CARDBOARD
AS A CONSTRUCTION MATERIAL FOR BEACH HOUSES

Title: Cardboard as a construction material for beach houses
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Abstract: In this paper the production and recycling process of the four most important cardboards are shown and explained. These are corrugated-, honeycomb-, tubes and solid- cardboard. For all these types the properties waterproof, fireproof, insulation, strength, weight, price and architectural freedom is compared. With this data the use of cardboard in a coastal area is discussed. For the coastal area the assignment is elaborated and a few possibilities for the use of cardboard such as foundation, one-season and element construction is shown. Concluded is that the properties of cardboard can definitely be benefited for the construction of a beach house.

Keywords: Cardboard, Coastal
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Program/Section/Other: Master Architecture, Urbanism and Building Sciences
Hand-in date: 7th January 2015
Language: English
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Introduction

For temporary structures a lot of materials are thrown away after its use. Isn’t cardboard a great material to use for these types of buildings? Cardboard can be thrown away with the paper trash and can be recycled for 100%. So why not use it in (temporary) buildings? Cardboard is nothing else then paper which has been reinforced and made stronger by adding extra layers, corrugations or shapes, a generic term for heavy-duty paper. People look at cardboard and directly assume its only possible use, as a packing material where it originally has been made for. In this research the use of cardboard will be investigated as a construction material for a coastal area. First by answering how it is produced, what types of cardboard there are with its different properties and how it can be used on a coastal area. This paper should give an idea how cardboard can be best implemented in the location and what it’s benefits could be.

Cardboard has been used in a few projects earlier and some research has been done. It is badly documented though, so collecting and gathering this data in this research paper would be a great step.

Method

Cardboard is a very hands on material which means that a lot can be done by making and testing it yourself. It is important not to start from scratch but to gain knowledge from different sources whom work or have worked with cardboard. Of course looking through the existing literature will help but since it is badly documented it is good to speak and visit for instance a cardboard manufacturer, an architect who has worked with cardboard before, the beach, Rijkswaterstaat etc.
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Production and Recycling process

Pulping and compressing

Cardboard is actually nothing more than fibers and water. The fibers are found in wood. Different kind of woods are used for the making of cardboard. Also the re-use of old fibers (mostly old cardboard and paper) is a method of making new cardboard. The production process starts with the collecting of these raw materials. A lot of raw materials are possible to add to the pulp mixture for certain goals. It is for instance possible to add grass to the mixture to let the paper digest rapidly or glue to make it water tight. We will get to this later.

When the right fibers are put together warm water and sometimes chemicals to break down the fibers are added to create a pulp mixture. After creating the pulp sometimes it is needed to clean the pulp. This is not needed when only new fibers are used but when old cardboard is used then for instance it contains ink, paperclips etc. These needed to be filtered out. This is done with different methods. Chemicals and bleach can be added to withdraw certain ink and to clean the paper. To remove staples a roller is used to separate these from the fibers by using their difference in thickness. After this process there are two ways to go on. One is to compress the pulp into a free-form, could be a block or for example an egg carton (Image 4). The other is to compress and rolled into sheets (Image 3).

In the pulp it is possible to add different fibers but also chemicals, glue and natural materials. Also the density of fibers, length and strengths can be different. Therefore it is possible to give the pulp properties such as water resistant, fire resistant, rapid digesting and others. This means that even before the cardboard has been produced it is possible to change its properties. For now we will assume that is possible to make to make any form of solid cardboard. We will discuss its properties later.

To create the paper sheets the pulp is compressed, dried and then rolled onto big rolls. These rolls are mostly sold to cardboard and paper manufactures. At these factories the rolls of paper are wrought to its certain needs. So for instance to create white A4 paper for printing the rolls is coated and cut into pieces. We will look into how different types of cardboard are created from these rolls.¹

Processing paper rolls

Corrugated cardboard

The most common cardboard we know is corrugated cardboard. This type of cardboard is the oldest kind and is mostly used for boxes. In this part is shown how it is made, the properties will be discussed later on.

Single corrugated cardboard consists of three layers of sheets. A top and bottom layer are connected by a corrugated sheet.

¹ (PRN, 2014), (Mujumdar, 2004), (Ghosh, 2011)
This corrugated sheet is created by firmly rolling it in between two ribbed rolls. After this the peaks of the paper are given a glue layer at a high temperature to make sure the glue enters the fibers. Then the two other sheets are pressed under light pressure to the glued corrugated sheet. After some drying, cooling and cutting to size there is a corrugated cardboard sheet.

Difference in corrugation can create different types. It possible to create different corrugation types and heights. These types and height are indicated with a letter (from big to small; D, K, A, C, B, E, F, G, O). The letters are not arranged on height but on frequency of the number of corrugations per distance. It is there for possible to create corrugated sheets from almost 7.5 mm to 0.30 mm thick. The frequency determines the strength of the sheet. It can be said that how thicker the sheet the stronger it is.

Another variation is the number of corrugations. Nowadays it is possible to make up to five corrugations on top of each other in a factory. For instance for a double corrugated sheet five layers are used and two are corrugated.

There is a limit in the width of which a cardboard sheet can be produced. The machine direction (MD, this is perpendicular to the corrugation) only has a height limit. The width of the sheet (CD, cross direction) is limited by the width of the machine. In The Netherlands up to three meters width can be produced.

Later on we will discuss the properties, advantages and strength.²

Honeycomb

Honeycomb can be produced in different ways and now is used for door panels and packaging materials. IKEA uses it for the filling of ‘planks’ to save weight. Honeycomb is relatively the most expensive kind of cardboard and this is due to the production. In Image 11 is shown how honeycomb can be made. In the top one single corrugated cardboard without a bottom layer are stacked and glued to each other. In the other one is shown that small strips of sheet are glued at certain points and then stretched to make a honeycomb structure. The distance and number of layers determine the properties of the honeycomb. Then on top and below two sheets or plates are added. This can be wood, solid cardboard or multiple sheets. The second method is newer and better because this can be produced continuously.

Honeycomb cardboard has been produced in various heights from 4 to 100 mm, the limit is just like the corrugated cardboard in the width of the machine.

Later on we will discuss the properties, advantages and strength.³

² (Piek, 2014), (van Iersel T. , 2014)
³ (van Iersel T. , 2014), (van Til, 2014), (Hooijmeijer, 2014)
Tubes

This kind of cardboard has been used more often in architecture, especially by Japanese architect Shigeru Ban. He made a lot of projects by using the cardboard tubes as wall or as construction for the roof.

The tubes are created by rolling sheets of paper around another tube and using glue to connect these sheets. The diameter of the tube where the sheets are rolled on determines the diameter of the tube and the number of sheets the thickness. The length is infinite.

It is possible to roll the sheets in two ways around the tube, linear and non-linear. Although the machine is more expensive the second method has the preference. This because of the better buckling strength. Also in the non-linear method it is possible to make the length infinite, with a linear this isn’t possible.

When Shigeru Ban started to use the tubes as a replacement for steel tubes he noticed that the connections of the tubes were the weakest link. Therefor later he designed a dome in which the tubes were produced in enormous length and were bended in place. Because the connections were done with a wire to the other crossing tube, no other connections were therefor needed.

Another principal which was used for the tubes are the walls. Because of the great compressive strength the tubes have, they are good to use in architecture.  

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4 (Shigeru Ban, 2014), (van Iersel T., 2005)
Cardboard properties

To determine which cardboard should be used for which element or purpose it is best to look at different properties of each cardboard type. Also will be taken into account that it is possible to add certain products to the pulp, use different fiber types (longer, newer etc.) and the number of fibers. These last three things can change the properties a lot.

Water resistance

The normal cardboard that we know is not water resistant. After being in contact with water or moist it falls apart and becomes useless. There are different methods to prevent this and for each possibility should be taken into account which is best for which situation. The most common solutions can be divided under compressing fibers, adding glue to the pulp, coating and covering. When compressing the fibers during the production a different problem appears. It is hard to glue the sheets to create the cardboard because the glue needs to go into the fibers. Therefore this is a good solution for solid cardboard and cardboard types with little glue connections. Next is adding glue to the process, this is a replacement of the water. This can be used for almost all cardboard types problem is that the cardboard isn’t very easy to recycle and it digest very slowly. The third way is to coat the cardboard. This is possible for smooth surfaces so this is difficult for corrugated and honeycomb cardboard. Great about this way is that coating can be applied for a certain lifetime. So it is for instance possible to coat for two or six months. This is also possible in a color and on site. The last way is to cover the cardboard. This can be done with a foil or with a vacuum system. This can be done on every kind although it gives problems with the recycling.

Another important aspect is making the connections of the cardboard water tight. This can be done by coating, covering and tapes. Coating and taping needs to be done on site when the connection is made. Covering as well but can be prepared better. To give a short summary of all the facts for the cardboard types see Table 1 and for the connections see Table 2.

Table 1: Water resistance solutions for cardboard types

<table>
<thead>
<tr>
<th></th>
<th>Compressing Fibers</th>
<th>Adding glue to pulp</th>
<th>Coating</th>
<th>Covering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Cardboard</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Corrugated Cardboard</td>
<td>+/-</td>
<td>+</td>
<td>+/-</td>
<td>+</td>
</tr>
<tr>
<td>Tubes</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Honeycomb</td>
<td>+/-</td>
<td>+</td>
<td>+/-</td>
<td>+</td>
</tr>
<tr>
<td>Gluing</td>
<td>--</td>
<td>+</td>
<td>+</td>
<td>+/-</td>
</tr>
<tr>
<td>Recycling</td>
<td>+</td>
<td>--</td>
<td>+</td>
<td>+/-</td>
</tr>
<tr>
<td>Digesting</td>
<td>+</td>
<td>--</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Lifespan Control</td>
<td>+</td>
<td>+/-</td>
<td>++</td>
<td>-</td>
</tr>
</tbody>
</table>

(Eekhout, Verheijen, & Visser, 2008), (Hooijmeijer, 2014)
Table 2: Water resistance solutions for cardboard connections

<table>
<thead>
<tr>
<th></th>
<th>Coating</th>
<th>Covering</th>
<th>Taping</th>
</tr>
</thead>
<tbody>
<tr>
<td>On Site</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Prepare able</td>
<td>-</td>
<td>+/-</td>
<td>-</td>
</tr>
<tr>
<td>Dismounting</td>
<td>+</td>
<td>+/-</td>
<td>++</td>
</tr>
</tbody>
</table>

Fire resistance

Fire resistance seems to be unachievable when using cardboard. On the contrary, solid cardboard works the same as wood. When burning solid cardboard a layer of coal is formed which actually protects itself. It is also possible to coat the cardboard with a fire retardant but also to put a fire retardant in the pulp mixture. This could be chalk for instance. By adding chalk to the pulp the cardboard is made more fire resistance. It has almost no problems with the recycling afterwards. It must be said that it is a fire retardant but it has a function to delay not to prevent. When using a fire retardant more smoke is formed than normal and when burning the gasses that escape are toxic. When exits are closely and the cardboard is not used as structure it might be wiser to choose a solid cardboard instead of a retardant.

Corrugated and honeycomb cardboard won’t do very well with both measures when fire penetrates the core of the two types. This because chambers are filled with air to keep the fire going and the core is filled with thin paper sheets. Only fire perpendicular to the surface can be delayed.  

Table 3: Fire resistance solutions for cardboard types

<table>
<thead>
<tr>
<th></th>
<th>Non</th>
<th>Coated</th>
<th>Retardant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Cardboard</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Corrugated Cardboard</td>
<td>-</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>Honeycomb</td>
<td>--</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>Tubes</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

Insulation

Thermal Insulation

Not much has been researched and/or documented about the thermal properties of cardboard because the use as a construction material is not very common. Buro Happold did do a research in thermal insulation for solid cardboard and corrugated cardboard. Buro Happold assumed that for plain sheets $\lambda = 0.22$ (W/mK) and for corrugated and plain sheets bonded: $\lambda = 0.047$ (W/mK). With these values some combinations of cardboard can be estimated. In Table 4 a few of these can be found. For cardboard tubes they say that filling the tube with loose paper will increase the value due to insulation with stationary air (like honeycomb and corrugated cardboard).

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6 (Eekhout, Verheijen, & Visser, 2008)
### Table 4: Thermal Insulation by Buro Happold

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 mm Solid cardboard</td>
<td>2,2 W / m² K</td>
</tr>
<tr>
<td>100 mm Corrugated cardboard</td>
<td>0,47 W / m² K</td>
</tr>
<tr>
<td>150 mm Corrugated cardboard</td>
<td>0,31 W / m² K</td>
</tr>
<tr>
<td>200 mm Corrugated cardboard</td>
<td>0,235 W / m² K</td>
</tr>
</tbody>
</table>

With the values and results of Buro Happold can be said that cardboard is a very good thermal insulator provided that the cardboard is filled with stationary air.7

### Sound Insulation

There are two ways to improve sound insulation. One is to put a lot of mass into the building to absorb sound the other is to make sound transport less easy. This last one is more likely for a cardboard structure because one of the main reasons to choose cardboard as a construction material is its lightweight. There is almost nothing documented about sound insulation except the use in interior walls. Combining the scarce sources we can assume that solid cardboard is best for sound absorption, corrugated and honeycomb for transport resistance and tubes can be filled for its purpose.

### Strength

For corrugated cardboard boxes strength researches have been done. With the formula of McKee it is possible to calculate the weight a corrugated box can hold. For the use of the cardboard in architecture different sources can be found especially in the form of compression tests. Because the different sizes of the cardboard types are limitless it would be an enormous work to put all the available data together therefor it is best for now to take a general statement for each kind.8

### Corrugated cardboard

In compression test with cardboard boxes the folds give a lot of strength. This is a good way to think about the design but for now we will look at the values of a corrugated cardboard plate. As said before corrugated cardboard has two variables which are important here, the height and the frequency of the corrugation. Of course the age of the age of the fiber is also very important. There are two directions in which the corrugated cardboard is interesting. The Machine Direction (MD) and the Cross Direction (CD). In the z direction the cardboard isn't strong at all so layers or a different material should be used when it is confronted with point loads.9

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7 (Cripps, 2001)
8 (Kahn, 2010)
9 (Hooijmeijer, 2014)
Honeycomb

Honeycomb has been used more often in architecture for example in doors therefor more data is available. For honeycomb there is only one direction relevant for the strength, this is the ZD direction (See Image 19). In a test done at the TU Delft during a master class for the Honours Program they tested honeycomb cardboard under a press. The honeycomb could carry a weight of 1.2 tons, this is almost 12,000 Newton's.\(^\text{10}\)

Tubes

Tubes have been used earlier in architecture and can differ in diameter and thickness. With the same test as the honeycomb pressure tests have been done. They used a tube of 250 mm diameter which could hold up to four tons of pressure. Tubes should be treated as a column when calculating.\(^\text{10}\)

Solid cardboard

This type will react the same in every direction because cardboard is antistrophe which means the fibers don’t have a direction. Therefor can be assumed the cardboard is the same strength in every direction. Although when solid cardboard is created from layers of sheet this doesn’t count. Solid cardboard can be compared to the tubes used for the compression test and for tensile strength a piece of 40 mm x 2 mm was tested and this could hold up to 2,030 N.\(^\text{11}\)

Price

For a single piece of cardboard the price is different than lots of the same pieces. Also when combining different types and gluing these extra costs should be taken into account. For now the price per type with its quantity as an indication (See Table 5). Solid differs extremely in type because of the pulp mixtures and is therefore not shown.\(^\text{12}\)

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\(^\text{11}\) (Latka, 2014)

\(^\text{12}\) (Tarieven, 2013), (Vandenberg Houtindustrie & Handelsmaatschappij BV, 2012), (Tupak, 2013)
Table 5: Price per cardboard type, size and quantity as an indication

<table>
<thead>
<tr>
<th>Height / Length / Volume</th>
<th>Quantity</th>
<th>Price per m / m² / m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrugated Cardboard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>h: 3 mm Single Wave</td>
<td>10</td>
<td>6.22 m²</td>
</tr>
<tr>
<td>h: 3 mm Single Wave</td>
<td>100</td>
<td>1.27 m²</td>
</tr>
<tr>
<td>h: 3 mm Single Wave</td>
<td>1000</td>
<td>0.59 m²</td>
</tr>
<tr>
<td>h: 5 mm Double Wave</td>
<td>10</td>
<td>6.58 m²</td>
</tr>
<tr>
<td>h: 5 mm Double Wave</td>
<td>100</td>
<td>1.63 m²</td>
</tr>
<tr>
<td>Honeycomb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>h: 30 mm</td>
<td>20 +</td>
<td></td>
</tr>
<tr>
<td>h: 40 mm</td>
<td>20 +</td>
<td></td>
</tr>
<tr>
<td>h: 50 mm</td>
<td>20 +</td>
<td></td>
</tr>
<tr>
<td>Tubes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ø: 50 mm, d: 10 mm</td>
<td>384 +</td>
<td></td>
</tr>
<tr>
<td>Ø: 100 mm, d: 10 mm</td>
<td>384 +</td>
<td></td>
</tr>
<tr>
<td>Ø: 150 mm, d: 10 mm</td>
<td>384 +</td>
<td></td>
</tr>
</tbody>
</table>

Weight

For this property we need guidelines for the design an indication will do fine. For solid cardboard the volume will give the weight. For corrugated and honeycomb the thickness and for tubes the diameter and thickness. In Table 6 is shown an indication of the weights. To calculate the different weights as an indication see the formulas below:¹³

Solid cardboard:

\[ G \text{ (weight in kg)} = 273 \cdot V \text{ (volume in m}^3) \]

Corrugated cardboard:

\[ G \text{ (weight in kg)} = 0.13 \cdot A \text{ (surface in m}^2) \]

Honeycomb:

\[ G \text{ (weight in kg)} = 0.0058 \cdot A \text{ (surface in m}^2) \cdot h \text{ (height in mm)} \]

Tubes:

\[ G \text{ (weight in kg)} = 0.00027 \cdot \pi r_{outer}^2 \text{ (Outer radius in mm)} \cdot \pi r_{inner}^2 \text{ (Inner radius in mm)} \cdot l \text{ (length in m)} \]

Table 6: Indication weights of cardboard

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid cardboard</td>
<td>273 kg/m³</td>
</tr>
<tr>
<td>Corrugated cardboard</td>
<td>0.13 kg/m²</td>
</tr>
<tr>
<td>Honeycomb</td>
<td>5.8 g/m² per mm height</td>
</tr>
<tr>
<td>Tubes</td>
<td>0.27 g/mm² / m length</td>
</tr>
</tbody>
</table>

Architectural Freedom and Expression

Maybe one of the most important aspects of cardboard for making a design of it. It is almost possible to make anything from cardboard so where are the limits?

¹³ (Hooijmeijer, 2014), (van Til, 2014), (Eekhout, Verheijen, & Visser, 2008)
When people think about cardboard they think about cardboard boxes but this is just the beginning. There are many projects in which cardboard has been used to benefit the expression of the cardboard itself (see Image 22, 22, 23). Fun fact is to say that the color of cardboard is actually grey and not brown. This is done because this is the associated color of cardboard.

For a good design with cardboard the architect should question if people should realize if the building is made of cardboard and when they do, should they associate this with something new or with the cardboard box they remember. When looking at the references of earlier cardboard projects it is amazing to see what is possible and what kind of expression with cardboard can be achieved. Challenge for now is that most projects haven’t been done in the form of a beach house and definitely not on the beach itself.\(^\text{14}\)

\(^{14}\) (Piek, 2014), (Hooijmeijer, 2014)
The location

Building on the beach is difficult enough, with cardboard this almost seems dramatic. The weather, the sea and the ethic value of the dunes make this extremely difficult. The assignment to develop a new type of beach house has been given by Rijkswaterstaat and will be explained below.

The assignment

Rijkswaterstaat is now pumping up tons of sand from the North Sea and spreads this all over the beaches in The Netherlands. During the season this sand should naturally move into the dunes by wind or sea. By doing this The Netherlands should be protected by the dunes when the sea level rises. It is a constant battle because the sea level is rising and therefor the dunes should do this as well. This is one part but also the position of the dunes. They are being pushed back by the sea while Rijkswaterstaat would like them to stay in position or even better forward.

Because the demand for living on the beach is rising so are the number of beach houses. When they are positioned in a row next to each other they form a blockade for the sand to reach the dunes after it has been pumped up. Beach houses nowadays are actually blocking the sand and one of the questions is, how a beach house can actually help the dunes instead of thwarting this affect.

With this as a starting point there is also the architectural question of what image do we want on the beach. Now lots of the same houses are put in rows next to each other. People enjoy this but are there better architectural solutions and what happens with the urban space if we want to change this or could we build in the dunes? The area of the assignment is not just the single beach house but actually the whole coast of The Netherlands which should be taken into account. Also the different zones perpendicular to the coast.

For now Rijkswaterstaat wants insight in beach houses in which people can sleep, are not year-round, not in the dunes but on the beach, help with the sand dusting into the dunes and can be managed by owners. To make it realistic there are three other parties involved. First the county and municipalities whom want attractive and safe houses that also suffice the Natura 2000. For operators it should be demountable, transportable or a house lasting just one season which can be demolished and which is feasible. The last group are the users who of course want a functional, well priced beach house (different classes could be an option).

Later on Rijkswaterstaat wants to investigate on beach pavilions which can be year-round and or not for sleeping and also building in the dunes itself. For the graduation studio this is also a possibility.15

15 (Mulder, 2014), (Ministerie van Infrastructuur en Milieu, - van Economie, Landbouw en Innovatie, 2012), (van der Valk & van der Meulen, 2013), (Studentenproject innovatieve strandbebouwing, 2014)
Implementing cardboard into the assignment

Thinking and researching about cardboard and looking at the assignment actually gives a lot of possibilities. Because cardboard can digest it can be used as temporary, it is cheap so it can be made feasible and almost anything is possible with the material. To make it clear a few functions for cardboard as a component of the beach house have been investigated here.

Building for one season

Because cardboard is a cheap material and can be recycled over and over it looks as if cardboard can introduce a new way of construction for the beach. During the normal season now houses are transported and installed for the summer and when the season is over they are demounted and transported to storage for the next season. With cardboard there is actually the possibility to make houses for one season that can go back into the recycling afterwards instead of storage. If this is possible people can have the freedom to buy a house for one season and don’t have to be stuck to it afterwards. If they don’t like the furniture, color or size next year they can choose a new one.

To make this realistic it needs to be feasible. At this moment the design is not finished so only an assumption can be made. Therefore we will take the simplest design where the house is made only from corrugated cardboard plates with a thickness of 10 cm. The house will be 3 x 5 meter and 2.5 meters high. Therefore at least (3 x 5) x 2 + (3 + 3 + 5 + 5) x 2.5 = 70 m² corrugated cardboard is needed. The price will be doubled for interior and production costs. The first calculation is shown in Table 7.

Looking at these first estimation the cardboard house looks quite promising. A good goal will be to keep the price at a 10th of the normal price. The selling price of cardboard can be higher because of the extra possibilities for owners like the option for colors, size and that they are flexible in ownership. Also taxes could be lower if the house is better for the dunes in the form of a fund. ¹⁶

<table>
<thead>
<tr>
<th></th>
<th>Normal Situation</th>
<th>Cardboard Situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>15,000 - 20,000</td>
<td>2750 - 5000</td>
</tr>
<tr>
<td>Selling Price</td>
<td>45,000 - 65,000</td>
<td>TBA</td>
</tr>
<tr>
<td>Tax of Location</td>
<td>1,000 - 1,500</td>
<td>1,000 - 1,500</td>
</tr>
<tr>
<td>Transport and/or Storage</td>
<td>1,000 - 1,200</td>
<td>200 - 500</td>
</tr>
<tr>
<td>Refund Recycling</td>
<td>0</td>
<td>0 - 22</td>
</tr>
<tr>
<td>Total</td>
<td>47,000 - 112,700</td>
<td>3,950 - 7,000</td>
</tr>
</tbody>
</table>

¹⁶ (Snijders, 2014), (Strandhuisjes, 2014), (Krimpenfort, 2014)
Foundation with tubes

After some study with cardboard the possibilities to solve the construction and de-construction problems can be solved although the way to help the dunes with cardboard haven’t. A theory that arouse and should be tested was founding the house with cardboard tubes. First in the vertical direction as a pole but later the possibility of stacking tubes horizontally as platform gave different possibilities.

In Appendix A: Cardboard tubes as foundation, a few options are tested in a wind tunnel. The results of this research can be found there, here the possibilities will be discussed.

The found results in combination with the facts given by Rijkswaterstaat can tell us which solutions could work and on which location of the beach the design is possible. The design will be placed at the edge of the dune but also in the middle of the beach is possible. Extra benefit is that the foundation can be used for each type of beach house. Design problems are the fixture of the tubes to each other to make it a stiff plate. This will be done during the design.\footnote{Zondervan, 2014}

Structural elements

The best use of cardboard for the common structural elements (walls, roof, floor etc.) in a beach house can be determined after the research. The given knowledge can give an idea which type can be benefited where. Knowing which type can resist forces in certain directions or which can be made water type in certain ways can give a good design direction. Although after the first research it was interesting to take a better look at how the cardboard can be connected to each other in for instance a corner. Therefor a small study has been done. This can be found in Appendix B: Cardboard connections. This research is never finished but it gives a good indication what needs to be taken into account for a good connection. The tests have only been done with corrugated cardboard but the weaknesses could be collected by a different kind. For the design recommended is to take one solution and make this as best as possible. The possibilities will be shown in the next chapter; Toolbox.\footnote{Latka, 2014, Hooijmeijer, 2014}

Openings and other materials

For openings such as windows and doors but also possible ventilation it is possible to say after research that these should be more permanent. Therefor these elements should be removed easily and be reused next season.

For some systems cardboard cannot be used like the power plugs, wires, PV-cells etc. For these the same as the windows and doors applies that they should be easily removed and reused next season.\footnote{Latka, 2014}
Furniture

The quantity of the cardboard that should be used in furniture is determined by the quality of the home. If it is possible to make high quality furniture with cardboard this should be done but using cardboard for instance dinner plates should be reconsidered as lower quality in comparison of normal dinner plates.\textsuperscript{19}

\textsuperscript{19} (Asselbergs, 2014), (Mulder, 2014)
Toolbox

The results below are the result of the combination between the researches in cardboard and the location. To show how specific items of a cardboard beach house can be done with cardboard, a case study has been chosen. From this case study four important elements have been explored and possibilities are shown below. These four elements are the foundation (the horizontal tubes), the connection between the tubes, the house with the structural panels (walls and roof) and the connections between these last ones.

Foundation

For the foundation four combinations can be made between certain properties. The position, movement, tube build up and recycle method. The first two are combined, the other two are in a new row. This can be found below in Table 8.

Table 8: Toolbox for foundation platform

<table>
<thead>
<tr>
<th>Dune</th>
<th>Dune</th>
<th>Dune</th>
<th>Dune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform</td>
<td>Platform</td>
<td>Platform</td>
<td>Platform</td>
</tr>
<tr>
<td>Sea</td>
<td>Sea</td>
<td>Sea</td>
<td>Sea</td>
</tr>
<tr>
<td>Layers</td>
<td>Layers</td>
<td>Layers</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>500</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Reuse</td>
<td>Recycle</td>
<td>Digest</td>
<td></td>
</tr>
<tr>
<td>High quality platform</td>
<td>One-season quality platform</td>
<td>Digestable platform</td>
<td></td>
</tr>
</tbody>
</table>

When looking at the table above, the thing that can be done with cardboard but almost not with a different material is digesting. Also recycling but, this can be done with other materials as well.

Foundation Construction

When using these tubes for the foundation there are a few ways to do this. The chosen solution from the previous toolbox has influence on the best solution. The toolbox for this can be found in Table 9.
Table 9: Toolbox for construction of the foundation

<table>
<thead>
<tr>
<th>Form</th>
<th>Profile</th>
<th>Floor-Frame</th>
<th>Surround-Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screw Form Bolt</td>
<td>Screw U-Profile Bolt</td>
<td>Screw Frame Bolt</td>
<td>Frame Screw</td>
</tr>
<tr>
<td>Top-Frame</td>
<td>Smaller Tubes</td>
<td>Profile</td>
<td>Halfround Tubes</td>
</tr>
<tr>
<td>Frame Screw</td>
<td>Plate Screw</td>
<td>Plate Profile Bolt</td>
<td>Frame Screw Bolt</td>
</tr>
<tr>
<td>Square Tubes</td>
<td>Frame Screw Bolt</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For this the last two are interesting in cardboard. The shapes can be made more easily in cardboard than other materials. Also the solution with the smaller tubes is interesting because the tubes can be made to a more specific diameter. For all can be said that the recycling and digesting possibility of cardboard should be kept in mind.

Panels

For the wall and roof a few possibilities can be found after the study of cardboard. These can be found in Table 10. Each has its negative and positive effects. The difference between the panels is quality, price and production. Also the weight is a property which should be kept in mind. For a cardboard panel it is a good method to compare the goal of the designer with a wooden panel. For example to ask the question, does the cardboard perform better if it comes to price then a wooden panel and does not lose too much attention to other properties.
Connections

To make clear what kind of connections are possible the last toolbox can be found below in Table 11.

Table 11: Toolbox for connections

For the connections quality and ease of construction are most important. When making a better connection the price will also rise.
Conclusion

Can cardboard be used as construction material for a beach house? Yes, definitely. This conclusion can be made because of the research in the production of cardboard and the methods to tackle certain problems.

How can the properties of cardboard be best benefit for a temporary beach house? For this question temporary is the key to what makes cardboard a good material. Cardboard can be used well for temporary structures because it’s cheap, lightweight, timed digestible, recyclable and can be made to very precise and specific forms. Now the combination of this knowledge needs to be used on the beach. The design will be the proof of this but how to do this will be explained.

The assignment can be divided into three parts. One is the house itself, second is the business model of the house for one season and third is the foundation.

First for the house it can be said that it is definitely possible to build the house completely from cardboard. Two question arise when doing this, do people want to live in such a house and is making it completely form cardboard the best option? To solve the first question multiple designs should be made and one of those must be elaborated. Difference is the comfort level inside and the visibility of the house being made of cardboard. The second question can be answered with a simple no. After doing the research concluded can be that not everything is best to do with cardboard. As example can be named that a replacement of a steel profile by cardboard is not a good idea. Also the use of cardboard for permanent structures isn’t because of the immediate loss of strength when damage occurs. It is possible to design in a way that steel is not needed, this should be done.

So for the house itself it is essential to make a design of cardboard in the quality that people want to see, which convinces that cardboard can do the job and where not everything is made out of cardboard where other materials are way better to use. Important is to make sure the components of other materials can be recycled or can be removed easily.

Second is the business model of the cardboard house. To make this possible during the design the price should be taken into account. The price of the different cardboard types are clear but also the way of production, can it be made by machine in batches? For the design flexibility must be taken into account in the form that the user can choose certain elements like color and position but also furniture types and size. This gives the cardboard an extra positive boost to be used as material. To prove that the house is profitable I am joining The Cleantech Challenge and the associated course Sustainable Business Game in which the design will be calculated in terms of profit and costs.

For the foundation a set of data from Rijkswaterstaat and the wind tunnel tests give the conclusion that the house and its foundation will be placed at the edge of the dune where it has the possibility to move easily if needed. With some simple adjustments
the same house can also be placed in the middle of the beach and the same foundation can also be used for any beach house.

Remaining

Questions that are still unanswered which will hopefully become clear during the design phase are how the cardboard will be used best in the design, if it is possible to make a profitable business model with the design and if the theory of the tests in the wind tunnel work in a large scale. Also after writing this paper I recommend the collecting of all data of using cardboard as a structure because in the future this could definitely become of great value. Definitely after the construction of the cardboard house, giving proof that for temporary structures cardboard is a great material.
Appendix A: Cardboard tubes as foundation

The theory of using horizontal cardboard tubes emerged after the visit at the Walki Group Factory in Haarlem. After some discussion six possibilities were set on paper and have been tested in a wind tunnel at the TU Delft. The wind tunnel made by three students for Bucky Labs is nothing more than a long container with sand in the form of a dune and a leaf blower which represents the wind.

Two remarks should be made:
1. The wind has a constant speed and direction. This is of course not in the real world but the machine still gives a good indication of the sand flow.
2. The grain of the sand is not in the scale of the house and tubes. Therefor it would be as if the grain would be 50 cm in diameter.

Nevertheless the machine still gives a good indication of what happens with different houses and foundation systems.

1. Blowing through the tubes
The first option is to put tubes in the middle of the beach and let the sand blow underneath the house through the tubes. In the wind tunnel this worked very well. Advantage of this method compared to the traditional way to put the house on poles is that there is no put arising beneath. Sand gets blown faster through the tubes at the end and therefor the exit is kept free.

2. Filling the tubes
In this option the tubes are put into the dunes on one side. The other is left open for the sand to blow in to fill the tube. The sand in the tube is the foundation and the tube needs to be big enough for one season. The possibility to leave the tube and let it digest is also an option. This option worked well. The tubes filled themselves from the end till the opening. Not as expected that the openings would be blocked after a while.

3. Filling the tubes and moving forward
In this way the foundation can be used for more years but also the house moves away from the dunes. The sand that has been collected in the tube is left behind and at the end of the season the tubes are emptied and can be reused next year. This option has been tested in the wind tunnel but the material of the tubes have great influence on this. There must be said that the scale of the grains of the sand have a too big influence on the result and therefor this cannot be tested on scale.
4. **Hanging the tubes in the dunes**
   In this way sand can still reach the bottom part of the dunes and there is space beneath the tubes for the sand to be collected.
   This option did not work very well. Beneath the tubes the sand has been blown away and the stability reduced slowly and eventually the structure collapsed.

5. **Hanging the tubes in the dunes with columns**
   This option was designed because of the results of option four where the tube had trouble to stay straight. To try and keep the structure more stable for a longer period columns have been put at the end. This did increase the lifetime but for safety reasons this solution is not advised.

6. **Direction of the tubes**
   Combining this option with option three and therefor the direction of where the house is moving can be adjusted and in that way the position of the houses parallel to the dunes can be adjusted.
   This angle of the tubes have great influence on the quantity of sand going through the tubes. With this result we advise for solutions with tubes to make sure the opening of the tubes is pointed in the right direction. Also combining this solution with option three can let the houses move perpendicular to the dunes as well. This is a potential option on a larger scale.
Appendix B: Cardboard connections

To get an idea what cardboard can do in relation to strength and stiffness, a few cardboard corner connections have been made and tested. All tests have been done with corrugated cardboard because this was easiest to get but for some connections honeycomb would do better. This knowledge has been gained after the research in different types of cardboard which has been done after the connection research.

Every connection has been tested on the fold ability, assembly time, assembly difficulty, stiffness and strength. The different types can be found to the right the results in Table 12.

Table 12: Cardboard connections

<table>
<thead>
<tr>
<th>Connection</th>
<th>Fold ability</th>
<th>Assembly time</th>
<th>Assembly difficulty</th>
<th>Stiffness</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical cut</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Bended in MD</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>--</td>
</tr>
<tr>
<td>Bended in CD</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>--</td>
<td>-</td>
</tr>
<tr>
<td>Finger joint</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Plug joint</td>
<td>--</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Hook slide</td>
<td>--</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Finger joint with stiffener</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td></td>
</tr>
</tbody>
</table>

This research has been done in an early stage of the total research and therefor the results should be used as an indication. It does give a good image in what is possible. What actually was very interesting to see is that during an excursion to the FabFac of Pieter Stoutjesdijk, was this exact research in wood for CNC cutting methods. Some of the exact same connections were there except the folding connection which is quite obvious since this is not possible in wood. The best connection they found hasn’t been tested in cardboard but should be done. This connection can be seen in Image 39.
Image 36: Hook slide (Own Image)

Image 37: Finger joint with stiffener (Own Image)

Image 38: Connections in wood (Own Image)

Image 39: Lock screw connection (Woodworker, 2014)
References


