THE DIGITALLY ABRICATED TRANSITIONAL SHELTER

An incremental shelter project from emergency relief to permanent dwelling

Technical research paper
Architectural Engineering Graduation Studio
By: Wouter Vlietstra
Tutors: Pieter Stoutjesdijk, Monique Smit

Abstract
Presented is a research project that examines the possibilities of more permanent shelter solutions for displaced people. This is now more relevant than ever, there are more displaced people than ever before in modern history and no durable solutions can be provided. People spend years, even decades in camps in poor housing conditions. This research is an attempt to offer a framework for the design of shelters that can grow incrementally into more permanent dwellings. Studies are executed on how shelter guidelines, case studies, existing incremental growth in refugee camps, incremental housing and digital fabrication methods can contribute to this goal.

Keywords: Emergency housing, transitional shelter, incremental housing, digital fabrication

Introduction
The most recent figures from 2013 show that there are 51.2 million forcibly displaced people worldwide. It is for the first time since the Second World War that this figure exceeded the 50 million. The increase of 6 million over the 2012 figures has mainly been driven by the war in Syria. By the end of last year, 2.5 million Syrians had fled across the country’s borders and 6.5 million were internally displaced – more than 40% of the population. Conflicts in the Central African Republic and South Sudan also contributed to rising numbers. The number of forcibly displaced people is so high that if they had their own country it would be the 24th most populous in the world (UNHCR, 2014). These 51.2 million displaced persons are divided in three categories: Refugees, internally displaced persons (IDP’s) and asylum seekers. Refugees (16.7 million) are people who have to flee their country because of an armed conflict. Internally displaced persons (33.3 million) are people in the same situation as refugees, but they stay within the borders of their own country. Asylum seekers (1.2 million) have applied for asylum in another (often developed) country. They can await the approval of this application in either their home country or their country of destination.

Once people are displaced they have to be temporarily housed somewhere else, for this there are six settlement options. These are:
- Host families
- Urban self-settlement
- Rural self-settlement
- Collective centers settlements
- Self-settled camps
- Planned camps (IOM, 2012)

The last option has the preference of UNHCR because services can be provided to a large population in a centralized and efficient way and you prevent that people disappear in illegality. These six options are only temporary solutions though. There are three durable solutions to provide for their well-being and to safeguard their rights on the long term. The first one is voluntary repatriation; the return of displaced people to their own communities based upon free and informed decision. This can be arranged by relief organizations or by the displaced people themselves. In 2013 only 414,600 refugees returned to their country of origin, the fourth lowest number in 25 years (UNHCR, 2014). Although this is for all the actors involved (mainly the host community, the aid organizations and the displaced people themselves) the preferred option, it is in practice often a utopia. Conflicts grow more protracted and complex than they were in the past. In 1993 a displaced person spent, on average, 9 years in a camp. In 2004 this has risen to an average of 17 years (Caritas, 2004). This is almost a year increase per year. With expectations that these numbers will rise even further, the chance on (quick) repatriation becomes smaller and smaller. They even suggest that very little people go home at all.

The second options is resettlement, when displaced people can get asylum in different countries than where they are temporarily accommodated. In 2013 only 98,400 displaced persons were resettled in other countries. Mainly in first world countries as the USA, Canada, Australia, Sweden and the UK (UNHCR, 2014). Total demand always exceeds the available places greatly, making it inadequate as a durable solution to the whole problem.

The third option is local integration. This is a gradual and complicated process by which refugees legally, economically, socially and culturally integrate as members of the host society. Measuring these various aspects of local integration is a huge challenge from statistical perspective and no real reliable data is available. The process of local integration should lead over time to permanent residence rights, a growing degree of self-reliance and becoming able to pursue sustainable livelihoods. Local integration requires large efforts from both parties concerned though. From the displaced people to adapt to the different culture and from the host society to welcome them and meet the needs of a more diverse population (UNHCR, 2014).

Although local integration is a slow and long-lasting process which requires a great deal of both parties it is the currently best durable option to house displaced people. These people have smaller and smaller chances of returning to their homes and resettlement places in alternative countries are nowhere sufficient to house everybody.

**Shelter priority**

Shelter is never really a priority of aid organizations such as UNHCR, these organizations have always been more focused on food, water, security and medical care. Partially because these first things are the most imminent; you can survive longer without a roof above your head than you can without a meal or clean water. But also because shelter is likely to fall into a gray area between aid, short term immediate relief, and development, which is focused on the longer term. Since these are two different legal types of development aid, shelter is often neglected (Lewis, 2008). Illustrative of this is the fact that in the most recent edition of the UNHCR’s “Handbook for Emergencies”, the ‘bible of relief planning’ only 19 of the 569 pages are devoted to shelter (UNHCR, 2007).

**Problems of current shelter solution**

The most used shelter solution today is the use of tents or frame structures covered with plastic sheeting. There are a lot of disadvantages with the usage of tents. The first problem is that they are not durable. They last about six to nine months and after that they become damaged and unusable.
Considering that people can stay in these camps for decades, this is not a durable solution. Secondly the options of expanding a tent are very limited; you cannot add another room to a tent. But the configuration of a household changes over time and people have the need to change the organization of their living space. When looking at it on a global scale, you see that there are barely non-nomadic people who are living in tents permanently. People rather look for other materials and ways of constructing their dwellings (Kennedy, 2008).

The problem with the current shelter types used is that they are designed to be temporary, but in reality they aren’t temporary but stay in use for years and even decades. The shelters have very limited options for upgrading their dwellings. A more permanent solution is needed.

To achieve this it would be very interesting to look at digital fabrication techniques. Digital fabrication has multiple advantages which can be very beneficiary for emergency situations. Firstly mass customizable design can be achieved with digital fabrication, this will mean that the shelters can adjust to different sites and users. Secondly higher efficiency can be achieved with standardization and modularization of the shelters. Parts can be produced in series, on site. There is no need for transportation anymore, which can gobble up to 60% of the shelter budgets (Kennedy, 2008). Finally the shelters can be easily adapted to growing needs when they are modularized. Digital manufacturing techniques can be divided in three main principles: subtractive, additive and transformative techniques. In this research only subtractive digital fabrication techniques are explored, because these are the most promising and realistic. Additive techniques are still fairly limited in the size of the objects they are able to produce. This factor, further nuanced with the considerable expenses of additive fabrication processes along with the considerable production time makes the potential of this technique too small to investigate (Hauschild & Karzel, 2011). Formative techniques can only be used to reshape or deform materials in their desired shape and are thus not relevant for this research.

**Research question**

*How can subtractive digital fabrication techniques be used to make locally produced transitional shelters that can grow into permanent housing?*

**Sub questions:**

1. What are the demands for an emergency shelter?
2. How can a transitional shelter grow into a permanent dwelling?
3. A. What are the constraints of introducing digital fabrication in emergency environments?
   B. What are the most promising digital fabrication techniques for the fabrication of transitional shelters?
   C. How are these techniques used to create shelter like structures?

A more extensive overview of the full research that will be conducted for the graduation project, also outside of the scope of this thematic research paper, can be found in appendix A.

**Method**

Multiple research methods will be used to answer the research questions. For the first question a literature study will be done in the demands for an emergency shelter, further case studies will be done to identify other factors that can contribute to a successful or unsuccessful shelter design. For the second sub question upgrading processes in existing shelter projects are analyzed and a literature study will be done about incremental housing. The third sub question will be answered by a literature study and a comparative case study.
**Limits**

People who will have to flee their home countries because of armed conflicts are most likely to end up in countries which have (economic) situations which are just as dire as the countries which they fled from. Very little examples exist were the border between two countries can make a large difference in economic situations, although the US-Mexican border is one (Lewis, 2008).

Nowadays developing countries host 86% of the world’s refugees, the highest number in over two decades (UNHCR, 2014). This fact is where the biggest dilemma regarding refugee aid at. You want to deliver the best relief aid you can get, but host governments won’t allow large numbers of foreign people in their country enjoying a higher standard of living than its own population.

Therefore the focus of the research will be on IDP’s. These are the largest group of displace people and they are in a political situation that is more likely to be fertile for a more permanent solution than those of refugees or asylum seekers.

The ambition is to design a mass customizable building system that can be customized to meet the needs of specific locations. Three locations have been preselected, being Colombia, the Central African Republic and Syria. Here are the highest numbers of IDP’s, see figure 1, and they are very divers in cultural and climatic circumstances. Location and culture analysis have been left out of this research and will be carried out in the second semester.

![Figure 1: IDP's. Source: UNHCR, 2014](image)

The focus of the research and the design will lie on the shelter itself and the upgrading process. The organization and growth of the whole camp is also important but will be elaborated in a more schematic way in the second half year of the graduation.

**Results**

1. **The shelter itself**

The UNHCR Handbook for Emergencies is generally accepted as the vade mecum of emergency aid. It prescribes certain requirements for emergency shelters. The most important are listed below:

Type of shelter:
- An individual family shelter is preferred by the UNHCR standards, since this gives the best privacy, psychological comfort and emotional safety. The family size of five people is used as a standard by UNHCR.

Program:
- The shelter should have a minimum size of 18 sq. m. (3,5 sq. m. per person is the minimum in hot climates, 4,5 in cold climates).
- The shelter should accommodate the following functions: Sleeping, sitting, storage of personal items and changing of clothes. Cooking facilities are located outside and sanitary functions are shared.

Comfort:
- The shelter should be suitable for the variance in the seasons.
- The shelter must provide protection from the elements.

**Construction process:**
- Wherever possible, displaced people should always build or assist in building their own shelter. This will help to ensure the shelter meets personal needs and creates a sense of ownership and self-reliance.
- An appropriate roof structure has the priority of the shelter (UNHCR, 2007).

Although the requirements provide a grip certain aspects are lacking. Therefore other sources have been investigated, like the Sphere Minimum standards in Disaster response. Although similar as the UNHCR guidelines it provided nuances in certain aspects and complemented the UNHCR standards. Where the focus of UNHCR lies on protection from the elements and ‘touchable’ aspects, Sphere provides a nuance regarding the psychological aspects and the usage of the shelters.

**Safety and Privacy:**
- Women and children are vulnerable to attack and care should be given to ensuring adequate separation from potential threats to their personal safety.
- In individual household shelters, opportunities for internal subdivision should be provided for to ensure personal safety.

**Activities:**
- Space should be provided for sleeping, washing and dressing; care of infants, children and the ill or infirm; the storage of food, water, household possessions and other key assets; cooking and eating indoors when required; and the common gathering of the household.

**Space provision:**
- The flexible use of the shelter space should accommodate different activities during the day and night.
- The design of the structure, the location of openings and internal subdivisions should enable the immediately adjacent external space to be used for livelihood support activities when required.

**Other functions of shelter:**
- It should be acknowledged that shelter in addition to providing protection against the elements also serves other purposes. These include the establishing of territorial claims or rights, the provision of post-disaster psychosocial support through the reconstruction process. It can also represent a major household financial asset (TheSphereProject, 2004).

**Reconstruction strategies**

**Three phase reconstruction**

The strategy which is normally aimed at in emergency relief is the three phase reconstruction. The first phase is an emergency response, which is usually a tent or a shelter consisting of frame materials and tarpaulin. This first phase is meant to accommodate the people in the first months after a crisis. When a durable solution is found people are housed in temporary shelters (phase two) until their permanent dwellings are being constructed (phase three) (IOM, 2012).

![Figure 2. Three phase reconstruction, own ill. after (IOM, 2012)](image)
Although this sounds good in theory, in practise there are certain drawbacks to this strategy. The durable solutions (repatriation, resettlement and local integration) are often utopias as figures listed before illustrate. People are therefore stuck for years or even decades in emergency shelters which are meant to be used only for a few months. Because these shelters are designed for temporary usage they have not the qualities for permanent usage. Often they only satisfy the basic housing needs; the protection against the elements, see figure 3. They offer little privacy, are small, have poor thermal qualities etc. These are more secondary needs but nevertheless also important, just as social needs. To satisfy these needs too, in this strategy, permanent housing needs to be constructed, with temporary shelters to bridge the intermediate period. For this large investments are required, but these funds are often lacking. This is another reason why this process fails and people get stuck in the first phase of the process.

In some refugee camps other type of shelters emerge, to replace the tent and tarpaulins used as emergency shelters. These are made out of salvaged or bought materials. But this is often unreachable for the majority of the people, materials are too expensive or not allowed by the UNHCR.

Transitional approach
Another strategy which can be used is the transitional strategy. This approach is often used in reconstruction after natural disasters. Instead of reconstructing in multiple steps, with different type of dwellings, this is an incremental process. A transitional shelter is placed after a disaster or crisis and is upgraded and incrementally improved to become a permanent house (IOM, 2012). This transitional shelter is often comparable in quality to the emergency shelter, but its main advantage is, with affordable upgrades the quality can be improved. This way the growing needs can be facilitated and the shelters become suitable for permanent usage.
This strategy would be more suitable to provide the displaced people with a more permanent solution, so instead of constructing an emergency shelter a transitional shelter will be build.

![Figure 4. Transitional approach, own ill. after (IOM, 2012)](image)

Unlike the approach of UNHCR where generic guidelines lead to more generalized shelter options, there are no standard transitional shelter designs or guidelines. Standards are agreed upon per crisis with participation from the affected population (IOM, 2012).

The chapter is concluded with a generic design brief for the transitional shelter in appendix A. After the location analyses in the design phase this will be supplemented with site-specific information.

2 The upgrading process from a transitional shelter to a permanent dwelling

To see how this upgrading process is taking place inside an existing refugee camp a case study is discussed here. Because there was no opportunity to visit one other options had to be explored. Dirk Jan Visser, Jan Rothuizen and Martijn van Tol made a cross-over documentary about camp Domiz, a refugee camp located in the Kurdish province of Dohuk in northern Iraq. This camp houses over 58,000 Syrian refugees, mostly Kurds. These refugees are given the same standard issue box containing a tent and other items like blankets, tarpaulins and cooking supplies. Interesting is that in this refugee camp semi-permanent shelters and even permanent houses are popping up, which are officially illegal, but are tolerated by the UNHCR. Large fires destroyed many of the tents and primitive huts, so now shelters constructed out of more lasting construction materials are tolerated. The majority of the refugees in the camp don’t have a lot of savings or a large source of income to afford these materials, so they still dwell in tents or other primal types of dwellings. Only a small portion of the population has the resources to construct comfortable (seen the context) and permanent houses. The majority of the construction work is done by the residents themselves. The construction materials are supplied by private firms started by refugees themselves. These firms are thriving because the aid organizations like UNHCR don’t have the resources to supply the refugees with more durable materials. Other businesses are also popping up and people start getting jobs in the camp or in neighbouring Iraqi towns. As a result of this people have money available to lift their standard of living (Visser, Rothuizen, & Tol, 2014).

The documentary gives a real clear image regarding steps taken in the process of moving up from a temporary emergency tent towards a permanent dwelling. In appendix B the eight types of shelters are further illustrated. These are:

1. The basic tent
2. The improved tent
3. Wooden frames structure
4. Steel frame structure  
5. Extended steel frame structure  
6. Plated steel structure  
7. Start sustainable structure (masonry)  
8. Permanent house (Visser et al., 2014)

Interesting to see here is the housing careers of the people in camp Domiz are not following a fully phased strategy nor a fully transitional strategy. A hybrid strategy has emerged which is party incremental and partly phased. Positive about this is the fact that the people are in the position of upgrading their dwellings and that this is allowed by the UNHCR. But still large sums of money have to be invested when switching from, for example, a wooden to a steel frame. This can be avoided when the transitional shelter has a durable structure from the start.

Next these eight steps are further analysed. For each step is analysed what upgrades are implemented, what problems these upgrades solve (or what value they add) and which problems or deficiencies still occur. See appendix C-F.

From this analysis can be seen that the majority of the upgrades is directed into making the frame structures more durable and resilient against extreme weather. The ambition is to design a transitional shelter with a durable structure from the start so this is no longer needed and the people can direct their attention and resources towards other types of upgrades.

**Upgrading process in Haiti**

In 2010 Architectue for humanity was asked to upgrade the temporary shelters of the people displaced by the devastating earthquake in Haiti on January 12, 2010. The hurricane season was coming, which the flimsy shelters wouldn't survive. They produced a report that assessed different shelter types and identified the problems which the shelters had. They also proposed simple, low-cost modifications to the temporary shelters which could extend their lifespan. One of the priorities was a package that included a floor / foundation upgrade. Another was focused on structural upgrades like corrugated steel roofing cladding and cladding the walls with pressure treated wood. Additionally to structural upgrades the team also identified other areas for improvement. Ventilation was a major problem so people added their own ventilation openings. Security was also a big problem, with the rise of crime in the chaos following the earthquake. People improvised back doors to have an emergency exit and sought for more permanent materials than the provided plastic sheeting, which was easily to invade (humanity, 2012)

The two examples of shelter upgrading, Domiz and Haiti, have been combined elaborated in the upgrade table of appendix G. This table makes insightful which problems occur in transitional shelters, subdivided in different categories, and how these can be solved with different types of upgrades. Also a rough estimation is done of how much these upgrades will cost.

**Incremental housing**

The concept of upgrade-ability and expandability is not new in housing projects, it is better known as incremental housing. Some of the principles can perhaps be translated to a sheltering project. Figure 6 shows the different types of ‘starter houses’ there are with incremental housing. These range from an empty plot with only the utility connections to a multi-storey apartment complexes. How further up the graph, how higher the control of the designer is but the less freedom the inhabitants have to expand their dwellings. This is the main dilemma with the design of incremental housing; do you give the power to the designer of the user of the dwelling?
Leading in the (academic) field of incremental housing nowadays is Elemental, an academic collective and “Do tank” from Chile. They have built many incremental housing projects in Chile and other parts of South America. In their book Incremental housing and participatory design manual (Aravena & Iacobelli, 2012) they illustrate their principles, which can be applied to this research in some extent or present interesting diversity. (Some of) Elemental’s principles are:

1. Harmonious growth over time
   The main conflict which arises from incremental housing is the high risk of urban deterioration by expansions of inferior quality. To control these expansions they have to be separated and framed. The idea of elemental is to build half of the house as a porous structure that supports the expansions. The pores are surrounded by solid structures so that the expansions only has to act as infill (Aravena & Iacobelli, 2012).
   Expansions in the design project don’t necessarily have to be framed with an existing structure as in the case of elemental. With elemental they assume that the self-made expansions are of a poorer quality than the first half of the dwelling, which is probably correct. With the desired building system the expansions and the original structure will be the same.

2. Collective space for the extended family
   A key matter for the economic development of a low-income family lies in the existence of a space where the extended family may develop. The multifamily occupation of a dwelling is not only an expression of the impossibility of owning a house on their own but also a survival strategy. Urban space in which public housing is inserted has a binary structure: there is either public or private space; there are streets and private plots (Aravena & Iacobelli, 2012).
   Sizes of the transitional shelters will be very small, so collective space could be, in practice the living room of the camp dwellers. Appropriate size and services has to be provided. Space for expansion of the family also has to be facilitated.

3. Building the essential half first
   When there are only resources to construct half of a house, one has to be very precise in defining the initial half and the other half constructed by the families themselves. The first half of the house should consider all the elements and operations that will be difficult for the family to deal with. The difficult part generally includes:
   - Structural partition walls
   - Firewalls
   - Kitchen
   - Bathroom
- Stairs
- Roof (Aravena & Iacobelli, 2012)

The difficult part of the transitional shelter will be the structural parts and roof. In the study of camp Domiz can be seen that a lot of effort and money was invested in making the shelter structurally stable and durable. If this was already solved from the beginning the scarce resources can be allocated to other purposes. The kitchen and bathroom are initially shared and situated outside of the shelter. Later this can be integrated into the shelter; the services like plumbing have to be installed from the start. A smart solution has to be found to integrate the connections for these services beforehand.

Where Elemental is more focused on enlarging the house, upgrades in Domiz are more focused on increasing other conditions like durability, privacy, and thermal conditions. Issues that are already solved in the first phase of the elemental dwelling. And where Elemental’s incremental housing projects are all classifiable as a shell, with half of a completed house and pores for infill of the expansions. In an emergency situation this will become too expensive and will take too long to construct. The shelter will more likely to become classifiable as a roof (completed roof structure, durable frame and plumbing connections).

3 Digital fabrication

Digital fabrication in emergency environments

The concept of the building system that will be designed in the second semester is not to import the shelters themselves but to bring in machines for digital fabrication and raw materials, and produce the transitional shelters on site. For this there are three main components needed, a power source, raw material and a machine that converts the raw material into building parts. These three components will form a local ‘factory’ where the building parts can be produced, see figure 6. Construction will be done by the people themselves.

![Figure 6. 'Factories', own ill.](image)

There are two main phases identifiable. First there is an emergency period. Important here is that the shelters can be produced quickly. For this it is plausible that the power is supplied by generators and the raw materials are brought in from another place. After this the upgrading process starts. This is a more graduate process and options can be explored to produce the building materials locally and to substitute the generators for a more sustainable power source. More research has to be done on this topic, see the chapter further research.
Advantages of digital fabrication in emergency environments

Production on site
With digital fabrication techniques the building parts of the shelters can be produced on-site. This is favorable in both the emergency period (no need for transportation, makes it quicker) and the production process becomes more approachable and has more local ownership. This is interesting in the upgrading phase, the threshold becomes lower.

Mass customization
With digital fabrication techniques it is no longer required to make mass produced products, in this case shelters, to become cost effective. With these techniques it is possible to produce high quality, unique objects, with the same efficiency and low cost production costs as objects produced in series. This way it is possible to produce mass customizable shelters tailor-made to different site and user requirements. This allows gives a greater sense of ownership to those recovering from trauma (Yeung & Harkins, 2010).

Feedback loop
Few aid organizations have established protocols to revisit the sites after shelters are completed. And even if there is some form of evaluation, this is often not translated into a new design (Yeung & Harkins, 2010). In digital fabrication, the design data is also the construction data, or at least very closely connected. With construction being executed on-site there is the possibility to easily solve deficiencies in subsequent designs.

Threats of digital fabrication in emergency environments

‘Alien’ technology
The main argument against prefabricated or ‘high-tech’ shelter is that these solutions involve importing high-tech or expensive components that are alien to these (mostly) developing countries. Here a conflict arises, because local people need to replicate and maintain their shelters with the technologies available to them (Yeung & Harkins, 2010). For example the Paper tube emergency shelter by Shigeru Ban. He designed a shelter out of paper tubes, plastic connectors and sheeting but the paper tubes were too difficult to replicate on-site, and it became too expensive to import them constantly. Thus the project was soon cancelled by UNHCR (Sinclair & Stohl, 2006).

The shelter that will be designed after this research paper will likely also be too complex to be reproduced without the help of (foreign) expertise. Since these shelters will be implemented in the controlled environments of camps initiated by UNHCR, budgets can be allocated to supply this expertise. After the initial emergency phase local people can be trained to take over (parts of) the work from the foreign experts, giving greater local ownership over the process.

Costs
Many promising projects run ashore because they become too complex or too costly. The high prices for these more high-tech shelters are justifiable in emergency situations where the need is the highest, but for transitional or permanent applications they need to be further explored (Yeung & Harkins, 2010). In the proposed shelter solution the majority of the costs are front-loaded, with the acquisition of the needed machinery; the highest costs are in the emergency phase when budgets are available. In the transitional and permanent phase only costs of upkeep and maintenance apply. People pay for their own upgrades.

The different subtractive fabrication techniques

As discussed in the introduction, only subtractive digital fabrication techniques are explored in this research because they hold the greatest promise and are the most realistic at the moment. An overview of the different techniques is shown below, after that the different subcategories and their potential and limitations are discussed.

<table>
<thead>
<tr>
<th>Material</th>
<th>Laser-cutting</th>
<th>Plasma</th>
<th>Water jet</th>
<th>Milling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 20 mm</td>
<td>Up to 350 mm</td>
<td>Up to 350 mm</td>
<td>Up to approx. 250 mm (with 100 mm drill)</td>
<td>Ø 700 mm to Ø 1150 mm</td>
</tr>
<tr>
<td>250 x 1280 mm</td>
<td>3000 x 4500 mm</td>
<td>2000 x 1000 mm</td>
<td>30,000 x 8000 mm</td>
<td>0.700 mm to 0.1150 mm</td>
</tr>
<tr>
<td>3070 x 1660 mm</td>
<td>4000 x 3000 mm</td>
<td>3900 x 1630 x 5000 mm</td>
<td>Large-scale mill up to 15 x 60 m</td>
<td>Approx. 10 m/min (dep. on router bit) Up to 40 m/min (dep. on router bit)</td>
</tr>
<tr>
<td>300 m/min</td>
<td>35 m/min</td>
<td>35 m/min</td>
<td>6 m/min</td>
<td>Approx. 10 m/min (dep. on router bit) Up to 40 m/min (dep. on router bit)</td>
</tr>
<tr>
<td>0.05 mm</td>
<td>0.025 mm</td>
<td>0.025 mm</td>
<td>0.2-0.5 mm (depends on type of material/shape)</td>
<td>0.1-0.2 mm</td>
</tr>
<tr>
<td>Very good, may leave behind black marks</td>
<td>Rough to very good</td>
<td>Rough to very good</td>
<td>Not as consistently smooth cut surface/surface roughness</td>
<td>Very good, in the µ region</td>
</tr>
<tr>
<td>0.1-0.5 mm</td>
<td>0.1-0.25 mm</td>
<td>1 mm</td>
<td>0.8-1.5 mm</td>
<td>Min. 1 mm, dependent on milling head</td>
</tr>
<tr>
<td>Slight, dep. on tool in to the µ region</td>
<td>Slight, dep. on tool in to the µ region</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td>2D</td>
<td>2D</td>
<td>2D</td>
<td>2.5D</td>
</tr>
<tr>
<td>100 kW</td>
<td>37 kW dep. on pump</td>
<td>37 kW dep. on pump</td>
<td>Approx. 80 A</td>
<td>18 kW</td>
</tr>
</tbody>
</table>

**Figure 8. Overview different subtractive techniques, own ill. based on: (Hauschild & Karzel, 2011)**

**Laser-cutting**

The high energetic light beam (laser) is generated in a laser medium through the inflow of energy and then tapped off in a controlled way. This energy is absorbed by the raw material as a result, it heats up intensely in a short period of time. This cutting technique produces highly accurate, clean square-edged cuts. This precision allows the designer to make complex and detailed shapes, or whose forms vary within a series. As the laser is only steered in the x- and y-plane only two dimensional shapes are possible. With a maximum speed of 40m/min high levels of economic efficiency can be reached (Hauschild & Karzel, 2011).
Water-jet cutting
In architecture, CNC jet cutting is used primarily for 2D blank cutting of solid materials such as stone, metal or plastic. In this procedure water is formed into a jet which comes out of a cutting jet at up to 1000 m/s. In doing so the potential energy is turned into kinetic energy which gives the jet its cutting effect. Pure water cutting is used mainly for soft materials like paper and foams. When abrasive agents are added to the stream, like garnet sand, the jet not only uses the energy of the water but also the additional grinding particles. This way it is possible to cut hard and thick materials like stainless steel and concrete (Hauschild & Karzel, 2011).

<table>
<thead>
<tr>
<th>M e i</th>
<th>eed</th>
<th>e e eed</th>
<th>Speed</th>
<th>A</th>
<th>M e i</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>*</td>
<td>+/-</td>
<td></td>
<td>**</td>
<td></td>
</tr>
</tbody>
</table>

Plasma-arc
With this technique an electric arc is processed through a compressed gas jet which turns the gas into high temperature plasma. This state change is subsequently reversed as the heat is transferred to cut the material. The main limitation of this technique is the fact that only conductive metals can be processed.

<table>
<thead>
<tr>
<th>M e i</th>
<th>eed</th>
<th>e e eed</th>
<th>Speed</th>
<th>A</th>
<th>M e i</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>*</td>
<td>+/-</td>
<td></td>
<td>**</td>
<td></td>
</tr>
</tbody>
</table>

CNC milling 3 axis
Millling refers to the processing of metals, wood or plastics by machine with a milling tool. In architecture the potential lies primarily in multi-axial processing of hard materials. There are also two axis CNC milling machines which has a milling head that moves along the x- and y- axis. With a three axis machine, the milling head can also move up and down, and it is possible to create 2,5D objects. Completely 3D is not possible with this because it cannot create overhanging shapes. Disadvantages of this technique are relatively slow processing speed, material waste caused by the milling head, and the restriction to milling-head-specific radii at internal corners (Dunn, 2012).

<table>
<thead>
<tr>
<th>M e i</th>
<th>eed</th>
<th>e e eed</th>
<th>Speed</th>
<th>A</th>
<th>M e i</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>*</td>
<td>+/-</td>
<td></td>
<td>**</td>
<td></td>
</tr>
</tbody>
</table>

CNC milling 5 – 7 axis
With 5 axis CNC milling you get the possibility to make more complex objects through further manipulation of either the cutting head or the cutting bed; extra axis of rotation are added. This technique is the most variable of the subtractive procedures, but the amount of material used, is very high, and therefore economically and ecologically questionable (Hauschild & Karzel, 2011).

<table>
<thead>
<tr>
<th>M e i</th>
<th>eed</th>
<th>e e eed</th>
<th>Speed</th>
<th>A</th>
<th>M e i</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>*</td>
<td>+/-</td>
<td></td>
<td>**</td>
<td></td>
</tr>
</tbody>
</table>

Technique of choice
After assessing the pro’s and cons of the subtractive techniques, three axis CNC milling is the most promising. The CNC milling can do (almost) the same as the 2D cutting machines but has a wider range of machining operations available. With additional options available drilling and carving the design freedom vastly improves, 2,5D shapes are possible. With this fabrication technique there are some points of attention though during the design process. Small parts, with dimensions less than the width the router bit, are often destroyed or chipped during the milling process. Elements of this size should be avoided. Typical bits are incapable of tight interior corners, where they leave a radial or fillet at any corner. This makes it difficult to create accurate
interior notching for connecting components perpendicular to each other as in a conventional two-
directional section model. This is unique from other CNC fabrication techniques, which often have a
much thinner tooling head (Beorkrem, 2013). Also cut sheets need to configured carefully to confine
material loss.

‘Shelters’ fabricated using CNC milling
Multiple examples are available of shelters constructed using CNC milling. The most interesting are the
Wiki-house, an open source building system, the instant house by Larry Sass, the Haiti shelter by Pieter
Stoutjesdijk and the Paviljoen at huis ter Heide by Econnect. Interesting for this project is to see how
these shelters are build up, and how they are split in different elements. This because the desired
shelter solution needs to be expandable and upgradeable, fore this some sort of modularization or
division in different elements is favorable.

The Wiki-house, see appendix H
The wiki-house building system consists out of repeatable spans that can be assembled on the floor
and then erected. They consist out of six parts connected with S-joints, these joints are located away
from the corners to avoid concentration of stresses. Two of these spans are connected with each via
connectors to make an element, these elements get extra stability from the inner and outer surface
panels (WikiHouse, 2013). These elements can be linked after each other, so the shelter is expandable
in one direction.
Depending on the design decisions to be taken in a later stage this structural system can be suitable

The instant house, see appendix I
The structural system of the instant house consists out of vertical studs, connected with small braces.
The outer and inner sheeting is connected to these studs with tabs (Sass, 2007). These studs are placed
so close together that they form a load-bearing wall, also because all four walls are build up in the
same way. This would make it very hard to modularize this system and it won’t be easily expanded.
The constructed prototype was structurally weak without the inner and outer sheeting, because the
stud joinery was not self-supporting (Sass, 2007). This would be another reason to not use this type of
structural system, in the emergency phase of the project is would not be unlikely that no outer or inner
sheeting would be used but substituted by tarpaulin.

The Haiti Shelter, see appendix J
The structural type of this shelter consists out of a system of columns which stand on a grid of 1200mm.
between these columns girders are placed. Interesting for this project is that this results in a modular
system which can be expanded in two directions.

Paviljoen Huis ter Heide, see appendix K
This structural system consists out of modular wall and floor elements. The floor elements are resting
on beams in one direction and can be repeated in this direction. By placing more beams the floor
elements can also be repeated in the other direction. The wall elements are connected to each other
by adjustment plates. By placing more next to each other you can expand the initial shelter. Also
interesting is the fact that these wall elements have only indoor plating and an integrated system for
placing outdoor cladding.

The last two structural systems show the most promise for the application in a transitional shelter.
They can be repeated and are modularized. They should be explored and developed further via
research by design to come to an own building system.
Connections
A first exploration has been made in the different parts and connections that are needed to construct a shelter out of plywood using CNC milling. This is not to be seen as a first design but more as an inventorisation.

Two different types of parts are classified by Sass, Michaud and Cardoso: surface parts and structuring parts (Sass, Michaud, & Cardoso, 2007). In this paper a further differentiation is being made, see appendix L. Surface parts are further differentiated into Floor, interior and exterior surface parts. Structure parts are further differentiated into Floor, wall and roof structure.

With these two different three main type of connections are needed: structure-structure, structure-surface and surface-surface. In appendix M are these illustrated and further diversified.

Conclusion
The two most important aspects of the research are incremental growth process and the constructing methods using subtractive digital fabrication methods. Firstly conclusions from case studies provided an excellent insight in what the problems are which occur in these shelters. A scheme has been made with the upgrades that can be performed. Together with the conclusions from the study on incremental housing a good overview is made how this incremental growth can occur. Secondly an exploration has been made in building systems for the selected digital fabrication methods. These two outcomes provide a basis for their merging, what in essence will be the design to be made in the second semester.

Further research
Further research has to be done in multiple facets. The building system needs to be further elaborated. A way needs to be found how the structure can be modularized and supply the proposed expansions and upgrades. Also further research has to be done regarding the type of joints that are required to build up such a structure. A start has been made, but more profound research has to be done to find the most suitable connections. Right has to be found in the following factors: milling time, complexity, strength, assembly process and tolerances. In the design phase this will need to be translated to different building parts, what will become my (final) design.

The production and construction process will need to be further elaborated, especially in how the power source and materials can become sustainable and local.

Finally the three locations will need to be analyzed. This will provide information to enrich the demands for the emergency phase of the project and needs to be translated in different building parts and configurations to make the transitional shelters culturally and contextually appropriate.

For a more graphic representation of this, see Appendix A.
References
LOCATION A

LOCATION B

LOCATION C

LOCATION ANALYSIS:
1. Climate: Temperature, seasons, height of the sun, rainfall etc.
2. Culture: Housing tradition, size of families etc.
3. Architecture: Building systems, housing lay-outs, building technology etc.

HOW TO EXTEND AND UPGRADE?
Research on upgrading processes in existing refugee camps.
Research on incremental housing.

DEMANDS EMERGENCY SHELTER
Size, facilities, climatic performances, comfort, privacy etc.
What gets the priority?
What are functions or features that can be added later?

BUILDING SYSTEM
A building system has to be designed that can facilitate the growth and upgrading of the shelter.
Research has to be done on:
- Joints
- Construction systems
Focus will lay on adaptability and expandability.

CATALOGUE OF BUILDING PARTS
A catalogue of building parts. Different parts can be configured to create shelters that are suitable for different locations.

APPENDIX A
GRADUATION PROJECT - RESEARCH OVERVIEW

TECHNICAL RESEARCH
ARCHITECTURAL RESEARCH
GENERIC SPECIFIC
PRODUCTION / CONSTRUCTION PROCESS
EMERGENCY PHASE UPGRADE PROCESS
LOCATIONS
PROJECT PHASE
P1 P2 P3 P4 P5
Entire project
Research paper
Design phase
Mapping of the three locations

BUILDING PARTS
Design brief for emergency shelters
Global strategy for incremental processes
Framework of the catalogue
Framework of the construction process
Appendix B

DESIGN BRIEF – TRANSITIONAL SHELTER

PROGRAM
- The shelter should be suitable for one family of max. 5 people
- It should have a minimum size of 18 sq. m. (3.5 sq. m. per person is the minimum)
- It should accommodate the following functions:
  Inside: Sleeping, washing and dressing, storage of household possessions, and other belongings, gathering, eating.
  Outside: cooking, livelihood activities.
  Sanitary functions are shared so are not in this design brief.

SAFETY AND PRIVACY
- The shelter should offer safety and privacy to all members of the household, but especially to the women and children, adequate separation from potential threats should be in place
- The shelter should have the option to easily place Internal subdivisions, these are not a priority, but should be able to put in place fairly easily.

CONTEXT
- The shelter has to be customizable to different contexts. It has to adapt to local climate, plot shape, subsoil, etc.
- The shelter should be culturally and socially appropriate and familiar.

DURABILITY
- The main construction should be suitable for a permanent house with a lifespan of more than 15 years.
- The main construction should be resilient to storms and other extreme weather.
- The initial cladding of the walls and roof can have a more temporary nature, this can later be upgraded to more durable materials.

EXTENSION AND UPGRADING
- The shelter should have the option for extensions and different type of upgrades (see table) to grow into a permanent dwelling.

COMFORT
- The indoor climate should have an acceptable level throughout the year. Later this can be improved by various upgrades.
- No mechanical cooling and heating should be used. Instead passive climate strategies should be applied.

CONSTRUCTION PROCESS
- The shelter should be assembled within a day, by the people themselves, with limited tools; the construction, or rather assembly process should be fast and easy.

MATERIALS
- Materials used should come preferably from a local source.
- Materials used should come from a renewable or abundant source.

WATER SUPPLY
- Water is collected from a shared tap, not water source has to be put in the shelter.
- In a later stage a private water tank can be placed to store water near the shelter.

ELECTRICITY
- Electricity is not a priority, but it should be taken into account that in a later stage electricity is desirable.

OTHER FUNCTIONS
Acknowledged should be the fact that the shelter is also an instrument to establish territorial claims and rights, provides psychosocial support through the reconstruction process and represents a major financial asset for a household
#1 People Already Are Actively Upgrading Their Dwellings

Housing Career in Camp Domiz

1. Basic Tent
2. Improved Tent
3. Wooden Frame Structure
4. Steel Frame Structure
5. Extended Steel Frame Structure
6. Plated Steel Frame Structure
7. Start Sustainable Structure
8. Permanent House

- Only partially and incremental process
- Steps to new shelter types verge a large investment, unreachable for many people
- An all incremental process would be better
Appendix D

NEW INSIGHTS

OWN ILLUSTRATION. SOURCE (VISSER ET AL., 2014)
**3 Wooden Frame Structure**

- Rooms 1
- Functions: dwelling, sleeping, changing, storage

**4 Steel Frame Structure**

- Rooms 1
- Functions: dwelling, sleeping, changing, storage

**Upgrades**
- Water tank added
- Satellite dish installed
- New wooden framework

**Problems Solved with Upgrade**
- No need to get water daily with jerry cans
- TV reception possible
- More solid framework, but still not resilient against extreme weather

**Problems**
- Very poor climatic performance, hot in summer, cold in winter
- Little privacy
- No durable materials
- Not resilient against extreme weather

**New Insights**

- Own illustration: Source (Visser et al., 2014)
OWN ILLUSTRATION. SOURCE (VISSE ET AL., 2014)
**7 START SUSTAINABLE STRUCTURE (MASONRY)**

- **UPGRADES**
  - New dwelling made out of masonry

- **PROBLEMS SOLVED WITH UPGRADE**
  - Durable cladding and structure
  - Permanent construction; shelter becomes at home
  - Better climatic performance in winter by more insulating walls and roof

- **PROBLEMS**
  - Air-conditioning needed, poor design

---

**8 PERMANENT HOUSE**

- **UPGRADES**
  - "Reef" windows and doors
  - Rebar placed in front of the windows
  - Porch added

- **PROBLEMS SOLVED WITH UPGRADE**
  - Better protection by casable doors and windows
  - More secure against burglary and other types of crime
  - Private outdoor space gained

- **PROBLEMS**
  - Air-conditioning needed, poor design

*Appendix G*
## Appendix H

### Problems in Dwelling

<table>
<thead>
<tr>
<th>Upgrades</th>
<th>Heat</th>
<th>Cost</th>
<th>Ventilation</th>
<th>Day/Light</th>
<th>Rain/Water</th>
<th>Sanitation</th>
<th>Size</th>
<th>Privacy/Security</th>
<th>Identity</th>
<th>Comfort of Living</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof Quality</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Insulation</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Skylights</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Windows</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Fixtures</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Wall Quality</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Insulation</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Fixtures</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Door and Windows</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Windows</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Fixtures</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Kitchen Facility</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Windows</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Fixtures</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Bar Room</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Windows</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Fixtures</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Eat Out</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Windows</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Fixtures</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Other Facilities</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
<tr>
<td>Add Fixtures</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
<td>🔄</td>
</tr>
</tbody>
</table>

### Finishing

| Add Electrical Connections | 🔄   | 🔄   | 🔄           | 🔄         | 🔄          | 🔄          | 🔄   | 🔄              | 🔄        | 🔄               |
| Add Fixtures              | 🔄   | 🔄   | 🔄           | 🔄         | 🔄          | 🔄          | 🔄   | 🔄              | 🔄        | 🔄               |

**Legend**

- 🔄 Building Items
- 🔄 Fixtures

- 🔄 1
- 🔄 2
- 🔄 3
- 🔄 4
- 🔄 5

**OWN ILLUSTRATION**
CONSTRUCTION SYSTEM

ELEMENT

EXPANDABILITY

Span system
Repeatable spans
Expandability in one direction
Appendix I, INSTANT-HOUSE

Four load bearing walls

Wall as element

Expandability in zero directions
Appendix J, HAITI SHELTER

CONSTRUCTION SYSTEM

ELEMENT

EXPANDABILITY

- Integrated beams and columns
- Modular elements
- Expandability in two directions
Appendix K, PAVILJOEN HUIS TER HEIDE

CONSTRUCTION SYSTEM

ELEMENT

EXPANDABILITY

Modular floor and wall elements

Floor and Wall 'boxes'

Expandability in two directions
Appendix L

DIFFERENT PARTS

1. FLOOR STRUCTURE

DIFFERENT CONNECTIONS

TYPES OF CONNECTIONS:

Floor structure - cross connection
Floor structure - double connection
Floor structure - running connection

2. FLOOR PANELS

TYPES OF CONNECTIONS:

Floor panel - floor structure
Floor panels, edges

3. WALL STRUCTURE - STUDS

TYPES OF CONNECTIONS:

Floor structure - wall structure
Wall structure - running connection

4. WALL STRUCTURE - BRACES

TYPES OF CONNECTIONS:

Wall structure - stud

Own illustration
5. ROOF STRUCTURE - STUDS

6. ROOF STRUCTURE - BRACES

7. INTERIOR PANELS

8. EXTERIOR PANELS / CLADDING

OWN ILLUSTRATION
Appendix M

OWN ILLUSTRATION. SOURCES: (WikiHouse, 2013) (Gros, 2013)