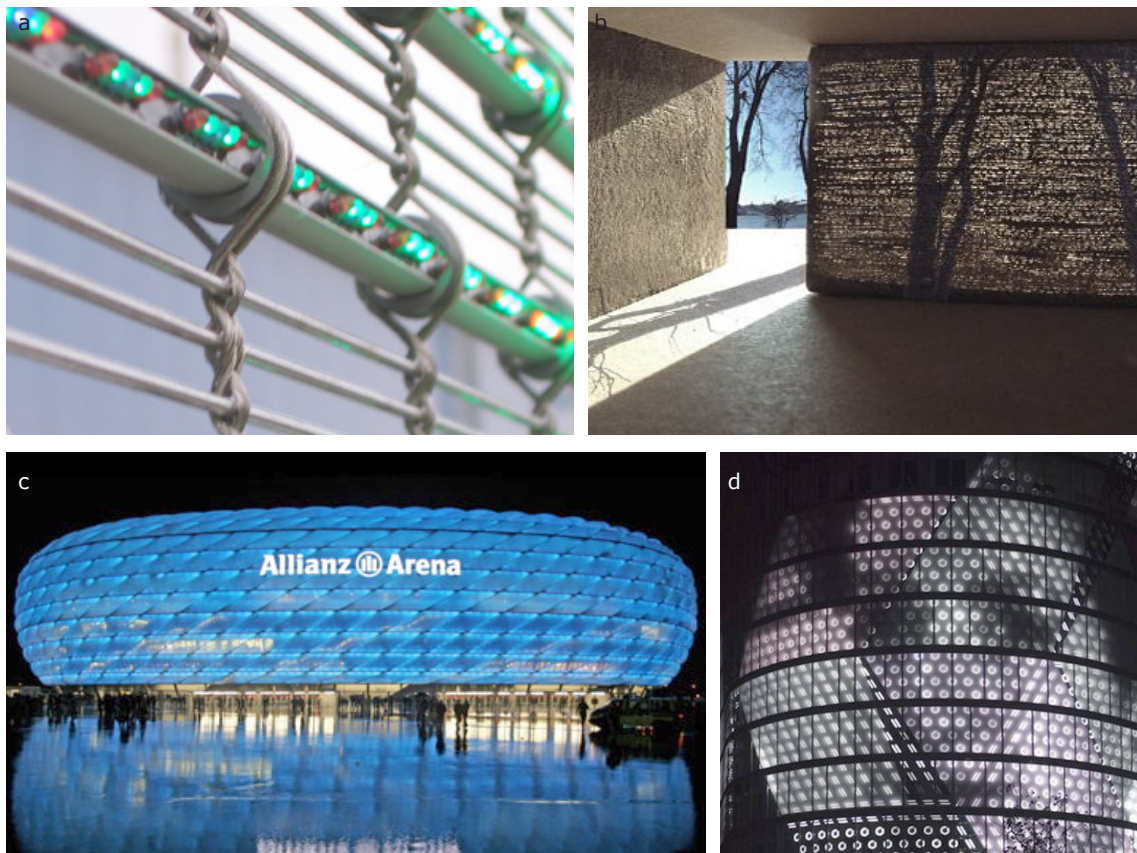


Figure 3.33 - Translucency in cardboard structures: (a) Litracon Translucent Concrete Wall; (b) Media® Mesh Medienfassaden<sup>2</sup>; (c) Allianz Arena<sup>3</sup>; (d) Postdamer Platz.<sup>4</sup>

<sup>1</sup> Áron Losonczi, Litracon Light-Transmitting Concrete.

<sup>2</sup> "Media® Mesh," GKD Gebr Kufferath AG, < <http://www.gkd-ag4-mediamesh.de/>>. 23 Mar. 2009

<sup>3</sup> Herzog & de Meuron Architekten, BSA/SIA/ETH (HdeM).

<sup>4</sup> John deKron, Media Façade, Potsdamer Platz, Germany.

**4.4.2. Highly Insulative Cardboard Wall (Gypsum Board):** This extraordinarily thick wall (72 cm) provides a synthetic option for the cardboard composite. It is load-bearing and fire-protective when impregnated. Using the latest generation gypsum board panels (and plaster system on facades), and the impregnation process, the wall composite maintains structural strength and stiffness even when confronted with moisture.

However, the impregnation process weakens the thermal insulating properties of the corrugated cardboard core, and therefore to reach the Minergie standard U-value of 0.2 W/m<sup>2</sup>K, the thickness of the wall must be 72 cm. Although this composite wall would occupy a significant portion of a property's space, thicker walls help to give the perception of increased strength and stability. This can help to mitigate the negative associations people have of cardboard.

In terms of dimension and form, gypsum fiber panels are manufactured in standard panel form, but they can be cut into smaller formats to be used in a variety applications. In this case, the composite wall do not function within the sandwich principle. The gypsum fiber facing's function stays only that of a protective skin (against local stress, moisture and fire).

**4.4.3. Insulative Cardboard Wall:** When this cardboard core's corrugation direction is parallel to the ground, its thermal insulation coefficient is 0.09.W/m<sup>2</sup>K (Figure 3.34(b)). With a thickness of 45 cm, this composite satisfies the Minergie U-value standard for exterior walls - 0.2 W/m<sup>2</sup>K. This type of composite consists of an unimpregnated core with relatively high thermal insulation qualities. The material is extremely lightweight, permitting the manufacture of larger prefabricated panels, which can then be manually transported onsite. The gypsum fiber panel skin is fire-resistant, but in order to ensure airtightness, additional moisture-proof layers need to be integrated between the outermost skin and the cardboard core to secure its structural strength and stiffness. With respect to its form-dimension, this type of wall component is suitable for application in both large and small geometric patterns. The skin can be plastered and painted, and can be used as a curtain wall, or load-bearing exterior wall.

**4.4.4. Conventional Industry-Type Sandwich Panel Wall (45 cm):** This composite, shown in Figure 3.34(a), is characterized by a corrugation direction that results in a thermal insulation coefficient of 0.05W/m<sup>2</sup>K. The fire and moisture related problems are addressed with a steel skin. The steel facade industry has introduced various mechanical solutions like extra-engineered connections for waterproofing, or more coating based chemical solutions as "fire retardant" paints for increased fire protection. Its 45 cm thickness also provides a significant degree of insulation at a low cost.

**4.4.5. Conventional Industry-Type Sandwich Panel Wall (30 cm):** This thinner cardboard core composite is characterized by a corrugation direction perpendicular to the ground (Figure 3.32(a)). This configuration results in a thermal insulation coefficient of 0.05W/m<sup>2</sup>K, and a U-value of 0.16 W/m<sup>2</sup>K. It can be applied as an exterior load-bearing wall, curtain wall, or interior dividing wall.

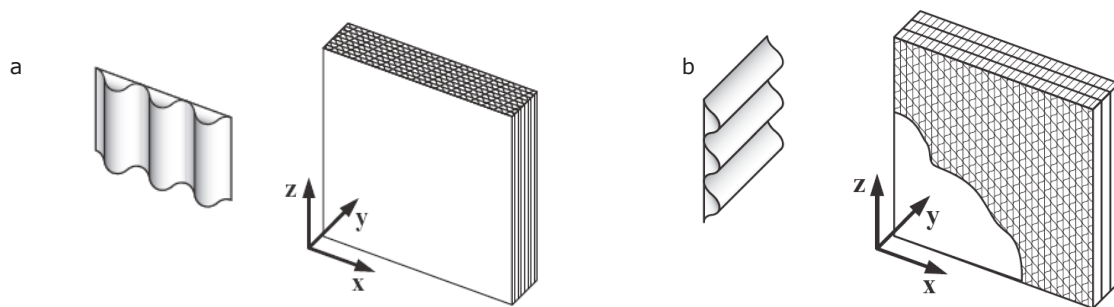


Figure 3.34 -Thermal insulation coefficients in relation to corrugation direction <sup>1</sup> (a) Corrugations perpendicular to the ground. Cardboard core with small corrugations (E): 0.29 W/mK; with large corrugations (A,B, or C): 0.045 W/mK (b) Corrugations parallel to the ground

## 5. Demolition, Recycling and Dismantling of Cardboard Buildings: Criteria Selection

The efficient recycling of byproducts and industrial waste during the demolition stage of a building are becoming increasingly important for planning and controlling industrial production systems. When a building is demolished, some of its materials can be reclaimed for reuse. This project aims to promote the cardboard building process and provide a clear and accurate assessment of its environmental impacts, including those that occur after the usage stage. For other common building materials, the dismantling process results in the following reuse of materials:

“...the reclaimable rates of several building materials are defined respectively as 90% metal, 50% brick, 20% wood, 10% cement. The rate of all other materials is defined as 0% of all the unclaimed materials become the solid waste after demolishment.” <sup>2</sup>

A recent study by C. Thormark, divided recycling into three distinct categories: 1) reuse (using the material for the same purpose); 2) material recycling (i.e. crushed concrete and clay brick as a gravel substitute); and 3) combustion (with energy recovery).<sup>3</sup> All these categories could potentially be applied to cardboard housing wall components.

When the environmental impacts are taken into account, in addition to minimizing embodied energy, it is equally important to construct buildings that have high recycling potential. Examples from Japanese, Swedish and German studies on potential energy saving in material production and energy saving through recycled materials consistently show a considerable amount of potential energy saving through the recycling of building materials.<sup>4</sup> These studies conclude that in order to reduce total energy use in buildings, the design phase must focus on

<sup>1</sup> Figures used in the thermal conductivity calculations of composites: Impregnated cardboard core: 0.15 W/mK, Glaswool, Rockwool: 0.035-0.05 W/mK, Wood fiber insulating board 0.04-0.06 W/mK, Polyurethane: 0.03 W/mK

<sup>2</sup> Zhang, et al. 671.

<sup>3</sup> Thormak, 1021.

<sup>4</sup> Jun Li, Michel Colombier, «Managing carbon emissions in China through building energy efficiency» Journal of Environmental Management, Volume 90, Issue 8, June 2009, Pages 2436-2447

Catarina Thormark, «A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential», Building and Environment, Volume 37, Issue 4, April 2002, Pages 429-435

Weijun Gao, Takahiro Ariyama, Toshio Ojima, «Energy impacts of recycling disassembly material in residential buildings», Energy and Buildings, Volume 33, Issue 6, July 2001, Pages 553-562

reducing not only operational energy needs, but also to the choice of building materials. It is not enough to conclude that a material is recyclable. Indeed, one must also consider the forms for recycling as well as how to provide for disassembly.<sup>1</sup> The proposed cardboard housing concepts address these environmental impact issues by selecting materials that can be reused and recycled after the building's useful life.

## 6. Conclusion

The LCA approach was selected as a tool for estimating the environmental impact of cardboard housing within the framework of this chapter and research project. LCA-guided environmental impact assessments of cardboard are an important measure for cardboard packaging industry's claim of being an eco-friendly industry. According to the United Nations Environmental Programme (UNEP), LCA studies help to place emphasis on the driving forces behind the lifecycle of cardboard as a packaging material. Up to this point, the LCA of cardboard has mostly been applied in developed and industrialized countries such as Denmark, Switzerland, England, Germany, the Netherlands, Japan and Italy.<sup>2</sup> However, much of this research is not well distributed. The reasons underlying the slow adoption of such environmental impact assessment techniques by cardboard manufacturers include weak legislation and lax regulations.<sup>3</sup>

Along with integrating the environmental management tools, the cardboard industry needs to be more proactive in promoting global forest stewardship, cleaner manufacturing processes, and improving the energy efficiency of the industry. Continuous improvement in the environmental management of the cardboard industry can be accelerated by government regulations as well as from non-governmental organizations, educational bodies, environmental advocacy groups and interested citizens.<sup>4</sup>

Nevertheless, the cardboard packaging industry constitutes a firm base that is capable of guiding cardboard building component production. The cardboard packaging industry today is capable of producing cardboard-based products with improved structural strength, quality, printability, and toxicology-protected usage for transporting frozen food, fresh vegetables/fruits, while securing the cost and environmental demands of the market. In this study, the developments of improved material technology in the packaging sector are used as a starting point from which the additives in the paper pulp, additional layers or skins on the surface of the cardboard can enhance its quality and performance. Accordingly, in this study corrugated cardboard core is improved to function as a composite sandwich material to work with facings and joint materials.

Pursuing the existing expertise of the cardboard packaging sector in improved eco-conscious cardboard applications, this study focuses on a more complex end-product - a cost effective

<sup>1</sup> Thormark 1020-1025.

<sup>2</sup> «In the past 3 years, the Corrugated Board Sector reduced its Carbon Footprint by 11.7 %», FEFCOconnect Produced by the European Federation of Corrugated Board Manufacturers, Issue 21, April 2010, pages 2-3

<sup>3</sup> Ongmongkolkul 1.

<sup>4</sup> R. Malinen, "Development Prospects for Pulp and Paper Industry in South-East Asia Environmental," *Issues of Pulp and Paper Industry in Asian Countries*, International Seminar, Thailand (19-20 Mar. 1997): 210-217.



construction system constructed using cardboard that reduces the environmental impacts caused in traditional construction. Therefore, the broad objectives regarding the lifecycle approach for ecological sustainability will be to a) analyze the existing environmental impact assessments associated with the entire lifecycle of cardboard packaging by the LCA tool during the production stage; b) identify and analyze the variety of other materials to be used in cardboard housing wall elements according to their environmental impact during the production stage; c) formulate and make a comparison platform between the chosen sample walls and traditional wall elements; and d) compare these cardboard wall composite samples in the lifecycle stages of production and usage stage.

These results will provide direction for the study by forming the strategy bases for an environmental approach. The goals of the following stages are as follows:

- a) integrate the environmental concerns into the cardboard building product and process;
- b) compare the advantages of improvements in the cardboard industry in terms of environmental studies and guidelines;
- c) demonstrate the low environmental impact of the corrugated cardboard and the composite system.<sup>1</sup>

<sup>1</sup> *European Database for Corrugated Board: Lifecycle Studies* (FEFCO-Groupement Ondué-ECO, 2003) 3.



## Chapter IV

# Constructive Approach: Basics Structural Conception of Cardboard as a Wall Component

"Looking Outside The Box:  
One Industry's Strength Is Another's Potential."

-Neil Steinkamp and Tom Dionne

### 1. Background

At first glance, the search for innovative building materials is driven solely by construction demands. But upon further inspection, the cultural and architectural expressions associated with the building material reveals its interconnectedness to several other fields, including urban politics, building regulations, demographics and environmental concerns. The starting point of this research has been to explore the potential of corrugated cardboard in these fields. On a conceptual level, this investigation aimed to reveal architectonic and constructive outputs regarding the generation of genuine spatial organizations to articulate the interest in this innovative building material.

The innovation process entails several different stages, including discovery, research and development, manufacturing and the marketing of a new product. Consequently, the construction demands of cardboard buildings are based on three pillars for efficiency of innovation: manufacturing, identification and product positioning.

#### ***i) Manufacturing, Process and Technology Transfer***

In constructive terms, the efficiency of cardboard buildings as an innovative building construction implementation depends on the total integration of all subsystems and components into an overall process that involves utilizing production, transportation and assembly techniques. The existing manufacturing technology and industry for cardboard are the initial points to start this search for integration.

### ***ii) Identifying the Constraints, Integrated Solutions and Standards***

The examination of the complex interaction of cardboard buildings with social, political, environmental and economic constraints determine what must be done to remove those constraints so that the suggested innovation can achieve its full potential on the new application. When cardboard buildings as a new innovative material and system is presented in the construction industry, an effort is to be made to compare and face the possible problems in its totality and to suggest integrated solutions that recognize diverse factors. These factors include the principles of design and performance standard, paying attention to the effect of building codes, volume production, building modules, the problems of evaluation, the introduction of innovation, governmental policy and finally the necessary organization for production.<sup>1</sup>

### ***iii) Product Positioning***

Numerous new materials and industrialized building system technologies are introduced to the construction industry every year, but none are applicable to all construction cases.<sup>2</sup> Innovation is used to fill the gaps left by the earlier substitutes. Nevertheless, there is never a perfectly adequate substitute for each and every scenario. This examination of the underlying principles and distinguishing characteristics of corrugated cardboard composites for use in full-size residential and commercial buildings attempts to fill this gap.

This study is limited in scope to the proposed construction of massive buildings composed of cardboard blocks. The use of prefabrication of the building components, particularly for residential buildings, will be a primary goal of this project. The comparative study of these constructive constraints with existing contemporary building systems will guide the strategical identification of the constructive approach for cardboard buildings.

### ***Chapter Structure***

Based on the outcomes of prior research regarding societal and environmental concerns for corrugated cardboard and cardboard buildings, this chapter will offer a systematic approach to potentials of the construction process. The chapter begins by taking general approach, describing the sociosphere of the construction industry today. Cardboard composite walls are categorized by their components and the building element level. The benefits and drawbacks of building with cardboard in the construction industry are analyzed with the aim of generating performance criteria for future projects.

In particular, the study focuses on providing a set of tools for exploring the different perspectives for using cardboard in massive construction. These tools will work as the basis for a developmental criteria. The choice of a massive structural system primarily consisting of corrugated cardboard is guided by the tests and analyses performed by the collaborative engineering team involved in this research project. The testing and analysis of the cardboard

<sup>1</sup> Albert G.H. Dietz and Laurence S. Cutler, eds., *Industrialized Building Systems for Housing* (Cambridge: MIT Press, 1971) 270.

<sup>2</sup> Dietz and Cutler 270.

composite material presented in this study is based on the PhD research of Almut Pohl of the ETH-Zurich Institut für Baustatik und Konstruktion (IBK).<sup>1</sup>

### **Focus Questions**

- *What are the parameters for the search of innovative materials in construction today?*
- *How can the functions of the packaging industry be applied to the construction industry for use in cardboard buildings?*
- *What do corrugated cardboard composite panels bring to onsite construction?*
- *How can the potential of cardboard buildings be demonstrated?*
- *How can the focus of today's architecture be used to support the growth of cardboard buildings in the near future?*
- *Which parameters influence the efficiency of cardboard composites? What are the dimensional limitations for cardboard core in wall composites?*
- *Is offsite fabrication in construction advantageous and cost effective? Are pre-joints and other preassembled components beneficial in user-customized architecture?*
- *How will the introduction of cardboard buildings influence the construction industry?*

## **1.1 Innovative Construction Awareness**

The implementation of new construction concepts and the transfer of production lines from existing industries into construction will be examined in this subchapter. Innovative building materials and their implications are investigated in the context of the consumer cycle. Additionally, a complete overview of recent innovations in construction related to cellulose fiber is laid out to help understand the construction approach for cardboard buildings.

### **1.1.1 The History of Innovative Materials and Cardboard as a Building Material**

The selection of materials used in construction experienced only minimal change until the middle of the 19th century. Until that point, materials were limited to substances readily available in nature like stone, wood, straw, masonry, concrete and basic metals.<sup>2</sup> However, following World War II, a great amount of theoretical and experimental research was devoted to the development of the new building materials and techniques with the goal of combining both low cost and efficient aspects of certain materials. As a result, a transformation in existing materials and manufacturing methods marked a revolution in the architectural and structural arenas. New progressive building codes have reflected this progress and helped to establish the wide use of these new building materials throughout the world.<sup>3</sup>

Consequently, new material categories have evolved. As Timberlake and Kieran discuss in a recent study, polyaramids such as Kevlar, Goretex and ETFE<sup>4</sup>, as well as polyurethane, metal

<sup>1</sup> Almut Pohl, "Strengthening Corrugated Paper Honeycomb Core for Application in Structural Elements," PhD diss., ETH Zurich, 2009.

<sup>2</sup> James Timberlake and Stephen Kieran, *Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction* (New York: McGraw-Hill Professional, 2004) 33.

<sup>3</sup> P.T. Mikluchin, ed. *General Design and Architectural Aspects of Masonry Building, ASCE-International Conference Proceedings*, Vol. III-27: Lehigh University, 1972.

<sup>4</sup> Ethylene tetrafluoroethylene; a type of plastic, largely used as pneumatic panels in architecture (I.e. Football stadium Allianz Arena, Munich by Herzog & de Meuron 2002; the Beijing National Aquatics Centre, by PTW Architects, 2008)

and adhesives, and other ceramics, aluminum and titanium have been transformed and their uses expanded in the past decades.<sup>1</sup> In recent years, the choice of building materials has greatly expanded, and thus provided us with an increased degree of multipurposeness, including such materials as plastics, polymers threaded with glass fiber, aramids, carbon and thin films applied to fabrics.<sup>2</sup>

Along with this increased choice in building material, other parameters influencing the choice of a construction material have also increased, and thus altered the expectations of multi-functionalism. Today, the classification ranges in the combination of parameters such as availability, cost, environmental impact, appearance, durability, weather resistance, and fire resistance. To determine what can support the efficiency in cardboard buildings and how to communicate these are relevant issues in preliminary conceptual approach.

On a macro scale, the outcome of these parameters and demands on multi-functionalism overwhelmingly favors the designers and producers. The specialization of the architectural design process in relation to the expansion of the number and characteristics of new materials demonstrates the struggle in effectively positioning an innovative product into an existing market. Barbara Nadel explains this in a recent study, noting that:

*"[i]nnovative architectural design is enhanced by careful attention to detailing, selection and specification of compatible materials and related component systems, with the constant awareness to innovative component installation methods and construction techniques. However, with so many advances in manufacturing processes, emerging new materials, and enhanced technology in the marketplace, along with ongoing updates of building codes and industry testing criteria, plus an often unskilled labor force; the required knowledge base for effective and innovative building design is constantly expanding."*<sup>3</sup>

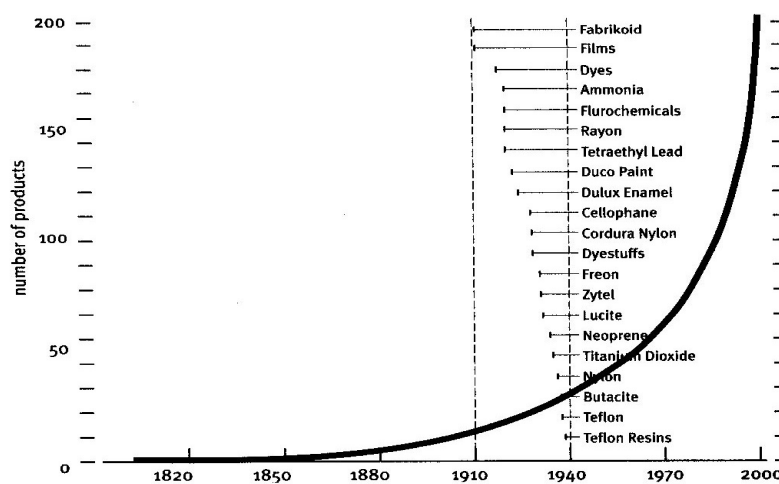


Figure 4.1 - Timeline of Dupont's introduction of new materials.<sup>4</sup>

<sup>1</sup> Timberlake and Kieran.

<sup>2</sup> Timberlake and Kieran 35.

<sup>3</sup> Barbara A. Nadel, "21st Century Building Envelope Systems: Merging Innovation with Technology, Sustainability, and Function," *Architectural Record* (Aug. 2006).

<sup>4</sup> Timberlake and Kieran 129.

The large-scale implementation of cardboard buildings also holds potential benefits for progress in the area of efficient technology transfer. The cardboard and paper packaging industry, which controls 70 percent of the world's packaging flow, continues to produce important research data on cellulose byproducts. Of last decade's extensive theoretical and experimental research, the cardboard packaging industry has directed various types of products, tested through specialized software, and conducted experiments promoting an already developed database for customized characteristics. The advances on the product level for the cardboard packaging industry are applicable to several of the functional prerequisites of wall components in construction. Both applications target durability, ensuring certain thermal, humidity and air-tight conditions.

The latest technical achievements in cardboard packaging industry to be transferred into construction field will enable a radically new approach articulating efficiency to design architectural spaces through cardboard based construction systems. But the structural application of corrugated cardboard on a building scale is a new field, differing in manufacturing techniques. Not until recently has any progress been made in the field with regards to either theory of design or permanent practices.

### **1.1.2 Building with Innovative Cellulose Fiber Materials**

The existing technology transfer from the cardboard packaging into the construction industry is limited to microscopic fiber applications. No efforts have been made to use progressive manufacturing lines using CAD/CAM or thematic diversity for new applications. Existing transfer applications focus on implementing cellulose fibers in various building products in combination with gypsum or cement mixes. Combining diverse minerals with either virgin or recycled fiber offers viable options for composite building products that are also low impact, organic, low cost, as well as thermal and fire resistant. These combined materials are also relatively lightweight and are almost completely moisture resistant, as a result of the high-density cement composite's low porosity and permeability.

These inorganic-bonded wood and fiber composite technologies are beginning to demonstrate substantial growth opportunities, guided by studies and papers presenting a broad overview of some of these manufacturing concepts. These technologies specialize in four stages of development: 1) fiber treatment; 2) formulation; 3) method; and 4) final product.

Concurrently, various composite structural panel manufacturers have entered the construction market. They include firms which produce cellulose fiber, wood fiber, cement and gypsum. These materials can be fine-tuned for application to specific problem areas such as the differentiation between reduction of rate of water absorption, lower water migration, and lower water permeability. As an example of customization among this new generation of products, *Shin Kwang* board product exhibits an improved freeze-thaw resistance, reduced efflorescence,<sup>1</sup>

<sup>1</sup> Efflorescence is the growth of salt crystals on a surface caused by evaporation of salt-laden water.

reduced chemical dissolution and re-deposition, and improved rot and fire resistance, compared to conventional fiber cement products. The product achieves these qualities without losses in its dimensional stability, strength, strain or durability.<sup>1</sup>

i) Examples of cellulose fiber byproducts:

- Papercrete (in brick form)<sup>2</sup>
- Taco brick<sup>3</sup>
- Gypsum cellulose fiber composite board<sup>4</sup>
- Gypsum wood fiber structural insulated panel<sup>5</sup>
- Paper Fiber-Reinforced Gypsum Panels<sup>6</sup>
- Cellulose Fiber Reinforced Cement Boards
- *Shin Kwang* High density cellulose fiber cement (CNR) Boards<sup>7</sup>
- Concrete sandwiched insulated wall panels (PCSP)<sup>8</sup>

ii) Examples of cardboard building components:

- *Experimental applications*: cardboard ventilation ducts (Jouke Post), cable ducts (Taco van Iersel), and space formed with cellulose based egg boxes;<sup>9</sup>
- *Filigran tubular cardboard applications*: cardboard tubular projects (Shigeru Ban), Delft's Apeldoorn Theatre<sup>10</sup> (Peter Verheijen)
- *Cattle Shed* (P.B. Hangelbroek)<sup>11</sup>
- *Winding House* (Rene Snel), a machine was developed to wind cardboard into a continuous form
- *Cardboard School* (Architects Cottrell & Vermeulen and Engineering Buro Happold)<sup>12</sup>
- Cardboard experiments by digital manufacturing techniques: Dome with stitched on boxes of cardboard or human figures by T. Pawlofsky and Ludwig Hoverstadt

<sup>1</sup> Donald J. Merkley and Caidian Luo, "Fiber cement composite materials using cellulose fibers loaded with inorganic and/or organic substances," U.S. Patent 20040139891. July 2004.

<sup>2</sup> *Papercrete* consists of re-pulped paper fiber combined with Portland cement, clay or soil.

<sup>3</sup> A new brick designed by researchers at TU Delft, modeled after a cardboard box. The top layer of the brick is treated with vinyl and the panels are treated with chemical flame retardant.

<sup>4</sup> Mirza A. Baig and William O. White, "Multiple layer gypsum cellulose fiber composite board and the method for the manufacture thereof," U.S. Patent 2008085243. July 2008.

<sup>5</sup> David B. McDonald, "Gypsum wood fiber structural insulated panel arrangement," U.S. Patent 20080245007. Sep. 2009.

<sup>6</sup> Wolfgang Klöck and Simon Aicher, "Size Effect in Paper Fiber-Reinforced Gypsum Panels Under In-Plane Bending," *Wood and Fiber Science Journal* 37, no. 3 (Jul. 2005) 403-412.

<sup>7</sup> Donald J. Merkley and Caidian Luo, "Fiber cement composite materials using cellulose fibers loaded with inorganic and/or organic substances," U.S. Patent 20040139891. July 2004.

<sup>8</sup> Concrete sandwiched insulated wall panels have recently become more widely used in the building industry due in part to their economic feasibility, and superior thermal and structural efficiency. PCSP consists of two layers of concrete, called wythes, separated by a layer of insulation.

<sup>9</sup> M. Eekhout, F. Verheijen and R. Visser, eds., *Cardboard in Architecture: Research in Architectural Engineering Series, Volume 7* (Delft: Delft University Press, 2008).

<sup>10</sup> Apeldoorn Theatre, designed by Prof. Dr. Peter Verheijen is a cardboard tubular structure constructed out of rods in triangular formations, in which six rods form a node on half a cylinder form.

<sup>11</sup> *Cattle Shed*, designed by P.B. Hangelbroek was constructed using slabs of corrugated cardboard, folded and then stitched together. The cardboard consists of a top layer of PE (polyethylene, 50 grams/m<sup>2</sup>). The corrugated board itself was glued together with water-proof glue. Some areas of the shed were painted to increase its water resistance.

<sup>12</sup> *Cardboard School*, by Cottrell & Vermeulen. The project was constructed using cardboard, wood, and natural fiber tiles. The cardboard was made water resistant using the following techniques: 1) a substance was added to the pulp for vapor retardancy, while still retaining its recyclable nature; 2) an interior coating was applied to stop vapor and a water resistant building paper was applied to the exterior; and 3) panels were made more damage resistant by adding a 1 mm cardboard layer on the interior, as well as a product on the exterior wood fiber cement panels. The cardboard and the air pockets between the layers provide the building with adequate insulation. Additionally, cardboard tubes and wooden beams were used in the structure.



An overview of the literature on cardboard building applications shows a lack of research into the full potential of these applications. This research study offers input on three levels:

- *Macro*: Connecting the constructive demands with the socio-sphere and the environmental concerns
- *Constructive Typology*: An examination into the potential of massively built corrugated cardboard blocks forming the multifunctional load bearing and insulating composite wall component as a specific construction system
- *Technical*: An analysis into the limitations of corrugated cardboard (through analytical and experimental studies such as stress-strain distribution and other mechanical limitations) to be used as a composite core component, ensuring structural safety and comfort

A further goal of this project is to create an architectural language based on the constructive findings while securing reduction of production costs and forming an efficient customized prefabricated manufacturing process for cardboard components.

## 1.2 Positioning Cardboard Construction: Concepts in Practice

Today, architectural practice promotes an understanding of standards in building and building envelope design by integrating several parameters, which include building type, customer demands, cost, regulations, and location, as well as architectural language and expression. The introduction of a new product like cardboard in this established system requires focus on potentials in design, construction, manufacturing, and the characteristics of the new system or material. However, the role of the construction culture plays as much importance as the other parameters.<sup>1</sup> Additionally, several themes and dynamics exist which will guide this process of

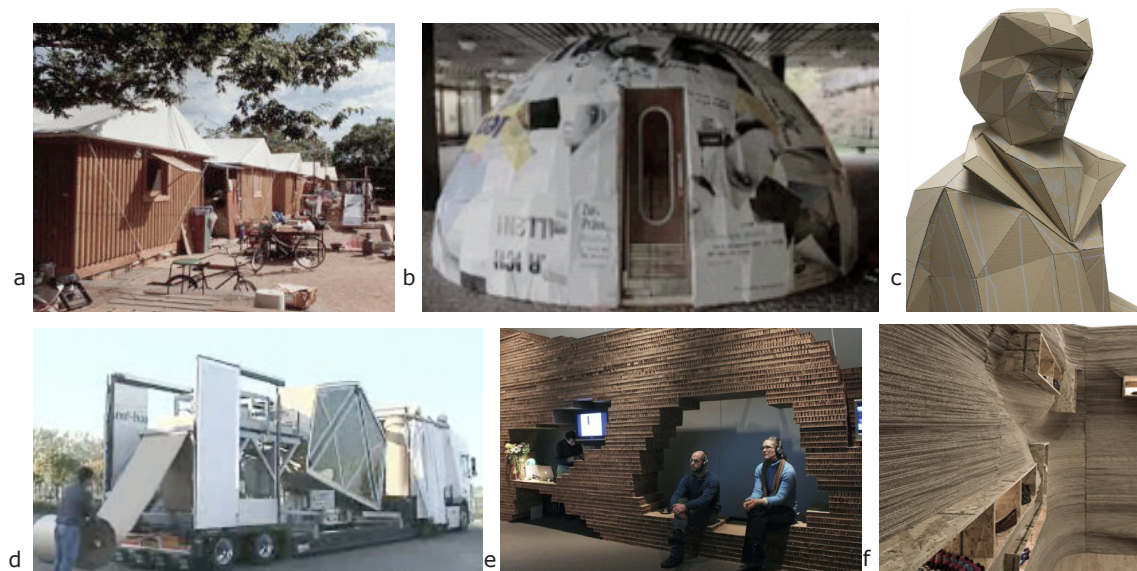


Figure 4.2 - Examples of recent cardboard-based buildings and structures.<sup>2</sup>

<sup>1</sup> Andrea Deplazes, Sascha Roesler and Cordula Seger, *Theory of Massive and Filigree Construction: Intercultural Perspectives in the Construction of Architecture* (ETH Zurich).

<sup>2</sup> (a) *Paper Log House*, by Shiegeru Ban, Kobe, 2005; (b) *Cardboard Igloo*; ETH Zurich, Department of Architecture, 2008; (c) *Inshallahpappoma7*, ETH Z; (d) *Wrap-around Cardboard Home*, by Rene Snel, Netherlands, 2005; (e) *Off the Wall*, Jewish Museum Exhibition design, New York, 2008 (f) Interior by Yiorgos Eleftheriades, Athens,



integration. For example, the so-called “new customer mandate” regarding “quality x scope > cost x time” is one of the essential aspects guiding today’s construction culture. A recent study by Kieran and Timberlake explains this phenomenon:

*“The design and execution of architecture is increasingly subject to a new role of economy. Architects find themselves having to increase quality and scope disproportional to the execution cost x time consumed. Clients are demanding more for less.”<sup>1</sup>*

In order to compensate for the new dynamics of increased client demands, a *Quality= Integrated Component Construction* approach must be established. As proven by recent case studies and developments in the automotive industry, expanding the supply through offsite preassembly processes improves the quality of the end product while simultaneously reducing the costs. Achieving *quality* by improving the supply chain and regulating the assembly process offsite is therefore increasingly becoming a reality defining the efficient means of construction practice today.<sup>2</sup>

This subchapter aims to address the concepts affecting implementation and recognition of cardboard buildings in housing within the contemporary understanding of quality, customer demand and construction efficiency. These concepts are discussed briefly with regard to their history and development, and how they have affected the construction culture to provide a base for the positioning of cardboard housing within the sector. The following themes have been selected to provide a further understanding for the implementation of cardboard buildings: 1) *Prefabrication in relation to mass customization*, 2) *Design focus in spatial flexibility and adaptability*, 3) *Effective use of synthetic materials*, and 4) *Multi-functional and environmentally conscious solutions*.

### 1.2.1 Prefabrication and Mass Customization

Prefabrication<sup>3</sup> was made feasible with the advancement of production techniques and equipment for transportation and erection, particularly after the World War II. Comprehensive prefabricated building systems (including prefabricated slabs, vertical structural elements, façades, partitions, stairs and sanitary units) were developed with the support of public authorities to cope with the pressing and increasing demand for housing. The demand was at its peak in the 1950’s, 1960’s and the early 1970’s in eastern and western Europe for the construction of new towns, suburbs, and large scale public housing developments.<sup>4</sup> During this period, various precast concrete building systems were created. In the early 1970’s, the U.S. government also explored several prefabricated building systems.

2009.

<sup>1</sup> Timberlake and Kieran 18.

<sup>2</sup> Timberlake and Kieran 17-19.

<sup>3</sup> Prefabrication is a general term for the manufacturing process in which various materials are combined to form a component part of the final installation. The manufacturing process may be undertaken in a factory environment (factory prefabrication) or at the site (site-prefabrication). The term off-site fabrication is used when both prefabrication and pre-assembly are integrated. The three categories of off-site fabrication are non-volumetric, volumetric and modular building.

<sup>4</sup> Abraham Warszawski, *Industrialized and Automated Building Systems* (London: Taylor & Francis, 1999).

However, instead of elevating living quality and decreasing cost and complexity of construction, this growth led to a banality. The result of this period is now linked with the ever changing politics of the era and the decision to focus on single typology, especially in housing.<sup>1</sup> As Kieran and Timberlake note that:

"... the modernists of the 20th century made many attempts to adopt mass production, prefabrication and modularization techniques in their buildings, none of these endeavours ever achieved success or popularity and soon were abandoned."<sup>2</sup>



Figure 4.3 - Prefabricated Dwellings: 1910 - Present.<sup>3</sup>

<sup>1</sup> Timberlake and Kieran 106.

<sup>2</sup> Timberlake and Kieran 104.

<sup>3</sup> (a) 1910-*Pavillon Esprit Nouveau*, Paris-Exposition des Arts Décoratifs LeCorbusier; (b) 1920-image from a Buster Keaton film in which fumbling young newlyweds try to assemble a prefabricated house, demonstrating the conflict inherent in the so-called American dream. In many ways the prefabricated house embodies the tension between a desire for stability and a quixotic faith in social mobility (Source: The New York Times); (c) 1930-*Dymaxion House*, by B. Fuller; (d) Jean Prouvé's redesign of his 1948 *Maison Tropicale*, a prefabricated design conceived as a kit of standardized parts to be transported by air to the French colonies and assembled on site (Source: The New York Times); (e) 1945-49-*Eames House* (Case Study House #8), Pacific Palisades (Photo by Julius Shulman); (f) 1968-72: *Nakagin Capsule Tower*, by Kisho Kurokawa; (g) *56 Leonard Street*, by Herzog & de Meuron Architects, New York; (h) 2008-*Loblolly House*, by Stephen Kieran and James Timberlake, Chesapeake Bay; (i) 2008-*Klein Bottle House*, by Rob McBride.

Overlooking some of the negative associations and misconceptualized applications of prefabrication, several new prefabricated systems have recently been developed.<sup>1</sup> Today, fully and semi-prefabricated systems are increasingly being used to enhance productivity through improved quality control, ensure a less crowded workspace, and cope with a shortage of skilled labor. Additionally, prefabricated systems, when integrated with "right on time" building systems, save significant time and cost. They also help to reduce construction waste, water consumption, onsite dust and noise, which lead to a cleaner and safer working environment.<sup>2</sup>

### CATSE Cardboard Housing and Offsite Prefabrication

Offsite prefabrication is a necessity for the manufacturing process of CATSE cardboard building components. Controlled environmental conditions are needed given the vulnerability of the core material (corrugated cardboard) to weathering conditions, fire threats, and other environmental dangers. Coordination of these conditions onsite would require significant amounts of equipment and workload over regular construction practices. Accordingly, manufacturing fully or partially completed components offsite will be a primary goal for the production of cardboard buildings. Advanced coordination between professionals, detailed planning, and early design decisions are required as a result of the physical characteristics of the core material, cardboard sheets. With cardboard block components, there is less flexibility for modifications in the later stages of construction.

To overcome some of the negative preconceptions that people have regarding prefabrication, and to be able to pursue its benefits via modularization and mass production, the importance of incorporated flexibility must be communicated.<sup>3</sup> In their study, Kieran and Timberlake discuss the increasing efficiency in construction accomplished by promoting "customization" via innovative flexible production systems, and therefore avoiding the repeated and standardized product cycle in yesterday's mass production systems. Today, especially among innovative wood construction systems in Switzerland, prefabricated and customized mass-produced components have experienced increasing popularity.



Figure 4.4 - Mass production visions in architecture (a) by Le Corbusier; (b) housing development in Sun City, Phoenix, Arizona, 1960s; (c) an example for misconceptualized applications of mass production, USA

<sup>1</sup> The building elements are brought in near-ready condition to the construction site, where installation of insulation, electrical, and plumbing can be accomplished.

<sup>2</sup> Lara Jaillona [9, 10 [3], [6], [7], [8] [11].

<sup>3</sup> Timberlake and Kieran 110.

Recent studies investigating construction efficiency have shown parallels between the operation mechanisms of the automotive and construction industries. One of the most recent relevant approaches of the automotive industry to be implemented in construction is achieving less costly and more efficient manufacturing techniques by increasing the amount of pre-assembly completed offsite. However, the focus on pre-assembly may lead to larger dimensions for cardboard building's components. This may prove to be problematic in the case of "just-in-time" construction management. The dimensional limitations in cardboard components may also cause problems with (i) transportation and lifting equipment, (ii) limited site dimensions in dense urban area, and (iii) a lack of onsite storage area for pre-assembled components.<sup>1</sup>

Another transferable approach from automotive industry is related to avoiding traditional gravity-based manufacturing. By no longer being fixed to linear lines of manufacturing, and avoiding moving from the bottom up (by gravity), extensive efficiency can be achieved (in automotive), opening new dimensions for the production of cardboard housing components.<sup>2</sup>

Despite the development of a prefabrication industry based on precast concrete systems, there are currently no extensive projects investigating the prefabrication operation mechanism of structural cardboard composite components in low-rise buildings. With the guidance of current innovations in prefabrication techniques (both wood and precast concrete panel sectors), this research study intends to create a preliminary study regarding prefabricated cardboard low-rise buildings that are architecturally flexible and adaptable.

### **1.2.2 Focus on Flexibility and Adaptability: Building to Last?**

In today's age of convenience and speed, where consumerism, individualism and quality-consciousness are becoming more prevalent, so too has the demand for flexibility and adaptability in architectural spaces. At first glance, this may be viewed as a natural consequence of the times. Ever changing consumer needs and lifestyles may seem to force users to demand more flexibility and adaptability in spaces. However, the history of architecture also confirms that flexibility or adaptability are part of a evolutionary necessity for the building environment (Figure 4.5).

The CATSE project, which has focused particularly on residential housing, acknowledges this phenomenon and recognizes it as one of the most defining parameters of future dwellings. Mass customization is an inherent advantage of offsite cardboard panel production. A dwelling that is practically demounted and rebuilt according to user needs every ten to fifteen years conforms to many of the societal strategies developed in Chapter II.

<sup>1</sup> C.M. Fitzgibbon, "Component type building construction system," United States Patent No. 4165591 (August 1979).

<sup>2</sup> Timberlake and Kieran 93.





Figure 4.5 - Dwellings of flexibility and adaptability: (a) vertical or horizontal adaptability in archeological times; (b) change in function; (c) user-defined constructed space; and (d) fast-adapting dwellings.<sup>1</sup>

<sup>1</sup> (a) *Limyra*, archaeological site near Antalya, and *Başur Höyük* archaeological excavations, Siirt, Turkey; (b) *Theater of Marcellus*, built by Emperor Augustus in 13 B.C.E.; (c) Social Housing Project in Iquique (RCH); user defined and reformed dwellings as a part of "Elemental Initiative" by Alejandro Aravena, 2005; (d) Kibera Slum, Nairobi, Kenya.

### 1.2.3 Quest for Synthetic Components: Fewer Layers and Less Complexity

Combining separate functions, decreasing total weight, cost and work load, while using fewer joints, but yet preserving a high level of quality and performance is now a goal of most homebuilders. Timberlake and Kieran have set forth the theoretical background for this theme in their research, noting that:

*"[a]rchitecture of 20th century initially taught us the simplicity and purity was the way to achieve a richness in meaning. This ultimately gave way to complexity, and contradiction as an attempt to achieve the same thing. The 21st century, however, has combined both precedents and aims at generating even more content while spending and using less. It is a principle of lean economy.<sup>1</sup>*

The building components that form a CATSE cardboard building will be constructed primarily from corrugated cardboard, and will therefore possess some of these multi-functional characteristics. Cardboard composite components combine the structural, insulative (thermal, acoustic) and space-defining functions that help to lower the total weight and the price of the building components. By decreasing the number of layers or materials involved, a building becomes not only economical but it also minimizes some of the negative ecological impacts.

### 1.2.4 Environmental Consciousness and Sustainability

Cardboard is generally considered a eco-friendly product due in part to its renewable nature and low environmental impact during the production of its component parts. Composed as a corrugated cardboard composite within a sandwich wall element, it possesses a high degree of thermal insulation, saving energy during the building's operation phase. Cardboard wall composites also have a low environmental impact as a result of emitting less carbon into the eco-system compared to other conventional building materials. As a result of highly organized network for paper and cardboard byproduct's recycling, seventy to eighty percent of the fiber used in the production of cardboard packaging comes originates from recycled fiber.

To prove the viability of cardboard buildings in terms of environmental benefits, a comparison with other materials is useful. The environmental impact of cardboard blocks can be evaluated by looking at a comparison with light wood panel construction. Although both originate from the same organic renewable raw material, the amount of wood used per cubic meter for massive-used corrugated cardboard composite panels is estimated to be significantly less than what is required for light wood panel construction. Additionally, the cardboard composition contains a much higher percentage of the recycled fiber. This hypothesis is supported by the considerations regarding excess usage of forest products and the timber building products, along with the significant changes that the industry is facing today. Pressures continue on multiple fronts to decrease the usage timber. These pressures are set forth by Moslemi in a recent study on the availability of timber for construction. He notes that: (a) the federal

<sup>1</sup> Timberlake and Kieran 90.

government continues to restrict access to the federal timber lands; (b) the quality of timber available is significantly lower than it used to be; (c) the price of timber is increasing; and (d) the market continues to demand low maintenance, durable building materials.<sup>1</sup>

### 1.3 Constraints of Cardboard Building Studies in Architecture

The designers and promoters of cardboard buildings must effectively and widely communicate its potential within the market by introducing cardboard as a viable building material as well as introducing the building system applied within its constructive parameters. Cardboard building systems within this study are based on three main *perspectives* that differentiate cardboard from other materials in structural terms: i) a *typology* focus in housing; ii) a *structural* focus in massive construction with corrugated cardboard blocks; and iii) a *component* focus with sandwich wall composite with corrugated paper honeycomb core.

#### i) *Application Typology: Demand for Cardboard Housing*

There has been an increasing focus on prefabricated buildings as the demand for housing accelerates and outstrips the capacity of traditional construction methods. Housing production and delivery systems desparately need to provide more and better housing, as well as more affordable housing.<sup>2</sup> A recent United Nations study demonstrates the severity of the housing shortage, noting that one billion human beings still lack adequate shelter and are living in unacceptable conditions of poverty.<sup>3</sup> Considering this immense and urgent need, CATSE cardboard buildings research elected to focus on this category of housing.

This selection was also made based on the limitations of cardboard structures. Structurally massive cardboard constructions may also find application in residential construction in the form of low-rise, low budget, yet high quality residents and dormitory buildings. Constructively, it follows the structural concept of solid (massive) construction, using composite wall components. Small spans (max. 2.50 - 3.00 m wide), suitable for residential spaces, are suitable for the first stage. Composite panels with wooden beams as secondary supporting components can potentially be used as floor slabs. The mixed system approach, rather than simple cardboard for floor slab construction, is employed due to the lack of comprehensive studies and testing on floors slabs and the low tensile strength of simple cardboard.

#### ii) *Construction with Corrugated Cardboard Blocks*

Cardboard buildings as massive structures have yet to be applied in practice. Prior applications only focused on tubular cardboard structures or filigree types or semi-massive cardboard as wall components, integrating rather thin composite walls. Focus in massiveness in this study enables corrugated cardboard blocks to demonstrate the benefits of the thermal and acoustic control potential and structural strength and stiffness of a light weight, yet solid wall component.

<sup>1</sup> A.A. Moslemi, "Emerging Technologies in Mineral-Bonded Wood and Fiber Composites," *Advanced Performance Materials* 6, no. 2 (Oct. 1999): 161-179.

<sup>2</sup> A.D. Bernhardt, "The Mobile Home Industry: A case study in Industrialization," in Dietz and Cutler 172.

<sup>3</sup> *Habitat Agenda* (United Nations Habitat II Conference, Istanbul, Jun. 1996) 53.



### iii) *Sandwich Wall Composites with Corrugated Paper Honeycomb Core as a Building Component*

The increasing demands for comfort and safety in common building practices requires the use of multifunctional and innovative materials that can fulfill several tasks. Several specialized materials unite to create the properties not attainable by the constituents acting alone.<sup>1</sup> In this research, cardboard, a low-tech and lightweight product, is used as the base material for the research in order to promote its multifunctional qualities as a viable building material. A noticeable decrease in its structural strength and stiffness when confronted with humidity and fire is one significant drawback of the material. As a result, sandwich composite structures as wall components are developed with cardboard core and facings to protect the cardboard core material from these elements.

The constructive approach for cardboard buildings within this study is guided by the following titles: a) project identification; b) technical design; c) conceptual design; d) context; e) construction as a process; and f) related themes and trends.

#### a) *Project Identification* (project type, intervention type)

- small span, two-floor high residential buildings

#### b) *Technical Design*

- *Structure*: configuration of massive structural cardboard composite panel components
- *Components*: sandwich with corrugated paper honeycomb core wall panels (exterior wall, curtain wall, interior load-bearing/partition)<sup>2</sup>
- *Building Element*: cardboard used as primary structural element (via composite structure)<sup>3</sup>
- *Raw Material*: corrugated cardboard, adhesive - joint material, facing material (natural cellulose fiber materials such as wood byproduct panels (OBS, MDF, plywood), gypsum board, cement board, aluminum, steel, glass fiber reinforced plastics, mineral fibers panels and other innovative composite materials)
- *Technical performance*: In the framework of the CATSE collaborative research project, thermal hygrometric, fire-safety, statics-stability, dynamics, and weathering performances were analyzed by the engineering team<sup>4</sup>
- *Service systems* (water, HVAC, lighting, communication, security, electrical systems)<sup>5</sup>

#### c) *Conceptual Design*

The prototype project to be generated will implement the conceptual design into practice by project cues (metaphoric reference, expression form), project actions (composition, disposition, distortion), relation with context: (positioning, conceptual relation), form characteristic (formal composition concept, geometric figures), and perceptive qualities.<sup>6</sup>

<sup>1</sup> Albert G.H. Dietz, "Building Technology: Potentials and Problems," in Dietz and Cutler 16.

<sup>2</sup> Excluding roof (exterior-interior shape), floor slab, openings and substructure/foundation components.

<sup>3</sup> Excluding substructure/foundation elements, installation/service elements.

<sup>4</sup> Excluding energetic, acoustic, lighting, chemical/bio factors and radiation.

<sup>5</sup> Excluded in this study.

<sup>6</sup> Perceptive qualities include psycho-perceptive, visual and tactile qualities.

- *Functional typology*: The research will focus on the application in residential buildings - single family houses, multifamily houses, row houses , dormitories of low-rise, small-span volumes

d) *Context* (Urban context, geographic context): Experimental cardboard buildings in urban and suburban contexts, where land use is being transformed, building legislation exists for limited usage, and in areas where simple assembly and disassembly is required (i.e. disaster areas).

e) *Construction as a Process*: Specialized construction processes and activities, machinery/equipment for offsite manufacturing and onsite assembly, construction management (planning, quality, control, health, safety) are required quick production of cardboard buildings on a large scale.

f) *Related Themes and Concepts*: concepts and trends related to cardboard buildings (culture related, philosophical, computer science, psychological concept, socio-economic, geography concepts, concepts in arts, forms of expression, transportation, urban and related concepts).<sup>1</sup>

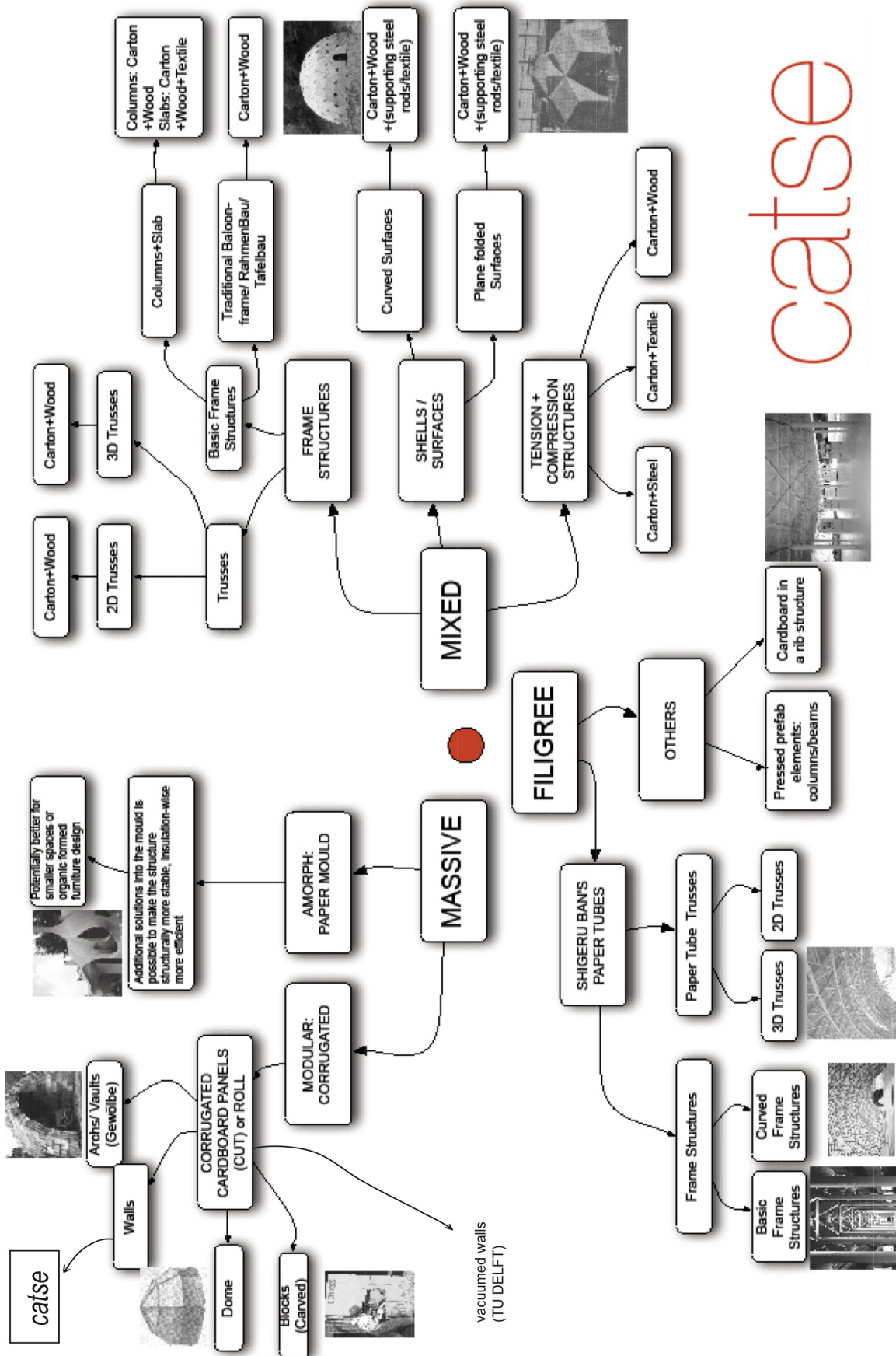
## **2. Structural Conception of CATSE Cardboard Buildings**

The identification of the morphology of structural applications for cardboard is sought under the guidance of technical experiments regarding the characteristics and behavior of corrugated cardboard. The direction revealed by the societal and environmental inquiries form the overall structural contextualization for cardboard buildings. As a method, the constructive approach is examined by studying its adaptative potential within existing load-bearing structural systems. As a result, sandwich wall panel components with corrugated paper honeycomb core have been selected as the structural concept for the case study. To prove the viability of cardboard as a building component, the structural performance of CATSE cardboard sandwich wall components are examined herein.

### **2.1 Overview of Structural Systems in Cardboard Buildings**

Methodologically, an overview of the existing structural systems is necessary to investigate the potential for the structural use of corrugated paper honeycomb core. The building classifications retained from the traditional morphology of structural systems are categorized in two fields. The first is the structural classification of the characters of load distributing components revised from filigree and massive systems. The second is the monolithic structure characteristics demonstrating the continuous manufacturing potential of stacked layers forming the corrugated cardboard core, inspired from masonry.

<sup>1</sup> The above titles represent the open-endedness of this research regarding the implementation of cardboard housing. However, some aspects are left to be evaluated in subsequent stages of the project.



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Figure 4.6 - Genealogy of load-bearing cardboard buildings.

### 2.1.1 Structural System Typology in Cardboard Buildings

a) *Structural system classification vs. Load distributing cardboard components:* The structural performance required for a building is primarily a function of the structural system employed to resist loads and forces. Accordingly, three classifications are observed:

i) *Linear/Filigree Structural Systems:* These systems are composed of specially arranged sets of linear elements in form of beams, columns, girders and arches, constituting basic and complex three-dimensional structures. Various applications including wide spans are possible, such as the cardboard tubular architecture of Shigeru Ban. Due to the high strength to weight ratio of space frames and space trusses, tubular space frames are the most prevalent category of lightweight cardboard spatial structures.

ii) *Planar Structural Systems:* These systems are composed of organized sets of planar or two-dimensional elements in the form of a plane or curvilinear vertical walls, horizontal slabs or panels, forming basic three-dimensional structures.<sup>1</sup> The planar structural systems, composed of cardboard shear walls and box-type structures may find wide application in the CATSE cardboard building research project, due to their high compressive strength values.

iii) *Composite Structural Systems:* These systems consist of various combinations of cardboard linear, filigree and planar structural systems. There may be a considerable functional division in the use of both systems integrated in cardboard buildings (linear systems: roofs and floor slab; planar systems: walls and facades).<sup>2</sup> There continues to be an absence of this category in the literature. The *Westborough Cardboard School* project remains the closest example of this type (Figures 4.7(d) and 4.8(d)).

#### **b. Structural Classifications and Monolithic Character of Corrugated Cardboard Core**

Corrugated cardboard paper honeycomb core consists of stacks of corrugated cardboard sheet layers. In theory, a continuous form of walls with monolithic characteristics is possible with this structure. Inspired by massive-solid construction *leitmotiv* in masonry, in practice, this applies to major onsite construction. Prefabrication will therefore be used to meet potential dimensioning, weathering and transportation problems of the monolithic materials such as bricks, stones and cardboard.

i) *Monolithic Structures:* In masonry, bricks constitute fully continuous monolithic structures. Although constructed from heterogeneous materials, with different types of masonry units and mortars, monolithic performance of masonry is safeguarded by proper design and construction. However, such continuous operative method cannot be applied to cardboard walls with existing manufacturing systems. Onsite manufacturing restrictions of the material weaken this category's potential (Figure 4.8(c)).

<sup>1</sup> Mikluchin 962.

<sup>2</sup> Here, the term "cardboard component" refers to the corrugated cardboard honeycomb material used as a structural component forming a building system.

ii) *Polyolithic Structures*: Originally used for masonry, these structures are constructed from a series of larger units in the form of prefabricated elements: block, panels, wall and floor units interconnected by means of bonding devices, anchors and special connectors. The relative size of such units in masonry has a certain ratio to the whole structure's dimensions and height to be calculated, while the presence of joints making these structures noncontinuous. CATSE cardboard buildings, structured as prefabricated panels, fall into this category and currently offer the simplest and most efficient implementation solution.

iii) *Hybrid Structures*: Originally applied only to stone-brick masonry, these structures are constructed out of various combinations of continuous linear or planar frameworks (cardboard tubes, wooden studs, reinforced concrete, structural steel) with cardboard infill panel walls, and connected to the basic framework of the structure.<sup>1</sup> Such structures have high potential to be used in low-rise, small-span buildings, and also in higher rise building with larger span volumes. In contrast to masonry, the structural performance and behavior of such principally cardboard structural systems have yet to be fully tested.

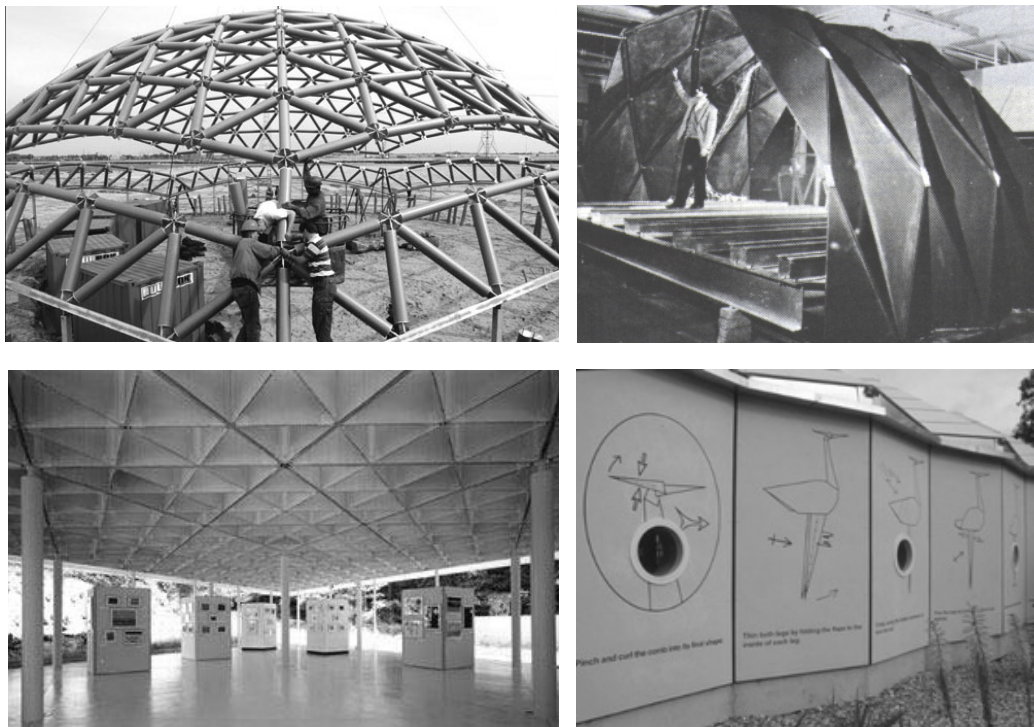


Figure 4.7 - The structural diversity of innovative cardboard buildings from 1950-2000.

<sup>1</sup> Mikluchin 962.



### 2.1.2 Structural Applications of Corrugated Paper Honeycomb: An Overview

Corrugated cardboard paper honeycomb for structural applications have been investigated in the CATSE collaborative research project, under which this architectonic research study is taken. The technical aspect of the research, conducted through a series of tests, modeling and analyses, attempted to reveal the limitations and behaviors of corrugated cardboard paper honeycomb material.

Preliminary tests on corrugated paper honeycomb indicated the material's substantial thermal control properties, structural strength, stiffness and stability for its applications in structural elements.<sup>1</sup> However, factors such as humidity, moisture, combustibility, local stress failure, and secondary threats such as biological attacks and decay due to direct sunlight clearly demonstrated the necessity of a protective layer for applications in structural elements. Two of the primary areas, humidity-moisture penetration and combustibility, will make up the base of the protective strategies, and are briefly discussed below.

#### i) Humidity and Moisture Penetration

Humidity and moisture pose serious threats to cardboard as a building material. Like most timber byproducts, cardboard is hygroscopic with a low vapor resistance that absorbs water vapor from the environment until equilibrium is achieved, depending on the vapor transport

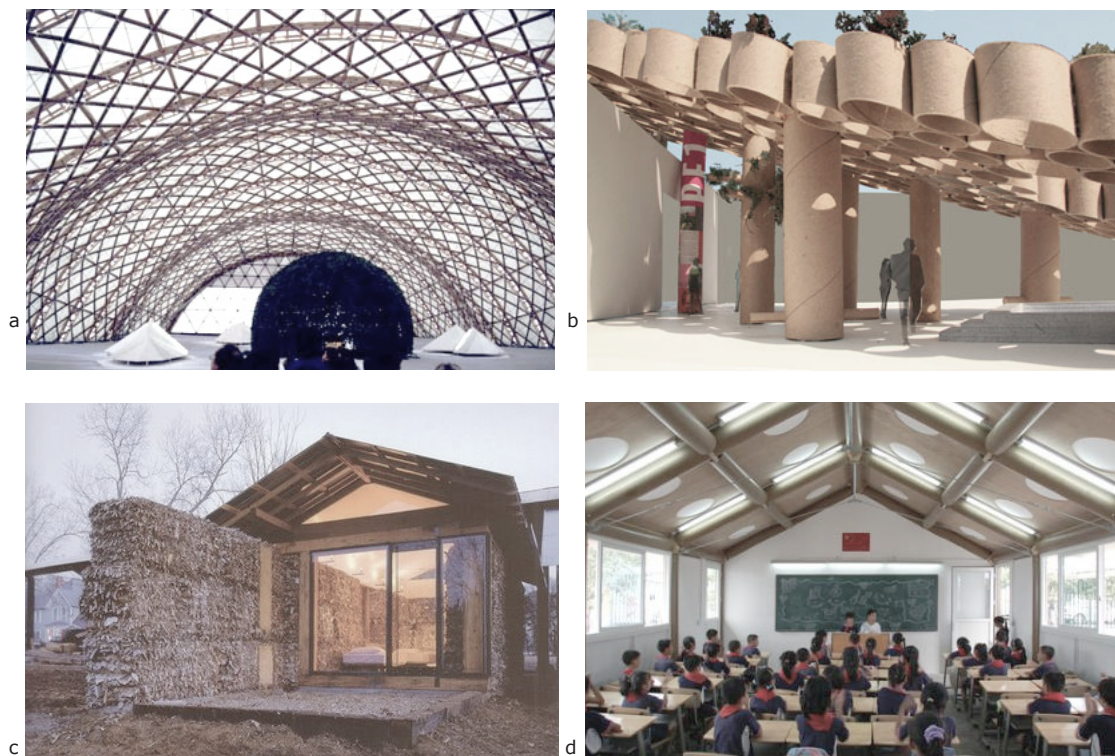


Figure 4.8 - Structural classification and load distributing cardboard building components in literature.<sup>2</sup>

<sup>1</sup> CATSE Experimental Preliminary Tests, Appendix 1 and 2 (2005).

<sup>2</sup> (a) *Japanese Pavillion*, by Shigeru Bann (Expo 2000); (b) *A Farm of P.S.1*, WORK Architecture (2008); (c) *Cardboard Wall House*, the Rural Studio by Mocbee (2001); (d) interior of *Westborough Cardboard School*, by Cottrell & Vermeulen.



coefficient (function of temperature and relative humidity). Moisture can penetrate and destroy the bonds between paper fibers in the corrugated cardboard.<sup>1</sup> During the experimental testing, substantial loss of structural performance under load were observed when the material was confronted with humidity and moisture.<sup>2</sup> Apart from the loss of structural performance qualities, humidity and moisture penetration can lead to other weaknesses and risks in the building envelope, such as mold and mildew, damage caused by wind loads, high energy costs, and ongoing maintenance problems.<sup>3</sup>

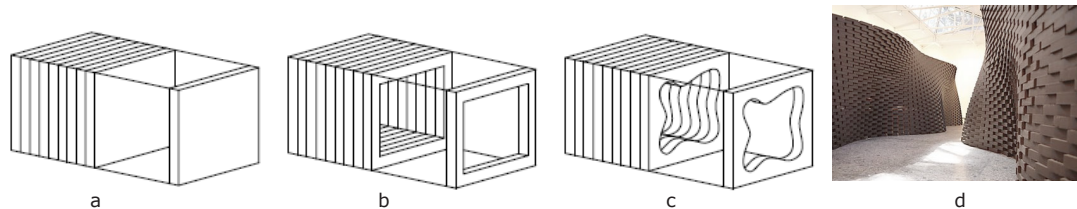


Figure 4.9 - (a), (b) and (c) Monolithic wall principle for corrugated cardboard sheets; (d) monolithic curved brick wall.<sup>4</sup>

### Humidity/Moisture Treatments Applied to Existing Cardboard Buildings

- *Westborough Cardboard School Project*: Considering the effect of long-term damage to paper from ultraviolet light, hail and other elements, one of the first steps in the project was to apply a protective cladding to the material with fiber-cement mix panels. Also, a recycled plastic outer layer, both on the interior and exterior, were used to protect the inner core side. This also served as a vapor barrier to top layer of the card. To protect against humidity, a PE foil cladding was applied.<sup>5</sup>

- *Cardboard Wall Project*: For this load bearing wall panel project, which was constructed using honeycomb cardboard, an exterior breather foil and an interior vapor retardant layer were applied to provide easy detailing, less manual production, less waste and quicker assembly of the prototype.<sup>6</sup>

### ii) Combustibility

Corrugated cardboard and timber materials are classified as "easily combustible" (DIN 4102<sup>7</sup>) B3. Cardboard's lack of fire resistance is considered a serious problem in the packaging industry. This issue has been addressed with significant studies in an attempt to reduce the risk. These safety issues, along with strict building regulations require that cardboard buildings convincingly demonstrate their structural strength and fire resistance before large-scale implementation.

<sup>1</sup> Achilles Karagiozis, *Building Enclosure Hygrothermal Performance Study, Phase I* (US Oak Ridge National Laboratory, Apr. 2002).

<sup>2</sup> Almut Pohl, "Strengthening Corrugated Paper Honeycomb Core for Application in Structural Elements," PhD diss., ETH Zurich, 2009.

<sup>3</sup> Nadel.

<sup>4</sup> Fabio Gramazio and Matthias Kohler (Venice Biennale, 2008).

<sup>5</sup> *Westborough School Project*, by Andrew Cripps (2005).

<sup>6</sup> M. Eekhout et al. 176.

<sup>7</sup> DIN 4102 stands for German Institute for Standardization for fire behaviour of building materials and elements; classification of building materials, requirements and testing. B3 stands for «Easily inflammable» Category.

Another safety issue related to cardboard's combustibility is its emission of toxic gases, smoke and heat. The experimental testing in this study did not investigate this aspect of the material, but further studies in subsequent stages are required. Given cardboard's vulnerability to water, such an investigation should look at the capabilities and effectiveness of a fire extinguishing system in a cardboard building.

### **Fire-Proofing Treatments Applied to Existing Cardboard Buildings**

- *Westborough Cardboard School Project*: Architect Andrew Cripps reported that the *solid card* facing used in this project burns at a slower rate than paper; similar to the burn rate of timber. Moreover, the *solid card* material tends to char rather than burn. The surface of the building was treated with a proprietary flame retardant paint.

- *Cardboard Interior Furniture Project*: Architects Ad Kil and Ro Koster furnished their office interior using only cardboard elements. The worktops were covered with a transparent acrylic plate to keep the moisture out and the vulnerable edges of the tables. Also, each building element was impregnated with a fire-retardant substance pursuant to governmental and insurance company demands.<sup>1</sup>

- *Other Products*: Several products, including "light flame-retardant paper honeycomb sandwich wall panel" are currently available in the market. This honeycomb sandwich wall panel product is made using a flame-retardant paper honeycomb core, paper covering plasterboard, magnesia board, calcium silicate board, and a galvanized steel plate as facing materials, and composited by a flame-retardant bond.

### **Strategies for Protecting the Structural Integrity of Cardboard Buildings against Moisture and Fire**

Experimental tests have established the significant role of moisture penetration and fire in the structural performance of cardboard buildings. A three level protection strategy will be used in this project to secure the cardboard core material against the fire and moisture penetration.

#### *i) Protective measures during paper pulp manufacturing stage*

Protection against moisture and fire through the chemical bonding of the fibers on the microscopic nano-technical level is technologically feasible. This innovative technology has been applied in the packaging industry, with the guidance of chemical engineering experts. This protective measure was not investigated further during the testing phase of this project.

#### *ii) Protective measures at the corrugated cardboard level*

This level involves intervention of the cardboard honeycomb after the manufacturing of corrugated cardboard sheets. The treatments that can be applied following manufacture of the corrugated cardboard sheets require two steps. The first step is the identification of

<sup>1</sup> Elise Van Dooren and Fons Verheijen, "Cardboard in Architecture; an Overview," in M. Eekhout et al.

the parameters that influences the resistance of the corrugated cardboard paper honeycomb core and implementation of precautions to these components. The relevant parameters are paper type, paper weight, flute type, flute height, and the direction and configuration of the flutes within the core. When the corrugated cardboard paper honeycomb core is to be used in a sandwich structure, then additional parameters such as facing material choice, facing material thickness, and to a lesser extent, adhesive type become relevant.

The second step is the application of external treatments or impregnation of the corrugated cardboard sheet block. In this collaborative research study, preliminary experimental testing was conducted on corrugated cardboard paper honeycomb core samples of varying thicknesses, with a focus on modeling for loss of structural strength, stability and stiffness when confronted with humidity and moisture. The testing also involved impregnation of the cardboard material with cement-milk, gypsum, silicate-materials, textile-hydrofibers, wood primers and polyurethane. Tests were conducted in preconditioned normal (20°C, 65% relative humidity) and a more humid environment (20°C, 95% relative humidity).



Figure 4.10 - Cardboard usage in architecture <sup>1</sup>

<sup>1</sup> (a) *Westborough Cardboard School* panels - basic honeycomb, edged with wood, UK, 2001; (b) *Westborough Cardboard School* interior, UK, 2001; (c) Honeycomb cardboard for the interior of the Schetsontwerp office, Architects Ad Kil and Ro Koster, Eindhoven, 2005; (d) Example of textile skin façade used as wind and rain protection.

Another method of external protection involves the use of a material to fill in the corrugations in the cardboard block with materials such as EPS, a new generation thermo-set foams- Basotect® TG<sup>1</sup>, impregnated cellulose fibers, polystyrene, polyurethane foam, and phenolic resins. However, the full implementation of this technique is predicted to be exceedingly complex and costly, especially for small corrugation sized cardboard blocks.

### *iii) Protective measures at the component level*

This strategy is applied to the structural component level, and involves the application of an additional layer (i.e. facings, sheet panels, foil, foam, paint, textile) on the facades of the corrugated cardboard block. A composite sandwich structure is applied to the component while the facings result in the material's air-tightness and function as a protective layer for the corrugated cardboard core, and as additional support.

The collaborative technical research partners in this study conducted tests on sandwich structured specimen. The specimen were composed of corrugated cardboard paper honeycomb core and several facing sheet materials and paperboard. Their research found that even the slightest leak in an air or vapor barrier can lead to potential moisture control failure. Air and pressure alone can cause significant amounts of moisture-laden air to flow through cuts, rips, and joints, which can seriously damage the integrity of the cardboard. Thus, the selection of the facing material and the joint/closure mechanisms is a significant decision with regard to the performance of this method.

An additional protective strategy can be employed using external air-cavity facades on the structural component level. This method works by filtering the penetrations into the corrugated cardboard honeycomb core. Involving architectural precautions, such as employing furniture as a protective layer, can also be applied on the component level to minimize combustibility as a secondary precaution (Figure 4.12).

## **Research and Development Opportunities for Cardboard Composite Wall Panels: Technology Transfer**

Technology transfer offers an effective way to guide and develop efficient and innovative applications in diverse fields. The research and development of corrugated cardboard honeycomb building components in structural applications is connected with two industries: packaging and structural insulated panels (Figure 4.13).

### *i) The Cardboard Packaging Industry*

The cardboard packaging industry has developed sophisticated approaches for its products, particularly in the last decade. This progress is based on established engineering principles, extensive material testing, field quality control and precautions made pursuant to environmental and economic regulations.

<sup>1</sup> Basotect® TG is a flexible, open cell foam made from melamine resin.



As a result, extensive databases has been accumulated on the mechanical and physical properties of the material, the production process, and the durability of corrugated cardboard paper applications. Despite the differences in the scale of the end-product, these applications can be used as a guide for the further development of cardboard composite building components.

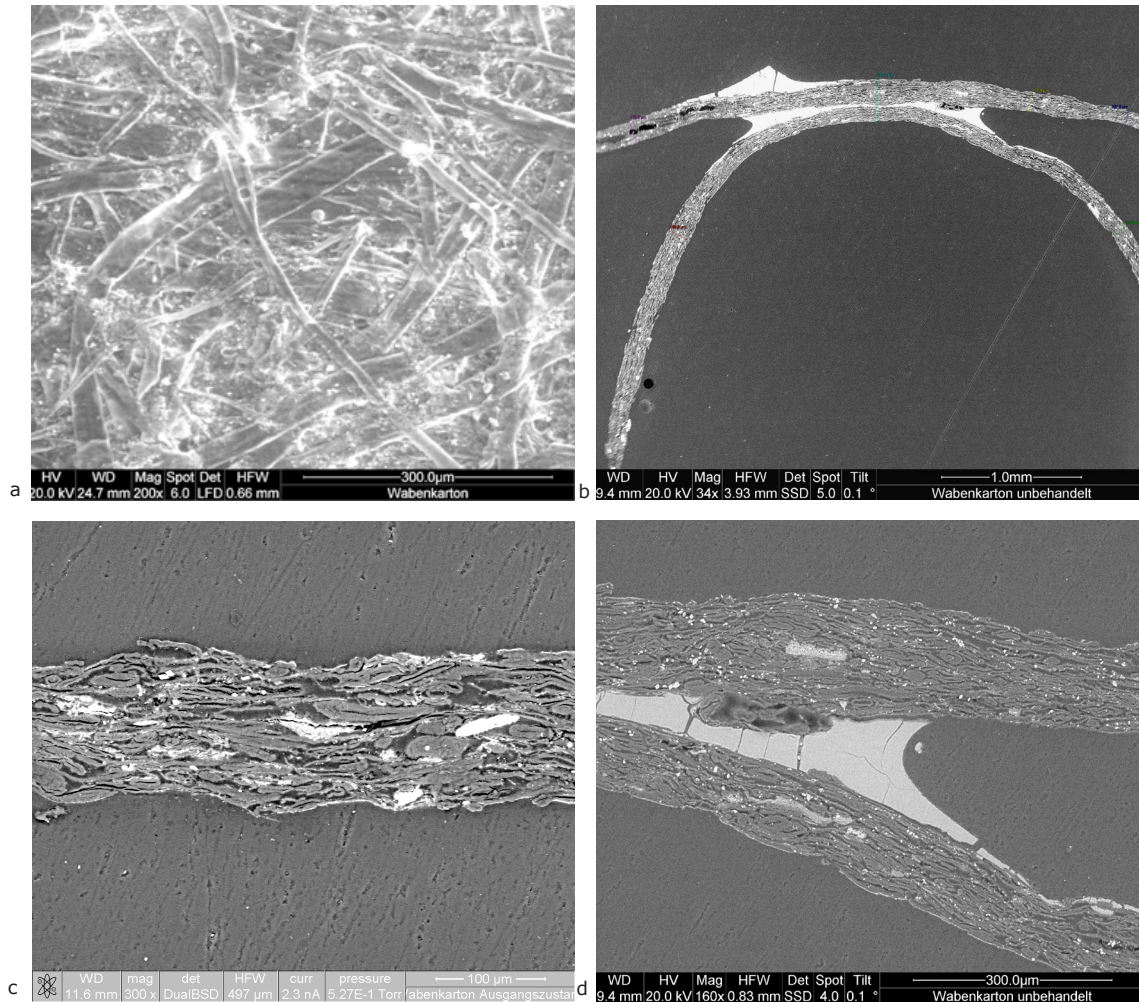


Figure 4.11 - Scanning Electron Microscope (SEM) analysis micrographs, showing: (a) the paper surface of ca. 1mm<sup>2</sup>; (b), (c) and (d): fiber configurations and cardboard paper vs. adhesive relationship on the corrugations.<sup>1</sup>

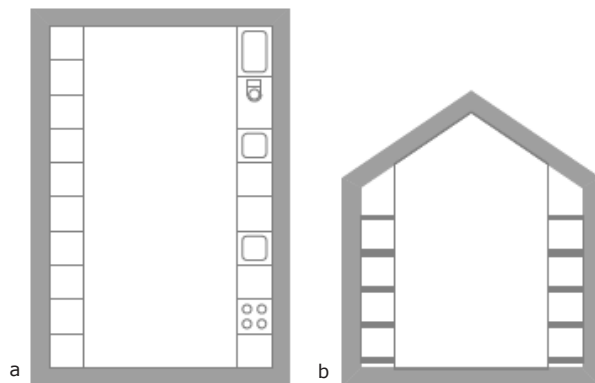


Figure 4.12 - Furniture as a secondary protective layer for cardboard wall components<sup>2</sup>

<sup>1</sup> Source: Gabriele Peschke, ETH Zurich.

<sup>2</sup> Furniture as a secondary protective layer for cardboard wall components (a) Plan: the role of the furniture when wall-along placed; forming a protection layer between the interior and the wall component itself (b) Section: the role of the furniture which is room height; protecting the wall component against a possible fire combustion, happening in the interior.

ii) *The Structural Insulated Panel Industry:*

Sandwich composites are a simple solution for corrugated cardboard paper honeycomb to be used in structural applications. In many respects, corrugated cardboard honeycomb core sandwich structured walls are similar to structural insulated panel industrial walls. In particular, both use a similar implementation of panel-joints, openings, and facings. Computer models developed for structural insulating panels can easily be transferred into cardboard building manufacturing.

Automated manufacturing lines have been developed to incorporate several facings with flat, lined, crimped/micro-crimped and trapezoidal-formed geometry made from metal (i.e. steel, aluminum, copper, stainless steel), oriented strand boards, and GFK. These facings feature extensive fixing options (direct screws and hidden fixings).<sup>1</sup> Cardboard building wall components can benefit from these applications technically as well as visually.

## 2.2 Case Study

### Structural application of corrugated cardboard honeycomb: Sandwich wall panels

Janine Benyus's recent book, *Biomimicry: Innovation Inspired by Nature*, asserts several new applications for cardboard components in construction.<sup>2</sup> She discusses several examples from nature that have provided inspiration for innovative applications for sandwich composite structures (Figure 4.14). Inspired by some of these natural examples that provide various models for corrugated honeycomb structures, preliminary tests were conducted within this collaborative research. Results regarding the loss of structural strength and stiffness from exposure to humidity and moisture were obtained. Based on these results, the sandwich structure was selected as the case study for structural application of cardboard.

The theory of sandwich panels in structural applications has been well documented and, as a result, several products have been developed in the construction market. Today, paper-based honeycomb core sandwich composite applications are commonly used in interior of the buildings. Examples include kitchen tops with metal facings, furniture, door and floor tiles construction, and partition walls with gypsum facing cardboard cores (Figure 4.14).



Figure 4.13 - Product examples of packaging industry and structural panel industry.<sup>3</sup>

<sup>1</sup> See also publications from the Structural Insulated Panel Association at <www.sips.org>.

<sup>2</sup> Janine Benyus, *Biomimicry: Innovation Inspired by Nature* (New York: Harper Perennial, 2002) 1-10.

<sup>3</sup> A. Allanson A. and B. Svård, *Stability and Collapse of Corrugated Board*, Master's Thesis, Lund University (2001).



The distinctive characteristics of this architectonic study are found in the structural conceptual approach, which differs in scale and function from existing industrial applications. The function is altered as wall components will be applied to both indoor and outdoor conditions. The expected performance will also be effected as building components have other limitations pertaining to their failure parameters. The safety criteria for buildings is also noteworthy, as performance quality and manufacturing efficiency cannot tolerate a structural malfunction of cardboard building components.

### ***Sandwich Panels: History and Industrial Development***

Sandwich structured panels today are composed of two facing layers between an insulating core layer. The core layer is typically composed of expanded polystyrene foam (EPS), fiberglass, extruded polystyrene foam (XPS), or polyurethane foam. Other core materials are categorized as non-homogenous support, such as punctual support (textile-truss cores), regional support (cup-shared cores), unidirectional support (corrugated cores) and bi-directional support (honeycomb cores). Sandwich panels with a honeycomb structure result in lightweight, yet high strength construction. Their usages range from construction and aerospace to automotive and shipbuilding applications (Figures 4.15 and 4.16).

The research and development of sandwich panels began in the 1930's, but following World War II, with an increased demand for cold stores and freezers, this construction method gained popularity for functional buildings and industrial units.<sup>1</sup> The first case study of structural



Figure 4.14 - Honeycomb sandwich structures in nature and as industrial products.

<sup>1</sup> Rolf Koschade, *Sandwich Panel Construction Handbook* (Berlin: Ernst & Son, 2002) 14.

insulated panels with corrugated cardboard cores dates back to 1947. With the foam-core panels gaining more attention in the 1970s, they began being used for several building types in the construction sector.

The advantages of sandwich panels, apart from their structural strength to weight ratio, are its durability, high energy absorption characteristics, and the possibility for a smaller building envelope. The industry is innovation oriented, making continual advances in profiling, connection techniques, price to performance ratio, and reduced construction time. With their high strength to weight ratio, sandwich composites are now installed as load-bearing walls, the finishing of interior spaces, floor and roof systems, and non-structural components, such as interior non-load bearing, dividing walls. Some types multifunctional- serving as the structure, insulation and exterior sheathing.

However, there are several disadvantages associated with the use of sandwich composites. These include a modularization degree which decreases design flexibility and incompatibility of the facing material with their intended purposes, which can result in the need for additional exterior skin layers. Other costs include a need for customized dimensioning and transportation depending on the location of the project, and onsite consulting costs for customized solutions regarding joints and facing materials.

### 2.3 Case Study

#### Configuration of the cardboard sandwich wall: Raw material characteristics

The above overview indicates that structural sandwich panels as a viable structural application for corrugated cardboard. Thus, corrugated paper honeycomb core sandwich components with diverse facing configurations will be used as a case study. Building components formed from structural sandwich panels are planned to be used for this study's cardboard building systems.

The loads and forces to be applied to the structural performance are not only a function of the structural system but also the size of the building, the materials used, and the type of members joined at the connections. Therefore, the characteristics of the component raw materials that form the sandwich panels have a strong impact on the building's performance. This also includes their interrelated roles that define the performance criteria for the component and the system.

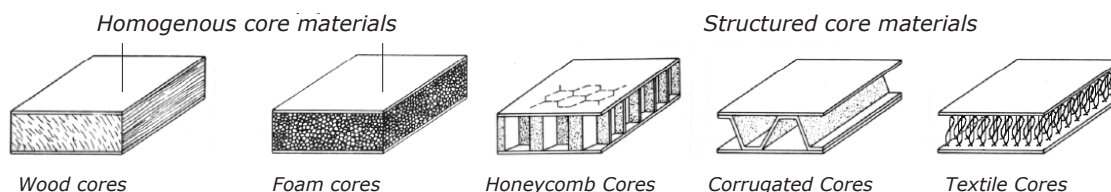
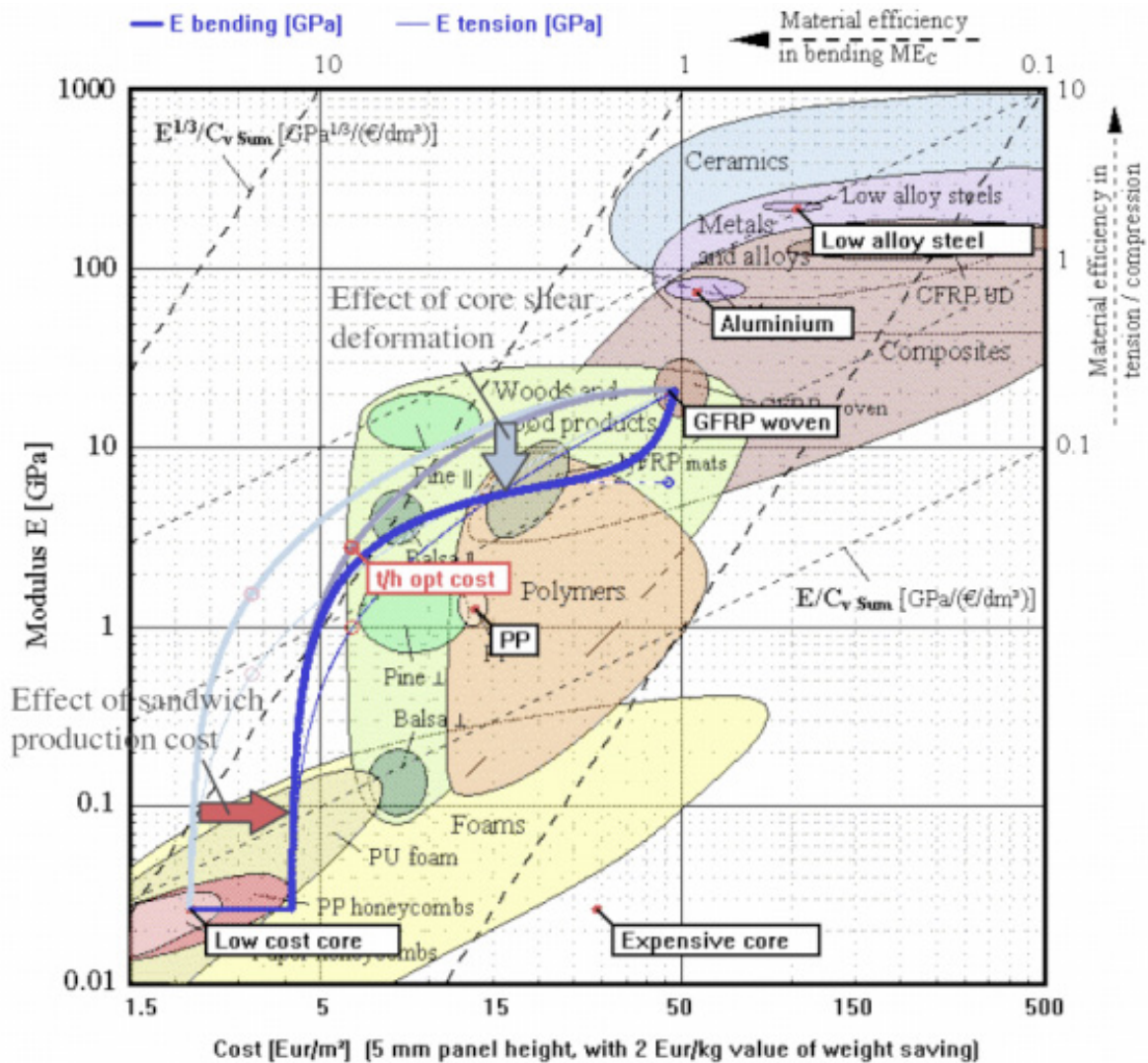


Figure 4. 15 . Homogeneous and structured core materials (J.Pflug, 2003)<sup>1</sup>

<sup>1</sup> Jochen Pflug, Fan Xinyu, Bart Vangrimde, Ignaas Verpoest, Philipp Bratfisch and Dirk Vandepitte, "Development of a Sandwich Material with Polypropylene/Natural Fiber Skins and Paper Honeycomb Core," *Proc. of 10th European Conference on Composite Materials (ECCM-10)*, 2002.



**Skin material :**

GFRP woven  
 Modulus  $E_s = 20 \text{ GPa}$   
 Density  $\rho_{\text{os}} = 1.7 \text{ kg}/\text{dm}^3$   
 Cost  $C_{\text{ws}} = 3.3 \text{ Eur}/\text{kg}$

**Core material :**

Low cost core  
 Modulus  $E_c = 0.025 \text{ GPa}$   
 Shear  $G_c = 10 \text{ MPa}$   
 Density  $\rho_{\text{oc}} = 0.085 \text{ kg}/\text{dm}^3$   
 Cost  $C_{\text{wc}} = 3.3 \text{ Eur}/\text{kg}$

**Optimal sandwich :**

Height  $h = 5 \text{ mm}$   
 Span length  $l = 150 \text{ mm}$   
 $t/h = 0.0231$      $t = 0.115 \text{ mm}$   
 Modulus  $E = 2.666 \text{ GPa}$   
 Panel cost =  $6.228 \text{ Eur}/\text{m}^2$   
 $D = 27.769 \text{ Nm}$   
 Material Efficiency per cost :  
 $ME_c = 1.021 \text{ GPa}^{1/3} / [\text{Eur}/\text{dm}^3]$   
 $\Phi_{\text{cost}} = 3.389$

Value of weight saving  
 $C_{\text{wv}} = 2 \text{ Eur}/\text{kg}$   
 Sandwich production cost  
 $C_{\text{ap}} = 2 \text{ Eur}/\text{m}^2$

Support: simple  
 Load: central force

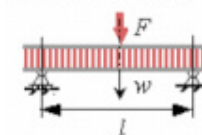


Figure 4.16 - Sandwich materials selection chart bending performance per cost optimization.<sup>1</sup>

<sup>1</sup> O.T. Thomsen, E. Bozhevolnaya and A. Lyckegaard, eds., *Sandwich Structures 7: Advancing with Sandwich Structures and Materials: Proceedings of the 7th International Conference on Sandwich Structures*, Aalbo (Netherlands: Springer, 2005).

### 2.3.1 Corrugated Cardboard Paper Honeycomb Core: Test Results

In general, cardboard paper is relatively weak with a low modulus of elasticity and a high vulnerability to humidity.<sup>1</sup> But experiments show that corrugated cardboard honeycomb core offers sufficient compressive strength to carry significant structural loads, and offers an alternative to concrete and steel, materials which are both highly energy intensive to produce. In terms of strength and durability, cardboard tends to creep and deform under load, and only a small portion of strength can be used for long-term purposes. With regard to its impact resistance, cardboard performs well, but is less robust than concrete brick. Moreover, it must be secured from local impact, and thus a protective layer is often applied for protection.<sup>2</sup>

Since corrugated cardboard sheets are already widely used by the packaging industry, the material standards have been explicitly defined by the industry. As noted earlier, the parameters for rigidity in corrugated cardboard packages are directly related its corrugation direction, flute thickness, flute type, flute height, flute/liner paper fiber type, adhesive type and amount, paper dough mix chemical characteristics, and factors in the manufacturing process. These characteristics are used as a guide for the use of corrugated cardboard material in prospective structural applications.

CATSE testing results indicate that, depending on the thickness of the facing sheets of the sandwich and their material type, a load bearing sandwich wall with impregnated honeycomb core must have a thickness of at least 150 mm to 200 mm to resist the withstand the design loads for a two-story office building and to efficiently transmit the loads to the system. In the framework of this collaborative project, two directions of test series were conducted on the corrugated cardboard core: (1) the treatment for protection against humidity and moisture; and (2) the identification of the role of the facing in the protection of the core within a sandwich composite structure.

1) *Core*: To prevent the corrugated cardboard core sample<sup>3</sup> from loss of strength, stability and stiffness due to humidity /moisture and combustibility, the sample was impregnated with several different inorganic substances.

2) *Facing*: A sandwich composite structure was used, which consisted of corrugated cardboard paper honeycomb core with various skin materials. Testing series were conducted into the structural behavior of the composite samples, including humidity and moisture reactions.

### ***The Effect of Corrugation Direction on the Performance of Wall Components***

The relationship between the corrugation direction of cardboard block, the impregnation process, and various parameters defining the structural applications is shown in Figures 4.20 and 4.21. The first six samples tested exhibited six different corrugation directions; where

<sup>1</sup> Eekhout et al. 176.

<sup>2</sup> *Cardboard School Project*, by Andrew Cripps (2005).

<sup>3</sup> The sample for this series had a flute height of 5 mm, and a total thickness of 50mm (492 gr/m<sup>2</sup>).



corrugations are positioned parallel along either the x, y or z axis, relative to the wall surface panel. The last sample (Type 7) consisted of two different corrugation direction layerings that were either vertical and horizontal to the wall surface.

The testing indicated that the impregnation process was the most influential in defining the categorization of end-characteristics for the cardboard building component since impregnation secured the material against fire and water. The hypothesis is that the effectiveness of impregnation is limited to certain thicknesses of the wall element, due to the existing manufacturing technique. For the tests, impregnation was applied to 5 cm thick honeycomb cores. In this preliminary study, it was assumed that up to 10-15 cm thick corrugated cardboard cores can be impregnated as efficiently as 5 cm samples.

During the preliminary study, the sample sandwich wall thickness were tested at 30, 48 or 72 cm thicknesses. Depending on the thickness, two or three layers of corrugated cardboard blocks are planned to first be impregnated. Then the impregnated cardboard blocks will be stacked together to form the cardboard core wall segment with the required thickness.

Figure 4.19 sets forth the results for seven styles of corrugation, among nine relevant parameters for structural applications of corrugated cardboard paper honeycomb core in sandwich structures, as shown in Figure 4.18. Testing was not completed on all seven samples, which limited the comparison to preliminary outcomes. Further detailed testing and comprehensive theoretical studies are needed to determine the effect of corrugation direction and the following impact categories.

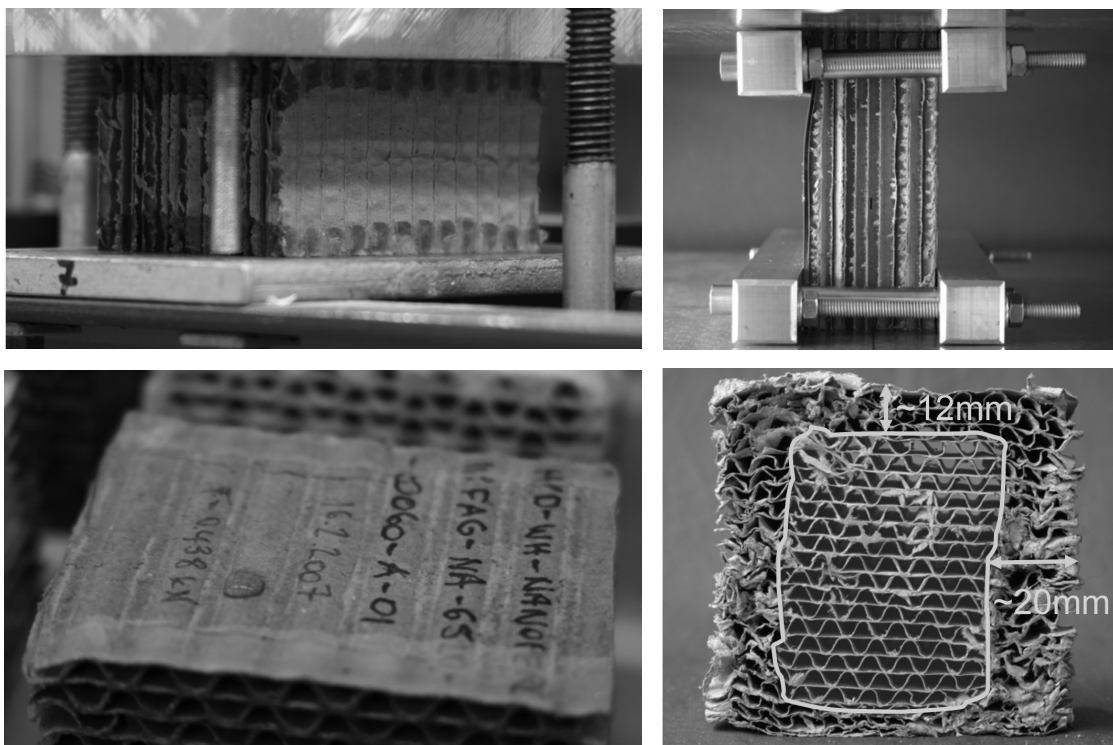


Figure 4.17 - Experiment photographs of corrugated cardboard honeycomb core.

**Category "Form-active"** defines the possibility of using the direction of layering to produce geometric patterns on the wall element by stacking layers of cardboard next to or on top of each other using CAD/CAM. This feature can be used to achieve architectural atmosphere, acoustic control in interiors, and UV protection to building exteriors. Test Types 1 and 3, due to their core configuration direction, do not permit geometric patterns on the facade.

**Category "Thermal"** discusses the benefits of thermal control quality achieved by core direction within a sandwich composite wall. For the hypothesis, it is assumed that the number

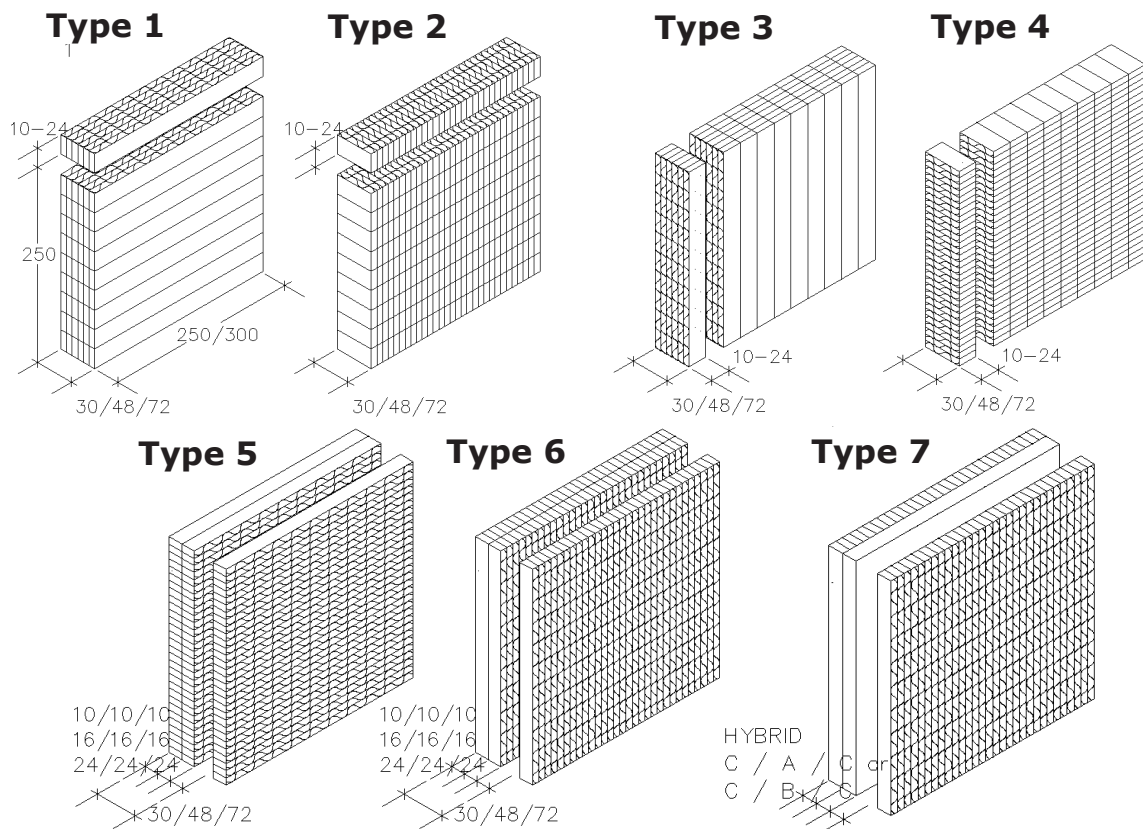


Figure 4.18 - Types of corrugation direction possible with corrugated cardboard cores (pursuant to impregnation manufacturing assumptions).

	<b>Type</b>						
	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>
<b>Form-active</b>	-	+	-	+	+	+	+
<b>Thermal</b>	++	-	++	+	-	-	+
<b>Easy</b>	-	--	-	--	+	+	+
<b>Impregnation</b>	-	-	-	-	+	+	+
<b>Structural</b>	+	-	+	-	++	++	+
<b>Humidity</b>	++	+	++	+	-	-	+
<b>Fire</b>	++	+	++	+	-	-	+
<b>Sound</b>	++	+	++	+	-	-	+

Figure 4.19 - Preliminary study on the characteristics affected by corrugation direction of corrugated cardboard paper with a honeycomb core.

\*(+) indicates a positive result, while (-) indicates a negative result.



of paper layers confronted from interior to exterior of the core is directly related to the thermal conductivity. Types 1 and 3 were selected on the basis of certain parameters such as the total number of paper layers in the direction of heat transfer or loss. The paper type used in liners and flutes, differing in density, provides another variable for this evaluation category.

**Category "Easy"** discusses the ease in manufacturing for the corrugated paper sheet samples according to the direction of layering. The number of cuts on the corrugated cardboard sheet required to reach the specified sample and the impregnation process were the primary evaluation criteria. The manufacturing process is complicated each time that a plain cardboard sheet needs to be cut, stacked and glued on top or next to another to form the desired sample type. During testing, Types 5 and 6 demonstrated the most advantageous properties with regard to ease of manufacturing particularly when the impregnation step was limited to 15 cm wall segment thickness.

**Category "Impregnation"** describes the level of complexity required for impregnating the cardboard core layers based on the direction of layering. Preliminary testing of the process on 5 cm thick samples were used as a guide. Other parameters included the complexity of impregnating large panels, the decrease in the adhesiveness quality after impregnation<sup>1</sup>, and the number of joints needed to form the stacks. The corrugation direction in Types 5 and 6 proved to be the most advantageous in this category.

**Category "Structural"** refers to the structural load-bearing capabilities of sandwich panel composite. Evaluations were based on the test results of the collaborative research set forth in A. Pohl's dissertation, "Strengthening the Corrugated Paper Honeycomb Core for Applications in Structural Elements."

**Category "Humidity"** examines humidity resistance based on the direction of layering. The primary testing parameter was the speed of moisture transfer from the interior to the exterior facade. Corrugation direction that was perpendicular to the facing, with open flutes from interior to exterior, was most negatively by the moisture and allowed a faster rate of transfer for humidity. In this category, Types 5 and 6 demonstrated the lowest resistance to humidity and moisture.

**Category "Fire"** refers to the behavior of the samples when exposed to fire combustion. The evaluation criteria for this category examined how fast fire spreads from the exterior to the interior of the wall element. The number of paper layers confronted in the cross section of the element affects the speed of the spread. Impregnated corrugated cardboard core tested in fire class Gq3 (quasi non-combustible), according to Swiss safety standards. Types 1 and 3 demonstrated the highest level of resistance to combustibility during testing.

<sup>1</sup> The hypothesis is that the material's adhesiveness is negatively affected by the impregnation process for the 10 cm thick sample.

**Category "Sound"** refers to the behavior of the wall element's acoustic control qualities. Corrugated cardboard block is composed of several corrugation flutes to form a cellular structure when stacked. This allows the material to bear acoustic control mechanisms, depending on the wall mass and resonance frequencies; corrugation direction, total thickness, tightness of the panel, and the facing properties.

The main criteria tested in this category was the number and direction of air-filled flutes that controls sound between two adjacent spaces. The wall types where corrugation perpendicular to the facing are predicted to perform poorly in the sound insulation category. Additionally the directional possibility in filling the corrugation cavities with sound-absorbing fill-in materials was taken as a criteria which enhances the acoustical quality together with the sound insulation function.

### **2.3.2 Facing Sheets for the Cardboard Composite Wall Component**

Sandwich composite wall elements, as a case study for the structural application of corrugated cardboard honeycomb, consist of two facing sheet skins, which are selected according to the intended function of the wall element and the core. The two skins will be placed on each side of the corrugated cardboard paper honeycomb core (impregnated or unimpregnated), and function as a protective closure layer for the core.

Commonly used facings for insulated sandwich panels are OSB panels, plywood, Heraklit, pressure-treated plywood, stainless steel, aluminum, cementitious-fiber panels and fiber-reinforced plastic. In this architectonic research study, Fermacell (gypsum board), glass fiber-reinforced plastic, plywood and steel are analyzed and tested as the primary facing options for the corrugated cardboard composite walls.

Structural strength, stability and stiffness are requirements of the cardboard composite wall component. Additionally, the wall must exhibit characteristics that mitigate the effects of weathering, limit its degree of combustibility, and increase its thermal and acoustic insulation measures. Apart from threats such as local stress, exposure to water and the function of the wall (facade, interior wall, load-bearing wall, dividing wall) defines the performance criteria for the facing material, classified by material, geometry, thickness and configuration.

Unavoidable irregularities due to imperfections in facing material demand a higher degree of care in securing the air-tightness of the cardboard core material, especially with molded thermo-set facing materials, used on form-active sandwich wall types. Another potential issue is the connections of the facings. The danger lies where the corresponding eccentricity moments are not counteracted by other constructive means, and the wall becomes subject to long-term bending moments in addition to long-term compression. The two facings are connected to the core by either customized adhesive for the interface of both materials or by connectors (with or without connection to the core) to provide the requisite structural integrity.

In the case of adhesive application, it is essential to take advantage of the strength of the two skins, and to prevent individual skin buckling. With shear connectors, full shear transfer between the two skins must be applied pursuant to the sandwich theory. In order to maintain the insulated rating and to prevent a thermal short-circuit, non-metallic tie connectors, such as fiber-composite ties, must be used.

The characteristics of the facings used in this architectonic study of cardboard core sandwich components are discussed briefly below:

**Wood Byproduct Facings:** Wood byproducts such as plywood and pressed hardboard have a relatively low cost, low structural strength, heavy weight, high degree of flammability, and a high rate of moisture absorption. When used as an exterior wall, wood-based facings are vulnerable to exposure to weather conditions, such as UV rays, wind, rain, humidity. Other potential issues associated with wood byproducts are its hygroscopicity and susceptibility to damage when exposed to moisture.<sup>1</sup> Moreover, in extreme summer and winter weather conditions, the exterior wooden facing can suffer serious damage. Specialized chemicals or coatings are often used for protection of wood-based exterior facings.

**Metal facings:** Metal composite facings are typically durable, structurally strong, recyclable, and require a low level of maintenance. Their use often decreases the need for washing or toxic chemical cleanings.<sup>2</sup> Aluminum and steel are the most widely used metals for structural panels in the industry. Copper cladding, fire retardant paints, plasters and drywall can also be used in this capacity (Figure 4.20).

Aluminum and metal alloys have a high rigidity to weight ratio, as well as high degree of stiffness and core shear. These materials are also non-combustible, corrosion free when treated, simple to fabricate, and have a high heat contribution and conduction. Steel facings with carbon, on the other hand, are low cost, highly stiff, heavy, but extremely prone to corrosion. Stainless steel facings, in contrast, have a high structural strength and rigidity, are self-cleaning, durable, and can often be used with cementitious materials. Finally, titanium facings offer a strong yet light option as facing, but it is a relatively expensive material that is known for its inability to bond with other materials.

**Fiber-Reinforced Plastic Facings:** Fiber-reinforced plastic facing, E-glass fiber facing, carbon fiber-reinforced plastics, and S-2 glass fiber facings are all corrosion resistant facing materials. They are also transparent and have a low specific gravity. The unidirectional facings in this group have a high puncture resistance, high specific strengths in specific directions and strong abrasion resistance. The woven options are simple to form and cut, resistant to lamination, and possess strong bi-directional properties. E-glass, a moderately priced option,

<sup>1</sup> Simon Aicher and Lilian Höfflin, "Long-Term Performance Test of Eccentrically Loaded Sandwich Wall Elements with Wood-Based Skins," *Otto-Graf-Journal* 10 (1999): 129-143.

<sup>2</sup> Nadel.

has strong mechanical properties and resistance to moisture and chemical heat. S-2 glass, a slightly higher priced option, possesses high tensile strength and notable puncture resistance. Carbon fiber-reinforced plastics are extremely lightweight and stiff and have excellent fatigue strength and wear resistance. It also has a low density and thermal expansion, but performs poorly on impact strength tests.<sup>1</sup>

**Gypsum Board and Cementitious Fiber Facings:** Cementitious products such as cement board (consisting of glass and cement fibers), fiber cement (consisting of sand, cement and cellulose fibers), and gypsum board are extensively used in construction for dry wall, interior finishing, kitchen counters and exterior wall surfaces. Their impact resistance and strength, passive fire protection, and low cost have led to its increased popularity.

New products continue to be developed in this field. Reinforced concrete composite sandwich systems, consisting of two layers of reinforced or pre-stressed concrete and an insulating core, combine lateral, gravity and in-plane loads.<sup>2,3</sup> This particular application, with a thick layer of concrete, is not suitable for cardboard buildings within this architectonic research, as it would result in a drastic increase in weight and lead to additional manufacturing, transportation and onsite assembly costs and problems.

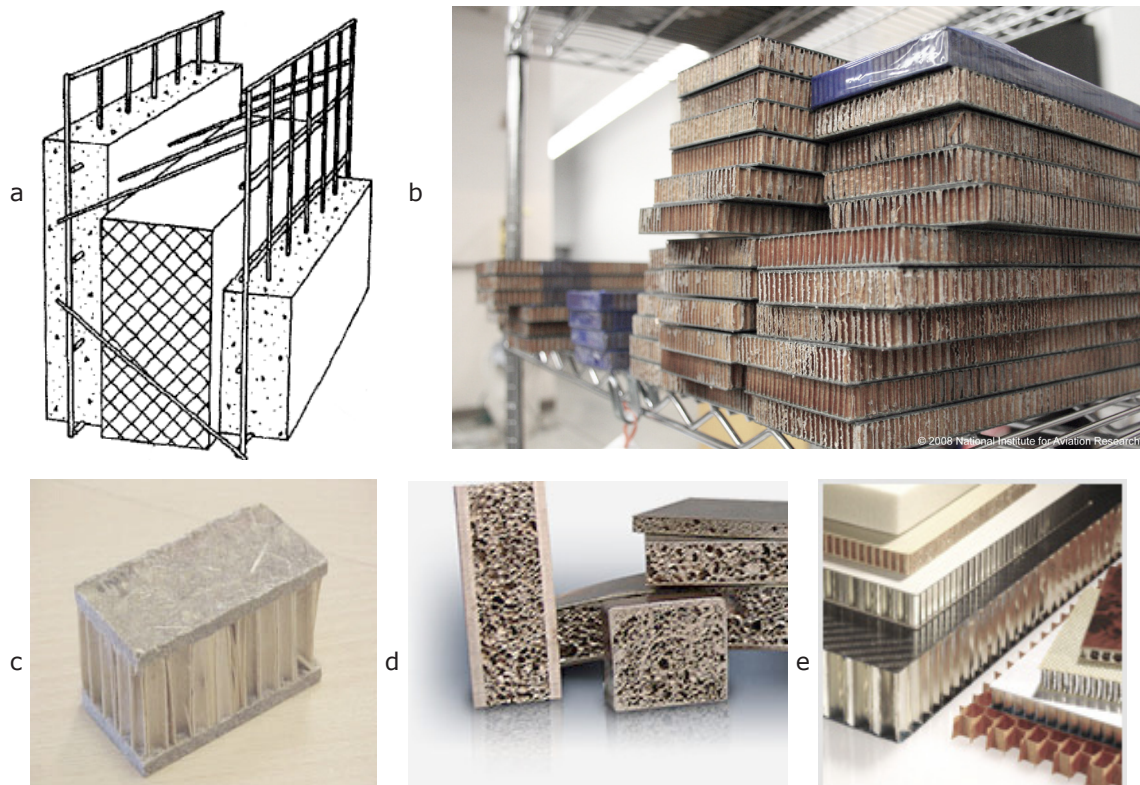


Figure 4.20 - Facing examples for sandwich composites.<sup>4</sup>

<sup>1</sup> Engin M. Reisa and Sami H. Rizkallab, "Material Characteristics of 3-D FRP Sandwich Panels," *Construction and Building Materials* 22, no. 6 (Jun. 2008): 1009-1018.

<sup>2</sup> Max Porter, *Full-Scale Composite Sandwich Walls: Theory and Behavior* (National Science Foundation, 1993).

<sup>3</sup> Vesa Karhu, "Product Model Based Design of Precast Facades," *Journal of Information Technology in Construction* 2 (Apr. 1997) 1-31 (noting that stainless steel fasteners allow for thermal expansion and eliminate the need for penetration through the sheets thus ensuring a watertight system).

<sup>4</sup> (a) concrete facing sandwich composite; (b) steel facing, honeycomb-core structural sandwich composite; (c)

### 2.3.3 Connectors, Adhesives and Joints for the Cardboard Composite Wall Component

The integral performance of the sandwich panels depends not only on the mechanical behaviors of the cardboard core and the facing but also on the adhesion between the cardboard core and the facing skin, as well as the location, dimensions, geometry and material type of the joints to the adjacent building components.

#### 2.3.3.1 Adhesives

Epoxy and urethane are widely used adhesives for sandwich panels. Modified epoxy is relatively low cost and a variety of formulations are available for different end uses. High temperature epoxy produces durable bonds to 175° Celsius. Urethane is low cost, and can be used with continuous surface materials, however, it has a low water resistance and several environmental drawbacks.

Functionally, there are two positions on the corrugated cardboard paper honeycomb paper composite sandwich panels in which an adhesive is needed. The first location is for attaching corrugated cardboard layers into a honeycomb block. Several of these adhesives have been extensively tested and developed by the packaging industry to reach acceptable levels of durability, safety, toxicity and thermal-moisture control. The industry generally uses starch or PVA-type adhesives. These adhesives also play a minor role in moisture resistance improvement. However, one drawback of this type of adhesive is that it reduces the recyclability of the product.

The second position which the adhesive is applied is for attaching the cardboard core to both of the facing skins and the frame component. Further research and development is needed to determine which skin and core type (impregnated or unimpregnated) would best fit for optimal performance.

**The Manufacturing Process:** An automated process for the adhesion of the facing and the core could potentially be developed for cost reduction, quality, and performance purposes. In 2008, an automated adhesive spreading machine that is able to apply a precise thickness of adhesive layer on cardboard sheets was developed by Tom Pawlofsky at ETH Zurich.

**Sealant between panels:** The sealant between the two adjacent panels in cardboard buildings will require customized properties for the function and position on the component. In areas where humidity is high or where there is a high likelihood of air or humidity flow at the point of the seal, moisture damage to the panel may result. Panels can be manufactured to include the sealant channels (keyways) to expedite efficient application of the sealant.

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natural fiber structural sandwich; (d) aluminum composite sandwich consisting of aluminum foam matrix, compressed between two metal cladding layers; (e) skins of woven glass fiber-impregnated with epoxy resin and a lightweight aluminum honeycomb-core (Cellite 620 Fiber).

### **2.3.3.2 Joints: A Conceptual Approach for Cardboard Composite Wall Components**

Properly detailed joints are critical to ensuring both safety and effectiveness in prefabricated structures. Efficiency of the corrugated paper honeycomb core composite wall component is significantly affected by the characteristics of the joint material both within the composite panel and between the adjacent panels that form the wall component.

Based on the slender and orthotropic sectional structure, the connections merit particular consideration from two points of view, namely the connections of the building units and the introduction of local loads. The extraordinarily filigreed sectional parts require an even and planar distributed load transfer at the joints of the building elements. The second aspect, the local load introduction, concerns the concentrated stress in the transverse direction of the building unit. The original undulation crushes and folds at relatively low stress levels and therefore only allows for loads distributed over correspondingly large areas.

The CATSE collaborative study lacked the the ability to conduct quantitative or qualitative experimentation and analyses of joint design and behavior under loading. Thus, current building codes will be used as a guideline for the conceptual approach of the role of joints in the fabrication and erection processes of cardboard buildings.

#### ***Prefabrication in the Joint Configuration Process***

Joints are invariably locations of stress concentration. Tolerance calculation errors can cause variations in the location and distribution of the forces acting on the connection. The offsite prefabrication process can help increase quality by providing a controlled environment. Accordingly, today less joints are assembled onsite due to the improved quality of factory conditions, which often reduces the complexity of the process (Figure 4.21).

The dimension of the panels also impacts the joint design. If the width-to-height ratio varies between the facade panels, or if the wall contains openings for windows, corridors, or doorways, then a more sophisticated approach is required to make accurate assessments about the stresses and deflections, particularly near structural discontinuities.<sup>1</sup> To define the required capacity or cross-section of the joint, the design procedure requires: (a) determination of the forces at joints considering appropriate loading condition (an analysis including the effects of creeping, shrinkage, temperature, and settlement); (b) identification of the proportions of the members; (c) computation of the forces on the model; and (d) comparison of the compressive shear stress test results with the permissible values.<sup>2</sup>

Honeycomb core composite wall panels will be prefabricated and pre-assembled offsite due to the vulnerability of the cardboard material to external conditions. Prior applications have used customized joint elements to be applied onsite and developed with conventional fixings.

<sup>1</sup> B.S. Smith and A. Coull, "Elastic Analysis of Tall Concrete Buildings," Proceedings of the International Conference on Planning and Design of Tall Buildings, Bethlehem, PA (1972) 159.

<sup>2</sup> J.O. Jirsa, "Cast-in-Place Joints for Tall Concrete Buildings," Proceedings of the International Conference on Planning and Design of Tall Buildings, Bethlehem, PA (1972) 195.



**Panel Closure Joints:** A timber edge can be applied to the corrugated paper honeycomb core composite panels, and incorporated into the adjacent component using conventional joint methods to ensure airtightness. The timber edges improve the structural performance of the panels by acting as a simple frame, while the panels act as the skin, stiffening the structure.<sup>1</sup>

### Typology of Joints

The three principal considerations for the design of joints are: 1) identifying the loads and actions to be resisted; 2) ensuring the structural function of the joint, and 3) clarifying the fabrication and erection process. The joint types, categorized in terms of their flexibility, function and location are set forth below:<sup>2</sup>

1) *Flexibility:* Joints and connections are divided into hard and soft connections. For hard connections, movements and rotations within the connection are limited. These are generally used in rigid frame applications (i.e. beam to column) to resist lateral forces. Soft connections permit a limited amount of movement in the connection.<sup>3</sup> Hard and soft joints shall be integrated to meet the functional demands of the components in cardboard buildings.

#### 2) Location Classifications

i. *Gravity joints:* These joints are positioned where lateral forces are resisted by the friction at the bearing surface. As joint details between floor and wall panels, these are critical in cardboard buildings, and may have a major impact on the structural behavior of the cardboard building system as a whole, and may even constrain the dimensioning of the structure.<sup>4</sup>

ii. *Vertical Joints:* These joints connect adjacent composite wall panels. They will be developed to be capable of transferring stresses by the shear-induced lateral loads as well as by non-uniform loads on adjacent panels.<sup>5</sup>

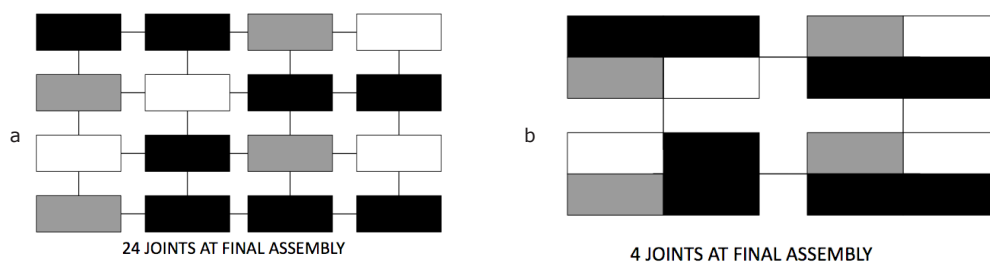


Figure 4.21 - Reduction of joints onsite: (a) Past applications: many joints on site (b) Today: less joints onsite<sup>6</sup>

<sup>1</sup> A. Cripps, «Cardboard as a construction material: a case study», *Building Research & Information*, Volume 32, Issue 3 May 2004, 207 - 219

<sup>2</sup> H. Hilsdorf, «Masonry Materials and Their Physical Properties,» Proceedings from the International Conference on Planning and Design of Tall Buildings, Bethlehem, PA (1972) 981-982.

<sup>3</sup> B. Lewicki and A. Pauw, «Joints, Precast Panel Buildings» Proceedings from the International Conference on Planning and Design of Tall Buildings, Bethlehem, PA (1972) 172.

<sup>4</sup> Lewicki and Pauw 173.

<sup>5</sup> Smith and Coull 172.

<sup>6</sup> Timberlake and Kieran 94.

### 3) Function Classifications

Joints for the composite building components such as curtain walls, interior walls, exterior load-bearing walls, roofs, and floor slabs play a major role in the load carrying and distribution activity of the cardboard composite structure. However, other specialized functional joints such as building expansion joints, control joints and isolation joints (joints at structural members to allow movement without stress in the wall) may also be needed. These joints would require careful detailing, specification and installation.<sup>1</sup>

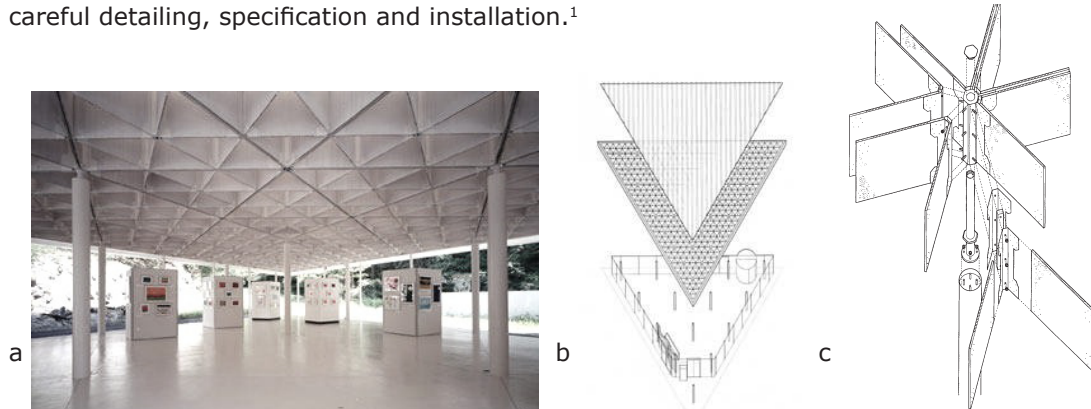


Figure 4.22 - Cardboard panels jointing examples (a), (b) and (c) Nemunoki Art Museum Project details, by Shigeru Ban <sup>2</sup>

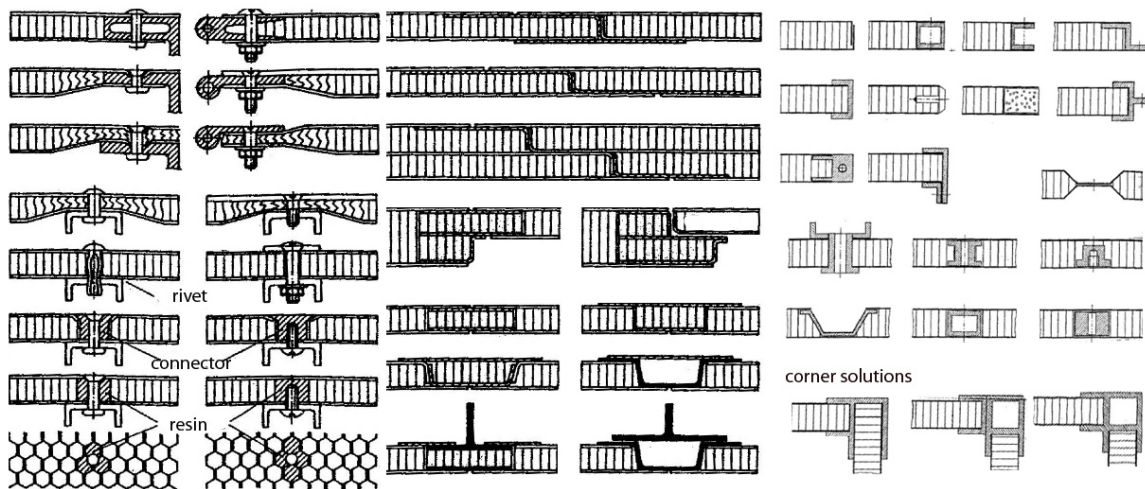


Figure 4.23 - Commonly used joints for structural or division wall panels.<sup>3</sup>

## 2.4 Case Study: Structural Performance of CATSE Cardboard Sandwich Wall Components

The engineering performance of the material properties and behavior of cardboard core sandwich panels was examined within the technical framework of the CATSE collaborative project. Corrugated paper honeycomb core samples were tested to analyze the mechanical properties and behavior, followed by longitudinal compression (compressive strength, stability), and shear test series on cardboard sandwich component samples with facings. The

<sup>1</sup> Louis G. Redstone, *Masonry in Architecture* (New York: McGraw- Hill, 1984) 161.

<sup>2</sup> In Shigeru Ban's Nemunoki Art Museum Project, honeycomb panels were used for the load-bearing rib structure on the roof. 100 cm x 60 cm panels were joined with pre-formed aluminum sheets into a triangular structure, and set on steel columns at six meter intervals. The sheets act like bolted clamps with honeycomb panels set in between.

<sup>3</sup> Nida Core Structural Honeycomb Materials, International Brochure, <http://nida-core.com>, 2009

parameters that impacted the failure mechanisms for applications in structural wall elements were identified. The results of these tests guided this architectonic conceptual research. Results are classified by component and composite level. Each test examined the mechanical behaviour and impregnation process against humidity control and fire protection.

### ***i) Building Component Level***

Testing demonstrated that the most effective implementation method was the use of structural corrugated paper honeycomb in the form of composite sandwich elements. This form mitigated the various threats and increased conventional jointing possibilities between components.

The mechanical behavior of corrugated paper honeycomb core sandwich composites follows the basic sandwich structure principle. The honeycomb core takes on the shear forces (supporting the skins to avoid them from buckling), while the facing takes on the bending forces. The core, experiencing the shear forces, as well as some degree of vertical tension and compression, determines the stiffness of the panel based on its material properties and thickness (Figure 4.24). A tighter bond-interface of the connection, and a stiffer core layer, reduces the tendency for buckling under bending pressure. For this reason, the load-bearing capacity of a cardboard sandwich panel will be increased when the rigidity of the honeycomb core increases.<sup>1</sup> Facing sheets will be selected according to the intended function of the wall component (i.e. interior, exterior, load-bearing, dividing or curtain walls). The joints will be developed based on the standards of the insulated sandwich wall system industry, and thus effortlessly incorporated with the conventional joining methods.

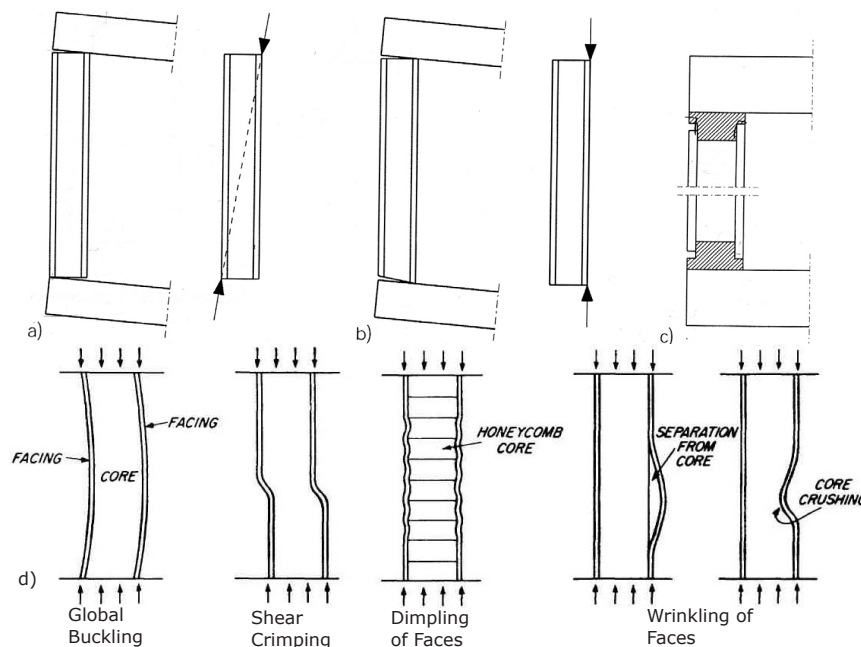


Figure 4.24 - (a) and (b) Eccentric load stress on the sandwich wall component; (c) suggestion for the framing of the sandwich wall to bear the loads adequately<sup>1,2</sup> (d) Possible modes of failure of sandwich composite under edgewise loads<sup>3</sup>

<sup>1</sup> Koschade 29.

<sup>2</sup> «Composite section of load-bearing wall components, made out of wood-based materials», Final Report, prepared by Fraunhofer-Institute for Wood Research - Wilhelm-Klaudt Institute and Technical University of Braunschweig. Available only in original language, German, "Verbundquerschnitte aus Holzwerkstoffen für lastabtragende Wände", 2005

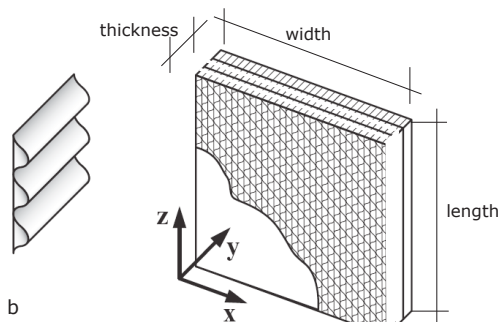
<sup>3</sup> Structural Sandwich Composites, Standardization Handbook, Department of Defense, USA, 1968, 30

### ii) Composite Level

The experiments and modeling analysis demonstrated that the paper type and weight, type, height and corrugation direction of flutes, as well as the adhesive are the primary factors that affect the wall's mechanical behavior. They are also affected by:

- core thickness
- direction of corrugation
- paper type
- corrugation type
- facing material type
- facing thickness characteristics

a



b

Figure 4.25 - (a) Factors affecting the performance of the composite (b) illustration of the specimen indicating corrugation direction choice for optimum performance.

In particular, these characteristics have an essential impact on the manufacturing process of the cardboard core block. The impregnation on the cardboard core block is also accordingly affected by the choice of these factors. Additionally, the end material behaviour of the composite is highly defined the jointing behavior between the cardboard core and the facing. The optimum performance in mechanical behaviour is demonstrated by corrugation direction of honeycomb core; corrugation axis perpendicular to the facing corrugation. (Figure 4.25)

The test results indicate that depending on the thickness and material type of the facing sheets, a load-bearing sandwich wall with impregnated honeycomb core must have a thickness of at least 200 mm to withstand the required design loads of a two-story office building.

### iii) Compression Test Results

Sandwich struts with corrugated paper honeycomb core thicknesses of 52 mm and 17 mm, and steel facings with thicknesses of 0.5 mm, 1.0 mm, 1.5 mm and respective lengths of 750 mm, 1350 mm, width 100 mm were tested<sup>1</sup>. The specimen with 52 mm core thickness and 1.5 mm steel facing thickness (length 750 mm, width 100 mm) was able to sustain an axial load of 66 kN; indicating an optimum performance according to the direction of corrugation. (Figure 4.25) The failures occurred on sandwich struts when loaded in compression are observed as face yielding, face wrinkling, face dimpling, global buckling and core shear failure.

### iv) Shear Test Results

Sandwich struts with core height of 32 mm and 17 mm were both experimentally and analytically tested, showing a relatively high shear stiffness compared to many sandwich materials. These samples provided for the unimpregnated sandwich composite the shear modulus  $\approx 100$  MPa, shear strength  $\tau_{max} = 0.85$  MPa.

<sup>1</sup> Tests were carried out by the collaborative engineering team, IBK ETH Zurich, on universal testing machine: Schenck 480 kN, testing speed 0.2 mm/min

Additionally 17 mm high cement-impregnated specimens were also tested on a shear area of 50 mm wide and 210 mm long. These impregnated specimen provided around 50% increase in shear strength, compared to the unimpregnated specimen in experimental tests.

#### **v) Improvements Against Moisture-Humidity Penetration**

Moisture ingress was studied through several compression test series on the paper honeycomb cardboard core samples in order to observe the loss of structural strength and stability in normal (20°C, 65% Relative Humidity) and humid environments (20°C, 95% Relative Humidity). Test results showed that the compressive strength in humid environments drops to down to %25, compared to in dry environments and doesn't offer any resistance to compressive loads when wet.

Tests guided two protective strategies on resistance improvement of cardboard against moisture: 1) impregnation of the cardboard core with a cementitious liquid and 2) structuring the cardboard core component as sandwich composite with a facing material. Impregnation on the cardboard core proved to be an effective tool for securing the material's structural strength and stability under humidity exposure.<sup>1</sup>

Resistance to combustibility was also accomplished with the impregnation method on the cardboard honeycomb core. The maximum comprehensive strength of an impregnated material, when wet is tested to be 1.24 MPa, around the same value of an unimpregnated material. On the other hand, thermal conductivity is observed around twice as high as that of an unimpregnated sample. Additionally, the results demonstrated high compressive strength values - up to 193% of the dry strength of the unimpregnated materia, and six times the strength retained by the unimpregnated material. The impregnation process, however, requires additional optimisation for thicker external walls and load-bearing interior walls with respect to thermal, fire safety and acoustic requirements. New methods of production are also required in the subsequent stages for walls with greater thicknesses, while samples with only 5 and 10 cm thicknesses of honeycomb core were able to be effectively impregnated in these tests.

#### **vi) Fire Resistance**

The combustibility problem facing cardboard was evaluated using the two different protective methods: 1) impregnation of the cardboard core with a cementitious liquid and 2) structuring the component as a sandwich composite with facing materials. The impregnated samples were tested by the *Institute of Safety and Security* in Bern. The testing indicated that the impregnated samples satisfied combustibility grade "6q3: quasi combustible".<sup>2</sup>

When the cardboard is arranged as a core in a sandwich composite, additional fire-proofing treatments can be applied to the facings, such as fire-retardant paint applications on steel

<sup>1</sup>Tests on impregnating the material were run with several materials such as a commercial textile waterproofing agent, aluminum acetate and a gypsum slurry of high water-gypsum ratio, next to the developed optimum cementitious slurry by the engineering team.

<sup>2</sup>Based on Swiss VKF standards by Association of Cantonal Fire Insurances; flammability test, combustibility test, smoke test and determination of the calorific value were used as methods.

sheets or airtight solutions. The safety factors related to the fire hazards posed by the emission of toxic gases, smoke and heat release level in case of fire in cardboard buildings are not addressed in this study.

#### **vii) Thermal Conductivity**

Tests were based on the comparison of impregnated and unimpregnated cardboard core specimen.<sup>1</sup> Two types of impregnated specimens were analyzed experimentally and analytically by the engineering team. As a result thermal conductivity of the cement-impregnated paper honeycomb core at room temperature is calculated as approximately 0.18 W/mK.<sup>2</sup> This showed that the thermal conductivity is increased to twice on tests with impregnated sample, compared to the unimpregnated samples.

### **3. Conclusion: Towards the Structural Conception of Cardboard**

This chapter aimed to provide a preliminary constructive approach for the structural application of corrugated cardboard. The structural conception of corrugated cardboard honeycomb as a wall component is a feasible method in today's construction sector. Its success in implementation is dependent on increased mass customization in prefabrication and pre-assembly options.

The focal points provide a set of tools and an approach based on the sociosphere of the construction industry for exploring the diverse perspectives of structural applications of cardboard. Utilizing these tools as the basis for development, the search for a workable massive structural system with cardboard-based components was analyzed. The first examination of the underlying principles and distinguishing characteristics of corrugated cardboard was explored for its potentials in prefabrication and the massive/solid construction of cardboard building systems, particularly in the context of housing. The comparative work with contemporary structural systems accompanied the main argument of the research, discussing the possibilities of corrugated cardboard honeycomb's structural application implementation in construction, and describing the strategies for design and the theoretical context of cardboard buildings on a larger scale.

The scarcity of information on the mechanical properties and behaviors of the corrugated paper honeycomb core for structural applications resulted in the need for experimental testing, which was conducted by the collaborative team. The experimental testing and analyses indicated that prefabricated cardboard honeycomb core sandwich composites were suitable for use as wall components in residential buildings. The chapter also looked at characteristics of certain materials within their role in the sandwich structure. The and drawbacks of building with cardboard in the sandwich panel industry are discussed in the context of the goal performance criteria.

<sup>1</sup> These tests were not conducted on sandwich struts.

<sup>2</sup> A. Pohl, 166.



The testing and modeling of sample results demonstrated excellent structural strength and stability. However, substantial loss in structural strength and stability of the honeycomb was observed when the cardboard was confronted with hazards such as humidity/moisture, weathering, fire, and local stresses.

In sum, corrugated paper cardboard honeycomb composite for use as both exterior and interior wall components exhibited promising physical and mechanical behaviors during experimental testing. Investigations with experimental testing also revealed the wall's extensive thermal insulation characteristics and their potential for overall energy and cost reduction. Furthermore, results showed that the impregnation of the material with an inorganic suspension secured the material against loss of strength and stiffness due to moisture.

### Further Steps

- *Development of full-scale wall components:* Further steps will include the construction of full-scale wall components structured as sandwich composite, testing the impregnated cardboard honeycomb core at several different wall thicknesses.

- *Examine long-term mechanical behavior:* To solve the practical problems of cardboard buildings related to the design, fabrication, construction, costs and use of the building, a ten

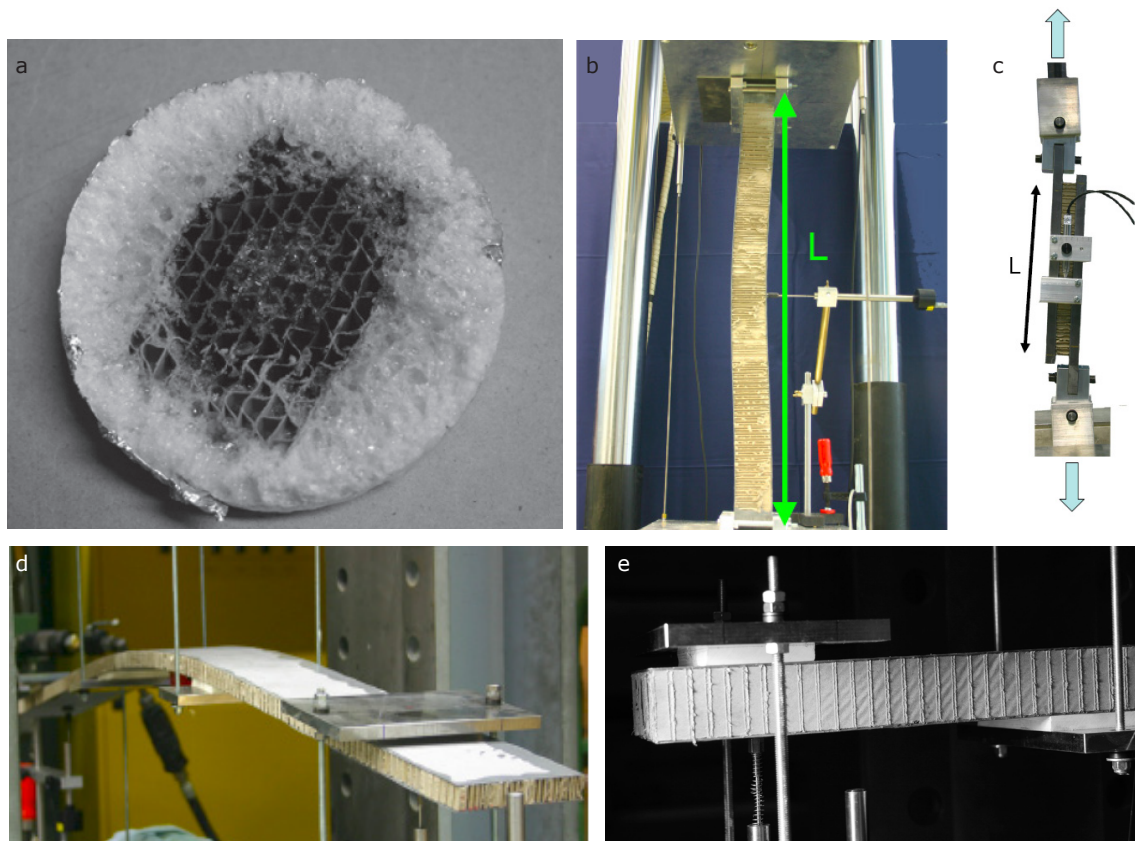


Figure 4.26 - Experiment photos on testing of cardboard composite sandwich panels.<sup>1</sup>

<sup>1</sup> Experimental testing of (a) moisture (b) compression:buckling (c)plate shear (d)(e) bending. Photo ©A.Pohl

to fifteen year lifespan is planned. Thus, long-term compression test results must be pursued to finalize the life-span characteristics of both impregnated cardboard core and unimpregnated core wall panels.- *Development of impregnation as an engineered process*: In particular, decreased complexity of the impregnation process, its effect on the mechanical and structural behavior of the composite panel, and further automation will be pursued.

- *Further development of joint mechanisms*: the joints between facings, cores, and adjacent panels, as well as connectors between other components must be investigated further

- *Investigation and integration of a full system in cardboard buildings*: The effect of other external loads (wind, earthquakes), buildings physics themes (sound control, vibration), and service systems and equipment ( sanitary modules, HVAC, electrical, lighting, communication, water sewage) require additional studies. The impact of secondary concerns like insect-vermin infestation and burglary, as well as long-term effects on the cardboard component also require additional examination.

## Chapter V

### Architectonic Approach: Outcomes A Conception of Cardboard Buildings

"A dream with courage is innovation,  
A dream without courage is a delusion."

Anonymous

#### 1. Introduction: System Thinking for Cardboard Buildings

In connection with the existing political, economic, and social climate, construction systems have evolved to form architectural space by utilizing new building materials and innovative techniques. The linguistic and technical expressions of a building and its constructed form are used to position the new input, which are then examined within its context, purpose and use. A systematic approach is employed to ensure a quick, efficient and economical process during the erection, modification and dismantling of a building.<sup>1</sup>

The functional efficiency of the relationship between the architectural form and structure relies on the structural construction concept defined by strength, safety and cost effectiveness criteria. A building's load capacity is a function of the size of the building, the structural system, as well as the materials used and the type of members joined at the connections.

In this study, after a preliminary examination of corrugated cardboard as a building material, architectonic boundaries regarding cardboard building's design and planning criteria were investigated. Then, a massive construction system was selected for cardboard buildings for the initial implementation. Multifunctional cardboard composite wall components were found to be ideal for rapid erection with unskilled labor and ease in prefabrication. Additionally, corrugated cardboard components within a massive structure will allow a complete structural framework that is capable of supporting necessary loads. A complete definition of architectural space, expression and atmosphere using CAM/CAD automated production techniques<sup>2</sup> is detailed.

<sup>1</sup> Gerald Staib, Andreas Dörrhöfer and Markus Rosenthal, *Components and Systems: Modular Construction-Design, Structure, New Technologies* (Germany: Birkhäuser, 2008).

<sup>2</sup> These techniques are mainly used during the processes of cutting, folding and gluing the materials.

From the onset, a low cost, environmentally low impact, mostly pre-assembled product is planned to be developed and produced on a large scale. Massive cardboard honeycomb composite wall components are multifunctional, and can be simultaneously used for cladding, space-enclosing and load-bearing functions.

In functional terms, cardboard core composite panels will be used as a superstructure and an exterior skin. However, the material does not allow it to be used in interior rough work, interior finish work, or in the substructure as a foundation. Stability is achieved through the friction resistance in the joints, giving a significant role to the joints between cardboard wall members while the solid cardboard wall acts as a plate.

The overall efficiency of the cardboard building system will rely on several tools of analysis, design and planning criteria and the characteristics of cardboard composite walls. Among these, a structural analysis serves as the primary platform to experiment the viability of cardboard buildings as well as their architectural qualities. Using the building analysis design and planning criteria proposed by M.Y.H. Bangash, the basic structural analysis of cardboard buildings is categorized into the following:<sup>1</sup>

- a) system choice - frame/planar/hybrid structures;*
- b) loads on buildings - dead-live-temperature and construction load survey;*
- c) accidental loading analysis - loads and responses, blasts, frequency of occurrence, and damage analysis;*
- d) risk-based design and performance criteria for a thorough analysis of the building frame, using stiffness, flexibility and finite element methods, and plastic analysis for the overload behavior;*
- e) stability of individual members, stability of three dimensional structures, stability under dynamic and repeated loads;*
- f) fatigue and fracture analysis for specific and vital components, and the behavior of connections and joints;*
- g) earthquake loading response - ground motion, soil structure, interaction effects, structural behavior, comparative study with relevant codes, damage evaluation;*
- h) wind loading and wind effects/dynamics - response analysis, compliance with codes, torsion analysis;*
- i) fires and fire load analysis - fire load on structure, response analysis, analysis of structural safety and structural behavior;*
- j) structural safety and probabilistic failure models analyses;*
- k) design of shear walls, design of openings and exterior cladding with cardboard components and substructure.*

<sup>1</sup> M.Y.H. Bangash, *Prototype Building Structures: Analysis and Design* (Thomas Telford Publishing, 1999) 47.

In this chapter, a preliminary architectonic approach is discussed for the main structural decisions relevant to cardboard buildings. For the categorization of wall components with specialized qualities, a structural hierarchy between cardboard wall and floor slab components, an interrelating analysis regarding jointing directions, a typological classification of massive construction discussing cardboard box systems, planar wall systems, and facade and interior wall components are used as tools in the rematerialization case study.

Architectural qualities of cardboard buildings in design will also be discussed within the following themes:

- *Structural strength and stiffness vs. Architectural space*
- *Structural massiveness vs. Architectural expression and plasticity*
- *Mass customization and production vs. Acoustical and atmosphere control*
- *Modularity vs. Effective cardboard panel dimensioning*
- *Architectonic expression and visual concept vs. Texturing and bonding patterns with corrugated cardboard*
- *Reduction of skin layers and complexity*

## **2. Architectonic Qualities of Cardboard Buildings**

A full examination of the structural, functional and architectural qualities of space derived from modern demands serve as the fundamentals for the conceptualization of a new product. Based on Buckminster Fuller's performance criteria for maximum efficiency (Figure 5.1), cardboard buildings are best communicated through a description of what they offer. The distinctive architectonic qualities and benefits of cardboard wall components and the affiliated massive cardboard building system are described below, focusing primarily on their space defining and ease in construction process function.

### **2.1 Structural Strength and Stiffness**

The critical point for implementation of corrugated cardboard in construction is formed around the question of its structural strength, stability and stiffness as a viable and distinctive building material. Within this study, structural limits are sought by the collaborative technical study, focusing on experimental testing and modeling of corrugated cardboard honeycomb core samples that exhibit excellent structural strength and stability.<sup>1</sup> According to the test results, prefabricated cardboard core sandwich composites were found to be suitable for use as wall components. Promising physical and mechanical behavior were observed when cardboard is used as both exterior and interior wall components. Furthermore, results showed that the impregnation of the material with an inorganic suspension secures the material against loss of strength and stiffness from moisture.

<sup>1</sup> Almut Pohl, "Strengthening Corrugated Paper Honeycomb Core for Application in Structural Elements," PhD diss., ETH Zurich, 2009.

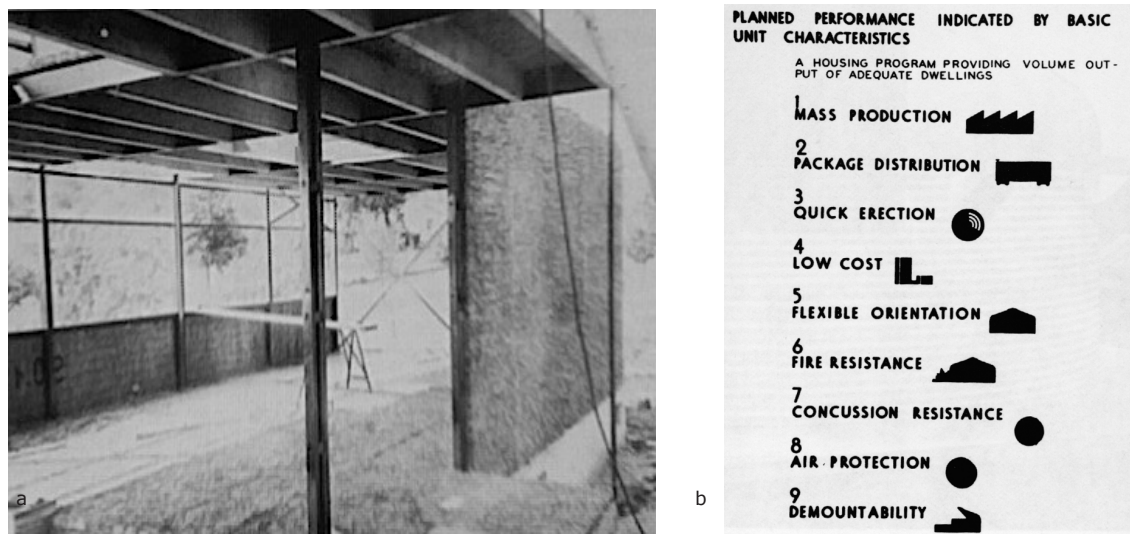


Figure 5.1 - Examples of conceptual approach in new techniques in architecture: (a) *Villa Ruf*<sup>1</sup>; (b) Buckminster Fuller's planned performance indicated by basic unit characteristics developed for new houses.

## 2.2 Structural Massiveness and Related Architectural Expression

*Massiveness* with corrugated cardboard blocks are produced by corrugated cardboard layers stacked on top of or adjacent to each other in a certain corrugation direction. Other conventional building materials produce massive structures through complex manufacturing and onsite, labor-intensive procedures, mostly resulting in costly and high weight solutions, especially in Switzerland where labor is expensive. Corrugated cardboard blocks with structural and also visual massiveness can generate load-bearing or non-load bearing components, according to their specific function, categorized with qualities such as "low weight massiveness," "plasticity in massiveness," and "light transmitting massiveness."

**a) Lightweight massiveness:** Several replacement options are being tested for the conventional heavy masonry structures with a lightweight contemporary monolithic wall system. Corrugated cardboard honeycomb composites forming a sandwich panel can be a sufficient answer to this search in building applications. Currently a common structural application field for honeycomb cardboard sandwich composites are use in aircraft applications, where weight is critical. The benefits of using massive cardboard composites are as follows:

i) *Construction as a process:* Traditional systems require skilled onsite labor. Lightweight cardboard composite panels will be an advantage in this aspect as a replacement system that strives to be quicker, less expensive to install, and less dependent on onsite skilled labor.

ii) *Function vs. Weight:* In conventional masonry, an overweight and disproportionate weight distribution for the system is necessary. External walling systems require durability and substantial load-bearing capacity.

<sup>1</sup> *Villa Ruf*, by E. Wanner, Le Corbusier and F. Quetant (1928) - Cardboard used as filling material in wood post construction.





Figure 5.2 - Cardboard structural strength and stiffness in bridge constructions.<sup>1</sup>

Lightweight and load bearing corrugated cardboard composites provide significant advantages, particularly in the reduction of the load placed on foundations enabling removable or lighter foundations. Being more than twenty percent lighter than traditional masonry, precast stone concrete is a feasible alternative in this area of the construction sector.<sup>2</sup>

iii) *Cost*: Transportation and overall onsite labor costs are reduced by using a lightweight prefabricated system. Offsite construction with lightweight cardboard wall and floor panels offer a more efficient onsite installation process.

iv) *Resistance*: Depending on the facing material, lightweight corrugated cardboard honeycomb sandwich wall systems can be highly resistant to weathering and external local stress impacts. They are also thermally and acoustically efficient and suitable for applications in different finishes in contrast to other lightweight massive wall systems.

**b) Plasticity via Massiveness:** Plasticity via massiveness is generated with corrugated cardboard blocks in two design directions; in structural massiveness and visual massiveness (Figures 5.3 and 5.4).



Figure 5.3 - Examples of massive plasticity using corrugated cardboard<sup>3</sup>

<sup>1</sup> (a) *Cardboard Bridge Project*, by International Paper Inc. (carried 5-ton truck); (b) *School Project Cardboard Bridge*; (c) *Paper Tube Bridge*, by Shigeru Ban (France, 2007)

<sup>2</sup> Dietz 16.

<sup>3</sup> Contemporary Experimental Cardboard Projects: (a) Ronchamp Chapel and Le Corbusier; (b) *SBB Building*, by Herzog & De Meuron; (c) *Peter Zumthor Bruder Klaus Chapel*; (d) *Inhabitable Cardboard Rooms*, by Esa Ruskeepää, Martti Kalliala and Martin Lukasczyk

i) *Structural Massiveness*: Building materials such as concrete, stone or brick masonry are stacked form the structure and the massive architectural expression. Minimal or no openings are allowed structurally to ensure the stability of the system.

ii) *Visual massiveness*: Monumentalism via plasticity has become a distinctive tool of a certain architectural language in the last decades. Several contemporary architects including Zaha Hadid and Herzog & de Meuron have used high strength precast concrete façade elements to achieve plasticity in their projects. However, precast beton façade elements or concrete panels are economically unfeasible, considering the production costs of amorph components, traditional gravity and component load problems that are exposed on the system. Due to these costs, construction inefficiencies, weight and detailing disadvantages, cladding such as stone, bricks, sheets of metal as façade elements are becoming increasingly popular in modern construction. The massiveness excludes structural function, and promotes only visual appeal and construction efficiency.

Construction efficiency is negatively affected by the long and expensive process of production of form-active (amorph, organic formed) panels used because of their massiveness qualities. Although digital production makes the design and planing stage easier, it still requires complex manufacturing mechanisms. The construction procedure for an organically formed concrete panel provides a helpful example. First, a special steel mold is carefully engineered to the required profile and dimensions. Then, steel rods are by hand-laid for each amorph-form panel. Finally, production begins by pouring the beton into the form. Production time here is substantial, the costs of reproduction

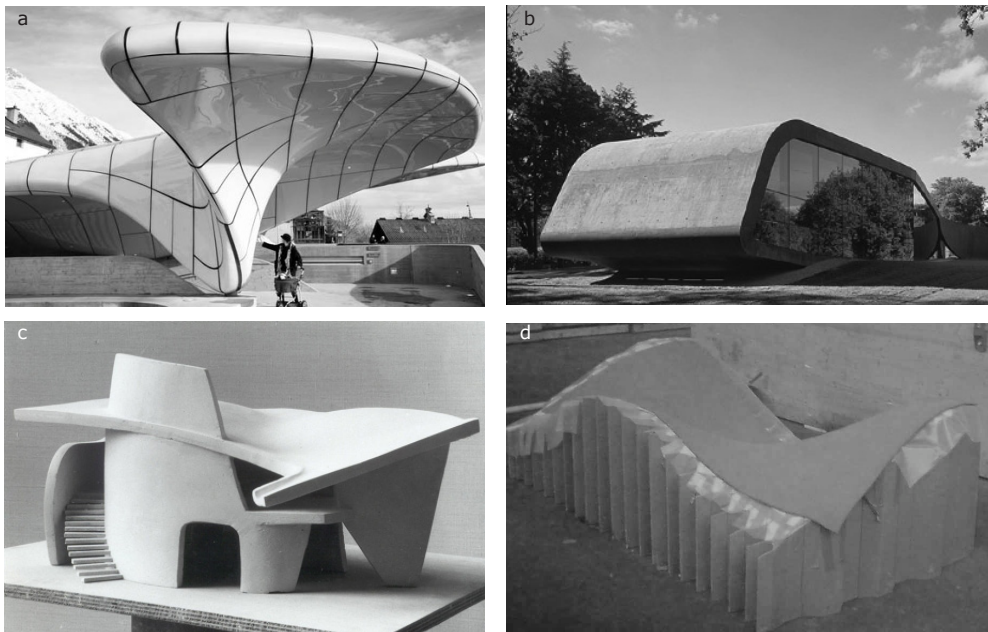


Figure 5.4 - (a), (b) and (c): Form-active building envelopes and plasticity (d) Cardboard used for forming eternit sheets<sup>1</sup>

<sup>1</sup> (a) *Nordpark Cable Railway*, by Zaha Hadid (Innsbruck, Austria, 2007); (b) Zaha Hadid; (c) Model, by André Bloc (1960); (d) Tom Pawlofsky, *Cardboard Architecture* (ETH Zurich, 2008).

and maintenance are high, and the process is highly affected by the conditions. Also, the process of molding and freezing require additional controlled storage spaces. Moreover, the entire process requires skilled workers to work under strenuous and difficult conditions.<sup>1</sup>

As an answer to these problems, form-active and lightweight corrugated cardboard honeycomb composite panels may be produced offsite using CAM/CAD controlled environments. This offers a secure replacement for precast beton. The simplest implementation would be cardboard panels to be used as non-load bearing façade and wall panels.

**c) Light-transmitting Massiveness:** Corrugated cardboard layers can be configured in a parallel or vertical orientation so that the flutes are open on two faces, as shown in Figure 5.6(f). This allows transmission of light between two facades according to the flute height, impregnation percentage, wall thickness and facing material properties for the sandwich structure.

Massive translucency generates an architectural expression that relates two opposites in its definition. Light transmission between two adjacent spaces or indoors and outdoors is a common feature in spatial design (Figure 5.5). New innovative products are positioned when massiveness is also secured with the translucency as a function. An example can be the implementation of light transmitting concrete products into the market.

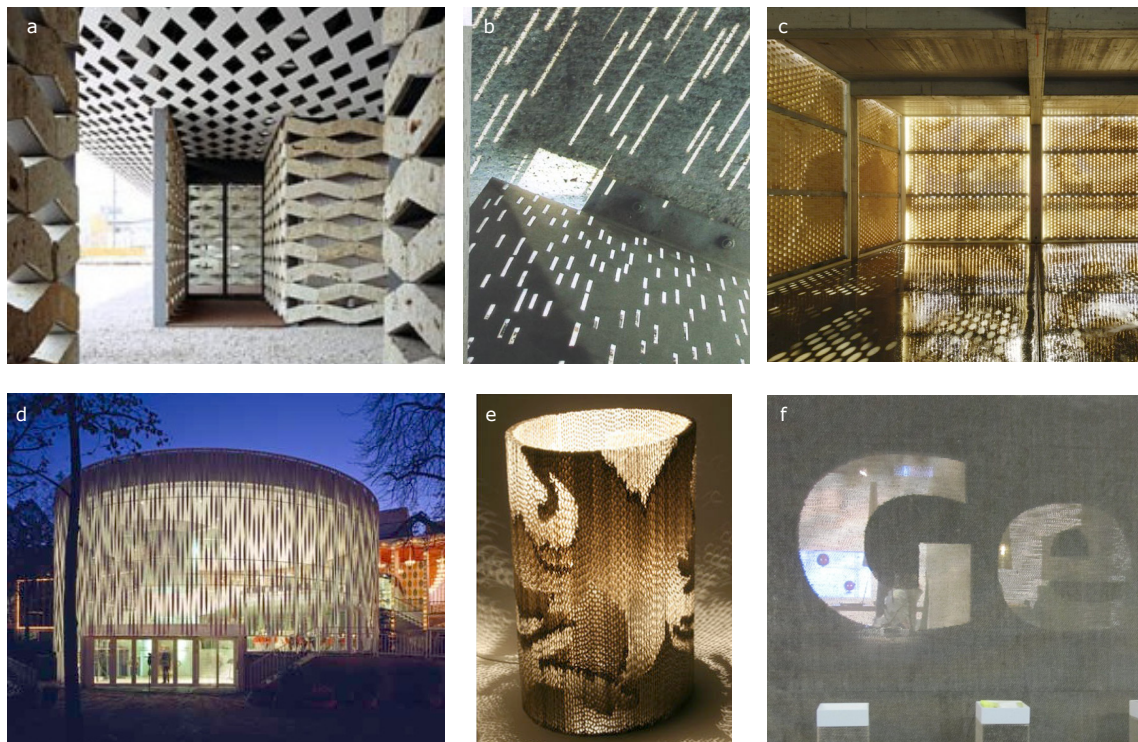


Figure 5.5 - Light transmitting massiveness examples in design and architecture.<sup>2</sup>

<sup>1</sup> C.S. Poon, "Precast Concrete Elements, Concrete Work" (The Hong Kong Polytechnic University, 2009).

<sup>2</sup> (a) and (b): *Chokkura Plaza Project*, by Kengo Kuma (2006); (c) *Vineyard Estate Gantenbein*, by Bearth & Deplazes Architects (2001); (d) *Concert Hallin* (Tivoli, Denmark), by 3xn Architects (2004); (e) *Corrugated Cardboard Lamb*, by Giles Miller; (f) *Corrugated Cardboard Translucent Stand*, by Firma Gehri AG (Basel SwissBau Fair, 2010).



On the opposite end of the spectrum from concrete and brick facades, the translucency function of corrugated cardboard core panel facades is highly related to the building skin, the transparent facing and joining sheet material for the composite, such as molded GFRP or glass.

Sunlight and interior light are not the only types of light that can be transmitted through cardboard wall composite walls or facades. Massive cardboard cores, by integrating light engineering into the facade construction, can be used to transmit artificial light and to broadcast media. Technically, the media facade can be equipped with a LED grid, a wide-meshed net of picture elements capable of receiving video and data. The main advantages of cardboard facades compared to other media facades is its direct connection to the interior through the

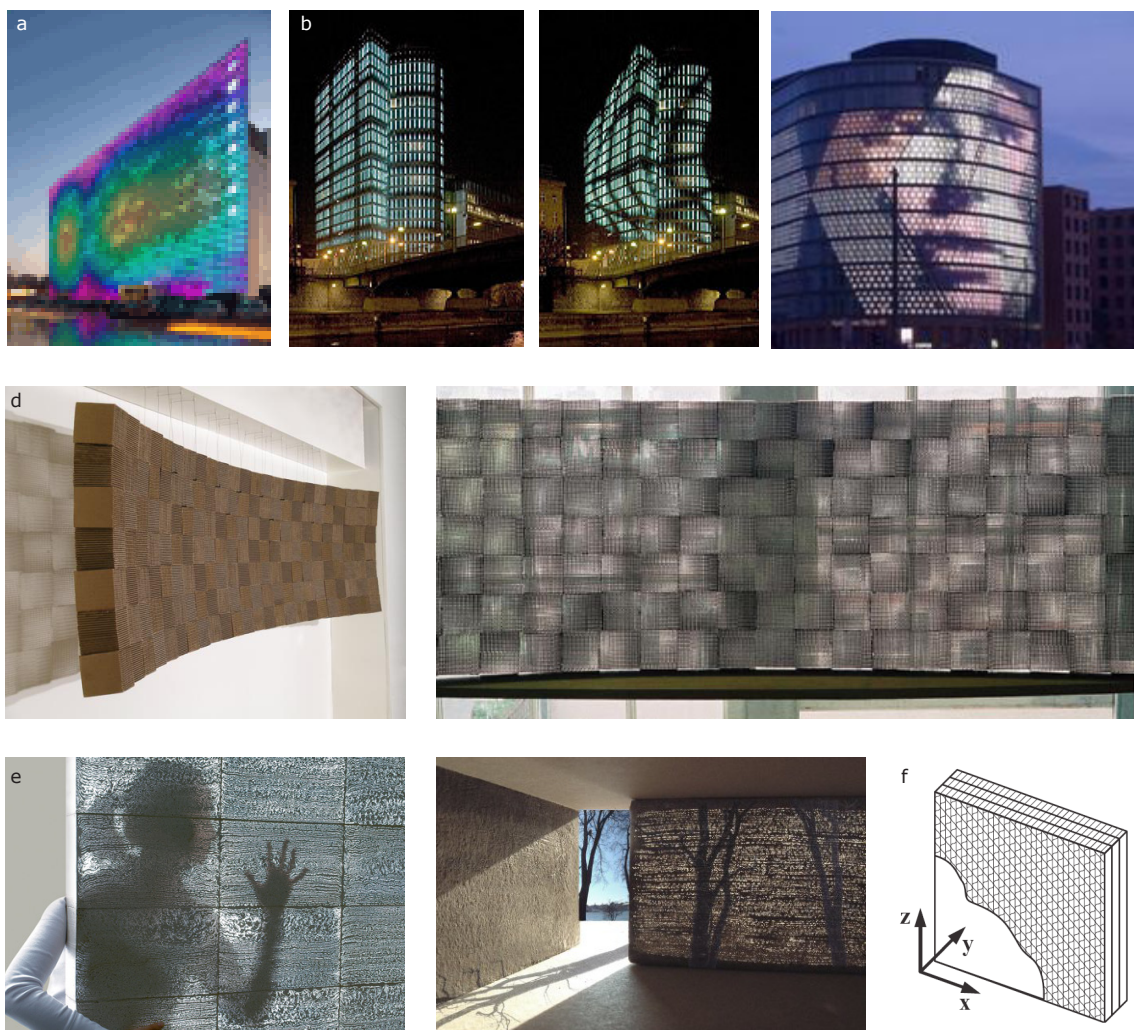


Figure 5.6 - Translucency and media facades.  
 (a), (b) and (c): Media façade examples; (d) artwork with cardboard translucency; (e) translucent concrete; (f) corrugated cardboard honeycomb sandwich panel with transparent facing forming media façade by light cables.<sup>1</sup>

<sup>1</sup> (a) *Mediamesh von ag4 Media Facade*; (b) *Uniqa Tower* (Vienna, 2006); (c) *Media Facade SPOTS* (Berlin); (d) cardboard corrugation for translucent massiveness, by Trevor Oakes (d) *LitraCon: Translucent Concrete Application*.

corrugation. This allows ease in maintenance and initial construction as well as low cost, lightweight and low electrical conductivity. Converting the skin of the cardboard building into a tool that responds to internal and external data, steady or active light design, and directing media broadcast provides cardboard structures with an additional function of communication (Figure 5.6).

### 2.3 Mass Production and Customization of Cardboard

Introduced by the Ford Motor Company in 1908, mass production focuses in division and specialization of labor and mechanization to facilitate the manufacturing process of designing or engineering a product in order to reduce manufacturing costs. High demand as a result of the second World War led to the demand for low cost products, which inevitably improved the mass production and standardization techniques. This eventually led to the idea of “mass customization,” which:

*“...proposes new processes to build using customized production, but with the ability to differentiate each artifact from those that are fabricated before and after...At this time, in this world, Ford’s ‘one size fits all,’ no longer makes a successful product, project or service.<sup>1</sup>*

Mass customization is rapidly replacing mass production today as a result of the rise of individualism in the user profile and needs that are subject to faster changes. Users today demand more individuality, power of choice and self-expression. Thus, more diverse, flexible and adaptable products are replacing yesterday’s low cost, low quality products. This phenomenon has affected a wide range of products from computers to houses, although the time period of the adoption has been much slower in case of non-transferable or infrequently exchanged goods such as houses. The effect of individualism and the demand for mass customization in the construction sector being slow to take hold is due primarily to limitation of materials, and the manufacturing line and labor relationship. For example, when building with concrete precast elements, repetition of prefabricated components is essential in order to meet quantity for cost effectiveness by mass production. Cardboard buildings on the other hand, have the advantage of not requiring an expensive mold or form-work to be done. Moreover, mass customization of irregular components is low cost, lightweight and less complicated to manufacture.

Another beneficial aspect of mass customization production with corrugated cardboard core components is the multifunctional component production capability where there is no structural difference between wall, floor or roof components. These components can also be integrated with parts of the furniture during the design phase. Cardboard building components manufactured using mass customization techniques can also be adjusted for atmosphere and acoustic control. Accordingly, mass customization during prefabrication of cardboard core components for cardboard buildings amounts to a feasible product for contemporary construction demands.

<sup>1</sup> Timberlake and Kieran 133

**i) Multifunctional Cardboard Building Components**

Cardboard core panel walls are produced by stacking layers of cardboard next to or on top of each other. Stacking irregularly cut layers of cardboard that are glued together, form walls that are integrated with three-dimensional patterns. As well as the 3-D patterns forming the walls, it is also possible to produce offset wall segments for use as permanent furniture through the use of mass customization. These multifunctional massive walls combine the function of load-bearing, separating and space defining by the already arranged furniture components. The building component combined with a steady furniture concept were experimented with in 1950's and 1960's, using concrete, as well as in 2000's by Shigeru Ban with wood components (Figure 5.7).

**ii) Atmosphere and Acoustic Control with Customized Wall Panels**

Cardboard wall components can be produced with regular stacks of sheet layers as well as with differently cut layers that generate complex wall forms with organic patterns. The form of the corrugated cardboard composite wall component depends on the geometry of the chosen cardboard core block, a logical consequence of the configuration of constituent corrugated cardboard layering or pattern.<sup>1</sup>

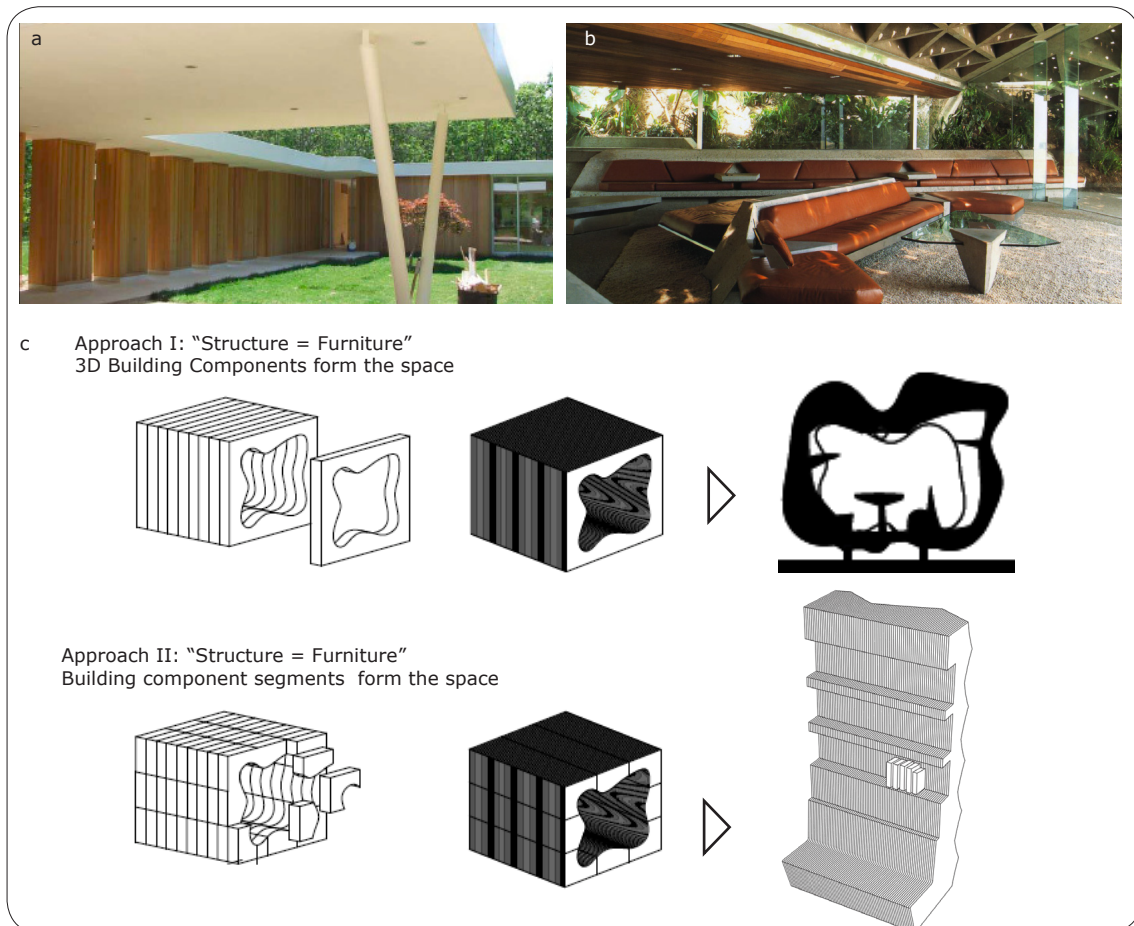


Figure 5.7 - (a) and (b): examples of walls as furniture; (c) example of cardboard wall as furniture concept<sup>2</sup>

<sup>1</sup> Mikluchin 959-960.

<sup>2</sup> (a) *Furniture House No. 5*, by Shigeru Ban (Sagaponack, NY, 2006); (b) *Sheats-Goldstein Residence*, by John Lautner (Los Angeles, 1963); (c) CATSE furniture-wall and wall segment strategies.



Customization of each layer of cardboard using CAM/CAD techniques produces form-active structures in architectural terms, while also utilizing the consumption and wastage of the material.

Geometric 3-D patterns result in benefits in thermal quality, interior acoustic controls and atmospheric space-defining function. Form-active cardboard composite façades, used in a building's exterior can also be used to regulate the ultra violet rays, and function as a passive solar system (Figure 5.8).

It is also possible to imbrade and print patterns to improve the space defining and communicative function of wall components, particularly for commercial usage, when the cardboard block is covered with translucent material like polycarbonate or glass as a skin. Within space defining qualities, it is also possible to adjust the layering process and produce inorganic openings in the cardboard core blocks forming massive structures.

Additionally, the mass customized manufacturing system of corrugated cardboard core allows complex cut-out details for joining building components such as floor slabs and walls, if secured with the appropriate durable facing material against local stresses (Figure 5.8(a)).



Figure 5.8 - Mass customization examples for corrugated cardboard <sup>1</sup>

<sup>1</sup> (a) CATSE cardboard volumes metamorphosis schema; (b) CATSE cardboard joint; (c) Canteen Interior, *Der Spiegel* Magazine Building; (d) cardboard artwork, Science Museum (London, 2010); (e) and (f): CATSE cardboard interior, formactive model-walls; (g) Cardboard Bedroom, by SeARCH and Christian Müller Architects (Vals, 2010).

### The Prefabrication Process

Prefabrication, when compared to traditional onsite construction, provides a greater degree of quality control, time savings, and cost reduction as a result of less onsite labor and time. According to the CATSE cardboard building societal research, due to the changing needs and demands of the users, increasingly modular, plug-and-play systems in structure and envelopes are required in today's market. This trend has shaped the cardboard building construction concept. The interchanging cultural lifespan of the building and the demand for change within the spaces is supported by limiting the lifespan of a cardboard building to ten to fifteen years, followed by deconstruction and reconstruction. This concept requires prefabrication offsite to increase quality control, reduce design errors, material waste, and associated liability for the defined required performance criteria.

A multi-component building system like cardboard that is engineered, fabricated, and assembled offsite can be tested as a full assembly in labs, avoiding costly and time consuming field-testing. Other benefits of prefabrication are the potential for greater supervision of quality of workmanship, protection of materials, and continued testing of joints and panel unit properties to ensure sufficient uniformity of the principal properties of the building components. These all help to significantly simplify the construction planning and shorten the overall project duration.<sup>1</sup> Prefabricated cardboard buildings offer high quality and overall structural strength onsite compared to other prefabricated alternatives such as construction with precast concrete panels that requires quality of workmanship and a greater dependence on weather conditions.

The production, preassembly and erection technology of cardboard buildings onsite focuses on materials, sequence and equipment.<sup>2</sup> The development of the prefabrication process for cardboard buildings is still in the preliminary testing stages for full utilization of its load carrying capacity, and the mechanical and physical properties of cardboard composite panels. Innovative construction production settings, such as independence from gravity based, traditional bottom-up, linear production and high degree pre-assembly are foreseen to simplify the fabrication and reduce the joints and labor onsite for cardboard buildings.<sup>3</sup> Further studies will investigate the prefabrication process and detailing from panels to components, components to building structures.

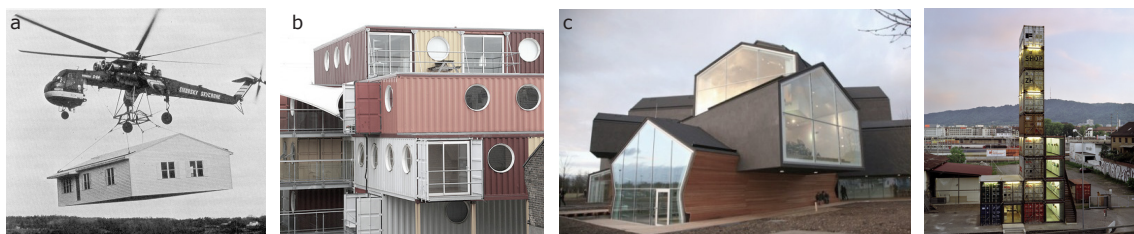


Figure 5.9 - Examples of prefabrication throughout architectural history<sup>4</sup>

<sup>1</sup> Tian Feng, AIA, FCS, Chief Architect, San Francisco Bay Area Rapid Transit, quoted in «21st Century Building Envelope Systems: Merging Innovation with Technology, Sustainability, and Function» by Barbara A. Nadel, (*Architectural Record*, 08/2006)

<sup>2</sup> Warszawski 148.

<sup>3</sup> Timberlake and Kieran 75.

<sup>4</sup> (a) Monolithic house transport, 1950s; (b) *Container City* (Trinity Bouy Wharf, Docklands, UK); (c) VitraHaus,

### **Onsite Assembly**

The two main fundamental problem areas on the construction site of a prefabricated cardboard composite panel structure are management of the erection process and the joining of panels that form the components.

1) Connections: Corrugated cardboard honeycomb sandwich structural composite panels are self-supporting black boxes, engineered for strength and longevity. Accordingly, it is critical that the panels are properly secured to one another and to the appropriate structural members. Guidelines need to be investigated for fastener spacing, adhesive and sealant on the panel plans as well as for ease of maintenance.

2) Organization: Just-in-time solutions need to be integrated for onsite management of cardboard buildings for transportation, storage, erecting and deconstruction procedures. Cardboard composite structural panel projects that are fabricated at the factory, shall be clearly labeled to coincide with the panel plans on site. Usually, the panels will be stacked to optimize shipping space, so it is critical to review the shipment as soon as possible to ascertain that all panels have arrived. Additionally storage conditions need to be regulated.

### **2.4 Modularity vs. Effective Panel Dimensions**

In principle, the size of the panels and components are to be determined by the design parameters. The panel design will aim to minimize the number of joints, maximum combination versatility and modular coordination, and balance several building physics properties such as acoustic and thermal insulation.<sup>1</sup> Other significant criteria in dimensioning are the dimensional stability within the component, resistance to cracking, and considerations of continuous thermal insulation avoiding thermal bridges.

Prefabricated building unit production is mainly composed of preassembled blocks, 3-D volumetric components or long panel wall components whose dimensions allow transport on roads, rails or air. Corrugated cardboard composite panels must be handled as structurally insulated panels (SIP), in order to avoid the need for special vehicles for transportation and comply with standard dimensions of containers for commercial transportation. Typical product dimensioning for SIP's are 300, 600, or 1200 mm wide and 2.40, 2.70, and 3.00 meters long, with roof SIPs up to 6.00 meters long. Prefabrication of cardboard panels in controlled environments can vary the preassembly degree of joining panels, blocks and building envelop onsite.

On the other hand, there is a certain flexibility in the dimensioning of cardboard components due to the fact that any cardboard core structural composite panel is produced from a basic corrugated cardboard layer. When the behavior of cardboard composite component under load is completely understood, the compressive and tensile strength of laboratory specimens from

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by Herzog & de Meuron, 2009; (d) Freitag Tower, Zurich, 2008.

<sup>1</sup> Dietz 104.

standard tests are performed and verified over the long-term for building components, and it will then be possible to predict the assembly line off and on-site. It will also allow for precise dimension-related limitations of the panels, affecting the flexibility and adaptability of the overall design and construction system.

As a hypothesis in this study, room unit sized panels are estimated to be adequate for the first prototypes of cardboard buildings. Although extended size panels limit transportation and facility site coordination, such as requirements for cranes to erect the building, they are economically feasible at the prototype stage, providing reduced labor onsite and high quality preassembled building components that offer high durability and fire resistance.

Applications improving the volumetric stability and increased strength would affect the dimensional limitations of cardboard composite panel size, and result in tolerances affecting the type, size and structural behavior of panel joints.<sup>1</sup> Hybrid combinations of cardboard composite walls with reinforced or post-stressed applications can add to the limits of extreme dimensioning and volumetric stability of cardboard composite components, similar to masonry. Experimentation and modeling can establish increased rigidity with reinforced or post-stressed applications to allow for construction of cardboard structures taller than two stories.

## 2.5 Architectonic Expression and Visual Concept

The spectrum of choices for innovative multifunctional building materials that offer numerous textures, colors and finishes is constantly increasing to allow for the availability of low cost, efficient, and creative spatial concepts and designs (Figure 5.10).

The cardboard packaging industry illustrates this versatility with the variety of products, knowledge and technology regarding cardboard. This demonstrates the potential for massive cardboard building construction to be combined with the technical advances in “engineered packaging.” Innovative visual concepts using corrugated cardboard panels can be discussed in three main directions: color, texture, and bonding pattern.

**Color:** Coloring is a basic design input for visual communication of the space, regulating its relationship with the surroundings by suggesting a nearly costless second skin to the building.

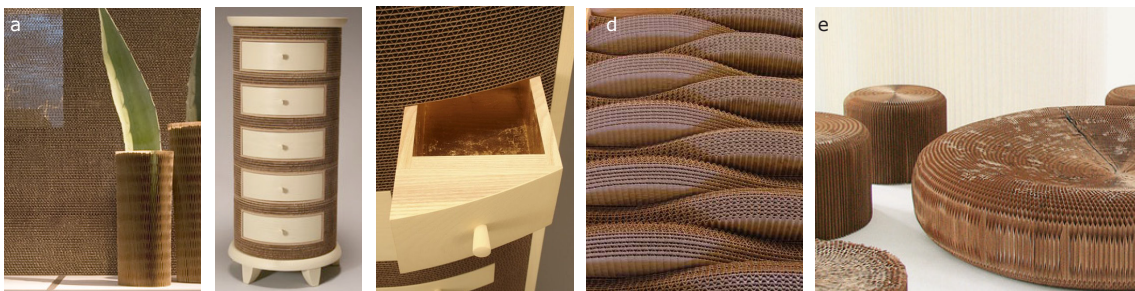


Figure 5.10 - Corrugated cardboard products<sup>2</sup>

<sup>1</sup> Hilsdorf 991-993.

<sup>2</sup> Various cardboard products. (a) Cardboard partition wall, vase and stand, by Firma Gehri AG (Basel SwissBau



Similarly, to produce colored corrugated cardboard sheets, blocks, panels or components, it is possible to add color pigments to the cardboard paper pulp or an additional coloring skin after manufacturing. When the colored cardboard core is combined with a transparent or light transmitting facing material, the cardboard sandwich composite reflects the inner colorful visual concept. Since people respond negatively to cardboard's brownish-grey color (see Chapter 3), this capability should aid in mitigating those negative feelings. Coloring the material can therefore overcome the negative psychological association of connecting it with cheap packaging material.

**Texture:** Textural surfaces can be manufactured on corrugated cardboard blocks by cutting and configuring irregular cardboard sheet layers. Through mass customization techniques and utilizing the appropriate facing material, textures as design elements hold potential for cardboard components in interior designs and facades (Figure 5.10). The choice of the facing material, therefore is an essential part of the design composition, as it must be non-labor intensive and cost effective, yet highly functional. The basic function of the facing material is to secure the inner core from humidity and fire and reduce the costs of installation of substitutes materials. Therefore, the cardboard project will use spreadable, semi-liquid and uniform molded facing materials like gypsum, molded eternit, foam plastic or molded GFRP. Other labor-intensive sheet materials such as plywood or OBS can be used in some cases if a more regular geometric texture is desired, as long as the facing material does not have a structural function in the composite or if the building physics requirements of the component permit.

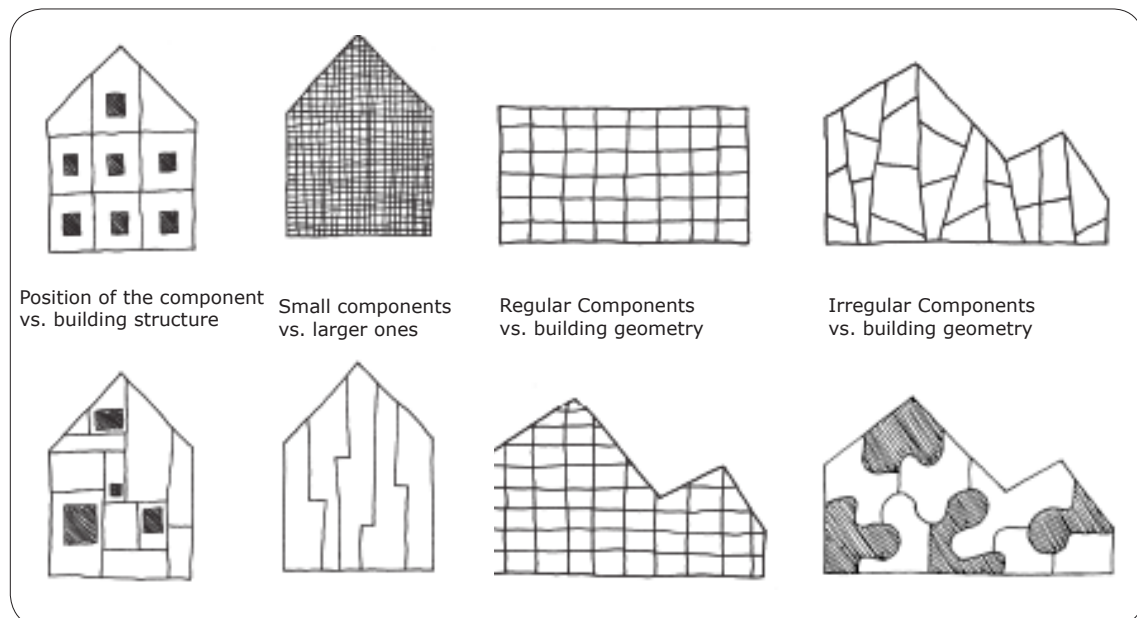


Figure 5.11 - Bonding patterns: a classification according to regularity, irregularity and dimensions of the patterns to be implemented to cardboard composite facades by Prof. Andrea Deplazes, ETH Zurich

Fair, 2010); (b) and (c): *Cardboard Drawer*, by Jason Schneider; (d) cardboard sculpture, by Mark Langan; (e) cardboard furniture, by Momo Design.

**Bonding patterns:** The configuration of panels forming walls and facades is responsible for the overall visual perception of the structure. Light and shadow effects promoted by the layering and configurations of the panel patterns and types of joints that have a significant role in the visual concept of cardboard composite buildings (Figure 5.11).

**2.6 Reduction of Skin Layers and Complexity**

The increasing use of multifunctional materials and products dominates the markets today. However, no current material satisfies the full integration of multiple demands of contemporary construction. Building components are constructed out of several mono-functional layers. This results in complicated, labor-intensive and costly construction, with a decreased degree of recyclability. The complications stem from the compatibility problems of frequently renewed detailing and application procedures in initial construction, the practicality of maintenance and long-term quality control (Figure 5.12).

CATSE cardboard buildings research focuses on generating design guidelines for a synthetic wall component. Next to load-bearing and insulating functions, the cardboard building component must offer a lightweight, formactive (organic forms), cost efficient and eco-conscious product, in relation to other conventional materials.

The mass customization techniques with additive character of corrugated cardboard layering and choice of exterior skin materials has guided the research to design a cardboard composite wall component. The multifunctional sandwich configuration reduces the number of layers and materials used on the wall section. Investigation into corrugated cardboard core sandwich composites within the framework of the research proved to be an efficient unification of several functions. The main outcomes were related to thermal insulation performance by reaching Minergie standards and structural performance by mechanical behavior testing on a two story building.

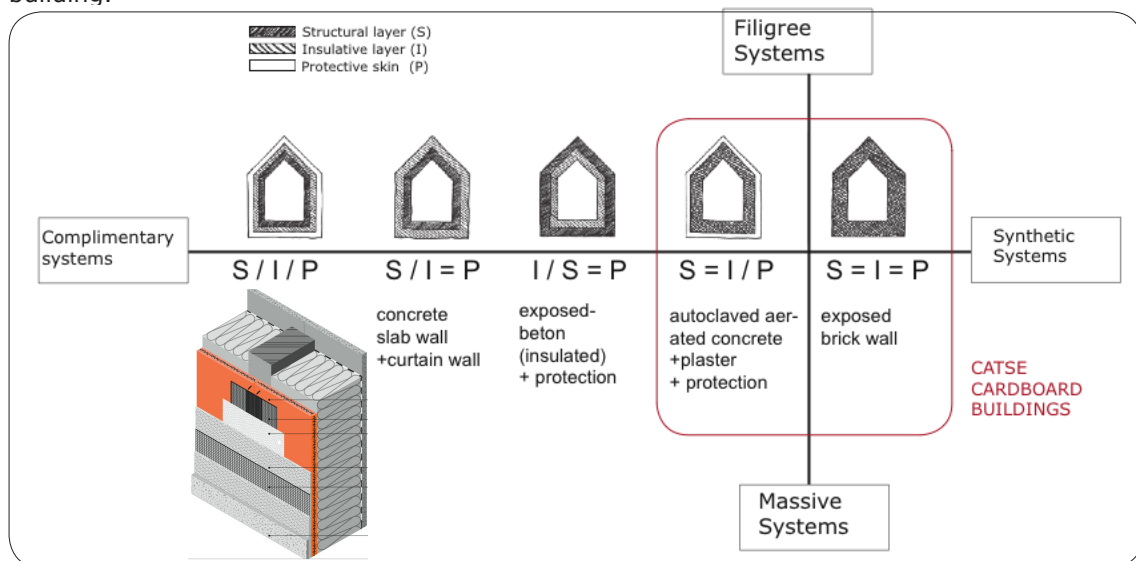


Figure 5.12 - Decreasing layers, unifying functions of building components.<sup>1</sup>

<sup>1</sup> Based on a figure presented by Professor Andrea Deplazes during his "Construction" lecture series, ETH-Z.



On the other hand, massive corrugated cardboard blocks applied with additional impregnation to protect against humidity and fire, provided sufficient load-bearing and insulative functions. This allows construction dimensions for cardboard components to require no surface finish internally, a coat of paint, and additional insulation for sound and thermal control layerings.

## **2.7 Environmental Impact**

The demand for multifunctional innovative materials has led to systematic investigations and engineering designs in building techniques and structures. The environmental impact of these building materials as well as their cost and availability are emerging as two complementary approaches for realistic and long lasting survival in the market. Users are becoming increasingly more conscious about energy saving and recyclability issues. Accordingly, the construction industry, particularly in developed countries, have started to convert their product range to include green labels. In recent years, environmental consciousness has become such a key issue that it is often controlled by governmental entities which assess additional taxes and impose regulations as described in detail on Chapter III of this study.

CATSE cardboard buildings focus on enhancing the ecological and economical sustainability of buildings by providing a highly recyclable, low cost and lightweight wood byproduct. The design approach adopts the concept of just-in-time organizational process, employing prefabricated building element components resulting with low-cost and readily adaptable and replaceable built elements.

The main benefits of cardboard buildings in the context of environmental impact are its high recyclability rate, ease of demolition and deconstruction, strong thermal efficiency control, lower emissions during productions, and usage of renewable resources.

**Recyclability Rate:** Cardboard is produced using virgin cellulose fibers containing a certain percentage of recycled fibers. During both the production and after usage stages, cardboard blocks are recyclable and can be reused in various wood byproducts. As all the other materials used in the manufacturing of cardboard are natural and non-toxic, a high percentage of recyclability rate for the cardboard buildings is predicted. Today seventy percent of all corrugated cardboard packages and boxes can be recovered and recycled today. The Cardboard School Project in the U.K. has proven to be over ninety percent recyclable; a fact which bodes well for the rate for similar projects.<sup>1</sup>

**Ease on Demolition and deconstruction:** After a building's use comes the often underestimated phase in the lifecycle of a buildings - deconstruction. Only recently has this theme been discussed directly in environmental debates. Now, it has even been suggested that owners pay a removal fee for the deconstruction of a building. This signals the an increased level of attention being paid to demolition of building components and their joint mechanism

<sup>1</sup> H. Mihashi, K. Kirikoshi and S. Arikawa, "Recycling of Used Paper as a Building Material," Proceedings of the International Rilem Workshop, Disposal and Recycling of Organic and Polymeric Construction Materials (Koriyama, Japan 1995).

design. Thus, the ease and quick demolition process of prefabricated cardboard structures will prove to be a significant advantage in this area.

**Advantages in thermal efficiency control:** Many building authorities are now requiring stronger thermal barriers within the building envelope, as energy conservation continues to be a priority in decreasing the use of non-renewable energy resources. Minergie standards were satisfied by cardboard wall panels that were tested in this research, demonstrating corrugated cardboard core block’s strong thermal insulation properties. Accordingly, cardboard composite panel construction intends to avoid thermal bridges that can seriously decrease thermal efficiency.

**Reduction of costs:** Preliminary cost estimates show that corrugated cardboard’s low cost as the core material indicates a potential for decreasing the overall costs of the building components. Additionally, energy costs will decrease as the loss of thermal energy interior is minimized in cardboard structures.

**Low emission release in production stage of raw materials:** Less emissions are expected to be produced as corrugated cardboard has less impact on the environment during the production stage compared to other contemporary materials that are energy-intensive.<sup>1</sup>

**Usage of renewable resources:** Corrugated cardboard, which is produced from a renewable resource, offers a responsible approach on limiting the use of non-renewable resources such as petroleum-based byproducts. However, the percentage and exact calculation was beyond the scope of this research. Past studies that compared timber to OSB sandwich wall panels were used as a reference point for this research. Studies indicate that about 95 percent of the tree is used to create wood chips for the OSB. In the case of solid timber products, only about 60 percent can be used.<sup>2</sup> Further studies will focus on precisely how much wood fiber is being used in corrugated cardboard panel compared with a wood frame building.

**Efficient onsite construction process:** Prefabrication, pre-assembly and mass customization oriented just-in-time construction processes for cardboard buildings will enable optimum usage of the material, and minimize onsite waste and labor. Additionally, lightweight cardboard components and panels decrease a building’s transportation costs and fuel consumption.



Figure 5.13 - Overall perspective of the input/output of building materials

<sup>1</sup> This aspect is described in detail in Chapter III of this study.

<sup>2</sup> OSB panel is composed of fast-growing softwoods, which are harvested from a tree farm at an early age.

## 2.8 Flexibility and Adaptability

Design problems with permanent dwellings began to occur when the Neolithic revolution man abandoned his nomadic lifestyle. Mostly due to safety factors and material knowledge, massive building techniques were employed with materials such as stone and bricks, leaving little space for flexibility in their first dwellings.<sup>1</sup> However, as life evolved, so too did the living space around it. The changing physical and psychological needs of users required constant spatial adjustments. These new needs stemmed from personal (expansion of the family), practical (onset of old age) or technological (updating old technical equipment and services) changes. The changing patterns might be demographic (rise of the single person household), economic (rise of the rental market) or environmental (the need to update housing to respond to climate change).

Flexibility in building design is an answer, developed as a notion to adjust to the changing needs and patterns, both sociological and technological.<sup>2</sup> In particular, for housing, users and owners have a certain degree of choice in how to occupy their dwelling, allowing them to make adaptations over the long term, which is referred to as "flexibility." "Adaptability," on the other hand, is achieved through designing rooms or units so that they can be used in a variety of different ways, primarily through the way that rooms are organized, the circulation patterns and the designation of rooms.<sup>3</sup> Flexibility, as defined by Stephen Groák, is achieved by altering the physical fabric of the building, by joining together rooms or units through extending them, or through sliding or folding walls or furniture. Thus, flexibility applies to both internal and external changes and to both temporary changes (through the ability to slide a wall or door) and permanent changes (through moving an internal partition or external wall), whereas adaptability is based around issues of use, flexibility involves issues of form and technique.

Prefabricated cardboard buildings will offer flexibility in the design, connected to the lifespan limitation and its demolition and reconstruction concepts. This concept allows users to adapt to changing needs by adjusting the mix of units, internal layouts, and accordingly increasing the value of their property. By deconstructing the building itself after a certain period of time, cardboard buildings offer a new structural and technical argument in contrast to the definition of *lifetime homes*.<sup>4</sup>

### The Quest for Flexibility in Architecture

The theoretical approach to the design of a building with goal of allowing change requires an acceptance that the building is incomplete, or even imperfect, a notion counter to conventional architectural values that values completion and perfection.<sup>5</sup>

Short term change in spatial organization had become a favorite in the architectural motif of the mid-twentieth century, as well as the notion of growing and evolutionary dwellings.

<sup>1</sup> Roger Sheppard Richard Threadgill and John Holmes, *Paper Houses* (New York: Schocken, 1988).

<sup>2</sup> Jeremy Till and Tatjana Schneider, *Flexible Housing* (London: Architectural Press, 2007) 4.

<sup>3</sup> Stephen Groák, *The Idea of Building* (London: Spon, 1992); Till and Schneider 5.

<sup>4</sup> A term used to describe dwellings that can be adapted to accommodate a user's changing physical needs particularly as they age or lose full mobility.

<sup>5</sup> Till and Schneider 8.

Wagner's *Das Wachsende Hause*, built in 1932, is a primary example of this style. *The Schroeder House*, designed by Rietveld in 1924, is another early example of a flexible house in which adaptation and short term change of use is achieved through movable partitions. Many iconic architects of the twentieth century, including Mies Van der Rohe (*Weissenhoff Siedlung*, 1927), Walter Gropius, and Charles and Ray Eames (1970's) have produced prototype-level projects with the growing flexibility concept in mind.<sup>1</sup> From residential to office spaces, experimental approaches of yesterday have been reexamined in contemporary design, as spatial changes become increasingly necessary in smaller time periods for less economical means and time. This has caused architects and the construction industry to grow a tradition of flexibility and adaptability in design, which is observed in the increased role of dividing walls and open spaces.

The conceptual understanding of CATSE cardboard buildings, in particular cardboard housing, adopts flexibility of transformation as the strength of its system. The lifetime for cardboard buildings is short compared to other conventional buildings, ranging from five to fifteen years, due to the current limitations of the material. Instead of classifying this as a disadvantage, this factor is focused on to lead an innovative notion of flexibility in design. At the end of its lifetime, following the demands of the user, a transformation process will occur, allowing for the possibility of prefabricated cardboard structure to add, subtract or combine volumes, demount and/or modify the interior spatial subdivision, including the exterior wall components.

Prefabricated, quickly assembled cardboard buildings, have the potential to begin in low-rise, low-density residential areas or areas under uncertainty in urban blocks, where the usage of the land is undetermined in a relatively short period of time. External service and infrastructure system modules are planned as "plugged in" modules to allow for the easy customized wiring and plumbing components, which are incompatible with humidity and fire-prone cardboard. Figure 5.14 shows the basic unit study for spatial flexibility - four steps of transformation are applied to each basic unit. Figure 5.15 illustrates a case study based on a residential row house project planned to be constructed with cardboard modules. The transformation of modules, the changes in income and demands according to the age groups in the Swiss society are described in the figure in accordance with the design to illustrate the potential of a flexible transformation concept.

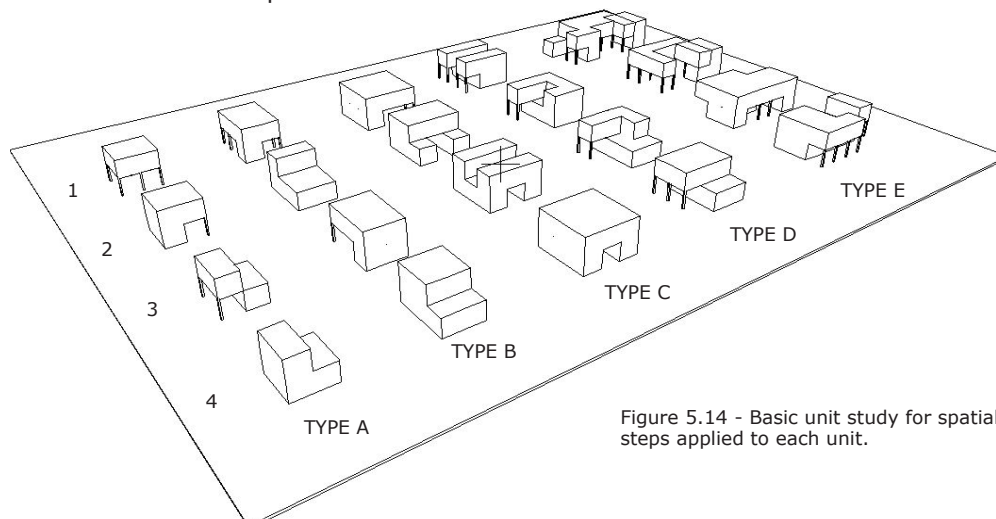


Figure 5.14 - Basic unit study for spatial flexibility: four steps applied to each unit.

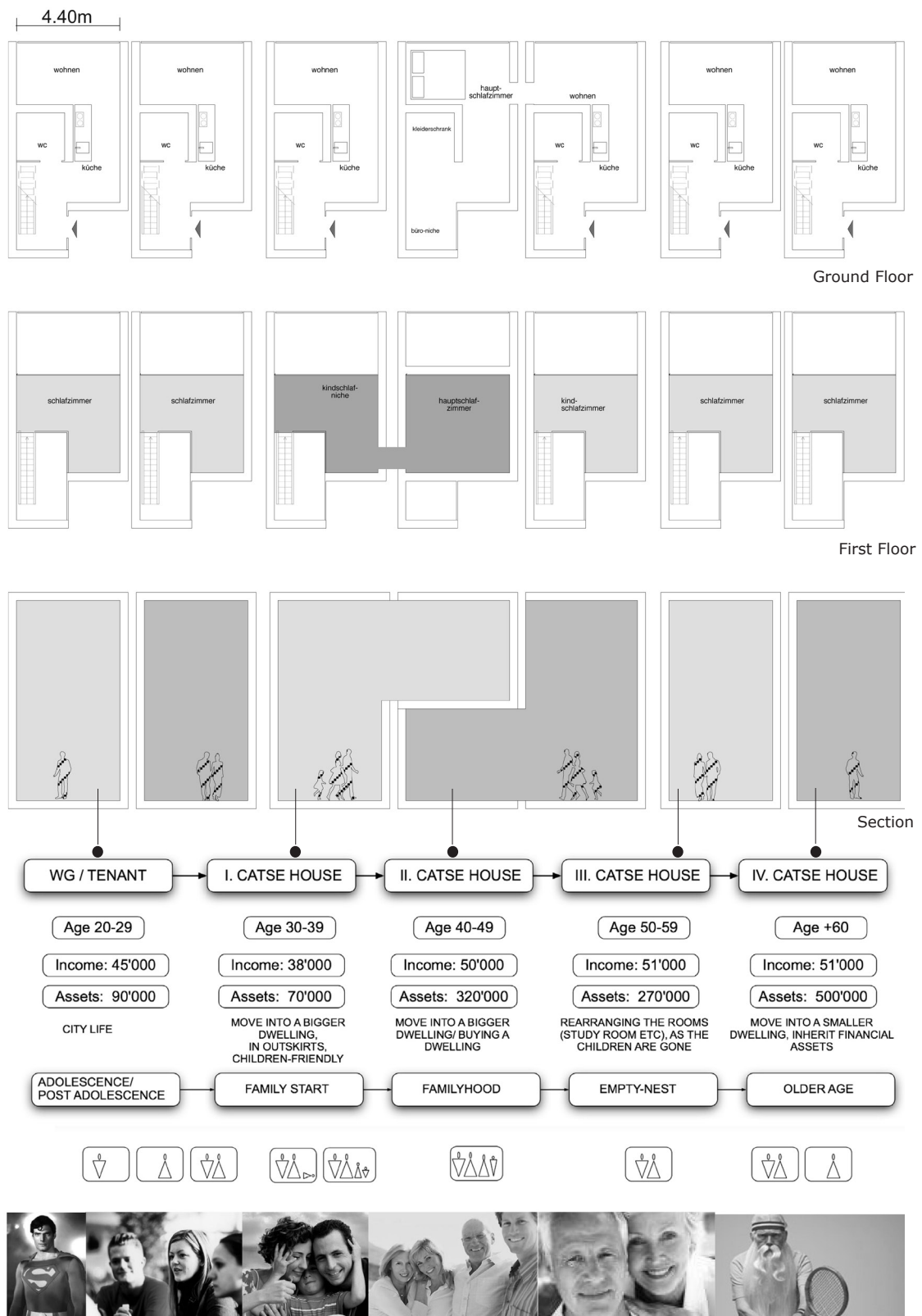


Figure 5.15 - Case Study: Flexible housing strategy implemented on the lifecycle of users - A vision for flexible and adaptable row cardboard housing.<sup>1</sup>

<sup>1</sup> Margrit Hegentobler, *Social Study* (ETH Wohnforum).

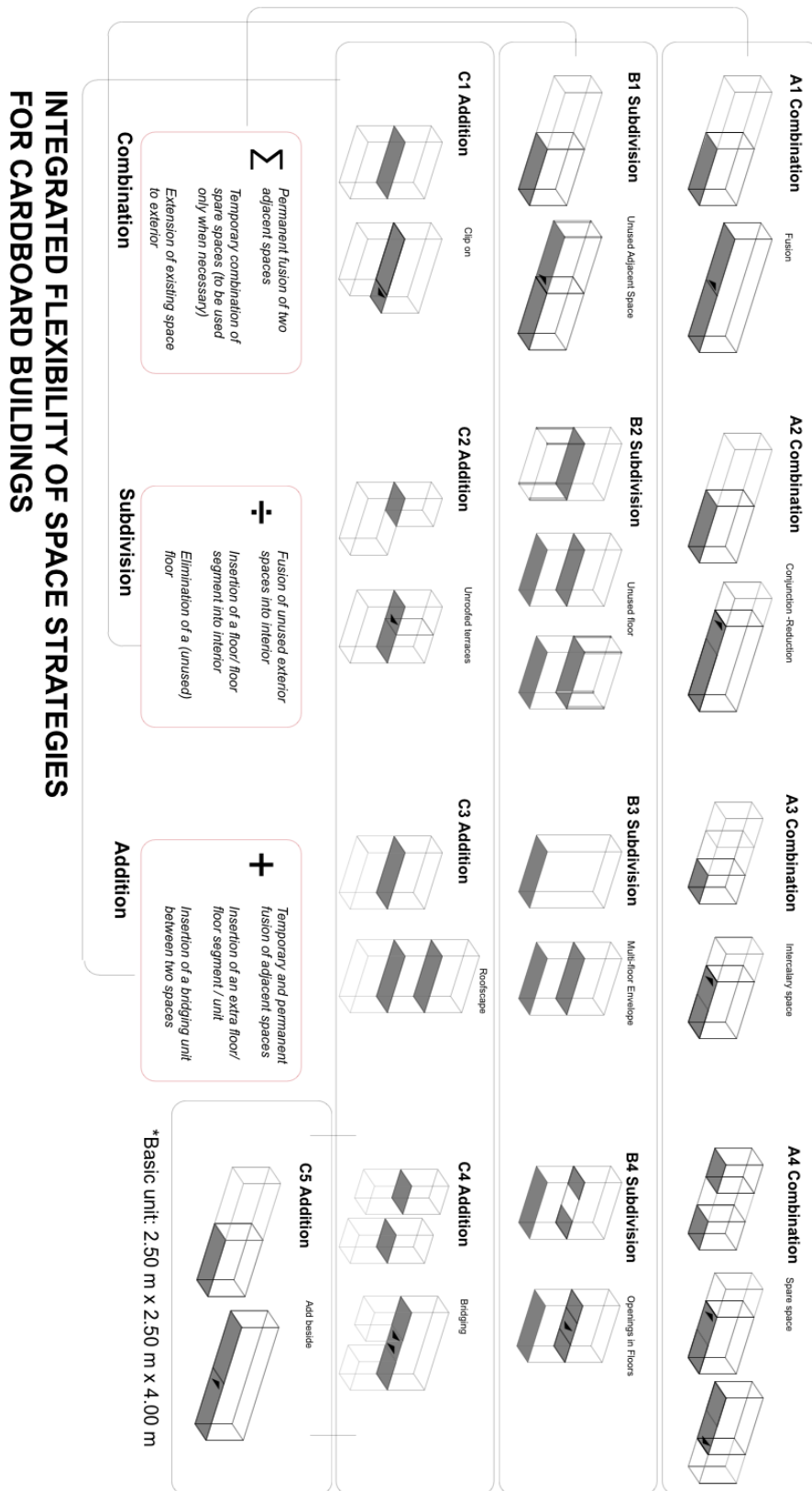
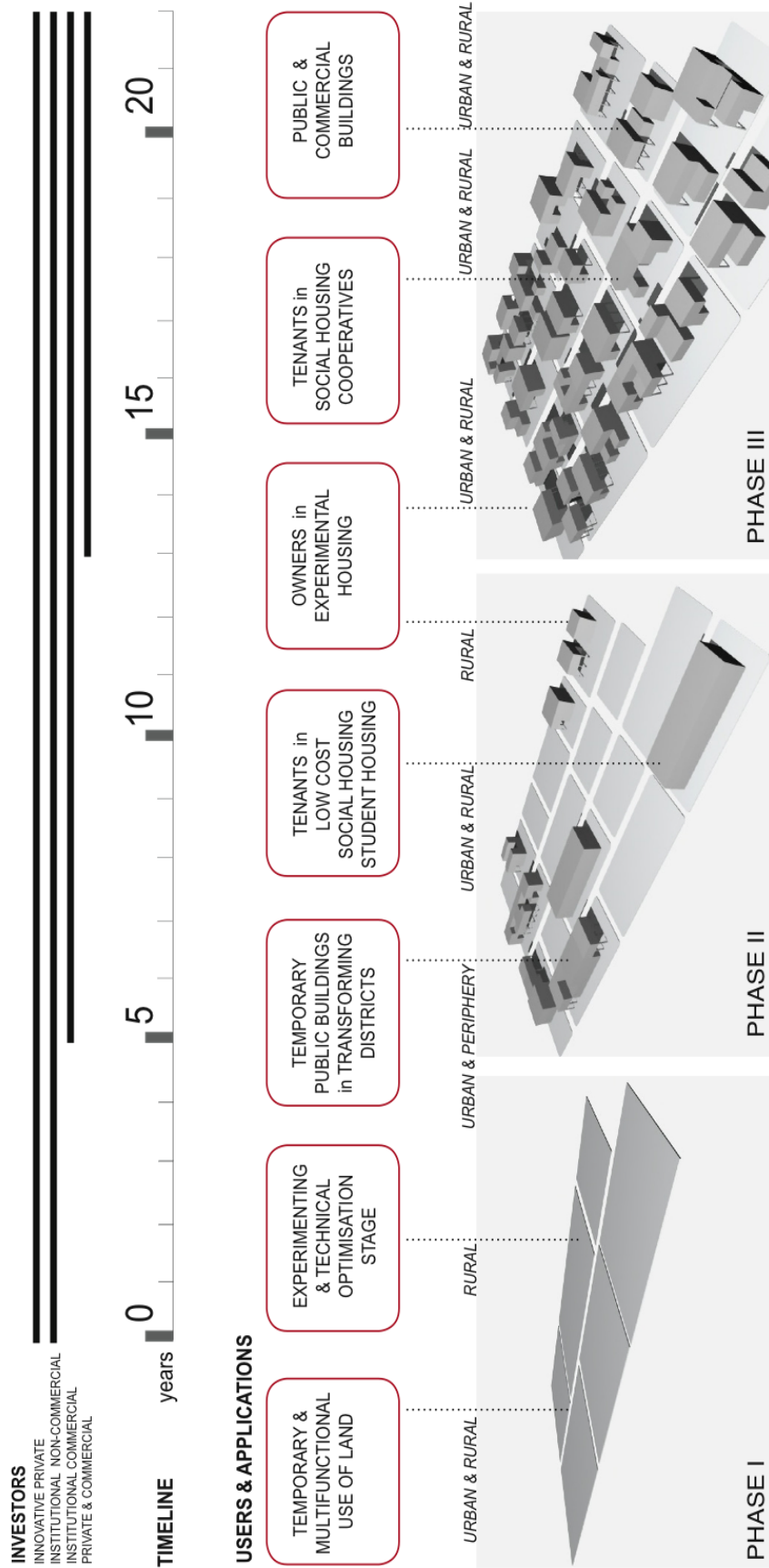


Figure 5.16 - Integrated flexibility of space transformation strategies for cardboard buildings<sup>1</sup>

<sup>1</sup> Oxman, 166-180 (setting forth that architectural strategy for flexibility is categorized into functions of expansion: combination, subdivision and addition).





DEVELOPMENTAL SCENARIO OF CARDBOARD BUILDINGS: USERS, INVESTORS AND APPLICATIONS

Figure 5.17 - Developmental scenario of cardboard buildings in a timeline: users and investors.

Figure 5.16 illustrates the integrated flexibility of space transformation for prefabricated module systems in cardboard buildings. The functions of intervention is divided into three main directions: combination, subdivision and addition. Each of these directions provide spatial transformations of volumes within the multiples of basic unit, 2.50 m x 2.50 m x 4.00 m.

Figure 5.17 shows a conceptual developmental scenario for cardboard buildings on a timeline for the first twenty years of its implementation. It examines several different market factors, including potential of locations and type of users. Phase I describes the potential of cardboard buildings in rural during the experimentation and technical optimization period, to be used temporarily and in the multifunctional use of land over a short periods of time. Phase II then moves to rural, urban and urban periphery locations, where temporary public buildings in transforming districts and tenancies for low cost social housing are envisioned for cardboard buildings. Phase III is described as the tipping point, the point at which cardboard buildings are demanded by tenants, while being supported by non-commercial institutions like cooperatives, state, and commercial entities.

## 2.9 Cost

Innovative system implementations in construction, such as cardboard buildings, require justification of economic benefits in three distinct areas in order to remain feasible: investment costs (production), operating costs (energy costs and preventative maintenance) and deconstruction costs (Figure 5.18).

*Investment costs:* Costs for the raw materials for the building and prefabrication process constitute a significant portion of the total cost in the building practice, while the role of the onsite organizational, control and erection processes is increasingly gaining attention. As more sophisticated building technologies for the investment period are more closely examined, the clearer it becomes that the demand sophistication depends not only on the material and characteristics of the building, but also on the technology management, organization, and control of the project. In fact, several studies indicate that economies of scale and cost reduction are achieved mainly through efficiency and speed, and are less affected by the choice of contemporary building materials.<sup>1</sup> Corrugated cardboard producer company SWAP states that the costs for corrugated cardboard production can be divided into three main categories: paper (35-45 percent of total cost), adhesives (10 percent of total cost), and production costs (45-55 percent of the total cost). Within this study, cardboard core composite panels are marketed as a low cost product, a highly efficient production process for prefabricated just-in-time process with minimal labor costs, weather resistant and fast onsite construction, and a high degree of offsite quality control.

*Operating costs:* The costs for internal environment comfort systems like light, sound, temperature, humidity, and circulation, taken together with with energy costs for heating,

<sup>1</sup> Dietz 26.

electricity and water, make up the total operating costs for a building.<sup>1</sup> With a customizable lifespan, time flexibility during reconstruction and a reduction in energy costs as a result of the thermal insulative characteristics of cardboard, will provide significant cost reductions in the operating costs of prefabricated cardboard buildings.

Detailed cost estimates for investment, operation, and deconstruction are not closely examined within this conceptual research study as it would require calculation of a complex series of interrelating factors. It mainly requires cardboard buildings to become a part of the existing economic system to provide a higher level of stability and efficiency, as both an ecologically and economically sustainable product.

The understanding of price positioning for cardboard buildings is based on economic feasibility, the input-output relationships of the lifecycle of cardboard buildings, and the economic concerns of the construction industry, often referred to as *economic sustainability*. Economic sustainability takes into consideration the impact of the whole production cycle, and follows a structure set for by United Nations Habitat, which underscores the importance of employing local or regional resources into productive use for long term use of raw materials without damaging or pillaging natural resources.

Investigating the cost efficiency of cardboard buildings, positioning the potential economic value in the overall construction market, and securing its position over the long term may require tools such as engaging the licensing of the patent and diverging results among the manufacturers, authorities and consumers.

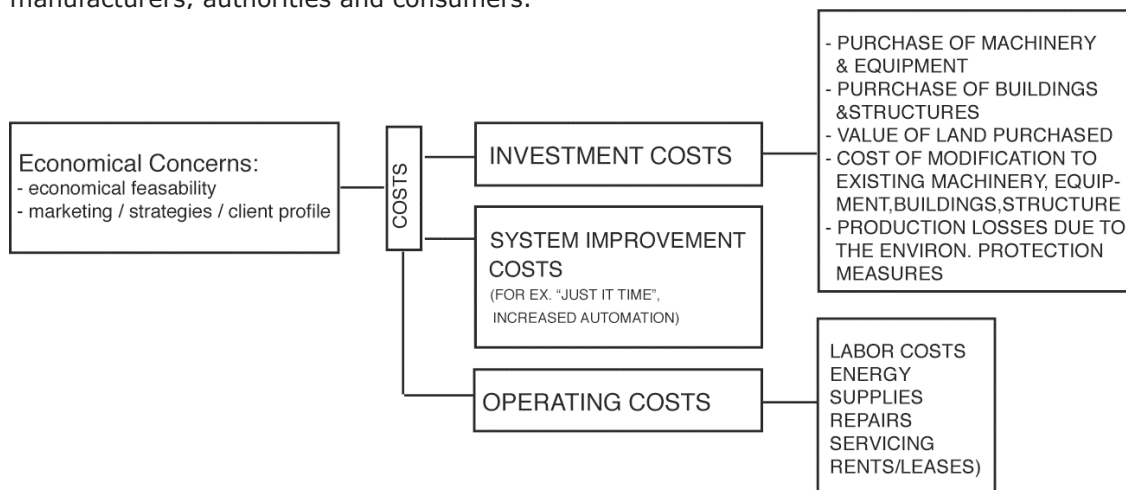


Figure 5.18 - Cost-related economic factors

## 2.10 Acoustic Quality and Control

Corrugated cardboard block is composed of several corrugation flutes to form a cellular structure when stacked. This allows the material to bear acoustic control mechanisms, depending on the wall mass and resonance frequencies; corrugation direction, total thickness, tightness of the panel, and the facing properties. An average acoustical attenuation of 35 Decibels, adequate for indoor residential purposes, will be the goal of CATSE corrugated cardboard core sandwich

<sup>1</sup> Dietz 20.

panels. Using mass customized form-active wall patterns or filling the corrugation cavities with sound-absorbing materials, it is possible to enhance the acoustical quality of an interior space, together with the sound insulation function. Additionally, sound insulation can be enhanced with suitable skin components on form-active cardboard walls. Further research into acoustic testing and modeling is planned to be pursued.

Figure 5.19 shows several examples from existing commercial acoustic-control products and insulation panels with geometric patterns. Figure 5.20 indicates model patterns and forms, produced by corrugated cardboard sheets in large and small scales for acoustic control.

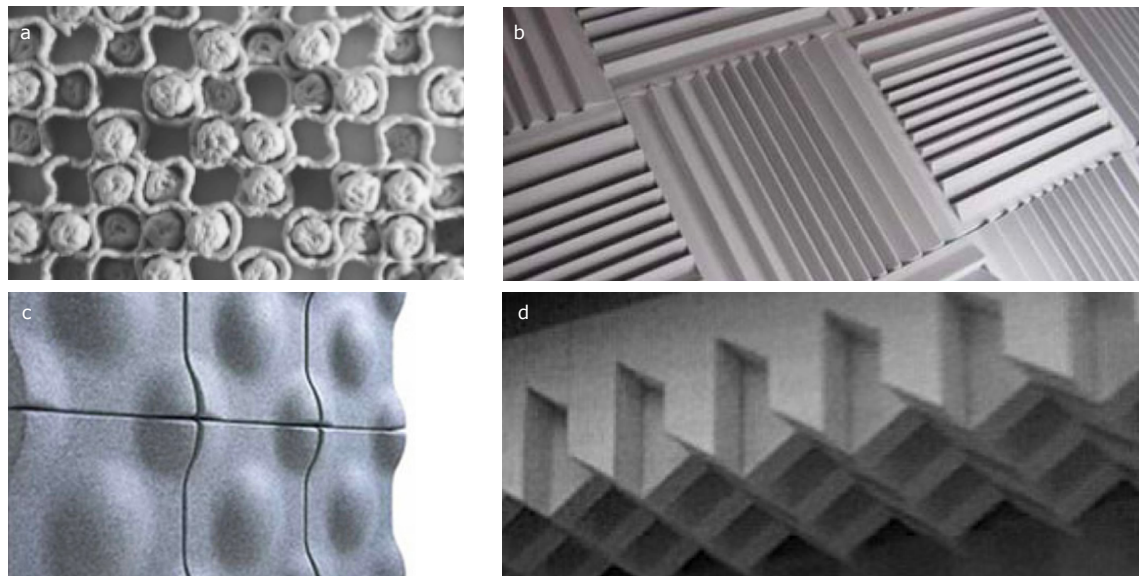


Figure 5.19 - Examples of acoustic panels<sup>1</sup>

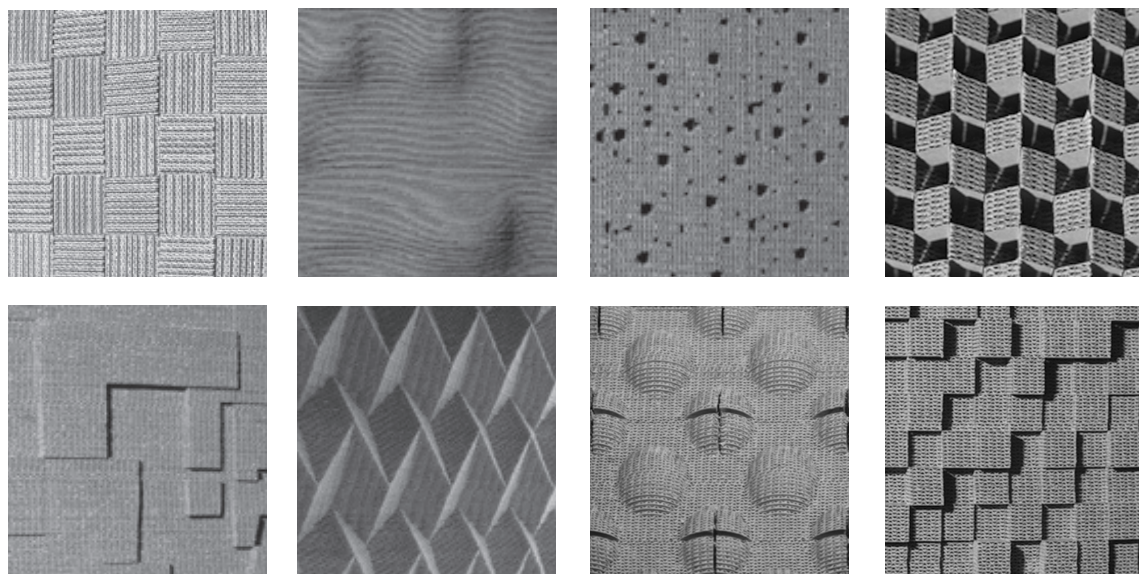


Figure 5.20 - CATSE Cardboard Buildings Case-Study: Acoustic Panel Samples<sup>2</sup>

<sup>1</sup> (a) Foam polyurethane panel for acoustic control (Source: Professors Fabio Gramazio and Matthias Kohler, ETH) (b), (c) and (d): various commercial applications.

<sup>2</sup> CATSE research cardboard façade models will be developed as a less complex, more eco-friendly, and lower cost alternative to polyurethane.

### **3. Building a System for Cardboard Buildings**

A building system must deal with the distribution of load and the structural relationship between the horizontal and vertical elements. The prioritization of building components is illustrated for the load distribution of this structural system by three different concepts: 1) the structural priority of the walls as vertical elements; 2) the structural priority of floor slabs as horizontal elements; and 3) the box systems where both the vertical and horizontal elements are equal in providing structural strength and stability to the system.

#### **3.1 Structural Hierarchy of Cardboard Walls and Floor Slabs**

The loads and actions to be resisted within a massive building system made of cardboard components are a function of the size of the building, and the choice of structural system, materials, and the type of members joined at the connections. Load bearing structural components within cardboard buildings are classified into two main categories: horizontal and vertical load-distributing components.

This study focuses on vertical load bearing wall components for purposes of a case study. The structural hierarchy of vertical load distributing components as compared to horizontal floor slabs is dependant upon component thicknesses, the related joining mechanisms and the form of the vertical load-distributing component. Other requirements for cardboard buildings are the employment of a construction system that is mass-produced at a factory and readily assembled onsite.

The joining of vertical and horizontal load distributing elements in a system are stress zones in the system, making the cardboard building system fragile in the moment reactions of its components. These stress zones lead to two different situation: the cases where the joint follows conventional detailing, and the cases where the connection of floor and wall is literally avoided. Figure 5.21 illustrates the structural relationship between wall and floor slab, applied on the basic model of two story, small-span cardboard building. House No. 1 illustrates when the first floor slab is not directly connected to the walls, but rather hung to another component, the roof. House No. 2 provides an example in which the directional opportunity of placing extra walls on the non-structural facade. These extra walls are only responsible for carrying the floor slab, one floor high, and avoiding any load transaction by the rest of the system. House No. 3 employs a secondary wall to secure the floor slab, directly next to the exterior walls. This two-layered wall provides additional thermal and acoustic qualities for the ground floor space. House No. 4 uses ripped wall segments to uphold the floor slab, avoiding a direct connection to the exterior structural wall. House No. 5 employs furniture components, positioned from floor to the ceiling, that are structurally stable enough to withstand the floor slab loads. However, this creates potential issues for the connection details and acoustic qualities. House No. 6 is the conventional connection used for the wall and the floor slab, in which the floor slab sits on top of the ground floor walls and the second floor is built above it. For cardboard housing, this option will cause complications particularly for the joints, as well as the thermal bridge occurring between the exterior and interior as a result of the positioning of the floor slab segment on



the façade requiring additional external insulation. House No. 7 exhibits a prefabricated closed system, in which the first and second floors are preassembled and stacked one above the other. In principle, applications of stacking and joining used for prefabricated box systems and shipping containers can be adapted for cardboard box system solutions. In House No. 8, the wall elements employ an intermediate element, a hinge, to support the floor slab. Lastly, in house No. 9, the floor slab and wall, and roof and walls are connected using the traditional wooden dove and tail joint technique. This option requires structural skins to avoid the local failures due to stress on the corrugated cardboard core sandwich composite walls.

The relationship between floor slabs and wall elements for cardboard buildings are illustrated in Figure 5.22 with regard to filigree and massive structural behavior. Building No. 1 illustrates a system that employs tubular cardboard columns as the vertical load-bearing component, allowing certain flexibility in the design of the space. Buildings Nos. 2, 3 and 4 employ 15 - 20 cm thick cardboard composite shear walls in order to distribute the load to the floor slabs. Building Nos. 2 and 3 are based on the dominance of the floor slabs. Here, the walls are thinner and the joint mechanisms are dominantly applied onto the floor slab. In Building No. 4, the walls are thicker and dominant in load distributing, acting as a building envelope, and leaving the floor slabs as a structurally secondary function. This also allows flexibility in the placement of floor slabs and the height of the space. Building No. 5 illustrates a prefabricated box system where the floor slab and the walls consist of identical prefabricated and preassembled components, distributing the loads within a cellular structure. Smaller spans are planned in this type of configuration due to the manufacturing, transportation and structural stability limitations of cardboard.

Joining strategies that position the relationship between floor slab and wall components are set forth in detail in Figure 2.23. Based on regular sandwich panel construction joining mechanisms, three different strategies for joining are identified and analyzed. Linear joints, point joints, and complex puzzle joints have all been determined to be adequate for use in corrugated paper honeycomb core sandwich panels. Using schematic joints, the figure additionally shows the adaptation potential concerning joint solutions of regular sandwich wall composites to be used for cardboard components regarding corner wall-to-wall, external wall-to-wall, wall-to-socket joints, outer wall-to-floor joints, and inner wall-to-floor joints.

Figure 5.24 illustrates a structural development skala of corrugated cardboard construction applied to a unit space of 2.70 m x 2.70 m. The classification is made according to corrugation direction, the number of prefabricated parts, and the direction of manufacturing. The evolution concept of forming space, interior or exterior skin using the additive nature of corrugated cardboard layering is also illustrated, and stresses the potential of mass customization in the manufacturing of space for cardboard structures.



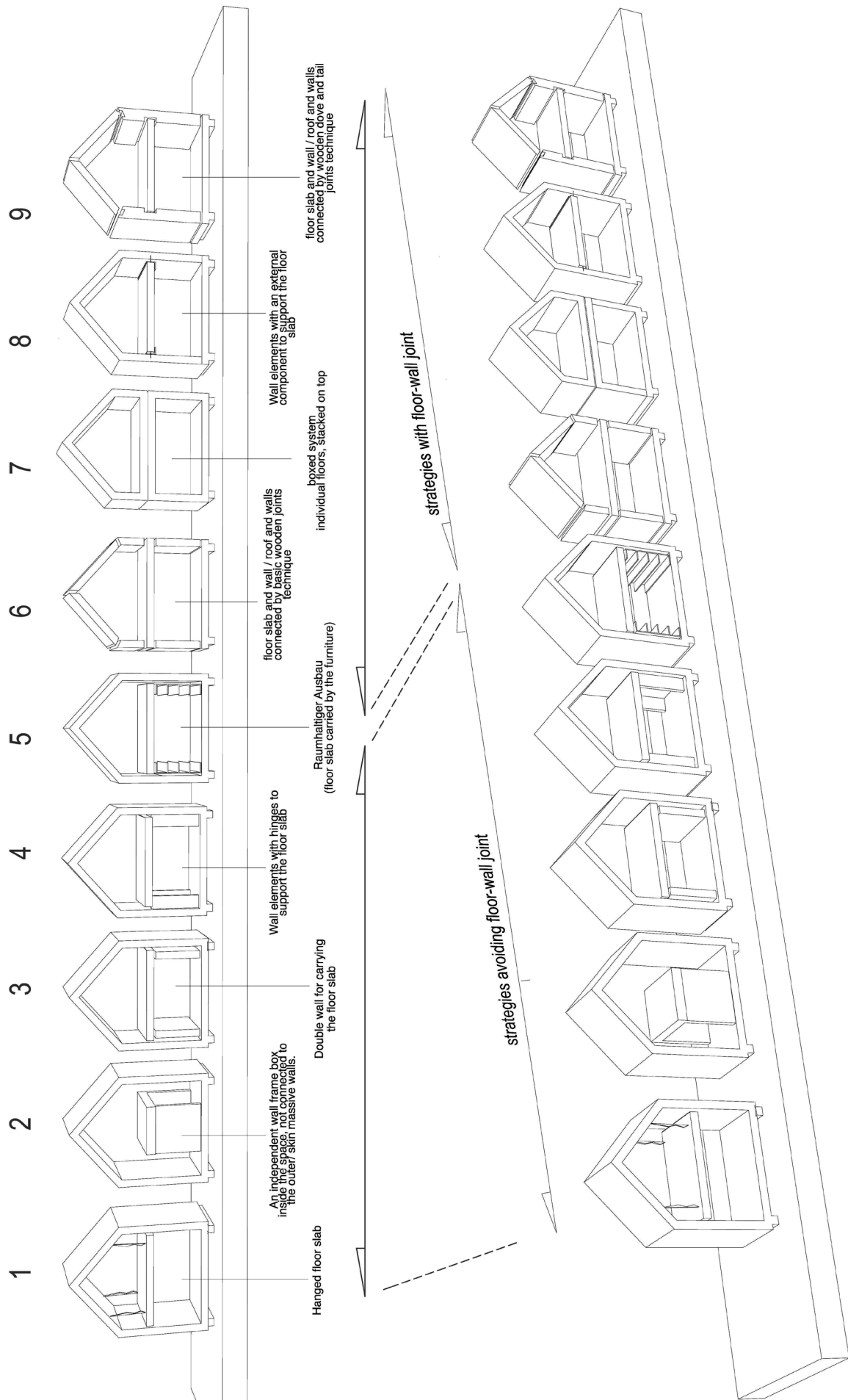


Figure 5.21 - Construction strategies for the relationship between floor slabs and wall elements in cardboard buildings.

## STRUCTURAL STRATEGIES

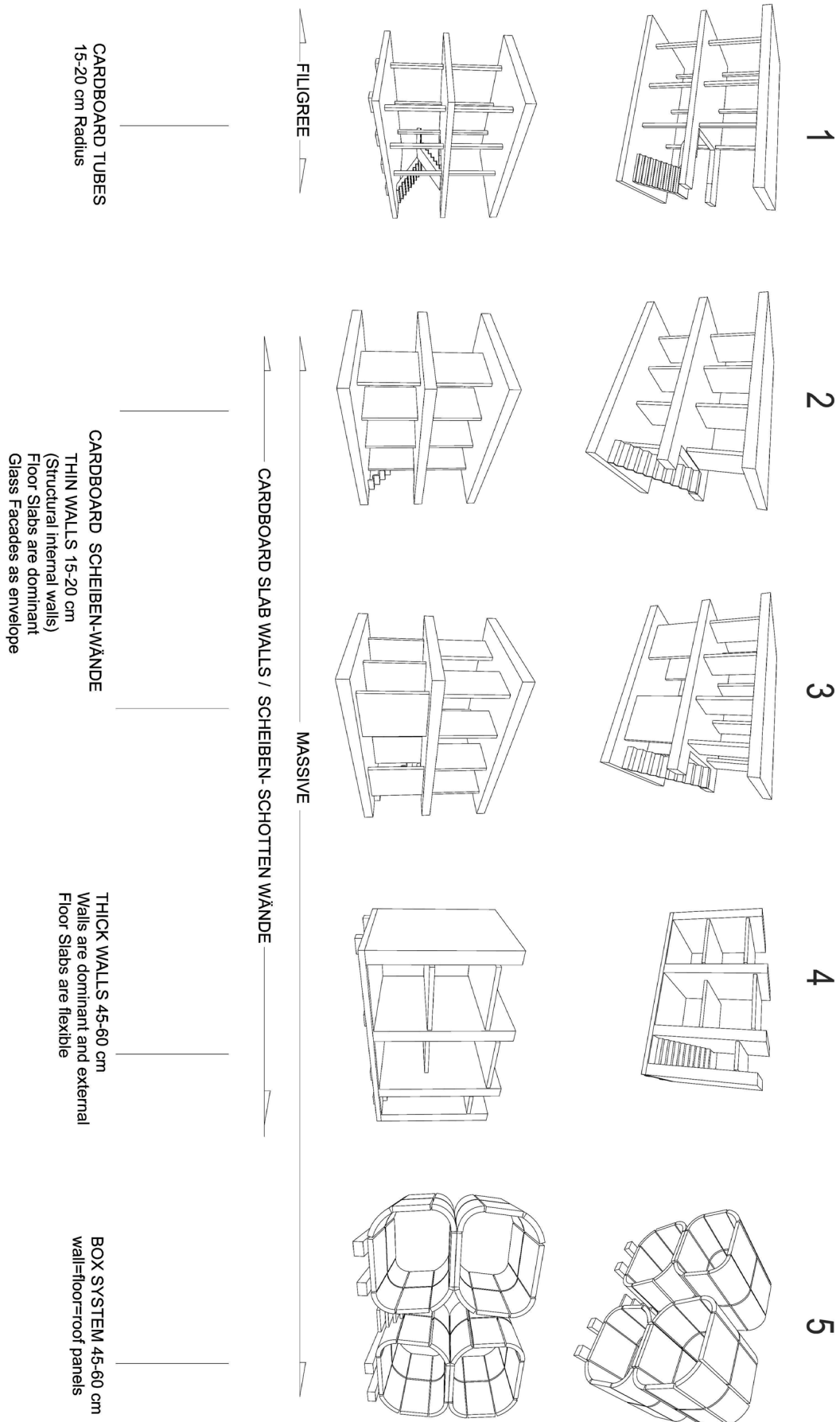


Figure 5.22 - Structural strategies for the hierarchy of building components in cardboard buildings.

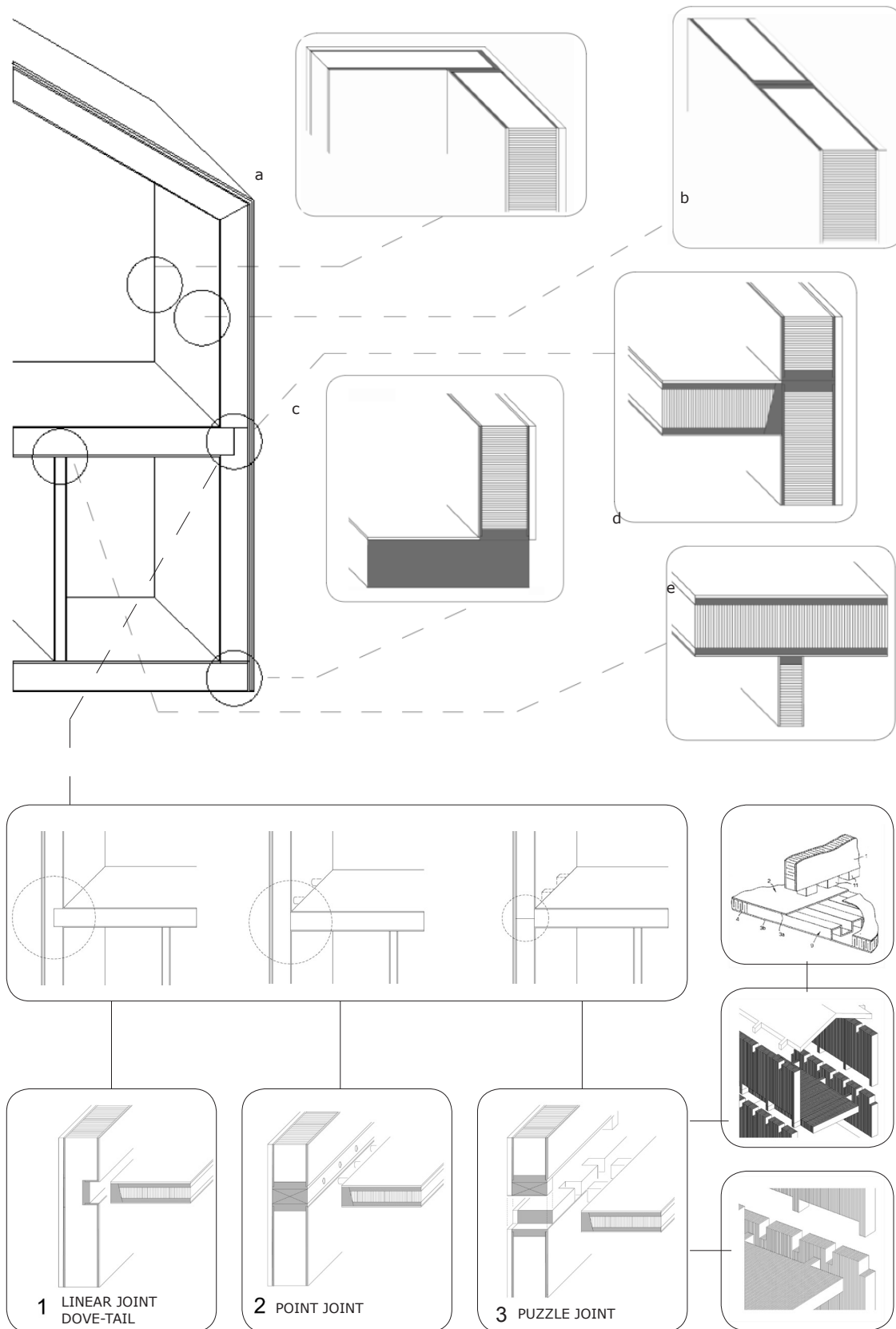


Figure 5.23 - Corrugated cardboard honeycomb core sandwich composites joining study: (a) corner wall-to-wall; (b) external wall-to-wall; (c) wall-to-socket joint; (d) outer wall-to-floor joint; (e) inner wall-to-floor joint.

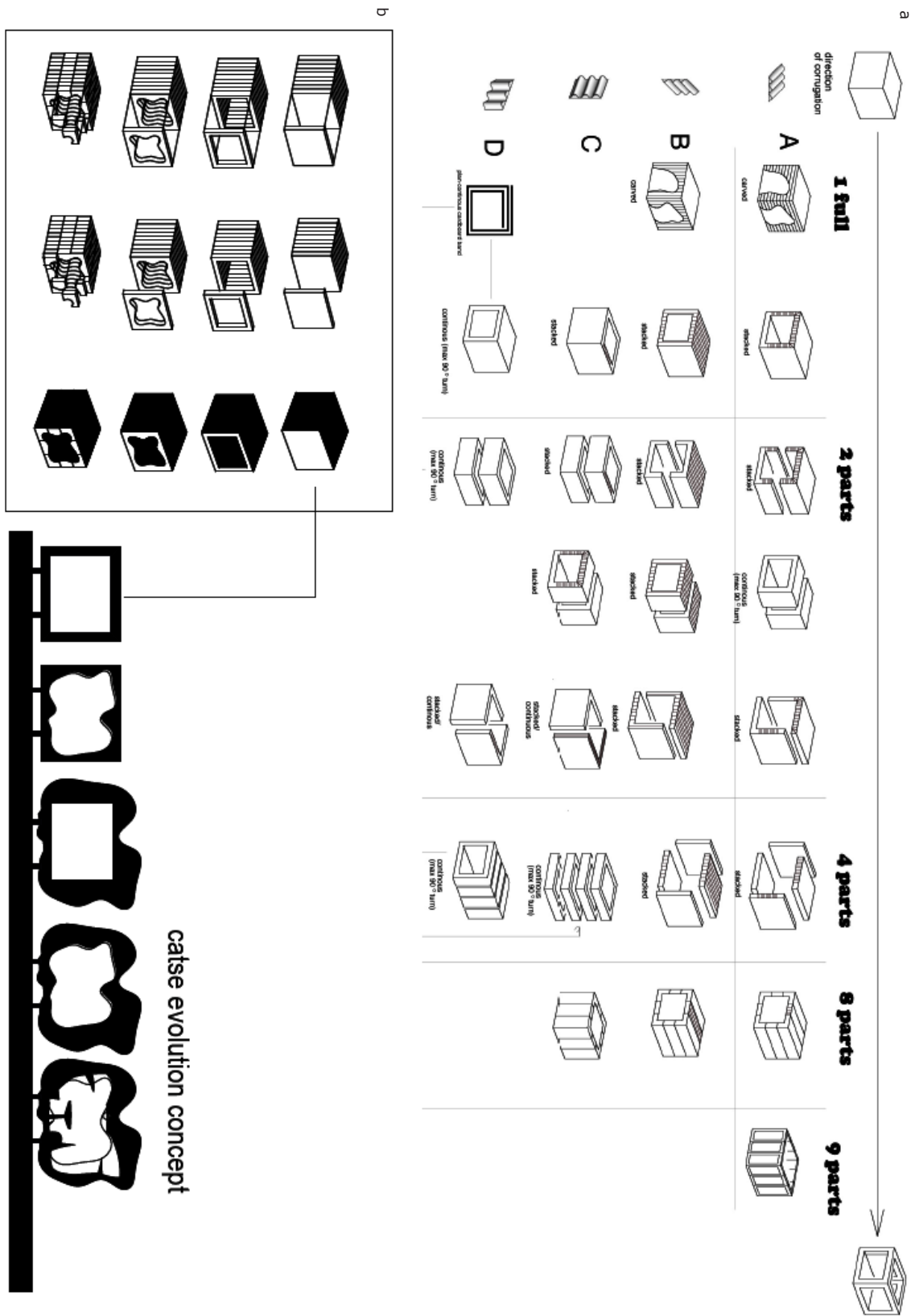


Figure 5.24 - (a) Structure Skala for corrugated cardboard construction according to direction of corrugation, number of prefabricated parts and direction of manufacturing; (b) The evolution concept of forming space, interior or exterior skin using the additive nature of corrugated cardboard layering.

## 3.2 Typology

### Corrugated cardboard honeycomb core sandwich walls as building components

Cardboard buildings employing corrugated paper honeycomb sandwich composite wall components are selected for this study for investigation as the primary load-bearing element. Unlike a linear member in timber frame structures, load is distributed by shear slab walls, which exhibit a high degree strength and rigidity in order to achieve structural plate action, similar to the solid timber panel in massive structured cardboard buildings. Unlike timber frame structures, the cancellation of timber ribs, which increases the buckling resistance in cardboard buildings, is compensated using a sandwich composite wall construction. The facing material and thickness of the corrugated paper honeycomb core of the sandwich composite works together to resist buckling. These shear walls are then assembled as large prefabricated planar panels or volumetric box systems, similar to Dietz's classification<sup>1</sup> of prefabricated systems. A low-rise dwelling with a basic unit of wall component is selected as a case study in order to provide a better understand of the basic structural configuration potential of cardboard structures.

#### 3.2.1 Cardboard Composite Box Systems

Box systems are formed by wall, floor and roof components which are structurally equivalent, creating a uniform structure. They are factory produced and preassembled as volumetric elements. With a high degree of finish and a minimum amount of required onsite erection time, box systems are structurally independent closed systems.<sup>2</sup>

Technically, constructing spaces with a box system limits the room size. Restriction of dimensioning of the box becomes a necessity due to behavioral and joint problems of the cardboard core composites as well as transporting issues.<sup>3</sup> As a solution, smaller volumes are planned to be constructed out of cardboard sandwich components. They can be grouped horizontally or stacked vertically to form the required space height, width and length as demonstrated in Figure 5.24.

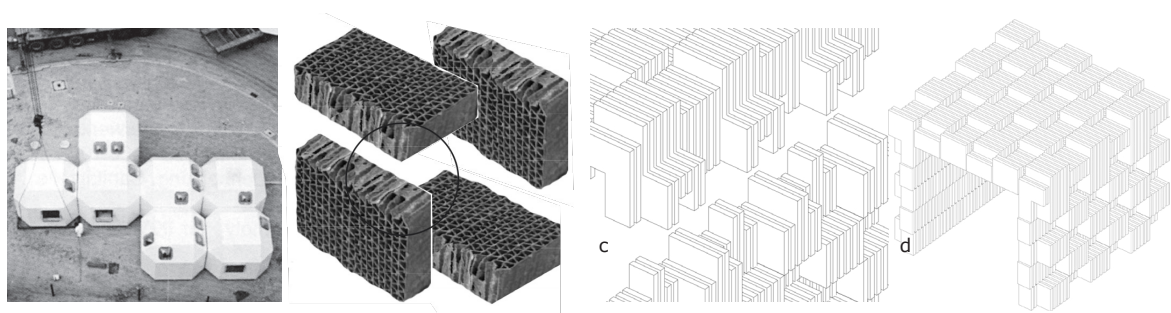


Figure 5.25 - Box Systems: (a) *Project Casa-Nova 3600* (by designers Peter Hübner and Frank Huster)<sup>4</sup>; (b) Corrugation directions for a box system; (c) and (d): Connection detail schema for box system study (CATSE).

<sup>1</sup> Dietz.

<sup>2</sup> Dietz 2.

<sup>3</sup> Dietz.

<sup>4</sup> Peter Hübner, Frank Huster, *Coques en Carton Plastifié pour habitat de loisir*, *Technique & Architecture*, (November, 1973), Nr. 295, 100-101.

Several box-type cardboard buildings were experimented with in the 1970's, including 3-H Design's *Pappeder*,<sup>1</sup> in which "rhombicunboctahedra" shape boxes were stacked and clustered with aluminum sheeting corrugated cardboard elements.

Further experimental research into volumetric box systems is not pursued in this study due to the lack of available technical data regarding the complex behavior of the composite panel in joints. The horizontal and vertical joint problems of box systems, which statically holds structural local load stresses, can be overcome by sandwich composite solutions and other hybrid solutions involving wood or its byproducts.

### 3.2.2 Cardboard Composite Planar Wall Systems

Prefabricated construction of corrugated cardboard composite systems can also be independently constructed with planar systems, rather than box systems. This requires the building components to be specialized for the location and the structural needs of floors, roof and walls.

Walls are divided by function and location into two types: interior and exterior. Solid cardboard corrugated core exterior walls can be load-bearing or non-load bearing curtain wall facades. The type of load-bearing cardboard exterior walls is dependent on the type of its outermost skin - with or without rear ventilation- and the geometry of the wall panel - standard sandwich

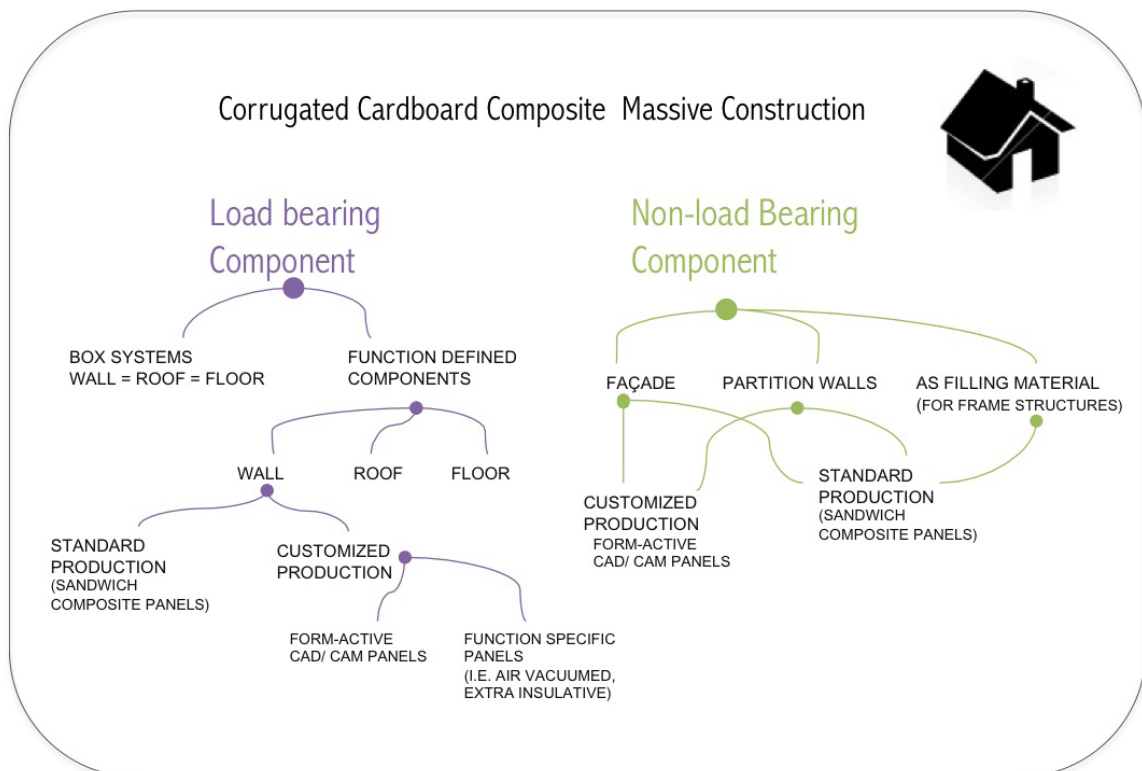


Figure 5.26 - Corrugated Cardboard honeycomb core sandwich component functional classification

<sup>1</sup> The project was designed for the 1972 Olympic Games in Munich and Kiel.



wall or form-active. For curtain wall façade components, the joints affect the building's outermost skin and geometry visually, its structural effect on local stress points, and weathering effects between the components.

Corrugated cardboard sandwich wall components can also function as interior load-bearing walls, partition walls, and supporting elements.<sup>1</sup> Both partition and load-bearing interior walls may have structural, acoustic and atmospheric benefits, depending on factors like the exterior geometry of the panel, its dimensions, and customized manufacturing type.

### ***Flexibility in Dimensioning***

Planar wall panel component systems for cardboard buildings are typically large lightweight shear wall slabs, prefabricated offsite. The panels are planned to be room-sized or cut into manageable strips. Smaller cardboard sandwich panel units can be assembled onsite to form bigger panels that will create entire walls, floors roofs, and partitions, allowing a certain degree of flexibility in design.<sup>2</sup> However, although design flexibility is increased, smaller panels assembled into a full panel onsite can blur the line between an industrialized product and traditional construction, potentially increasing the complexity, costs and time of erection.

Smaller components are not the only way to increase flexibility. Components can also be customized at the prefabrication stage of manufacturing. The construction of wall components for cardboard structures, based on the automatized CAD/CAM-oriented processes and on mass customization, helps to improve variety of architectural expression of cardboard buildings. This prevents the prefabricated cardboard structures from being limited, repetitive structures, typical of the current commercial industrial buildings systems with uniform components.

### ***The Construction Process***

The efficient construction of cardboard wall components requires specialized organization of the onsite process. Innovative building construction systems benefit from detailing and utilization of partially modular and customized components, especially when the components are prefabricated and preassembled at the factory. The manufacturing process of cardboard wall composite panels requires an investment into the design and development of new machinery, technology and processes to ensure efficiency under controlled environmental conditions. As such, the building erection process becomes more streamline. And as process management of other conventional prefabricated big panel systems will be employed, onsite costs and labor will be significantly reduced.

### ***Next Steps***

Subsequent studies will examine the utilization of cardboard wall components for joint solutions, the design and testing of wall components that have openings apart from structural openings,

<sup>1</sup> The supporting function can be similar to the insulation material filigree systems, secondarily performing a structural function.

<sup>2</sup> Dietz 3.

and integration of mechanical service module units (plumbing, electricity, heating, AC). Moreover, the relationship between the wall components and other building components, and further development and integration of the roof, floor and foundation structure for cardboard buildings also requires additional testing. Figure 5.26 illustrates the various classifications of wall components for massive buildings, divided into two categories as load-bearing and non-load-bearing walls in terms of structural function. Additionally, the sub-functions of non-load bearing “cardboard filling walls” will be examined in the future in an effort to incorporate steel or wooden frame systems, similar to the role of masonry in skeleton structures.

Mechanical service units will be designed and prefabricated using a non-cardboard, yet low cost and low impact material, to ensure conceptual and structural integration with the rest of the system. As the mechanical blocks housing the plumbing, ventilating and electrical work are usually produced with special machinery, the degree of subassembly will necessarily depend on the relationship between cost and the degree of customization.

Further technical research needs to be conducted in order to generate patterns and forms for the wall components and joint mechanisms. These modular and irregular units of sheet corrugated cardboard are to be technically analyzed for stress patterns in order to establish the modes of deflections, failure mechanisms and to list related building physics benefits (thermal insulation, acoustic quality, etc.). This will enable the project to establish quality standards and prerequisites for regular and irregular formed cardboard composite walls. Within this study, several samples are produced to help illustrate the visual potential of wall patterns in cardboard structures structurally or for thermal and acoustical insulation.

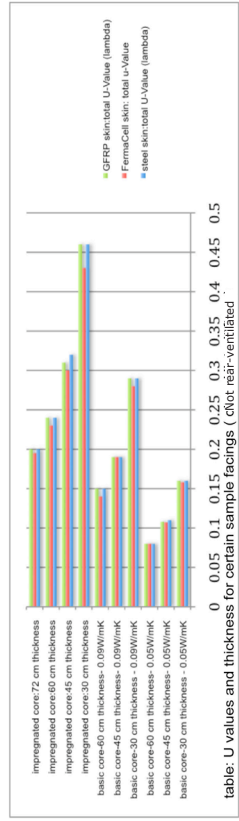
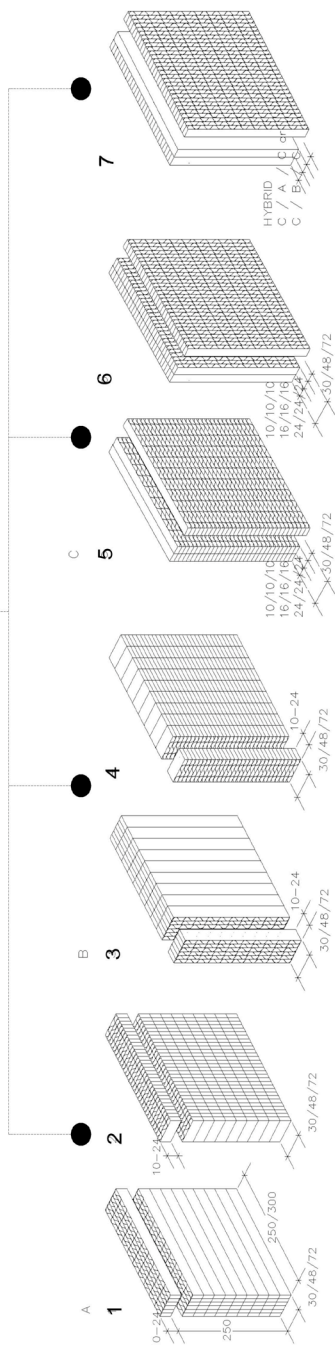
### 3.2.2.1 Exterior Wall Components

Prefabricated composite panels will be manufactured offsite to ensure a high quality product. Cardboard composite exterior wall components as *black box* systems, prefabricated and delivered to site with their internal structure no longer visible, are completely finished sandwich elements.

To secure external walls against weathering damage, exterior cardboard sandwich composite walls will be constructed within an additional rear ventilated cladding system. This layer serves as a protective skin for mechanical stabilization of the outermost cladding, forming an air cavity between the building surface and the outer protective skin to protect against weather and other local stress. The rear-ventilated cavity also allows a passage of air within the cavity, and forming an additional barrier against condensation, thermal or acoustic leaks.

Figure 5.27 illustrates the exterior wall options for corrugated cardboard core composites, categorized by skin options, corrugation direction, and characteristics such as weight and thermal insulation properties. In this study, cardboard composite panels used as exterior walls are divided into three main categories: i) load bearing standard panel exterior walls, ii) non-load bearing curtain wall façade elements, and iii) form-active irregular façade elements.

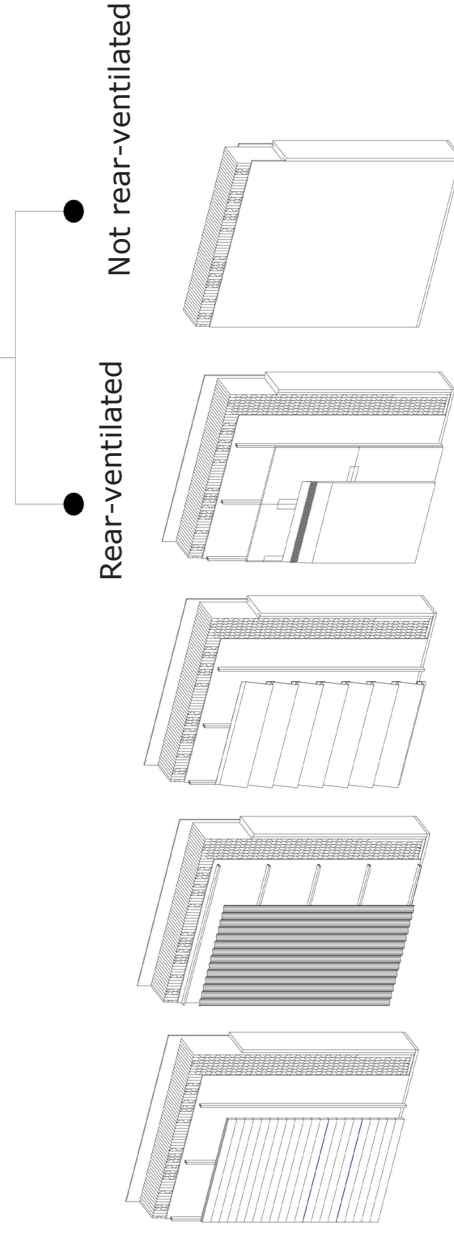
Corrugation Direction Choice



	1	2	3	4	5	6	7
<b>Form-active</b>	-	+	-	+	+	+	+
<b>Thermal</b>	++	-	++	+	-	-	+
<b>Easy</b>	-	--	-	--	+	+	+
<b>Impregnation</b>	-	-	-	-	+	+	+
<b>Structural</b>	+	+	+	-	++	++	+
<b>Humidity</b>	++	+	++	+	-	-	+
<b>Fire</b>	++	+	++	+	-	-	+
<b>Sound</b>	++	+	++	+	-	-	+

Table: A preliminary study on the characteristics effected by corrugation direction of the cardboard core

Standart Panel Construction



facade construction

- WOODEN SHEETING
- METAL/ ETERNIT SHEETING (vertical)
- METAL SHEETING (horizontal)
- GYPSUM BOARD FACING
- STEEL/ GLASS / GFRP / Heraklith / MDF / PLYWOOD / OSB FACING

Figure 5.27 - Potential configuration of corrugated cardboard honeycomb core sandwich wall components, according to corrugation direction, u-value and façade construction type (rear-ventilated cavity and facing choice).

*i) Load-bearing Exterior Walls*

Load-bearing cardboard core exterior walls are structural and provide thermal insulation. With a thickness of 15-20 cm, they are sufficient to distribute the loads of a basic two-story building. Depending on the fire and moisture protection strategy, impregnated cardboard core wall elements are capable of controlling stability and relative humidity even in large panel dimensions. However, impregnation also decreases a wall's thermal control capability, which results in an increased thickness weight of the wall element. If this needs to be prevented, airtight specialized joint systems can be installed to cure the water absorption, humidity and fire hazard dangers.

*ii) Form-active Facades:*

The additive nature of corrugated cardboard allows for the manufacture of massive plasticity with cardboard building that form fast, low cost and low impact form-active facades. The appropriate facing for the irregular cardboard core block depends on the geometry of the pattern. *Form-active* facades with adequate geometry can also work passively to eliminate rain from the facade, provide acoustical control, and a passive solar system by reflecting the ultra-violet rays as a result of the 3-D pattern of the surface. Additionally, non-load bearing walls can be installed with extremely thin thicknesses compared with conventional sandwich wall partitions, and still provide the necessary acoustic or atmospheric low cost input to the interior space. The technical testing of *form-active* walls is not pursued in this stage of the study.

Formactive panels in this study are classified into four different groups: large geometric patterns, small geometric patterns, organic forms, and layered walls (Figure 2.29).

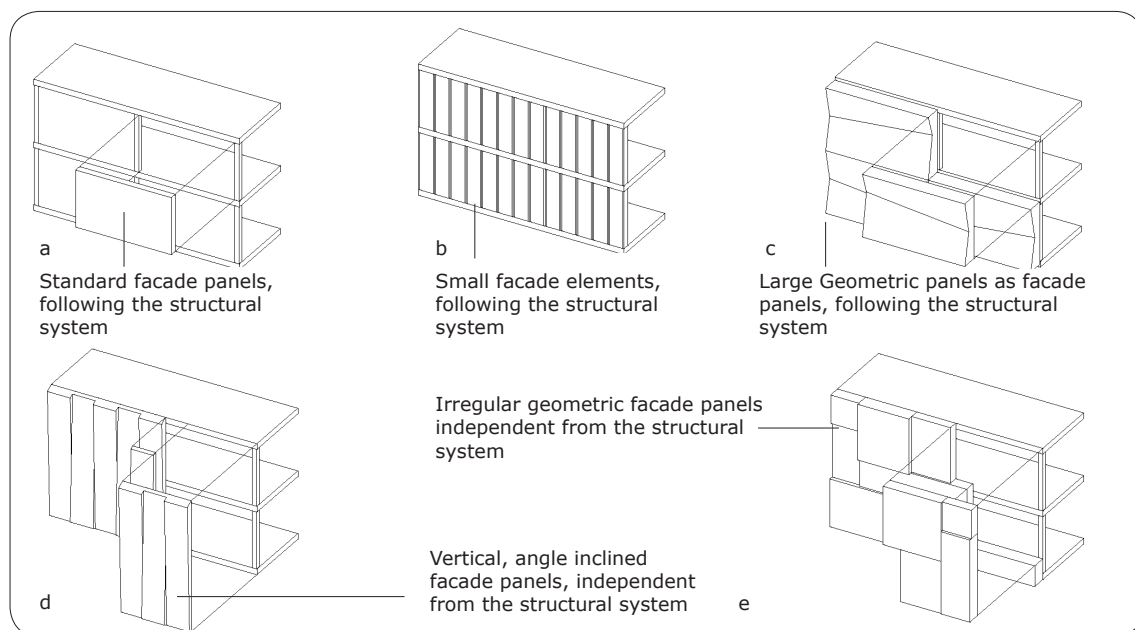
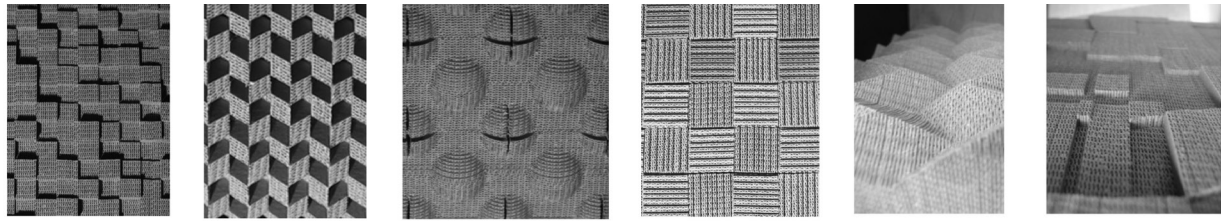


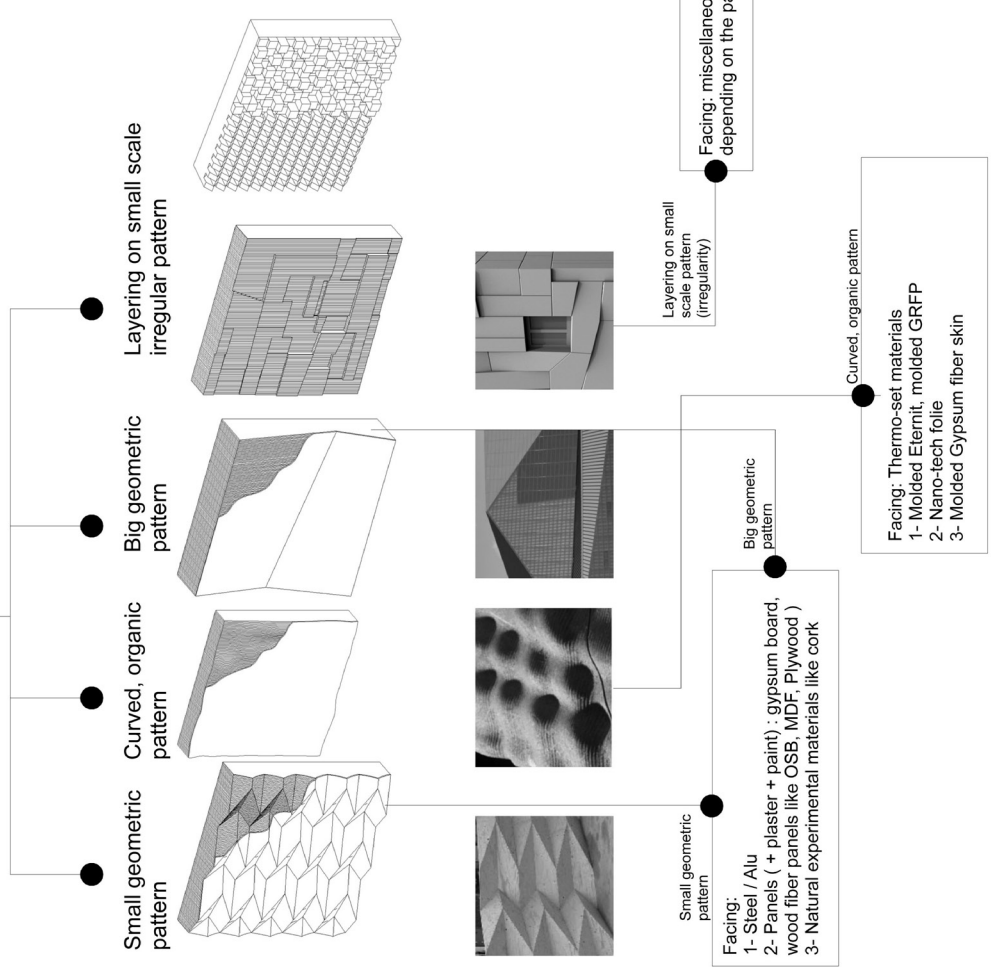
Figure 5.28 - Corrugated paper honeycomb core sandwich facade wall geometry and dimension as a structural system.



- UV / Thermal Control
- Visual quality - atmospheric / spatial quality
- Acoustic / sound control
- Less thickness - more stability

functions

form-active facades



facade geometry

Figure 5.29 - Corrugated cardboard honeycomb core sandwich wall component.

iii) *Curtain Walls*

Cardboard composite wall panels, flexible in geometry and dimensions, can function effectively as curtain walls when coupled with the adequate facing material for outdoor weather protection. Curtain walls do not carry any dead load from the building other than their own weight, and are designed to form a skin resistant to air and water infiltration while spanning multiple floors. Dead and dynamic loads are generally transferred to the main structure through connections with floor and building columns.<sup>1</sup>

The geometric and structural relationship between the facade element and the structural system of the building behind is illustrated in Figure 5.28. The typological study illustrates: (a) standard size panels following the structural system of the building; (b) smaller panels; (c) large geometric panels on the structural grid of the building; (d) form-active panels as facades following dimensionally the structural system of the building; and (e) form-active panels independent from the structural grid of the building.

**3.2.2.2 Inner Wall Components**

Technical experiments have shown that cardboard core composite panels can function as load-bearing inner walls with a thickness of 10 to 15 cm. However, non-load bearing partition wall composites can be as thin as 5 cm thick, and thus provide a lightweight and low cost solution. Cardboard core inner walls can also provide sound quality and control by using cardboard corrugation direction and geometric patterns to direct sound waves. The wall’s impregnation method and facing type are significant factors affect the fire-proof nature of cardboard core composite walls and partition walls.

*Partition walls:* Some of the inherent advantages of cardboard composite partition walls include its relatively low cost, low weight to strength ratio, recyclability, and its formactive possibilities for architectural expression. Non-load bearing cardboard core composite partition walls used in a building’s interior can be used in-situ construction of lightweight walls as a “dry wall system.” The application of this system is widely used today in construction, particularly for sandwich walls composed of timber or steel framing with a thin sheet of gypsum or fiber reinforced cement board applications.

INNER WALLS	Thickness	Facing Type	Additional Functions	Special Manufacturing
Load bearing	20 cm	- Steel/Alu - Gypsfaserplatte	- Sound insulation - Acoustic Quality	-Vacuum Insulated panels
Non-load bearing	5 cm	- OSB/Plywood(woodbased) - GFRP/Glass (transparency)	- Improvement - Fire protection - Thermal Insulation	-Engineered sandwich panel

Figure 5.30 - CATSE corrugated paper honeycomb massive interior wall model.

<sup>1</sup> Nadel.





Figure 5.31 - Classification of inner walls, listed by thickness, facing, and function.



Figure 5.32 - Examples of paper-based, non-load-bearing, dividing wall.

### 3.2.2.3 Engineered Wall Components with Corrugated Cardboard

Engineered wall systems using air-vacuum have entered the construction market with several different products. Airtight panel systems for conventional sandwich panels are currently used in cold storage applications due to their high thermal and mechanical resistance, dimensional stability, and their moisture repellent nature.<sup>1</sup> They also provide additional thermal insulation with very thin wall thicknesses, and are currently being tested at TU Delft. Additionally, Swiss firm The Wall recently started commercial production of the panels.

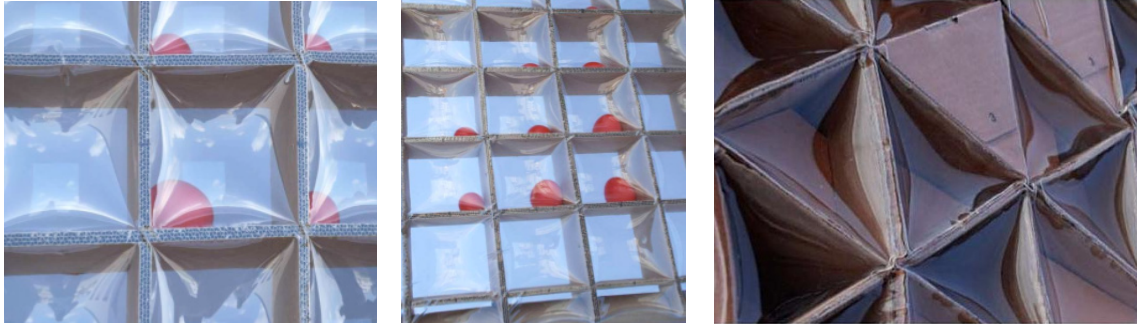


Figure 5.33 - Deflated cardboard facades developed at TU DELFT.

### 3.3 Case Study

In this study, the architectonic potential of cardboard buildings is diverted from the investigation of corrugated cardboard composite walls. As a tool to illustrate the outcomes, a case study of *The Rageth House*, a rematerialization of a residential project, was performed.

The building is a wooden hut house project designed by architects Bearth and Deplazes in Fanas-Cania, Switzerland. The two story building exhibits several parallels to the planned cardboard building prototype, including its size, simple spatial design, and function. Limited to small spans, it has no obvious openings or windows, and is monolithic in appearance. Two sliding shutters were installed for security and weathering, and the openings were covered with unified wooden sheathing facades. The rematerialization study aims to rebuild this building with massively structured corrugated cardboard core sandwich composites, permitting the use of different wall types developed with diverse facings and geometrical patterns. Nine types of walls were generated using the outcomes of the theoretical and experimental research based on their structural load-bearing quality, massive plasticity, multifunctioning, recyclability, environmentally low impact and massive translucency properties.

**1) Translucent and Structural External Wall:** This wall is load-bearing with an impregnated cardboard core and a translucent facing material. The translucency allows visual connection between the building's interior and exterior, permitting controlled sunlight to enter from the exterior and artificial light to exit from the interior. The thickness of the wall component is

<sup>1</sup> For example, *Frigowall*, with a thickness of 8-15 cm, has a moisture resistance  $\geq 1000$  h (ASTM D2247).





Figure 5.34- Photographs from the Rageth Mountain Hut project

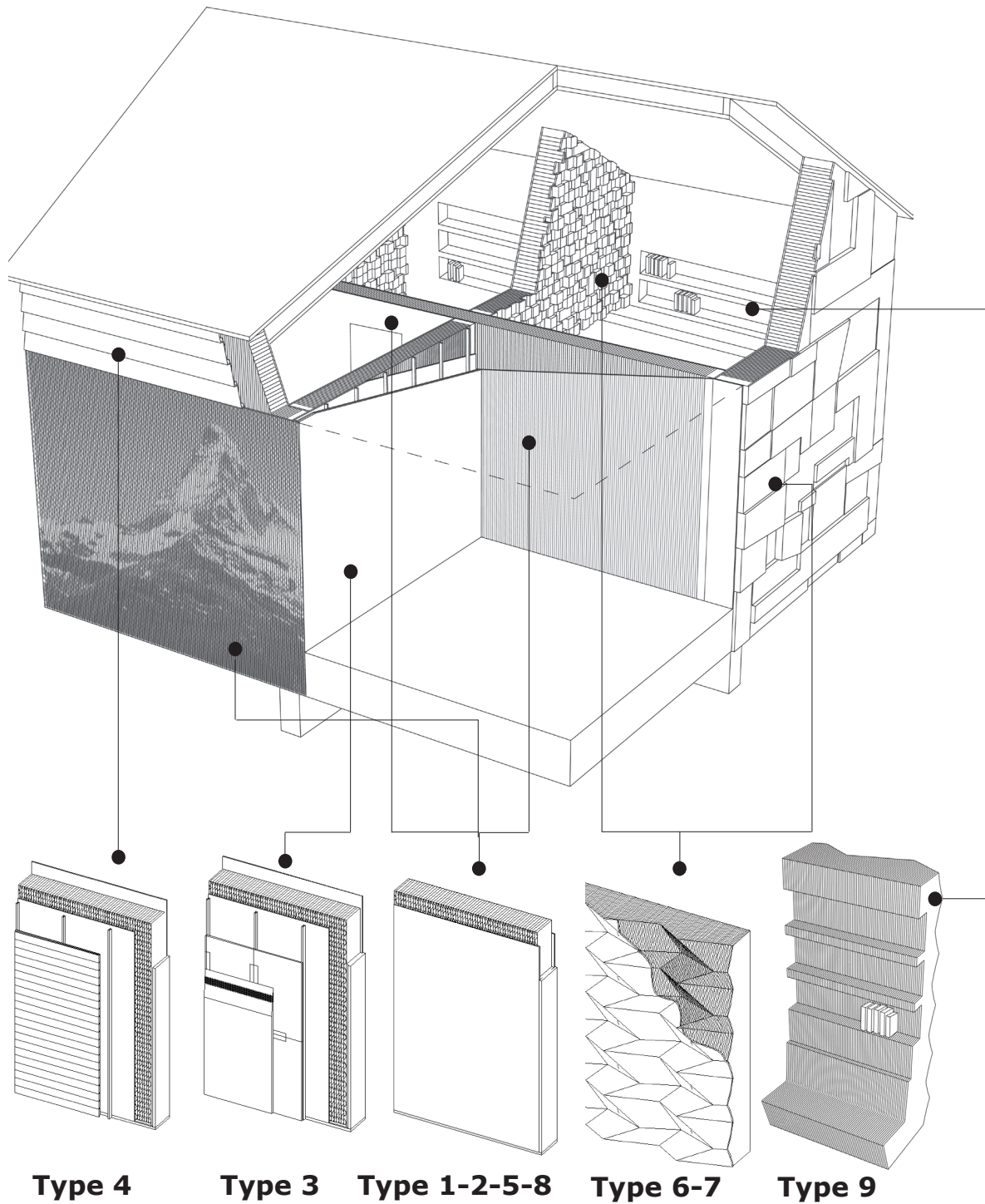
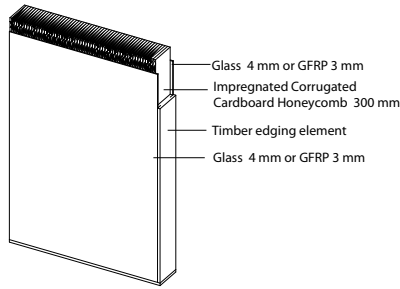


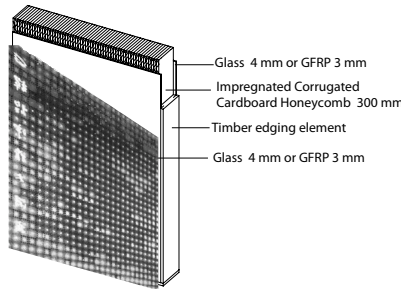
Figure 5.35 - Wall typology re-materialization study as an illustration for cardboard housing, employing diverse corrugated paper honeycomb sandwich panels. Numbers indicate to the definitions of walls listed.

**1** Translucent and structural external wall



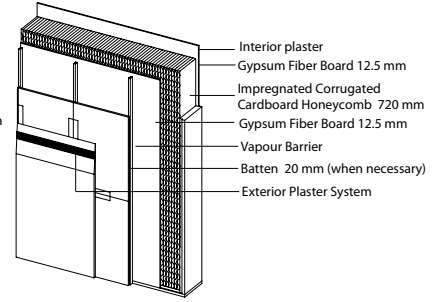
$U = 0.46 \text{ W/m}^2\text{K}$

**2** Load bearing media facade on exterior wall



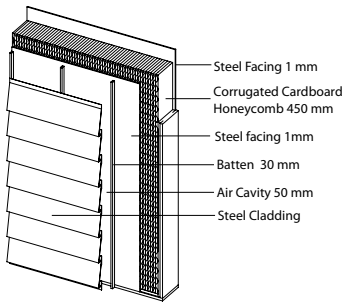
$U = 0.46 \text{ W/m}^2\text{K}$

**3** Highly non-combustible, insulative and structural external wall



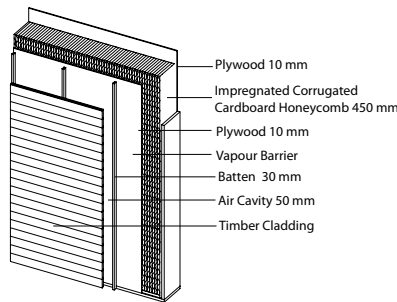
$U = 0.19 \text{ W/m}^2\text{K}$

**4** Durable, insulative and structural external wall

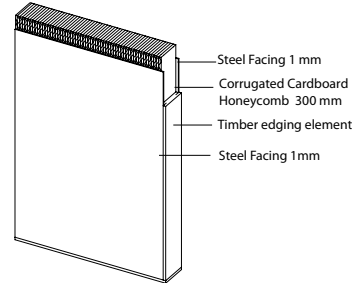


$U = 0.12 \text{ W/m}^2\text{K}$

alternative

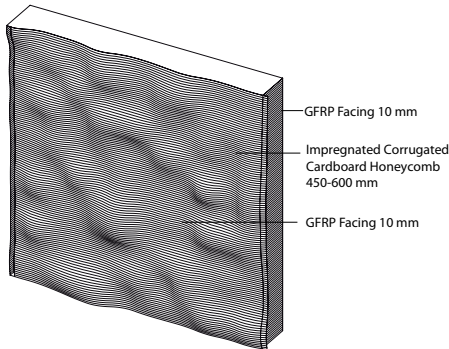


**5** Thin and light structural exterior wall

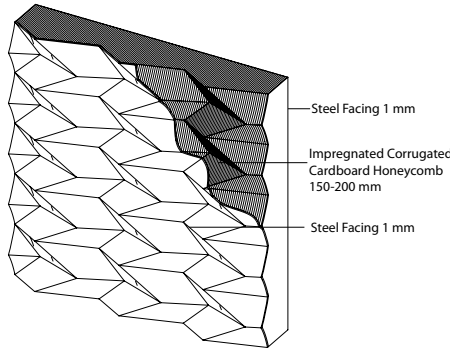


$U = 0.16 \text{ m}^2\text{K}$

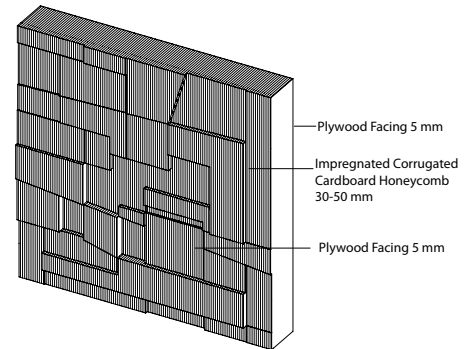
**6** Form-active plasticity walls as facade elements



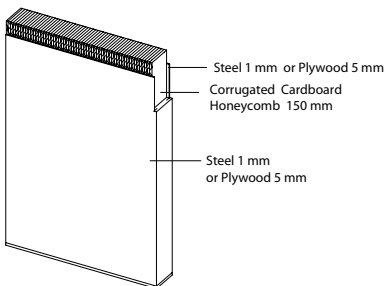
**7** Formactive interior wall (structural)



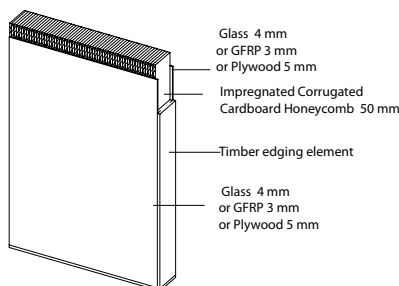
Formactive interior wall (partition)



**8** Interior structural wall



Interior partition wall



**9** Interior structural furniture wall

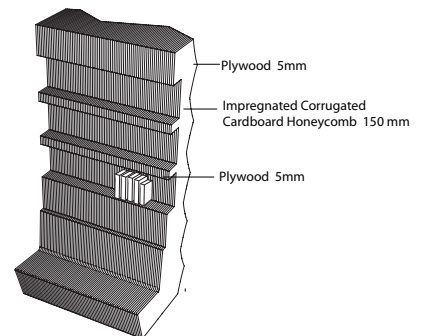


Figure 5.36 - Wall types developed with diverse facings and geometrical patterns

30 cm to cover a thermal insulation U-value of 0.46 W/m<sup>2</sup>K. This type of wall offers a new low cost dimension in massive translucency monolithic architecture.

**2) Load-bearing Media Facade Exterior Wall:** This wall is load-bearing with an impregnated cardboard core and a translucent facing material. The directional tubular structure of the cardboard corrugations allows cables and light applications to be installed on the interior facade with wires for broadcast media or light on the exterior screen. The thickness of the wall component is 30 cm to secure a thermal insulation value of  $U=0.46$  W/m<sup>2</sup>K. As the science of media facades continues to evolve, popularizing the concept of *communicating buildings* in architecture, materials such as corrugated cardboard that allow low cost technical solutions for media facades will gain importance.

**3) Non-combustible and Insulative Structural Exterior Wall:** This unconventionally thick wall (72cm) is load-bearing with an impregnated cardboard core, and FermaCell gypsum board as the facing material. It is highly insulative with U-value of 0.19 W/m<sup>2</sup>K, due to its thickness and massiveness. It is also non-combustible because it is impregnated and sealed with gypsum-based facing. This wall type has a potential to introduce a thick, yet multifunctional product with its structural, fireproof and insulative properties.

**4) Durable and Insulative Structural External Walls:** This wall is load-bearing with a simple unimpregnated cardboard core and durable steel facing material. Constructed with an additional rear ventilation system, the core is protected from exterior effects such as weathering or local stress. It is highly insulative with a U-value of 0.12 W/m<sup>2</sup>K and a thickness of 45 cm.

**5) Thin and Light Structural Exterior Wall:** This wall is load-bearing with a simple unimpregnated cardboard core and durable steel facing material. It has a thickness of 30 cm, is lightweight, and has a thermal insulation U-value of 0.16 W/m<sup>2</sup>K. Following the production and handling process of conventional structural insulated panels, this wall type can be quickly positioned and accepted into the construction sector.

**6) Form-active, Plasticity Walls on External Facades:** This wall can be designed as either load-bearing or non-structural, with an impregnated cardboard core formed with 3-D geometric patterns that are produced by the additive character of corrugated cardboard layering of the core. Possible facings for this type of wall are steel, plywood and plaster. The thickness of the wall component can vary from 45 cm to 60 cm for structural solutions. The thermal insulation value differs according to the pattern, but could potentially be used for passive solar energy systems by reflecting or transmitting UV-light into the interior.

**7) Formactive Interior wall, Structural or Partition:** This interior wall can also be either load-bearing or a non-structural partition wall with an impregnated cardboard core and a geometric pattern. The geometric pattern on the surface can be effective for atmospheric function for spatial quality, as well as acoustic quality and control. Possible facings are steel,



plywood and plaster. The thickness of the wall depends on its load-bearing properties. For non-load bearing walls, 5 cm thick walls are adequate for cardboard core composite form-active interior walls that are fireproof.

**8) Interior Structural Wall and Internal Partition Wall:** This interior wall can also be designed as either load-bearing or non-structural partition function, with an impregnated cardboard core. Possible facings are steel, plywood, and plaster. The thickness of the wall again depends on its load-bearing properties. This wall type also has the potential to be quickly adopted by the industry since there has been a noticeable increase in flexible, open space building designs, that require the use of lightweight partition walls.

**9) Interior Structural Furniture or Partition Walls:** This interior wall can be either load-bearing or non-structural partition wall with an impregnated cardboard core and a geometric pattern produced by the additive character of corrugated cardboard layerings of the core. The geometric pattern not only functions for spatial atmosphere and acoustic control, it can also be used as furniture within the wall. Possible facings are steel, plywood, and plaster. The thickness of the wall is also dependent on the wall's load-bearing capacity and required thermal insulation value.

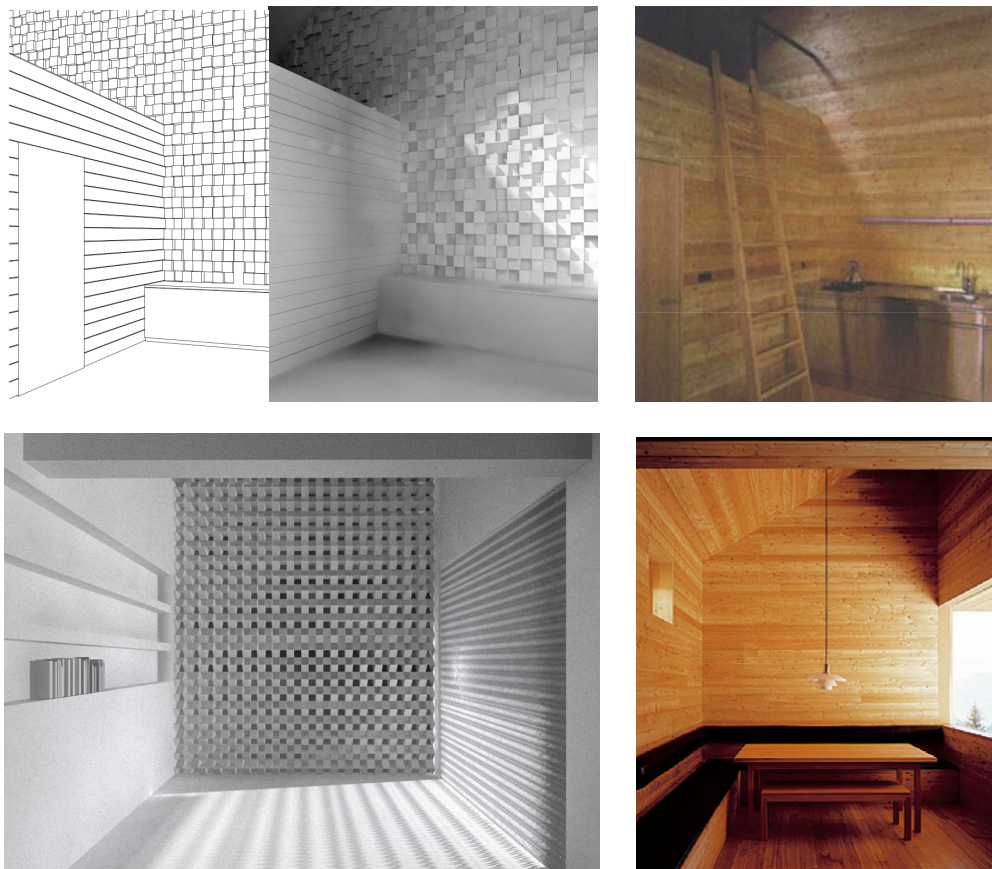


Figure 5.37 - Rageth Mountain Hut project, CATSE cardboard re-materialization renderings



#### **4. Conclusion**

Based on the technical discussions in Chapter IV, this chapter set forth to catalogue the characteristics of corrugated cardboard in the context of architectural practice and theory. The architectonic vision generated in this chapter, therefore aimed to tie cardboard buildings within a concept based on the experimenting outcomes, the environmental, societal, and the component-oriented portion of the study. In comparison to conventional building practices, the focal points have been the technical limitations and future strategies regarding the structural system application directions for massive corrugated cardboard blocks.

As the loads and actions to be resisted within a cardboard massive building system are connected to the size of the building, the structural system, materials used and the type of members joined at the connection, this chapter explored the building's overall structural system and its various functional components. As a tool, comparisons and the identification of concepts in the sector and morphology of massive construction systems with cardboard are utilized. This included investigation of monolithic systems such as boxes and panel systems, but excluded mechanical units and such special construction techniques. The boundaries of this research project are drawn between the morphological structure skala for corrugated cardboard from massive cardboard block systems to linear filigree building components built from cardboard.

Consequently, structural building components for cardboard buildings are classified into two main categories: horizontal and vertical load-distributing components. The structural hierarchy for cardboard vertical load-distributing components in a two story building is analyzed in the illustration of the role of component thicknesses, the related joining mechanisms and the type of vertical load-distributing component. The relationship between floor slabs and wall elements guided the systematic approach for cardboard buildings, and have been classified as either wall-dominant building systems, floor slab dominant systems, or box systems. The joining of vertical and horizontal load distributing elements in the system led to two different strategies: the cases where the joint follows conventional detailing, and the cases where the connection of floor and wall is avoided. Following the strategies that allow the connection between floor slab and wall components, basic joint details are identified as linear joints, point joints or complex puzzle joints.

The mechanical behavior and building physics related testing results indicate that corrugated paper honeycomb core within a sandwich composite as exterior or interior walls possess notable advantages in structural strength, stability and thermal insulation, leading to energy savings and cost reduction during the construction and operating stages of a building. Accordingly, in this study, structurally massive cardboard buildings are selected for further investigated under the light of corrugated cardboard honeycomb core sandwich components. These cardboard honeycomb core sandwich components have the potential to be used in structural applications to generate an alternative supply for new generation building systems that are environmentally low impact and low cost.

In particular, the chapter looked to examine the definition of architectural space using vertical load-bearing and massive corrugated cardboard honeycomb sandwich wall components. A typology study of corrugated cardboard honeycomb core sandwich wall components is presented to determine the effect of a wall's corrugation direction, thickness, intended thermal insulation value, façade construction type, and facing type. As a result, nine wall types consisting of corrugated cardboard honeycomb core sandwich composites were examined on a rematerialization case study based on the Rageth Hut Project.

In sum, the architectonic benefits of cardboard wall components have been determined in structural, thermally insulative, and acoustic aspects. Massive plasticity and translucency, in addition to the spatial quality and atmosphere of corrugated cardboard is accomplished by facade component samples. Corrugated cardboard is shown to have potential in a wide spectrum of environmentally low impact usages, including exterior curtain wall facades, load-bearing walls (exterior and interior), partition walls, and non-load bearing dividing walls with customized qualities (acoustic, thermal, form-wise atmospheric). Moreover, multipurpose walls where structural function is combined with an internal furniture function is shown as a feasible possibility for cardboard buildings.

# Chapter VI

## Conclusion

### Outcomes and Future Studies

"The greatest invention of the 19th century was  
the invention of the method of invention."

Alfred North Whitehead, 1925

Utilizing corrugated cardboard as the primary viable structural material, a conceptual approach for cardboard buildings is examined in this research. It is intended to be an interplay in building technology, generating environments with higher spatial quality with flexibility in design, while integrating sufficient thermal, air movement and acoustic control, and simultaneously reducing energy loss, emissions, and resource consumption. The approach also offers the concept of customized ownership; suggesting demolition and reconstruction of the building in line with the changing needs of the user, viewing the building's short life span into an positive aspect.

As a starting point, the commonalities between modern building practice and the structural morphology of corrugated cardboard are investigated. To guide this approach, a collaborative team tested corrugated cardboard for its mechanical behavior, building physics qualities, and its structural characteristics. Following these tests, prefabricated corrugated cardboard honeycomb core sandwich composites were determined to possess sufficient construction form to be used as wall panels. The typology of corrugated cardboard composite wall panels is further developed according to its function and characteristics, combining the architectonic, constructive, environmental and societal results of this study.

The specific limitations that guided this research focused on the constructive capability, environmental impact and the implementation potential for cardboard buildings as a viable product for the sector.

*Implementation:* cardboard buildings are planned to be introduced as a multifunctional system that offer a green, lightweight, low-cost product, flexible enough to adapt to changing user

demands.

*Construction requirements:* The use of massive corrugated cardboard in block form is planned to provide structural strength and stability for wall components in a two-story residential building (50 kN/m max. load). Protective strategies will be installed reduce the possibility of moisture and fire damage to the cardboard material. The system must remain durable, but yet allow for flexibility in design, and minimum maintenance during its five to ten year lifespan.

*Environmental requirements:* This study endeavours to create an environmentally low impact system based on the results of lifecycle studies. The system was required to have minimal environmental impacts during the production and operating stages, a high rate of recyclability, low energy loss, thermal and UV controls that conform to Minergie standards for exterior walls.

With these goals in mind, the following chapters further examine the conceptual approach to creating cardboard buildings:

*Chapter I* serves as an introduction to the theme and research framework of this thesis. It summarizes the existing research data from the previous attempts to use cardboard as a building material. It further seeks to investigate the background, interrelationships and basic technical comparisons between cardboard and contemporary building demands.

- *Chapter II* examines the societal aspects of cardboard construction within the framework of Switzerland's housing construction industry. In particular, it looks at the current perceptions of using cardboard as a building material in modern residences. This chapter also proposes to develop innovative ways to introduce cardboard construction into the existing housing market. It does so by analyzing user preferences and market trends in both the housing and construction industries. The end result is a workable solution to gradually introduce cardboard constructed houses as a feasible and flexible alternative for the changing needs of renters and buyers in the housing market.

- *Chapter III* provides an analysis of the environmental aspects underlying the development of corrugated cardboard as a building component. This chapter seeks to make an honest environment assessment using the lifecycle approach (LCA) as a model. The cradle-to-grave cost of corrugated cardboard is calculated by looking at the two main stages of the process: 1) the production stage, and 2) the construction-user stage. For the construction stage, the study evaluates the total environmental impact of manufacturing cardboard wall components. For the environmental cost of the construction phase, the energy costs of various cardboard wall components (constructed with different skin options and thicknesses), in terms of thermal U-value, are compared to the energy costs of other wall materials.

- *Chapter IV* focuses on the structural aspects of cardboard architecture, drawing on the testing and analyses of corrugated cardboard in a sandwich composite for wall components,

conducted by the CATSE engineering team. This chapter provides the groundwork for the subsequent chapter pertaining to the possibilities in the architectonic realm. It further looks at the structural and technical elements of cardboard housing in relation to user sector demands. In doing so, this section draws from and elaborates on previous chapters to set the framework for the architectonic approach.

- *Chapter V* examines the architectonic element underlying the use of cardboard as a wall component within its space-defining function. In this study, nine types of walls, each with varying characteristics, were identified for analysis. The geometric pattern of each wall was modified to control sunlight and its degree of acoustic insulation, as well as to adjust the indoor ambience and spatial qualities. The chapter further looks at other architectonic characteristics of cardboard buildings, including the potential use of cardboard in various other structural elements (i.e. floor slabs).

## **1. Primary Results**

This study provides a close examination of the technical, social and environmental impact on the positioning of corrugated cardboard in the Swiss building industry. Using a top down approach, it gives a basic understanding of the research, development and implementation for innovative materials and techniques in the construction sector. The main results can be divided into the corrugated cardboard research level, the implementative strategy level, and the innovation management level.

i) At the material research level, the study examines the structural applications, resulting in efficiency of the corrugated cardboard honeycomb as a core in sandwich panels. The investigations demonstrate significant potential for the load-bearing characteristics of structural cardboard, which offers substantial design flexibility and adaptability, a low thermal U-Value, reduced cost, and minimum maintenance due to its shortened lifespan. In particular, impregnated cardboard core provides a viable solution for increased structural strength and stability against the humidity and fire.

When used as a vertical load-bearing component, corrugated cardboard honeycomb core sandwich panels allow for the architectonic potential to include the diversity of expression on the wall function level as exterior walls, load-bearing interior walls, dividing walls, facades, and curtain walls. In particular, massive plasticity achieved through manufacturing is a distinct possibility. Wall and facade components, configured with 3-D patterns, define innovative spaces in terms of atmosphere, thermal and acoustic comfort, and quality.

Corrugated cardboard wall components also demonstrate an extensive spectrum of usage depending on its facing material and detailing forming facade. This architectonic study indicates a significant need to improve and validate corrugated cardboard composites as synthetic building elements. However, cardboard in general, and structural corrugated cardboard in particular, requires more testing and development to become a viable multifunctional product.

Additionally, cardboard can also be utilized to reduce construction layers and materials, and therefore complexity, costs and time in the building construction process.

ii) On the strategy level, the implementation of prefabricated cardboard buildings is examined across many dimensions within this study. Structurally insulated panel systems, prefabrication and preassembly guided the research and provided fundamentals of cardboard buildings and its implementation. It is foreseen that a better understanding of the social and technical failures and performance mechanisms of cardboard will allow higher utilization of its intrinsic strengths. In addition to the technical implementation options, and societal themes concerning the sector and the user, the relationship between cardboard material is investigated and results in an implementation approach set forth Chapter II.

iii) At the innovation management level, a multi-discipline collaboration has led to promising potential that focuses on the current needs of modern complex construction. In search of implementation of a new innovative building material, there is a clear need for architects to collaborate effectively with engineers and social researchers. Such a setting will certainly increase the testing, implementation and the eventual usage of cardboard buildings in contemporary architecture.

## **2. Technical Results from the Collaborative Engineering Group**

The technical aspects involved in this study (testing, analysis and modeling of corrugated cardboard honeycomb and composite sandwich) are the framework for the CATSE collaborative research project. The following experimental and analytical data were the basis of this study:

- The principle factors that affected the failure mechanisms were identified as core thickness, corrugation direction, paper type, corrugation type, and facing material characteristics.
- A load-bearing sandwich wall with impregnated honeycomb core requires a thickness of at least 200 mm to resist the design loads of a two-story office building.
- The greatest threats to corrugated cardboard honeycomb core's structural strength and stability are moisture/humidity and fire. These weaknesses were experimentally tested by impregnating the core with an inorganic substance. However, the manufacturing process of impregnating the material remains incomplete for very thick corrugated cardboard wall components and thus new methods of manufacturing are required.



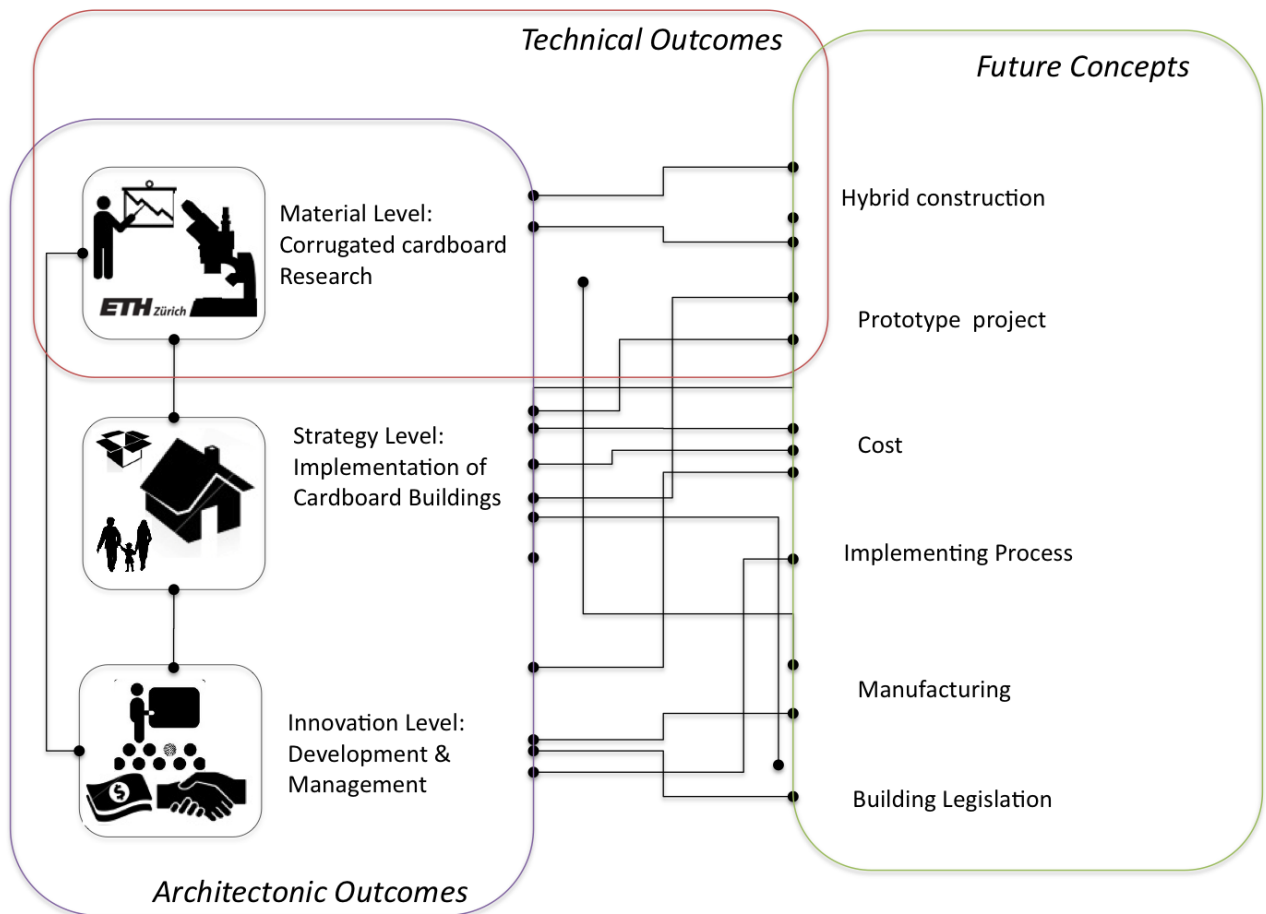


Figure 6.1 - Relationship between future concepts and architectonic results.

### 3. Future Approaches

The architectural and structural design of cardboard buildings is further dependent on various decisions and processes. This begins with a) the implementation of corrugated cardboard as a building system, b) evaluation of cardboard's hybrid construction potential, c) the generation of manufacturing lines and processes, d) the construction of prototype case study, e) an analysis of management issues related to cost economics, and f) an examination of potential legislation.

**a) Implementing Cardboard Buildings in the Construction Sector:** Along with all the above mentioned positive outcomes, it is also necessary to emphasize that cardboard will never completely replace traditional building materials. The niche for cardboard buildings will be defined and further explored by future projects and prototype that will provide more information to users about its multifunctional character and economic benefits which may raise awareness for the product in the structural panel industry.

The mission of contributing to today's architectonic conceptualization requires a broad spectrum of tasks. It requires the convergence of technological developments and implementation experiences from related sectors (packaging and structural panel) to the building sector and

to systematically underpin spatial designs using engineering testing results for corrugated cardboard. In order to justify the investment in facilities and commercial buildings, a comparative study identifying the likely results of constructing cardboard buildings needs to be undertaken.

With regard to a cardboard building's lifecycle, issues for further analysis include production (i.e. efficiency in manufacturing lines, the building's structural performance, dimensional stability, moisture, humidity and thermal control properties), construction (i.e. process management, onsite component protection), usage (i.e. long-term effects on strength and stiffness, proof of barrier properties, user health and safety concerns) and waste management (i.e. reusability, prevention and recovery).

In technical terms, improvement in the standardization of the cardboard panels, related joints and construction techniques will result in a competitive advantage. A prototype study, using standard performance testing for full-size building components within the system, will consist of a two-story building, and will further contribute to the technical improvement of the overall system. Other technical aspects of cardboard buildings, including cardboard flooring and roof components, their acoustic control and quality, energy absorption, and the ductility for vibration reduction will also be explored.

**b) Hybrid Construction:** Hybrid construction of the corrugated cardboard composites in combination with other materials is another alternative that will be examined. One possibility is to combine cardboard with steel or wooden frame systems, or incorporate it with other paper byproducts. Hybrid combinations using paper-based byproducts, such as structural cardboard tubes offer effective solutions. For example, they can be used in construction of floor slabs, since creep is a major issue for pure cardboard components. In principle, roof components can be configured with massive corrugated cardboard blocks in combination with lightweight cardboard for folding functions.

**c) Manufacturing Potential:** The industrial production of cardboard building components will impose new requirements on the development and production of machinery, as well as factories for the production of building components.<sup>1</sup> The quality and the standard of productivity of these machines will influence the standard, the productivity, and the quality of the entire building industry, qualifying cardboard buildings' implementation into the sector. Due to the limited technical data available regarding cardboard as a building material, further research is required on material technology, processing technology and cost efficiency to justify the required improvement in quality, cost and performance.

**d) Prototype:** The next stage of this research is the construction of a prototype to confirm this theoretical and experimental study, and to explore the limitations of massive structural cardboard housing constructed with corrugated cardboard sandwich composite components.

<sup>1</sup> Dietz and Cutler 97.

Widespread communication of the prototype to the public is significant as an evaluation platform for innovative building materials and systems to prove themselves within the existing building codes and standards.<sup>1</sup> A thorough cost analysis and economic study, as well as conformity with existing building codes will be investigated during the prototype project. Additionally, the prototype building as a system will help demonstrate the long-term behavior of the material and the system. The prototype will also be used as a tool to investigate the actual microclimate of cardboard buildings. The complex physical and chemical interaction of the constituents of the microclimate on the behavior of the cardboard building material composite can be observed and measured.

A close look at past cardboard building prototypes highlights the high costs for such projects. It is predicted to be relatively expensive to produce the first prototype buildings, despite the low cost of the primary material compared to other common building materials. The prototype will be a small demonstration of actual work flow, including stages of manufacturing, transportation, delivery, storage and onsite building. The prototype, therefore, will allow a close examination of the cost factors and strategies for lowering the construction costs of cardboard buildings, as a tool to base the finance of a large-scale commercial implementation.

**e) Economic Issues:** Cost efficiency is a significant factor when introducing a new product into the market, where there exists highly optimized product development measures that are resistant to change. The methodology for the cost-efficient implementation of sustainable innovative products needs to be examined and communicated through its low cost and environmental low impact, incorporating aspects of time, budget, production and assembly. As a first attempt to define the feasibility of the project, a strategic market assessment is required, identifying the strengths and weaknesses of the product in comparison to other competitors in the construction industry, followed by an in-depth cost-efficiency analysis and related economics of the various components and the total building.

To secure the sustainable implementation of cardboard buildings in the sector, the primary questions that need to be answered are as follows

- How can we drastically increase the speed of the product development process while maintaining quality and decreasing costs?
- How can we maintain and manage engineering knowledge and apply it to various lifecycle activities?
- How can we increase competitiveness in time to market, time to deliver, flexibility and variety?
- How can we build and apply tools for knowledge management in product development?

**f) Legislation:** No common building codes currently exist for corrugated cardboard honeycomb as a massive building material, cardboard composite wall structures or their structural performance. The permission to build and obtain insurance to build can only be obtained

<sup>1</sup> Ambrose 1.

when the governmental authorities confirm the performance and safety of an experimental building material. Thus, there is certainly a risk concerning the refusal of the building-planning permission request or building control approval for cardboard buildings. Accordingly, insurance for the completed building and potential failure during construction or use, will also need to be settled with the authorities prior to full implementation.

Architect Shiegeru Ban's experience in gaining official recognition and integration of his cardboard tube buildings presents a telling example of the long and complex procedure. A clear communication of common interests may help to speed the approval process with local governments. Thus, further collaborative and experimental research on prototypes of cardboard buildings, involving the construction industry, governmental agencies, and academia may result in an effective platform for the product development and implementation.

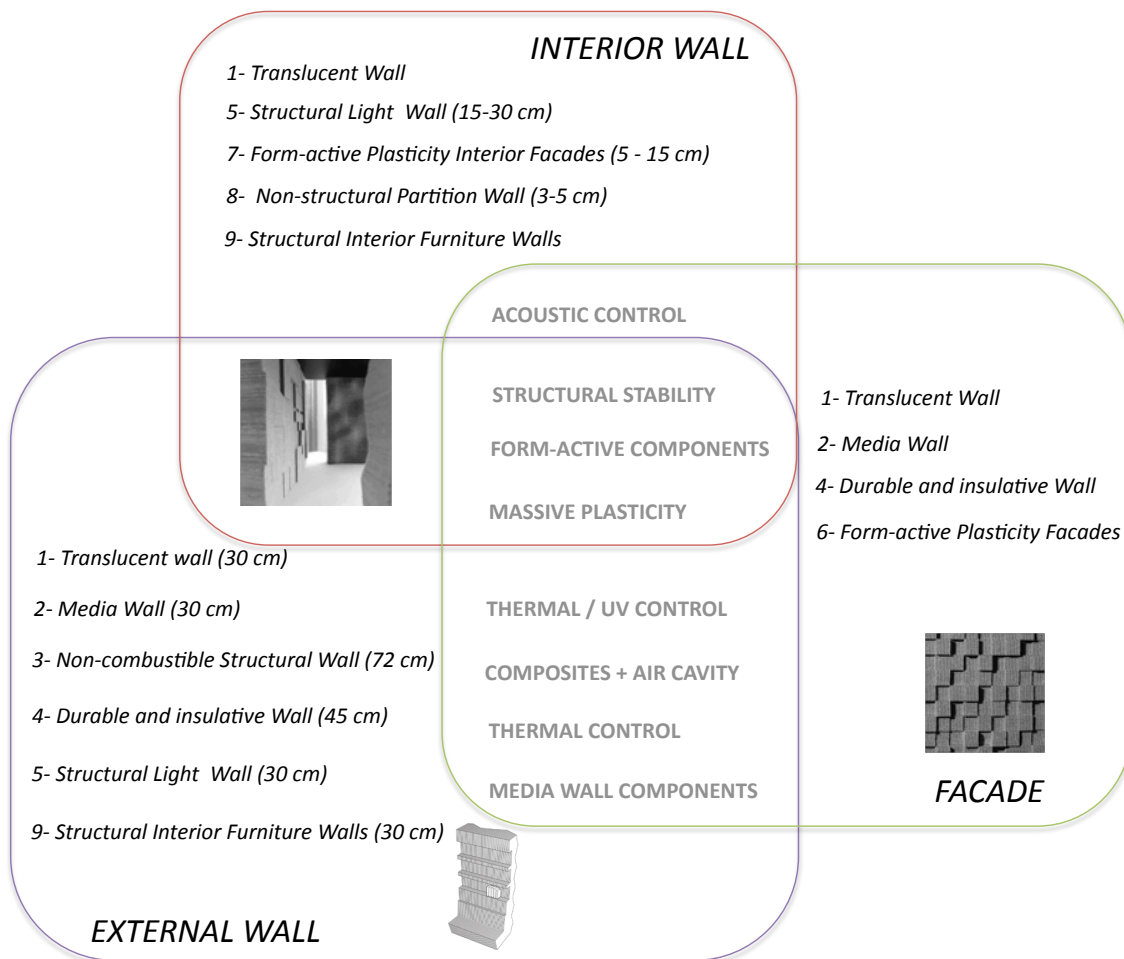


Figure 6.2 - Constructive Outcomes of Corrugated cardboard wall composites.

#### **4. Epilogue**

This research study has analyzed the technical constraints and alternative problem solving for modern construction demands through the use of corrugated cardboard as the primary building material within a system. Additionally, the research demonstrates the significance of the underlying problems, rooted in non-technical constraints such as social, economic and political factors. The effective implementation of cardboard as a viable innovative building material and the efficiency of its building building system and technology is dependent on these constraints for a sustainable contribution to the construction sector. The user, designer and manufacturer's own interpretation of the new building material forces the decision makers to take both the statistical and technical data into account. Nonetheless, early decisions will be heavily influenced by each decision maker's existing ideas regarding the viability of cardboard as a building material.

Therefore, the fundamental outcomes achieved with this collaborative research project strongly suggest that cardboard buildings' most significant hurdle is communicating this innovative material, component and building system to wider masses.





# Bibliography

## Books and Articles

**Aicher, S. / Höfflin, L. (1999):** "Long Term Performance Test of Eccentrically Loaded Sandwich Wall Elements with Wood-based Skins", *Otto-Graf-Journal*, Vol. 10, 129-143

**Allanson A./ Svärd B.(2001):** "Stability and Collapse of Corrugated Board", *Master Thesis*, Lund University, Sweden

**Ambrose, J. (1979):** "Simplified Design of Buildings Structures", John Wiley & Sons Press, USA

**Arvanitis et al. (1996):** "Percentage of Innovative Firms", *Swiss Federal Office of Economics*, Bern

**Arvanitis et al. (1998):** "Innovationstätigkeit in der Schweizer Industrie", *Swiss Federal Office of Economics*, Bern

**Asako O. (2005):** "Paper and Cardboard Food Packaging," *Journal of Urban Living and Health Association* 49, no. 3: 135-143.

**Baig, M.A. / White, W.O. (2008):** "Multiple Layer Gypsum Cellulose Fiber Composite Board and the Method for the Manufacture thereof", Patented, US

**Baird, G/ Chan, S.A. (1983):** "Energy Cost of Houses and Light Construction Buildings", *New Zealand Energy Research and Development Committee*, Report no.76, New Zealand

**Baldwin, J. (1996):** "Bucky Works: Buckminster Fuller's Ideas for Today", Wiley & Sons, Inc. publ. 126-127, USA

**Banfi, S./ Farsi M./ Filippini, M./ Jakob, M. (March 2008):** "Willingness to Pay for Energy Saving Measures in Residential Buildings", *Energy Economics* 30, no. 2

**Banfi, S./ Jakob, M./ Cepe (2008)** "Energieeffizienz und Komfort: Wie viel sind Mieterinnen und EigentümerInnen zu zahlen bereit?", *Tagung Novatlantis Bauforum*, 506-507.

**Bangash, M.Y.H. (1999):** "Prototype Building Structures: Analysis and Design", Thomas Telford, London, 47

**Bechthold M. (2001):** "Digital Design and Manufacturing", Harvard University, Cambridge.

**Benyus, J. (2002):** "Biomimicry: Innovation Inspired by Nature", Harper Perennial, New York

**Bernhardt, A.D./ Dietz, A.G. H./ Cutler, L. S. (eds) (1971):** "The Mobile Home Industry: a Case Study in Industrialization", *Industrialized Building Systems for Housing*, MIT Press, Cambridge

**Borsani C./ Salvi M. (August 2003):** "Analysebericht zum Minergie-Standard", *Internal Memorandum of Zürcher Kantonalbank (ZKB)* to CEPE-Team, Zurich

**Brayer, M. A. (1997):** „David Georges Emmerich“, by Collection du FRAC Centre, Conception et coord.: publ: Éditions HYX, Orléans

**Buchanon, A./ Levine, B. (1999):** "Wood-based Building Materials and Atmospheric Carbon Emissions", *Environmental Science & Policy*, December Issue No 2: 427-437.

**Buckminster, F./ McHale, J. (1963):** "Inventory of World Resources Human Trends and Needs ", proposal for International Union of Architect, MacMillan Publ., New York

**Buckminster, F. / Marks, R. W. (1973):** "The Dymaxion World", Doubleday & Company, Inc., New York, p119

**Chan, D.W.M./ Chan, A.P.C. (2002):** "Public Housing Construction in Hong Kong: a Review of its Design and Construction Innovations", *Architectural Science Review* 45, 4: 349–359.

**Chen, Z./ Croome, D.C./ Hong, J./ Li, H./ Xu, Q (2006):** "A Multi-criteria lifespan energy efficient approach to intelligent building assessment", *Energy and Buildings* No.38: 394, 393, 397, 398.

**Cole, R.J./ Kernan, P.C. (1996):** "Lifecycle Energy Use in Office Buildings", *Building & Environment* Vol.31 No.4: 308.

**Cripps A. (2004),** "Cardboard as a Construction Material: a Case Study", *Building Research & Information* 32, no. 3: 207-219

**Deplazes, A./ Roesler, S./ Seger, C. (ongoing):** "Theory of Massive and Filigree Construction: Intercultural Perspectives in the Construction of Architecture", *PhD thesis*, unpublished, ETH Zurich

**Deplazes, A. (2005):** "Constructing Architecture: Materials, Processes, Structures, A Handbook", Birkhäuser, Germany.

**Devlin, K./ Nasar, J.K (Dec. 1989):** "The Beauty and the Beast: Some Preliminary Comparisons of 'High' Versus 'Popular' Residential Architecture and Public Versus Architect Judgments", *Journal of Environmental Psychology* 9, no. 4: 333–344.

**Dietz, A. G. H. (1971):** "Building Technology: Potentials and Problems", *Industrialized Building Systems for Housing* , MIT Press, Cambridge.

**-/ Cutler/ Laurence S. (ed.) (1971):** "Industrialized Building Systems for Housing ", MIT Press, Cambridge.

**Eekhout, M./ Verheijen F./ Visser R. eds (2008):** "Cardboard in Architecture ", *Research in Architectural Engineering Series*, Volume 7 , Delft University Press, Amsterdam.

**Emmerich, D.G. (1983):** "Maisons en Carton", Paris

**Fernandez J. (2006):** "Material Architecture", *Architectural Press*, Italy.

**Fitzgibbon, C. M. (1978):** "Component Type Building Construction System", Description : United States Patent 4165591

**Gibb, A. G. F. (1999):** "Off-site Fabrication: Prefabrication, Pre-assembly and Modularization", Latheronwheel: Whittles Publishing

**Gordon, J. E. (1984):** "The New Science of Strong Materials", Princeton University Press, Princeton, 178-181

**Groák, S. (1992):** "The Idea of Building", Spon Press, London

**Grove, A.S. (1996):** "Only the Paranoid Survive: How to exploit the crisis points that challenge every company and career", Doubleday Press, New York

**Hilsdorf, H. (1972):** "Masonry Materials and their Physical Properties", *Proceedings from Planning and Design of Tall buildings International Conference*, Lehigh University: 991-993.

**Howard, N./ Kspoor, P. (2000):** 'Envest Software for Assessing the Environmental Impact of Buildings', Centre for Sustainable Construction, BRE ; Envest, March: 2, 67.

**Howard N./ Sutcliffe, H. (1994):** "Precious Jolues", *Building Journal*, March: 48-50.

**Hübner P./ Huster F. (1973):** Coques en Carton Plastifié pour habitat de loisir. In: *Technique & Architecture* Nr. 295 November, S. 100-101

**Hugentobler, M. (2006):** „Demographischer Wandel: Herausforderung für den Wohnungsmarkt“, ETH, *Tagung des Novatlantis Bauforums*, 20 Juni, Zurich, 15-28.

**Ilhan, Y./ Ayguen, M. (2006):** "Construction Classification of Continuously and Pointfixed Curtain Wall Systems", *1st International CIB Endorsed METU Postgraduate Conference Built Environment & Information Technologies*, Ankara

**Jakob, M. (2006):** „Marginal Costs, Cost Dynamics and Co-benefits of Energy Efficiency Investments in the Residential Buildings Sector“, *Energy Policy Magazine* No. 34 January :175, 182, 184, 186.

**Jirsa, J.O. (1972):** "Cast-in-Place Joints for Tall Concrete Buildings", *Proceedings from Planning and Design of Tall buildings International Conference*, Lehigh University, Bethlehem 195

**Kalin, Z. (1993):** "The State of Demolition Waste Recycling in Canada," University of Western Ontario, Centre for Studies in Construction

**Kaniut, C./ Kohler, H. (1995):** "Lifecycle Assessment- A supporting Tool for Vehicle Design?", *Proceedings of the IFIP WG5.3 International Conference on Life-cycle Modelling for Innovative Products and Processes*, Berlin

**Karagiozis, A. (2002):** "Building Enclosure Hydrothermal Performance Study, Phase I", April, USA: US Oak Ridge National Laboratory, Tennessee

**Karhu, V. (1997):** "Product Model Based Design of Precast Facades", VTT Building Technology Technical Research Centre, Espoo, Finland, *Journal ITcon* Vol. 2: 1-31

- Kline, J. E. (1991):** "Paper And Paperboard: Manufacturing and Converting Fundamentals"
- Klöck, W./ Aicher, S. (2005):** "Size Effect in Paper Fiber-Reinforced Gypsum Panels Under In-Plane Bending", *Wood and Fiber Science Journal*, Volume 37, Number 3 / July 2005: 403-412.
- Klöpffer, W. (1997):** "In defense of the cumulative energy demand", *Earth and Environmental Science Journal*, Volume 2, Number 2 / June, 1997, Page 61,
- Kohler, N. (1999):** "The Relevance of the Green Building Challenge: an Observer's Perspective", *Building Research and Information*, 24(4/5): 309-20.
- Koschade, R. (2002):** "Sandwich Panel Construction Handbook". Ernst & Sohn, Berlin, 14
- Krause, F.L. (1995):** "Potentials of Information Technology for Lifecycle Oriented Product and Process Development", *Proceedings of the IFIP WG5.3 International Conference on Life-cycle Modelling for Innovative Products and Processes*, Berlin
- Kua, H.W./ Lee, S.E. (2002):** "Demonstration Intelligent Building - a methodology for the promotion of total sustainability in the built environment", *Building & Environment*, March Vol.37: 232, 233, 239.
- Lacinski P./ Bergeron, M. (2000):** "Serious Straw Bale : a Home Construction Guide for all Climates", Chelsea Green Pub. Co., White River Junction
- Leu, B./ Priester, A. (1997):** „ Lebensqualität und Armut in der Schweiz., Paul Haupt, Bern
- Lewicki, B./ Pauw, A. (1972):** "Joints, Precast Panel Buildings", *Proceedings from Planning and Design of Tall buildings International Conference*, Lehigh University, Bethlehem, 172
- Li, J. / Colombier, M. (2009):** «Managing Carbon Emissions in China Through Building Energy Efficiency», *Journal of Environmental Management*, Volume 90, Issue June 8, Pages 2436-2447
- Lien, A. / Hastings, R. (et.al) (2001):** "IEA SHC 28 ECBCS 38: Sustainable Solar Housing - Marketable Housing for a better Environment" , EMPA-ZEN, September Issue, Dübendorf
- Mai, Y.W. (1980):** "Performance evaluation of sandwich panels subjected to bending compression and thermal bowing", *Journal Materials and Structures*, 13(3): 159-168.
- Malinen, R. (1997):** "Development Prospects for Pulp and Paper Industry in South-East Asia Environmental," Issues of Pulp and Paper Industry in Asian Countries, International Seminar, Thailand (19-20 Mar. 1997): 210-217.
- Malkawi, A. (2004):** "Developments in Environmental performance simulation", *Automation in Construction*, No.13: 437-445, 437-443.
- Maslow, A. (1943):** "A Theory of Human Motivation," *Psychological Review* 50 (1943): 370-396.
- Mcdonald, D. B. (2009):** "Gypsum Wood Fiber Structural Insulated Panel Arrangement", U.S. Patent 20080245007.

**McHale, J. (1961):** "Richard Buckminster Fuller", *Architectural Design Journal*, July, 289-315

**McHale, J. (1971):** "World Facts and Trends", *Futures*, Vol. 3: 216

**Mcquaid, M. (2004):** "Shigeru Ban", Phaidon, London

**Merkley, D./ Luo J. C. (2004):** "Fiber Cement Composite Materials Using Cellulose Fibers Loaded with Inorganic and/or Organic Substances", United States Patent 6872246

**Mihashi H. /Kirikoshi K. / Arikawa S. (1995):** "Recycling of Used Paper as a Building Material", *Proceedings of the International Rilem Workshop, Disposal and Recycling of Organic and Polymeric Construction Materials*, Koriyama Japan

**Mikluchin, P.T. (1972):** "General Design and Architectural Aspects of Masonry Buildings", "Proceedings from Planning and Design of Tall buildings International Conference", Lehigh University: 959-960

**Moholy-Nagy, S. (1957):** "Native Genius in Anonymous Architecture", Horizon Press Inc., New York

**Moslemi, A. (1999):** "Emerging Technologies in Mineral-Bonded Wood and Fiber Composites", *Advanced Performance Materials*, Vol. 6, No. 2: 161-179

**Nadel, B. A. (2006):** "21st Century Building Envelope Systems: Merging Innovation with Technology, Sustainability, and Function", *Architectural Record FAIA*, McGraw Hill Publ., August Issue.

**Naji, B. T. / McGown, G. (2000):** "Lightweight Wall Construction", US Patent Issued on June 21, Patent Description, US

**Ongmongkolkul, A. (2001):** "Lifecycle Assessment of Paperboard Packaging Produced in Medium Sized Factories in Thailand", *Master Thesis*, Thailand: Asian Institute of Technology, School of Environment, Resources and Development, 19

**Oxman, R. (1978):** "Flexibility in Supports", *Doctoral Dissertation*, Technion-Israel Institute of Technology, Haifa: 166-180

**Palokangas, A. (1997-2004):** "Development Prospects for Pulp and Paper Industry in South East Asia", *Paperboard- A Packaging Material for Future*: 210-217

**Paulapuro, H. (ed.) (2000):** "Paper and Board Grades", *Papermaking Science and Technology* ; book 12, Fapet Oy, Helsinki

**Pflug J. / Xinyu F. / Vangrimde B. / Verpoest, I. / Bratfish P. and Vandepitte D. (2002):** "Development of a Sandwich Material with Polypropylene/Natural Fiber Skins and Paper Honeycomb Core", *Proceedings of 10th European Conference on Composite Materials*, ECCM-10

**Pflug, J./ Verpoest, I. (2005):** "Sandwich Structures 7: Advancing with Sandwich Structures and Materials", *Proceedings of the 7th International Conference on Sandwich Structures*, 29-31 August 2005, Aalborg University, Aalborg

**Pohl, A. (2009):** "Strengthening Corrugated Paper Honeycomb Core for Application in Structural Elements", *PhD Thesis*, ETH Zurich

**Poon, C.S. (2009):** "Precast Concrete Elements, Concrete Work", The Hong Kong Polytechnic University, Hong Kong

**Porter, Max (1993):** "Full-Scale Composite Sandwich Walls: Theory and Behavior ", Iowa State University, National Science Foundation Award #9215567

**Redstone, L.G. (1984):** "Masonry in Architecture", McGrawhill Book Company, New York, 161

**Reijnders, I./ van Roekel, A. (1999):** "Comprehensiveness and Adequacy of Tools for the Environmental Improvement of Buildings", *Journal of Cleaner Production*, March 7(3): 221-5

**Reisa, E. M./ Rizkallab, S. H. (2008):** "Material Characteristics of 3-D FRP Sandwich Panels", *Journal Construction and Building Materials*, Volume 22, Issue 6, June 2008: 1009-1018.

**Richard, R. B. (2005):** "Industrialised Building Systems: Reproduction Before Automation and Robotics", *Automation in Construction*, 442-451.

**Rosenthal, E. (2005):** "Thinking Twice about the Garbage", *International Herald Tribune*, 23 April 2005

**Ruegg, A. (1987):** "Le Corbusier, Edmond Wanner, Francis Quétant und die Villa Ruf in Le Grand-Saconnex/Genf 1928/29 ", GTA Publication, ETH Zurich

**Savolainen, A. (ed) (1998):** "Paper and Paper Converting", *Papermaking Science and Technology*; book 12, Book Reviewer: David J. Bentley, Jr., Fapet Oy publ., Helsinki

**Sedlak , V.(1975):** "Paper Structures", *2nd International Conference on Space Structures*, London: 780-793

**Seddon, J./ Cork (2001):** "The Case Against ISO 9000", Second. Ed., Ireland

**Schmoch, U./ Jungmittag, A./ Rangnow, R. (2000):** " Innovation Standpoint: Switzerland" (in original language: Innovationsstandort Schweiz), a study for Swiss Federal Office for Professional Education and Technology (Frauenhofer Institute for System techniques and Innovation-Research).

**Schönwälder, J.(ongoing):** "Cardboard as a Building Material – Determination and Modeling of the Mechanical Behavior", *Unpublished PhD Thesis*, Supervisor: Jan Rots, TU Delft

**Schuler M./ Dessemontet P./ Jemelin C., Jarne A./ Pasche N./Haug W. (2007):** „Atlas des Räumlichen Wandels der Schweiz“, Verlag NZZ, ISBN: 3-823-215-7, Zurich: 278

**Schulz H.P. / Würmli P. / Farago P. / Brunner B. (2005):** "Wohnen 2000: Detailauswertung der Gebäude-und Wohnungserhebung" Swiss Federal Statistical Office, Federal Office of Housing.

**Sheppard R./ Threadgill R./ Holmes J. (1974):** "Paper Houses", Schocken, New York



**Skillius, A./ Wennberg, U. (February 1998):** „Continuity, Credibility and Comparability: Key Challenges for Corporate Environmental Performance Measurement and Communication“, European Environment Agency.

**Smith, B./ Coull, A. (1972):** “Elastic Analysis of tall Concrete Buildings”, *Proceedings from Planning and Design of Tall buildings International Conference*, Lehigh University, Bethlehem, 159

**Solomon, M. R., Bamossy G., Askegaard S. and Hogg M.K. (2006):** “Trends in Consumer Behavior”, *Journal of Consumer Behavior and Consumer Behavior: an European Perspective*, Prentice Hall Europe, Essex

**Spengler, T./ Püchert, H. / Penkuhn, T./ Rentz, O .(1997):** “Environmental Integrated Production and Recycling Management“, *European Journal of Operational Research*, March, 308-311

**Staib G. / Dörrnhöfer, G ./ Rosenthal M. (2008):** “Components and Systems: Modular Construction- Design, Structure, New Technologies“, Detail Publications Birkhäuser, Germany

**Stein R.G./ Serber D./ Hannon, B. (1976):** “Energy Use for Building Construction“, Center for Advanced Computation, Univ. of Illinois, US Department of Energy EDRA Report (3rd Ed.), Center for Advanced Computation, University of Illinois

**Sumi, C. (1989):** “Maison á sec /Immeuble-Villa /Plan libre. Das “Projet Wanner” (1928) und die “Clarté” (1930-1932) in Genf von Le Corbusier und Pierre Jeanneret“, Gta, Institut für Geschichte und Theorie der Architektur, GTA Publication, ETH Zurich

**Testa, C. (1972):** “The Industrialisation of Building“, Van Nostrand Reinhold, New York

**Thomsen, O. / Bozhevolnaya E. / Lyckegaard,A. eds. (2005):** “Sandwich Structures 7: Advancing with Sandwich Structures and Materials“, *Proceedings of the 7th International Conference on Sandwich Structures*, Aalbo, Springer, Netherlands

**Thormark, C. (2006):** “The Effect of Material Choice on the Total Energy Need and Recycling Potential of a Building“, *Building & Environment* 41, August No 8., 1019

**Thormark, C. (2002):** “A Low Energy Building in a Life Cycle—its Embodied Energy, Energy Need for Operation and Recycling Potential“, *Building & Environment*, Volume 37, Issue 4, April, 429-435

**Till J./ Schneider T (2007):** “Flexible Housing“, Architectural Press, London, 4

**Timberlake, J./ Kieran, S. (2003):** “Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction“, Irwin/Mcgraw Hill, New York

**Van Dooren, E./ Van Iersel, T. (2008):** “Cardboard in Architecture“, *Research in Architectural Engineering Series*, Volume 7, Imprint: Delft University Press, Netherlands

**Van Wezemaal, J.E. (2005):** „Investieren im Bestand: Eine Handlungstheoretische Analyse der Erhalts-und-entwicklungsstrategien von Wohnbau- Investoren in der Schweiz“, Publikation der Ostschweizerischen Geographischen Gesellschaft, Neue Folge, Heft 8, St.Gallen, 129

**Vock, P. (2001/7):** "An Anatomy of the Swiss Construction Cluster", Center for Science & Technology Studies, 16

**von e. Dooren F., Verheijen F., Eekhout M. (ed.) (2008):** "Cardboard in Architecture; an Overview", *Research in Architectural Engineering Series*, Volume 7, Delft University Press, Amsterdam

**Yannick, J. (2002):** "Biomorphic Design: Perspectives on its Aesthetic, Restorative and Ecological Value", *Proceedings of the Dresden International Symposium of Architecture*, Dresden

**Warszawski, A. (1999):** "Industrialized and Automated Building Systems", Taylor & Francis Press, London

**Weber T. (2008):** "The Language of Paper: A History of 2000 Years ", Orchid Press, Bangkok

**Weijun, G. / Ariyama, T. /Ojima T. (2001),** "Energy Impacts of Recycling Disassembly Material in Residential Buildings", *Energy and Buildings*, Volume 33, Issue 6, July 2001, 553-562

**Wuest & Partner (2006):** "Immo-Monitoring 2006", W & P Press, Switzerland

**Wuest & Partner (1999):** "Wiederbeschaffungswert Bauwerk", W & P Press , Switzerland, 8

**Zhang, Z./ Wu, X./ Yang, X./ Zhu, Y. (2006):** "BEPAS: a lifecycle building environment performance assessment model", *Building & Environment* 41, May Issue no. 5

**- / (1970):** "Paper House Review", *Architectural Design Journal*, October, 499-505.

## On line Journals, Articles, Papers and Websites

Bundesamt für Statistik - Swiss Federal Office of Statistics (2004)-[www.bfs.admin.ch](http://www.bfs.admin.ch)  
 "Wohnen2000": [www.bfs.admin.ch/bfs/portal/de/index/news/publikationen.Document.64887.pdf](http://www.bfs.admin.ch/bfs/portal/de/index/news/publikationen.Document.64887.pdf)

BUWAL Dokumentationdienst (March 2006): "SimaPro7 - Database Manual: The BUWAL 250 Library", p13 - [www.buwal.ch/publikat/oekobila.htm](http://www.buwal.ch/publikat/oekobila.htm).

CIRIA (1999): Standardisation and Pre-assembly Adding Value to Construction Projects, London, Report No:176-  
[www.thenbs.com/PublicationIndex/DocumentSummary.aspx?PubID=122&DocID=247541](http://www.thenbs.com/PublicationIndex/DocumentSummary.aspx?PubID=122&DocID=247541)

CMIT (2002): Commonwealth Scientific and Industrial Research Organisation(CSIRO), Australia "CSIRO Sustainable Built Environment Online Brochures: Embodied Energy, CSIRO Manufacturing & Infrastructure Technology"- [www.cmit.csiro.au/brochures/tech/embodied](http://www.cmit.csiro.au/brochures/tech/embodied)

Credit Suisse (February, 2005): "The Swiss Real Estate Market: Facts and Trends", p 10

Euromonitor (2007): "Household care in Switzerland Report" - [http://www.euromonitor.com/Household\\_Care\\_in\\_Switzerland](http://www.euromonitor.com/Household_Care_in_Switzerland).

FEFCO Organization Official Website (June 2006): "Lifecycle Analysis- Assessment" - [www.fefco.org/index.php?id=172](http://www.fefco.org/index.php?id=172)

FEFCO Organization Official Website (2003,Issue 3): "European Database for Corrugated Board:lifecycle studies", FEFCO-Groupement Ondué-ECO

Fermacell Dry Lining Systems (2009) Xella International Group GmbH, <http://www.xella.ch>.  
 Fraunhofer-Institut, (2005):"Verbundquerschnitte aus Holzwerkstoffen für lastabtragende Wände", Schluss Bericht, prepared for Holzforchung Wilhelm-Klauditz-Institut und Technische Universität Braunschweig, Germany

IEA (2006) : „Business Opportunities in Sustainable Housing A Marketing Guide Based on Houses in 10 Countries" - [www.iea-shc.org/task28/](http://www.iea-shc.org/task28/).

Industry Canada Department, Government of Canada Publication (2005) : "Market Highlights & Prospects" - <http://strategic.ic.gc.ca/epic/internet/inimr-ri.nsf/en/gr104586e.html>.

Industry Canada Department, Government of Canada Publication, (2005): "Market Highlights & Prospects", p2 - [www.ic.gc.ca](http://www.ic.gc.ca)

Interpraxis (2007), "Sustainability terms and concepts", [www.interpraxis.com/glossary.htm](http://www.interpraxis.com/glossary.htm)

International Organization for Standardization (2003), "ISO 14040-14044:1997; Environmental Management -lifecycle Assessment-Principles and Framework" - [www.iso.org](http://www.iso.org)

Observatoire de la Finance (2008) „Financial Performance: The New Stage in Socially Responsible Investing", [www.obsfin.ch/english/documents/conf-02-programme.htm](http://www.obsfin.ch/english/documents/conf-02-programme.htm)

Passive House Institute (2005): International Energy Association SHC 28/ ECBCS 38: "Sustainable Solar Housing " - [www.iea-shc.org/task28/publications/Sustainable\\_Solar\\_Housing\\_Brochure.pdf](http://www.iea-shc.org/task28/publications/Sustainable_Solar_Housing_Brochure.pdf)

Standford University (1999): "Online Report journal: Article "Libraries acquire Buckminster Fuller archive" - <http://news-service.stanford.edu/news/1999/july28/fuller-728.html>.

Swiss Agency of Environment, Forestry and Landscape (Jul. 2001), Third National Communication of Switzerland: 28-30 - [www.bafu.admin.ch/climatereporting/00551/00553/index.html](http://www.bafu.admin.ch/climatereporting/00551/00553/index.html)

Swiss Prime Site (2007): Project reports - [www.swiss-prime-site.ch](http://www.swiss-prime-site.ch)

Swiss Federal Statistical Office (2007): Statistical Yearbook of Switzerland - Statistical Data in a Nutshell - [http://www.bfs.admin.ch/bfs/portal/en/index/dienstleistungen/publikationen\\_statistik/statistische\\_jahrbuecher/stat\\_\\_jahrbuch\\_der.html](http://www.bfs.admin.ch/bfs/portal/en/index/dienstleistungen/publikationen_statistik/statistische_jahrbuecher/stat__jahrbuch_der.html)

The 2000W Society, Novatlantis (2007): „Smarter Living: Generating a new understanding for natural resources as the key to sustainable development“, in collaboration with SIA, Swiss Energy, pg 8,11 - [www.novatlantis.ch](http://www.novatlantis.ch)

Trade & Investment Publication (2001): "Back on firm Ground, The Construction Sector in Switzerland", Canada, p 2- [www.gs1.org](http://www.gs1.org)

UK Communities and Local Government Organization (1999): „Comparative study of the control & promotion of quality in housing in Europe" - [www.communities.gov.uk/archived/general-content/housing/housingresearchsummaries1](http://www.communities.gov.uk/archived/general-content/housing/housingresearchsummaries1)

UNFCCC (2001): Policies and Measures „The 3rd National Communication of Switzerland, pg 28-30,34,42 - <http://unfccc.int/resource/docs/natc/pam/swipamn3.pdf>

US Environmental Protection Agency (2009): "High Global Warming Potential (GWP) Gases"- [www.epa.gov/highwp/scientific.html](http://www.epa.gov/highwp/scientific.html)

US Department of Defense (2002): Structural Sandwich Composites, Standardization Handbook - <http://snebulos.mit.edu/projects/reference/MIL-STD/MIL-HDBK-17-5.pdf>



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