Bachelor Thesis

Healthy housing: Environmental and economic impact assessment and a house market feasibility research for a zero energy

Figure 1: 3D-model of terraced Tangramhouses plan in Ruurlo

UNIVERSITY OF TWENTE.

Wilmink Oosterveld
Jouw basis in de bouw

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Preface

In front of you lays the final report of my bachelor thesis '*Healthy housing: Environmental and economic impact assessment and a house market feasibility research for a zero energy house'* which I carried out at the contracting company Wilmink-Oosterveld. This thesis concludes my bachelor period of the study Civil Engineering at the University of Twente. In this research a type of zero-energy house called 'Tangramhouse' is analysed on its environmental and economic impact over its life cycle and a market research is conducted for evaluating how this house could be sold in the current housing market. I hope the research outcomes will be valuable and can contribute in this housing project collaboration.

In the past 10 weeks I have been able to get my first experiences with the work field thanks to Wilmink-Oosterveld. Despite the COVID measures, Wilmink-Oosterveld made it possible for to still work safely at the office. This was a great working environment and I was pleased to get to know the other colleagues and blend into the working atmosphere. Throughout this period I noticed that my individual skills both in setting up and conducting a research as in socially communicating in a formal and informal way have improved substantially.

Although this thesis is an individual assignment, I was never able to do it all on my own. I would like to thank my external supervisor at Wilmink-Oosterveld, Hans Ebbekink, for all his help and support throughout this period and for providing me with a desk at the companies' office. Next to that I would like to thank the employees at Wilmink-Oosterveld for treating me like a colleague and for openly giving insight into the work field processes in the construction sector. Subsequently, I would like to thank the estate agents in the area of Twente for providing me with answers on the market research interview. My internal supervisor during this period was Silu Bhochhibhoya, I would like to thank her for her guidance as well. Throughout the whole period, but definitely in the last phase, I could use the expertise of her to improve my research and report.

I hope you will enjoy reading my thesis just as much as I did conducting and writing it.

Niek Pouwels,

Enschede, January 21, 2022

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Summary

The goal of this study was to analyse the current Life-Cycle-Assessment and Life-Cycle-Costs of the 'Tangramhouse' and to evaluate the current housing market. Out of this, statements could be made about the environmental & economic impact and about the feasibility to sell the house in the current market with its high demand.

For the collaborating project team, consisting of the contracting company Wilmink-Oosterveld and the architectural company Tangramhuis R9, it was desired to gain more insight into the environmental and economic impact as well as into the feasibility to sell the Tangramhouse in the current Eastern housing market. The goal of the project is to help both the current housing crisis and climate crisis by building more Tangramhouses with optimized costs and GHG emissions.

Firstly, the environmental sustainability of the Tangramhouse in terms of CO_2 emissions from cradle to the end of the building process was evaluated as proposed by conducting a Life Cycle Analysis (LCA).

Secondly, the method used to assess and analyse the economic impact and long term cost efficiency of the Tangramhouse was conducting a Life Cycle Costing Analysis. This is a method for assessing the total costs of the Tangramhouse which takes into account the costs of building, acquiring, maintaining and in the end disposing the building.

Data has been gathered from the companies, and with that the goal and scope for the LCA and the LCC have been set up. All the life cycle phases are included in the analysis, except for B5 refurbishment and B7 water usage. The life span of the house is assumed to be a 100 years.

With the GaBi software the LCA has been modelled in three phases; production phase, use phase and end-of-life phase. The Climate Change Impact, or the Global Warming Potential, is the only impact category taken into account to assess the environmental impact. The results of the LCA were for the energy type 'grid mix of 2020' as follows: GWP: 8,88 kg CO2 eq. /year/m2. In comparison to a single family house in Sweden, Darnallas Villa, designed with the aim to reduce energy impact and achieving low environmental impact from life cycle perspective it is 5,7 kg CO2 eq. /year/m2.

The same three life cycle phases have been modelled in an Excel program to get results out of the LCC. The overall Life Cycle Costs of the Tangramhouse over 100 years is rounded €507.168. Breaking this down per phase gives the construction phase costs of € 2.406,08 /m2 ; the use or operation phase costs of € 1.516,96 /m2 and the end-of-life costs are € 134,31 /m2. In comparison to the same house in Sweden, Darnallas Villa, the construction phase costs are € 3066,20 /m2. The use phase costs are € 1149,83 /m2 and the end-of-life costs are € 95,82 /m2.

At last, the method used for gaining insight in the current developments of the housing market towards more sustainable and zero-energy houses was to take interviews with estate agents and other related people of the housing market in the region. A narrative analysis method was used to analyse the interview data, this method focuses on using stories and experiences of experts.

It could be concluded that, compared to the single famlily house in Sweden which is designed for reducing the environmental impact, the Tangramhouse results are quite similar so it can be said that the Tangramhouse is very sustainable in terms of CO_2 emissions.

Furthermore, in terms of costs, the construction phase is relatively cheap. The use phase costs are slightly more than the other houses and the end-of-life costs are almost similar in comparison with the other houses. To reduce costs and GHG emissions, an alternative foundation with steel piles instead of concrete could be considered.

The estate agents mentioned that sustainable measures in a house are nowadays standard up to a certain point. The awareness around sustainability and wanting to help the climate amongst the house buyers is more present nowadays. A Tangramhouse on a location closer to the larger cities of Twente would sell better in general, since the facilities of a city are nearby. A Tangramhouse type which is flexible or modular would be an option to reach a broader target. Moveability, flexibility and adaptability could be something to investigate further in the future of this housing project.

1. Introduction

There is currently a severe housing shortage in the Netherlands. The demand for housing is very high and the supply is very limited. We are in the midst of a housing crisis. Together with the bank crisis in 2008 the housing market in the Netherlands collapsed. From 2013 till 2021 the price of a owner-occupied homes in the Netherlands have risen by more than 50% (Verwaaij, 2021). This has a consequence that it becomes more difficult to buy a house, especially for starters.

In addition to that, there is a climate crisis in which there is an increasing emphasis on sustainability and ecologically responsible construction. To combat climate change, the government aims to reduce greenhouse gas emissions by 49% by 2030 compared to 1990 levels and a 95% reduction by 2050, as agreed in the Paris Agreement. The complete built environment as a sector in the Netherlands contributes about 10% to the total greenhouse gas emissions (CBS e. , 2020). Within this built environment by far the most emissions come from households. In that sense, it is very important to reduce the emissions of households in order to help reach the goals established in the Paris Agreement.

Figure 2: Currently for sale Tangramhuis in Bruinehaar; source: funda.nl

Wilmink-Oosterveld wants to respond to this by building a number of standardized zero-energy houses, equipped with solar panels and green roofs and walls, at the lowest possible price. The goal is to both help the housing shortage and the climate crisis by also making some profit. The design for this particular type of house is done by the architectural company called Tangramhuis R9. Above in Figure 2, the design of this type of detached 'Tangramhouse' that is currently for sale can be seen.

The concept of 'Tangramhouse' has some outstanding characteristics (Stache, Neutraal wonen, 2020). First the building is energy neutral by placing solar panels and having it professionally thermally closed. Secondly, the building is climate-neutral with the façade and roof vegetation, which takes greenhouse gasses out of the air and helps to insulate the building. The third characteristic of the building is its water neutrality, since all the incoming rainwater will be stored inside or locally infiltrated. The last characteristic is making use of the sun with a so-called solar chimney. This is a glass chimney in which the air will become warm when sun is shining on it. Warm air goes up and by placing air inlets at the bottom of the house a natural ventilation will occur. Due to the thermals, the solar chimney sucks the air upwards.

2. Context

2.1. History of the project environment

The project started with the company Tangramhuis R9, who sought for a contracting company for collaboration to set up the particular zero energy house type called 'Tangramhouse' in the Eastern of the Netherlands. Tangramhuis R9 got in contact with Wilmink-Oosterveld since the company seemed to have the same goal and view towards the future of housing. Within this collaboration piecewise other reliable companies were getting contacted if they wanted to participate in this housing project.

Tangramhuis R9 have already built a couple of the 'Tangramhouses' in the Western of the Netherlands together with other companies. However, in this case the goal is to create a strong and reliable collaboration between parties to build more of these houses within the Eastern of the Netherlands. The first designed house in this region, in a village called Bruinehaar, is already on the market. When there is a buyer, the processes of building this specific house will start. Right now there are also developments going on building 14 of these houses in Ruurlo. Of which two houses will be detached and three blocks of 4 terraced houses. Lastly, developments are initiated to possibly start building these terraced houses in the city of Hengelo too.

2.2. Case description

As mentioned, the location of the Tangramhouse will be in the village Bruinehaar in the municipality of Twenterand. This particular building is called Groenehaar. It is a sustainable and climate neutral house with a striking appearance due the partially vegetated facade and green vegetation roof (Stache, Koning, & Groothuizen, Groenehaar, 2020). In Figure 3 below

Figure 3: Appearance Tangramhouse Groenehaar, source: tangramhuis.nl

the appearance of the Groenehaar house can be seen. The house is timber frame prefab constructed, with damp-open timber frame walls (Figure 5) and triple glass. The total gross floor living area is 125 m^2. The floor plan can be seen in Figure 4. Solar PV panels will be installed on the roof to generate yearly as much energy that is required for heating and cooling the house, this classifies it as a zero-energy house.

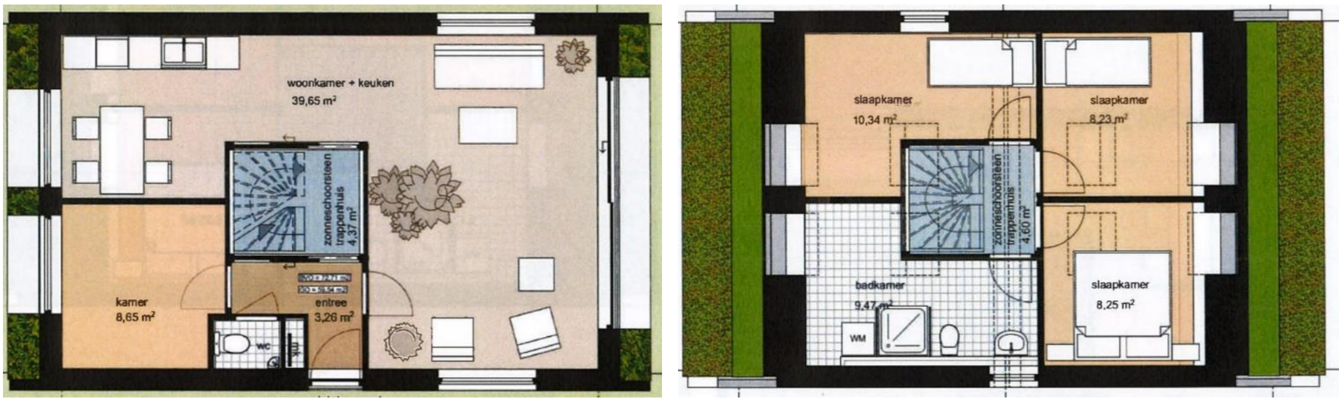

Figure 4: Floor plan Groenehaar, left: ground floor, right: first floor, source: tangramhuis.nl

Timber frame construction details wall construction

1. Timber frame frame of 140, 184, 235 or 285 mm thick stiles and battens.
2. Structural plate. If mineral wool is used for the insulation, a vapor barrier film is applied to the panel. This is not necessary when wood fiber insulation is used (vapor-open construction).
3. 45mm insulated installation zone.
4. Ventilation louvers provide a ventilation cavity of 28 mm.
5. Interior finish of extra impact-resistant plasterboard with hard pressing and/or wooden interior wall parts.
6. Mineral wool or wood fiber insulation.
7. Water-resistant vapour-permeable wood fiber board that protects the house against moisture and provides extra thermal and acoustic insulation.
8. We often use Western Red Cedar as wall cladding for timber frame constructions.

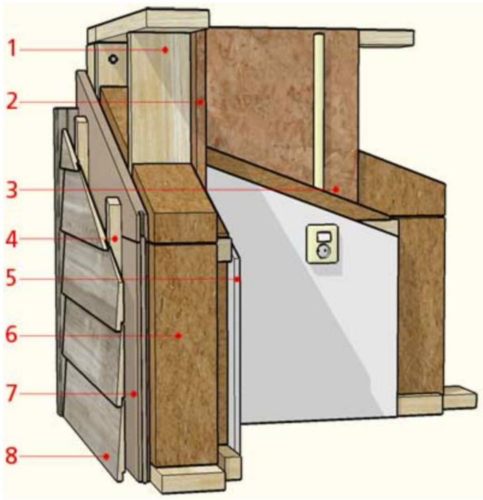

Figure 5: Details timber frame wall construction, source: scanabouw.nl

2.3. Involved parties

The main involved parties in this housing project collaboration will be mentioned together with their responsibilities and goals in this subsection.

At first, there is Wilmink-Oosterveld, which is the party who commissioned the thesis. Wilmink-Oosterveld is a medium scaled contracting company with a focus on developments towards sustainability and circular building. It is a company with a very progressive thought and goal towards the future of building fabric halls and houses. Wilmink-Oosterveld is responsible for the assembling of the house.

Thereafter is Tangramhuis R9, which is a small architectural company existing of two architects and one constructor. They have designed this type of zero energy house called ‘Tangramhouse’. Tangramhuis R9 is responsible for designing and delivering the 3D models, floor plans and dimensions. This company has the same view on the future of building as Wilmink-Oosterveld.

At last, there are two companies, Loohuis installation company and Scana Bouw. Loohuis is responsible for the piping system and the connection to the networks. Scana Bouw is the timber frame construction supplier for the house. They are responsible for supplying the timber frame including walls, windows, doors and other static building objects. These companies are reliable companies with also the same view towards the future of this collaboration project.

2.4. Relevance of the research towards the Tangramhouse project

This research will help the collaborating companies Tangramhuis R9 and Wilmink-Oosterveld to gain insight into environmental and economic impact of the house, how this works out on the long term with costs and the ability of the house to sell in the Eastern of The Netherlands. This study helps in better understanding of the environmental and economic performance of the Tangramhouse by looking into the life cycle GHG emissions and life cycle costs. As third, the research will help to assess the feasibility and ability for the Tangramhouse to sell in the current and future housing market. Moreover, an LCA and LCC of the Tangramhouse in order to identify major emission sources, where to potentially reduce the GHG emissions and what costs are involved with that, is not yet investigated. The goal of the Tangramhouse project collaboration is in the end to play a part in solving the housing crisis by building many of these zero-energy houses all around the Eastern of The Netherlands. This research could be a small step for the development of the project towards that goal.

2.5. Importance of conducting an LCA and LCC in the building sector

The LCA methods for the assessment of the environmental performance of the buildings have been developed since the early 1990’s (Passer, Kreiner, & Maydl, 2012). The International Standardization Organization (ISO) prepared the first standard that addresses the specific issues and aspects of the sustainability relevant to the building and the construction works. Currently, the application of the LCA also includes the analysis of the economic performance of the buildings in the form of an LCC (Braganca & Mateus, 2012).

LCA for the buildings provides the quantitative and comparative values of the environmental impacts of various building technologies (Singh, Strømman, & Hertwich, 2011). LCA is used for quantifying the emission, energy and material consumption of a building system in different life cycle phases starting from the acquisition of raw material, product manufacturing assembling and disassembly and disposal. (UNI EN ISO 14040 2006; UNI EN ISO 14044 2006; (Consoli, et al., 1993)).

Definition and aspect of LCA

LCA is a technique to evaluate the environmental impact of products or activities, starting from the extraction of raw materials, manufacturing, production, use and finishing with the final disposal, i.e. from cradle to grave (Sonnemann 2006; Fava 2006), which helps to identify and evaluate opportunities to affect the environmental improvement. Life cycle assessment (LCA) is an effective method to evaluate the environmental behaviours of products in a life cycle from cradle to grave (Jensen et al. 1997).

Definition and aspect of LCC

Life-cycle costing (LCC) is a technique used to estimate the total cost of ownership. It is a system that tracks and accumulates the actual costs and revenues attributable to cost object from its invention to its abandonment, so over the total life cycle. It allows comparative cost assessments to be made over a specific period of time, taking into account relevant economic factors both in terms of initial capital costs and future operational and asset replacement cost (CorrosionPedia, 2017).

3. LCA and LCC introduction, goal and scope

3.1. LCA and LCC introduction

Buildings in use and their construction together account for 36 percent of the global energy use and 39 percent of energy-related carbon dioxide emissions annually (Budds, 2019).

Within the Netherlands the build environment as a sector accounts for about 10 percent of the total greenhouse gas (GHG) emissions. Households account for almost all of these emissions. As the population globally and in The Netherlands is growing it requires construction of new housing. The housing sector, or build environment sector in general, is stated in many GHG mitigation policies as an relatively easy sector with a high potential to deliver long-term and cost-effective GHG reduction (Ghattas, et al., 2016).

The housing sector's energy intensity in terms of greenhouse gasses will have to improve by 30 percent by 2030 globally to meet the goals of the Paris Climate Agreement. Decarbonization of the sector and within the building industry is therefore necessary and can be done in many different forms. By 2050 all buildings must be net zero carbon, but there are very few buildings today which can be considered net zero. The designed type of zero energy house, Tangramhouse, has implemented various measures to be as sustainable as possible, especially in terms of energy use and production.

To quantify the environmental impact of housing and to estimate the potential reductions of GHG's often an Life Cycle Analysis (LCA) is used. LCA is a widely accepted and standardised method for estimating the environmental impact of products or processes.

In order to estimate the environmental impact of the Tangramhouse an LCA will be conducted. In this LCA the emphasis will be on greenhouse gas emissions, with a focus on carbon dioxide emission. In existing previous literature on LCA's on Residential buildings the use-phase accounts for the majority of the life cycle impacts. However, this goes for traditional build buildings and not for energy-efficient and zero-energy houses. In these type of buildings the materials and the construction have a larger influence in the environmental impact (Budds, 2019).

When the life cycle of a product, or in this case a zero-energy house, will be assessed, then what the life cycle contains must be defined first. In general, the product life cycle consists of five phases:

1. Extraction of raw materials
2. Production & Processing
3. Transportation
4. Use & Retail
5. Waste processing

LCA is a standardized methodology, which gives it its reliability and transparency. The standards are provided by the International Organisation for Standardisation (ISO) in ISO 14040 and 14044, and describe the four main phases of an LCA (Golsteijn, 2020).

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

3.2. Goal and Scope definition

The goal of the study was to evaluate the environmental and economic impacts of the Tangramhouse over its life-cycle. Both the results of the LCA and the Life Cycle Costing Analysis (LCC) of the Tangramhouse were compared with similar style building types.

The program used for the LCA is GaBi and an analysis gives many different impact categories. For this research, similar to other residential LCA studies, the impact category evaluated only includes the CO2 emissions with the Global Warming Potential or Climate Change impact category (Ghattas, et al., 2016). The functional unit was considered as the whole Tangramhouse for 100 years.

3.2.1. System Boundaries

In this study the entire life cycle is included into the system boundaries except for life cycle stages B5 and B7. In the following table, Table 1, life cycle stages and subdivisions can be seen according to the norm EN 15804:2012.

Table 1: Life cycle stages

A. Product stage	
A1	Raw material extraction and processing, processing of secondary material input
A2	Transport to the manufacturer
A3	Manufacturing
A. Construction process stage	
A4	Transport to the building site
A5	Installation into the building
B. Use stage, related to the building fabric itself	
B1	Use or application of the installed product
B2	Maintenance
B3	Repair
B4	Replacement
B5	Refurbishment
B. Use stage, related to the operation of the building	
B6	Operational energy use
B7	Operational water use
C. End-of-life stage	
C1	De-construction, demolition
C2	Transport to waste processing
C3	Waste processing for reuse, recovery and/or recycling
C4	Disposal

The substages of B5 Refurbishment and B7 Operational water use are excluded out of the system boundaries since it is assumed that the house in its whole life cycle will not be refurbished and also the water use is not taken into account for the ease of comparison with other studies. Both for the LCA and the LCC these are the total system boundaries.

3.2.2. Limitations

Limitations are the fact that the Ecoinvent database of GaBi does not have every material in it, so the material closest to the original material is chosen. This can, however, lead to slightly different emission results compared to reality (Petrović, Zhang, Eriksson, & Wallhagen, 2021).

For the LCC there are in general some limitations regarding the availability and accuracy of data. Especially on the long term there is much variability with the different parameters which could lead to high uncertainties. In some cases for the construction the average costs of certain materials or services have been taken, but this could in reality be slightly different. Also the long term costs for maintenance and replacements could differ because it is complicated to predict and this also depends on the user or occupant of the house and thus has some variations in use.

4. Problem statement and research objectives

Tangramhuis R9 as a company have designed this particular type of zero-energy house but this is a rather difficult task since one gets to deal with various options for shapes, materials and systems for very different costs. The goal is here to identify the right balance between environmental and economic sustainability of the house and the current housing market. Right now for Tangramhuis R9 and Wilmink-Oosterveld it is not exactly known what the quantification of environmental and economical sustainability throughout its life span from extraction till end of life (cradle to grave/cradle) will be. Another problem that arises is the non-traditional building process and the relatively 'new' type of zero-energy house in the market for which it is unknown yet how well it will sell on the current housing market.

Out of the problem statement given above the following research objectives could be drawn up:

1. To analyse the current Life-Cycle Costs and Life-Cycle-Assessment of this particular type of house 'Tangramhouse' to make statements on how sustainable this house is.
2. To evaluate the current housing market and gain insight in how well this 'Tangramhouse' could sell in the East of the Netherlands with its high demand.

5. Research questions

In order to get an answer on the research objectives as mentioned in the section above, the following two main research questions should be answered. Each main question is then divided into several sub-questions.

1. How cost-efficient and environmental friendly is the Tangramhouse?

1.1. What are the CO2 emissions from cradle to the end-of-life of the building and compare this with similar and traditional styles of building houses?

1.2. What are the life cycle costs of the Tangramhouse?

2. How would the Tangramhouse sell on the current housing market in the East of The Netherlands?

2.1. What are the developments on the housing market in the East of The Netherlands towards more sustainable houses and zero-energy houses?

6. Research Methods

To achieve the research objectives and to get a well-founded and well-structured answer on the main research questions different research methods must be used. The methodology for both main research questions will be discussed in this section.

The first research question is as follows:

1. How environmental friendly and cost-efficient is the Tangramhouse?

Firstly, the environmental sustainability of the Tangramhouse in terms of CO_2 emissions from cradle to the end of the building process was evaluated as proposed by conducting a Life Cycle Analysis (LCA). Both primary data (gathered from the companies) and secondary data (GaBi: Ecoinvent database) are used. Together with this data and information an LCA model has been created in the GaBi software. In LCA, we can distinguish four phases, The Goal & Scope phase, the Life Cycle Inventory, the Impact Assessment and belonging to all three but also on its own is the Interpretation phase at the end (Ecochain, sd). The methodology of conducting a LCA is commonly known and is established in the ISO 14040 / 14044 norms for Life Cycle Assessment – General principles and practices.

Second and last, the proposed method to analyse the long term cost efficiency of the Tangramhouse is by conducting an Life Cycle Costing Analysis. This is a method for assessing the total costs of the Tangramhouse which takes into account the costs of building, acquiring, maintaining and in the end disposing the building. The costs data needed are the current costs of the whole building process, the materials used, the services, but also estimated costs for the future for maintaining and disposing the house again.

A Life Cycle Costs Analysis (LCCA or LCC) is an assessment in which the total costs of a structure or product is determined. This is done by combining different pieces of information regarding costs. By comparing the final outcome of a LCCA with alternatives, decisions can be made. In this case, the LCC for the Tangramhouse will be compared to a house with a traditional building process.

Within the whole Life Cycle of this Tangramhouse one can distinguish different phases. At first there is the Investment / Construction Phase. In this phase the house is designed and the construction has started and finished. After that there is the Operation / Use Phase, which is where people get to live in the house and make use of it. At last there is the End of Life Phase, this is the phase where the house can no longer its purpose or it needs to be replaced. In this phase the demolition takes place.

The second research question is as follows:

2. How would the Tangramhouse sell on the current housing market when more of this type of houses are built in the East of The Netherlands?

At first, the method proposed for gaining insight in the current developments of the housing market towards more sustainable and zero-energy houses is to take interviews with estate agents and other related people of the housing market in the region. A narrative analysis method will be used to analyse the interview data, this method focuses on using stories and experiences of experts in order to answer the research questions (Delvetool, sd).

7. LCA implementation

In this study, a cradle to grave LCA from construction till end of life was performed using GaBi software. In this section the elaboration of the LCA conduction and implementation is given.

7.1. Geometric characteristics

The amounts and type of materials of every part of the house including the construction site energy and water inputs can be seen in Table 2 below. The data is gathered from the companies Wilmink-Oosterveld and Tangramhuis R9 and together with the technical drawings and a couple calculated estimations the table of the whole house could be made.

Table 2: Geometric characteristics, amounts and material types

System / subsystem	Main material	Quantity	Unit
1. Foundation			
Concrete base foundation incl. floor	Concrete (2400kg/m3)	22,78 54.672	m^3 kg
Steel rebar as reinforcement	Steel (90kg/m3)	2050	kg
EPS formwork/mould	EPS 150 mm expanded polystyrene (25 kg/m3) (De Vree, sd)	15,73 393,25	m^3 kg
2. Frame and roof structure			
Bearing walls	Wood/timber beams (550 kg/m3) Wood fiber insulation Construction plate Plate wood fiber insulation (Eurabo, 2021)	11,6 54,69 6,78 3,92	m^3 m^3 m^3 m^3
Façade cladding wood	Lunawood (thermic pinewood) 560kg/m3 (KOMO, 2021)	2,16 1209,6	m^3 kg
Ground floor	Steel EPS	894,4 16,07 401,8	kg m^3 kg
First floor	Wood/timber beams (Houtinfo, sd) Underlayment plate EPS 150 Insulation	Included in bearing walls 1,60 4,45	 m^3 m^3
Mezzanine floor	Wood/timber beams Underlayment plate EPS Insulation	Incl. in bearing walls Incl. in first floor Incl. in first floor	
Interior walls	Wood/timber beams Wood fibre insulation Construction plate	Incl. in bearing walls Incl. in bearing walls Incl. in bearing walls	
Wood fibre insulation	Wood fiber (50kg/m3) (BouwGezond, sd)	Incl. in bearing walls	
Stairs	Wood timber	2x60 = 120	kg
Roof structure	Wood/timber Same structure as walls	Incl. in bearing walls	

3. Complementary works			
Windows	Glass (2500kg/m3) Wooden frames	0,306 765 0,3203 176,165	m^3 kg m^3 kg
External doors	Wooden front door Frame front door Sliding door frame Sliding door glass Frame outer sliding door	750 0,02335 12,84 0,194 106,7 0,1368 342 0,154 84,7	Kg m^3 kg m^3 kg m^3 kg m^3 kg
Internal doors	Wood Plywood 30kg each	240	kg
Solar chimney	Hardened glass 10kg/m2	60 600	m^2 kg
4. Finishes			
Roofing sedum green elements	2168,25 kg CO2 eq. / 100m2 / 100 years as calculated in Appendix A.		
Solar PV Panels	About 40 g CO2 eq./kWh (Laboratory, 2012)		
5. Mechanical works			
HVAC and electrical systems	Steel Plastic Polyvinylchloride(PVC)	1850 900 400	Kg Kg Kg
6. Construction site			
Energy	Electricity Diesel	270 360	MJ MJ
Water	Water	264	kg

The LCA is in principle a narrowed down method of reality to assess the possible environmental impact of a product, or in this case, a house over its life span. Within this assessment a couple assumptions and decisions have been made in order to be able to fully conduct an LCA. Below the general assumptions for the model and materials are listed:

- The materials used in the building of the house have been implemented in the closest possible way into GaBi with the available data. So certain wood materials have been implemented in GaBi as one general type of wood for example.
- All the wooden or timber beams in the walls, floors and roof and the stairs are assumed to be the same type of wood.
- All the wooden construction plates / boards used in the house are assumed to be plywood underlayment.
- The concrete used in the foundation is the same as in the ground floor layer on top of the foundation.

7.2. Inventory Analysis

Before being able to conduct an LCA, the process of quantifying and identifying energy usage, collecting data, making educated assumptions and checking all environmental releases should be done (SEMTRIO, sd). In this section the data collection, the educated assumptions, the energy and environmental usages and releases will be given as well as the different flow diagrams of the life cycle phases as modelled in GaBi.

Both primary and secondary data were used in the life cycle inventory. Primary data on the quantity of materials used in the Tangramhouse, transportation distances and the use means of transport, energy consumption during building use were collected. The Ecoinvent database has been utilized to model the manufacturing process of the materials used and their associating emissions.

7.2.1. Life Cycle Phases

In this subsection the main three different life cycle phases as modelled in GaBi will be discussed. The life cycle phases are the following three phases:

1. Production phase
2. Use phase
3. End-of-life phase

In the modelling of the life cycle of the house, the three main phases are the production phase, the use phase and the end-of-life phase. The extraction of raw materials and transportation are included in the production phase. In order to assess the impact of the whole life cycle, it is first divided into these three main phases and in the end put together in a clear and structured way.

Production phase

In the production phase all the materials are extracted and subsystems and final house are assembled. It starts with all the different input materials as processes. The materials are assembled as prefab elements in order to eventually set up the timber frame structure of the house. After every element is transported everything will be assembled on site. The output of the Tangramhouse construction / assembly process eventually is the completed Tangramhouse. Figure 17 in Appendix C shows the total production phase of the Tangramhouse as modelled in GaBi.

Use phase

The use phase is included to account for the impact generated by the energy consumption of different house activities such as cooking, water heating, lighting and use of other electrical appliance during the building lifetime. The house is occupied by persons and this phase is a long period of time. In the GaBi software it is assumed that the life span of the house is 100 years. With using the house for such a long time comes maintenance and energy use. The sedum green roof and the PV solar panels need to be replaced in this time since the life spans are much shorter. However, in the model these maintenance and replacement operations have been left out because in the production phase this is already taken into account as a total sum of kg CO_2 eq. Electricity use over a 100 years is the only thing added in this phase. Figure 6below shows the use phase of the Tangramhouse as modelled in GaBi.

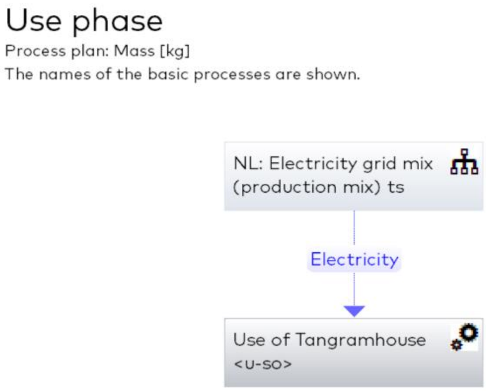

Figure 6: Use phase of Tangramhouse life cycle as modelled in GaBi

End-of-life phase

The end-of-life phase or disposal phase is where the whole house after its 100 years of use will be disassembled and deconstructed in order to be able to reuse or recycle as many elements as possible. If certain elements or materials cannot be reused or recycled, it will be land-filled and/or incinerated. Now recycle rates and assumptions come into place on how much of certain materials will be recycled, land-filled or incinerated. The end-of-life phase as modelled in GaBi can be seen in Figure 16 in Appendix C.

In GaBi itself some processes are pre-made specifically with a recycling purpose. In order to model the recycling of some products which do not have pre-made recycle processes, a so-called avoided product can be implemented. In this way the process of manufacturing a certain material is now inverted, so all inputs are converted to outputs or vice versa.

In the Netherlands the most waste is generated in the construction sector. However, the construction sector also has the highest recycle rate out of all sectors. Within the EU the Netherlands is on top of the list when it comes to the recycle rates (CBS E. , 2019).

The concrete foundation exists of concrete, steel rebar and EPS. Concrete is in fact 100% recyclable, but this is often not happening due to costs (CEMBureau, sd). After a 100 years it is however assumed that 90% of the concrete will be recycled, and 10% will be land-filled. Currently 85% of worlds steel is recycled and in the UK a study mentioned a 94% recycle rate for construction steel (TATAsteel, sd). In the model it is assumed that the recycle rate of construction steel is 95%, the rest will be land-filled. Also EPS is in fact 100% recyclable but this is not happening much (EUMEPS, EPS FAQS, sd). It is assumed that 80% will be recycled, 15% will be land-filled and 5% of the EPS will be incinerated.

Timber pine as material is used in the most components of the house. Currently the recycle rate in the in the Netherlands is about 77%, and after some time it is assumed this value will be 80% and the rest will be incinerated (Afvalfonds, sd). For pine log, plywood and other types of wood used in the house these recycle rates are assumed to be similar.

Pulp wood in Europe has currently a recycle rate of 72%, this is assumed to be 75% in a later time frame (Crèvecoeur, 2019). The rest, 25%, will be incinerated.

Float glass in the Netherlands is currently only about 25% separated and fully recycled (Vlakglasrecycling, 2019). In the future it is assumed this is about 50%, the other half will be landfilled.

When it comes to PVC as a building material, innovations and developments in the UK have led to about a 19% recycle rate (Taylor, 2020). In the future it is assumed this technology will get improved to the Netherlands, so 30% will be recycled and 70% will be landfilled.

Lastly, the plastic moulding parts are used in the house. Plastic has currently a 50% recycle rate in the Netherlands. It is assumed this will be about 60% later, so 40% will be landfilled (AISBL).

7.3. Impact Assessment Results

The following chapter presents the environmental impact results in terms of CO2 equivalent of the Tangramhouse life cycle. The results are as mentioned before of the entire life cycle of 100 years from cradle to grave. In the graphs presented the share of the separate construction phase, use phase and end-of-life phase to the CO2 emissions can be seen.

As life cycle impact assessment method the ReCiPe method was utilized in GaBi. The reason for choosing this method, or to be more specific: the ReCiPe Midpoint method, is because the individual impact categories can only be compared on the Midpoint level (Emami, et al., 2019). In this way the results of the Global Warming Potential in kg CO2 eq. can be compared to other studies and from that, statements can be made about the environmental impact of the Tangramhouse. Furthermore the ReCiPe method is the most scientifically approved methodology used in most LCA studies in Europe (Ghose, 2012).

In Figure 7 below the graph results out of the GaBi modelling total life cycle can be seen. This can be seen as the reference situation of the Tangramhouse Life Cycle. In this figure also the estimated CO2 equivalent over 100 years of the solar panels and the green roof are added since these could not be implemented in the model in a realistic and efficient way.

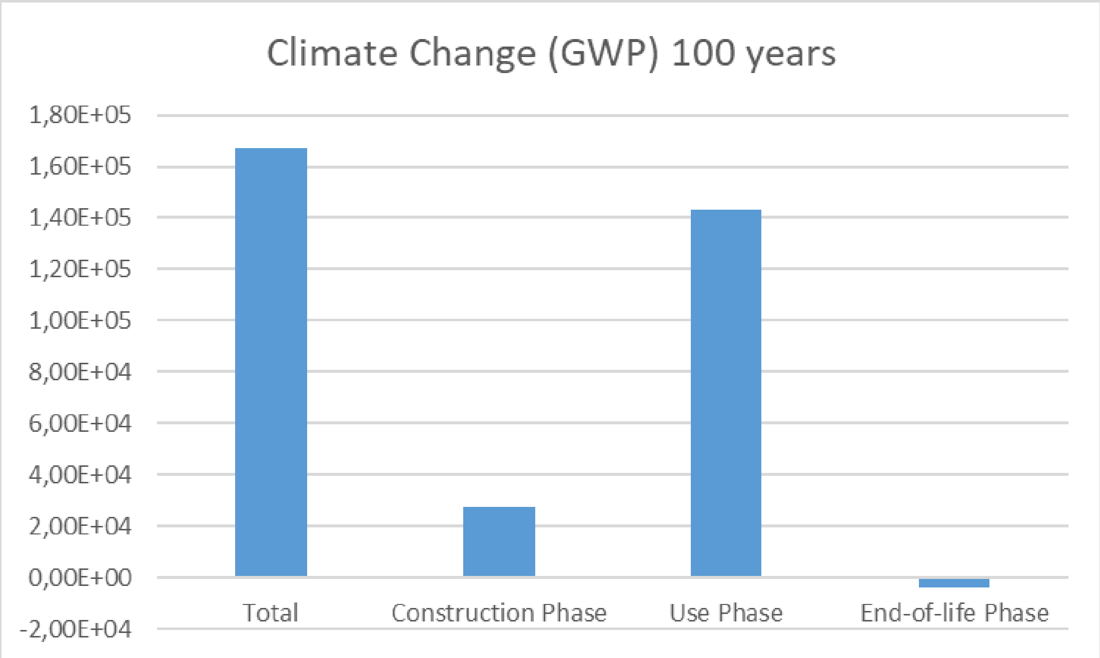

Figure 7: LCA Result Climate Change Impact

It can be seen that the use phase has an enormous share into the total CO2 emissions. This is of course because of the electricity use for 100 years, and in this model the electricity comes from the grid mix. This means it is electricity generated in several ways in which the most share is from non-renewable sources like coal and gas. Subsequently this gives the high CO2 share.

In the Figure 8 below the graph of the construction phase and its shares can be seen. In the construction phase too the electricity share is quite high.

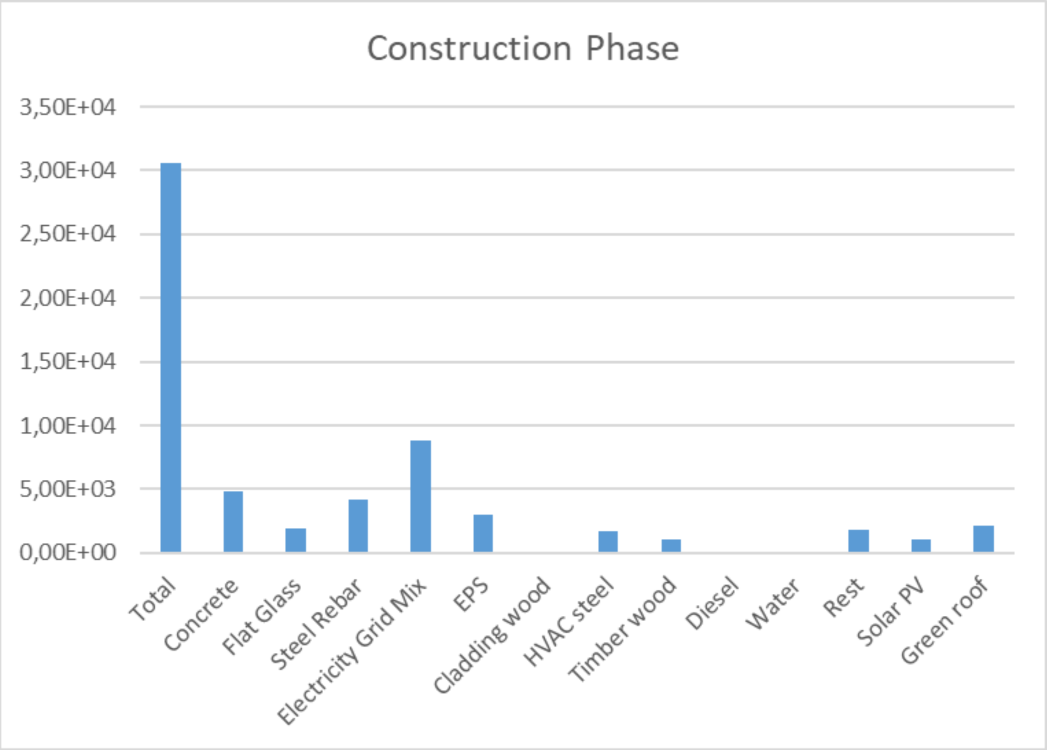

Figure 8: Construction phase results Climate Change Impact

In Figure 9 below the graph of the End-of-life Phase can be seen. Since a relatively high amount of the started materials are being recycled the share of the most materials have a negative impact on the CO2 emissions. In fact it is modelled in such a way that the CO2 emissions are 'inverted' when the material gets recycled.

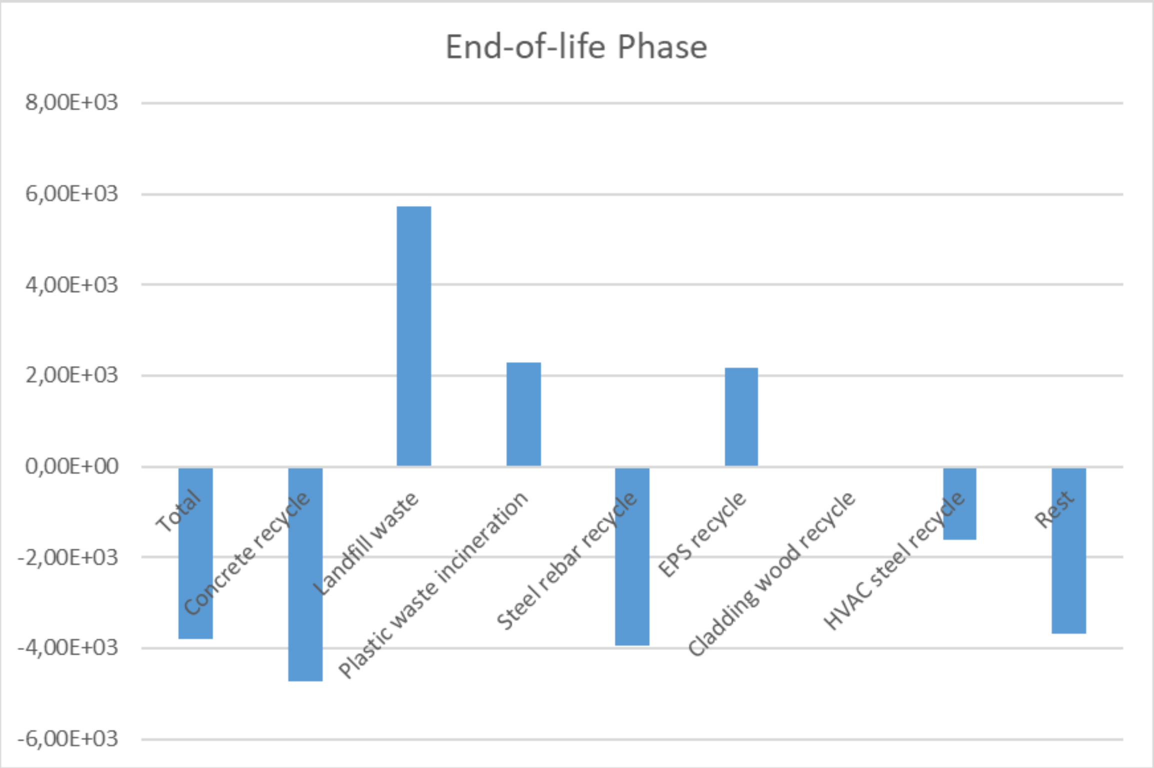

Figure 9: End-of-life phase Climate Change Impact results

The Use Phase graph is not relevant to show since that is equal to the use phase bar in the total graph since it only consists of electricity emissions.

7.3.1. LCA Sensitivity Analysis

Electricity source can make a huge difference in the total amount of CO2 emissions. In the Netherlands it is possible to have more green energy or full green energy depending on the energy supply company. As an example Vattenfall is an energy supplier which has 100% renewable green energy. The shares of this is 60% wind, 32% solar and 8% water (Vattenfall, sd).

Implementing this in GaBi gives the following use phase flow diagram in Figure 10.

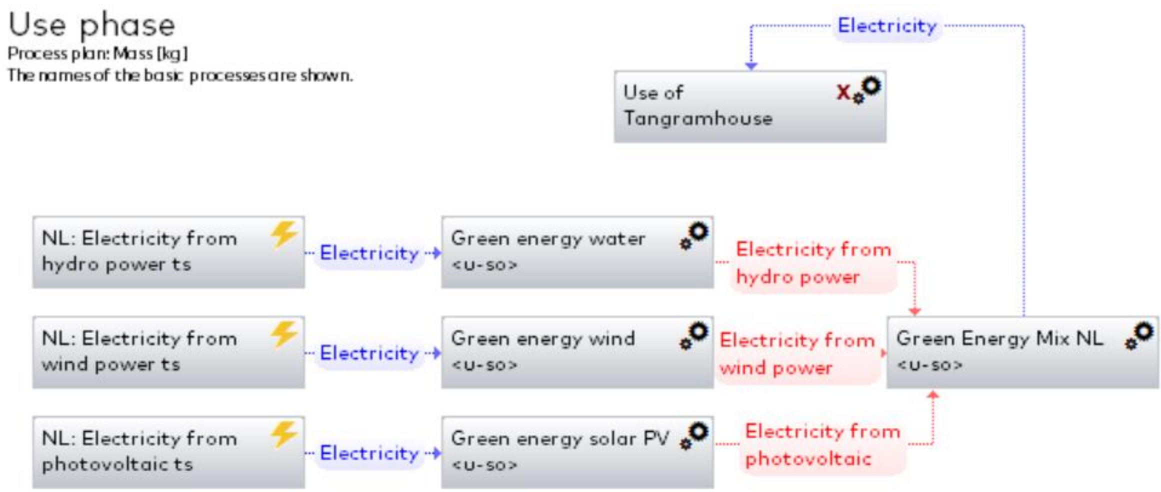

Figure 10: Green energy source flow diagram

This results in the following GWP CO2 emissions in Figure 11 a comparison of the different energy sources and its emissions can be seen. This shows an almost 96% drop in CO2 emissions from the use phase.

When applying the 2020 energy sources which gives electricity to the grid in the Netherlands, the shares are as follows (EnergieinNederland): 60% gas, 5% waste incineration, 5,5% coal, 3% nuclear, 8% solar, 12% wind and 6,5% biomass. So in total already 26,5% of the energy is renewable (Nuclearinfo, 2020) . The use phase as modelled in GaBi when this type of energy is implemented can be seen in Appendix C, Figure 15. This results in the following GWP CO2 emissions. This shows an almost 39% drop in CO2 emissions from the use phase.

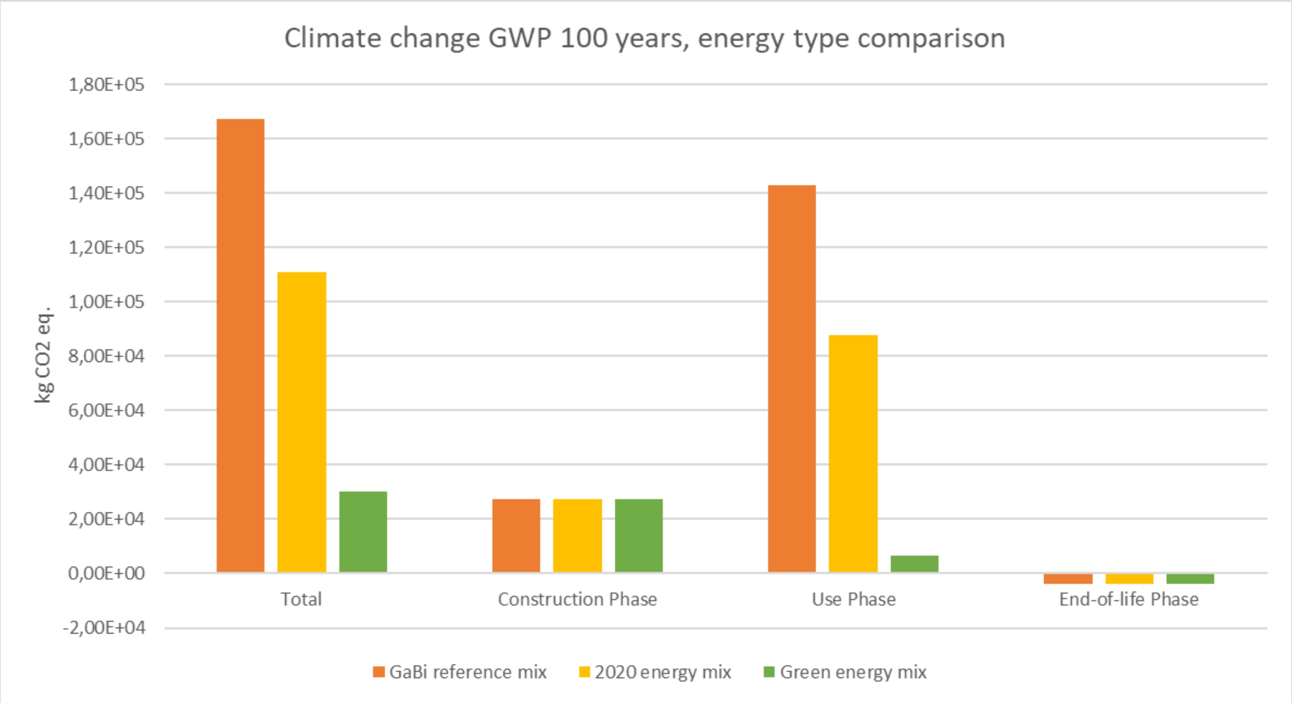

Figure 11: Energy type comparison Climate Change Impact results

7.4. Interpretation and comparison

The total Global Warming Potential is 167.000 kg CO2 eq. for the reference situation. As mentioned before, in other LCA residential detached house studies the functional unit was often bounded by one square meter house and the life span differs In order to compare the studies, the LCA results can be easily divided by its gross floor area and the amount of years (Ghattas, et al., 2016). In case of the Tangramhouse it should be divided by a 100 years and divided by the total gross floor area of 125m2. This gives the following GWP: 13,36 kg CO2 eq. /year/m2.

To compare, the best version of energy type to use in this case is the one with the grid mix of 2020, since it is the most recent. This has a total GWP of 111.000 kg CO2 eq. This will be calculated in the same way to compare, so divided by a 100 years and divided by the total gross floor area. This gives the following GWP**: 8,88** kg CO2 eq. /year/m2.

1378 kgCO2eq./m2 divided by 60 years: **22,97** kg CO2 eq. /year/m2 (Ghose, 2012). This is a single family residence in mid Norway, timber framed construction and also the cladding is wooden. And the gross floor area is 136m2. This has kind of similar characteristics as the Tangramhouse.

1657 kg CO2eq./m2 divided by 50 years: **33,14** kg CO2 eq. /year/m2 (Dahlstrøm, Sørnes, Eriksen, & Hertwich, 2012). This is a single family residence passive house in West Norway, wooden built and a two story building with a 187m2 gross floor area.

The two LCA studies mentioned above have a higher environmental impact in terms of CO_2. This could be because of the colder environment in Norway, there is more energy needed to keep the same level of heating which causes especially in the use phase a higher amount of CO_2 emissions.

The two LCA studies results to compare below have more an environment / climate comparable to the Netherlands.

547,945 kg CO2eq./m2 divided by 60 years: **9,13** kg CO2 eq. /year/m2 (Moňoková, Vilčeková, & Selecká, 2019). This is a single family house in Slovakia, 120m2, timber frame construction, two story, the roof is saddle shaped and has vegetation on it. This is very comparable to the Tangramhouse.

5,7 kg CO2 eq. /year/m2 (Petrović, Zhang, Eriksson, & Wallhagen, 2021). Single family house in Sweden, Darnallas Villa, designed with the aim to reduce energy impact and achieving low environmental impact from life cycle perspective. Gross floor area 180m2

To conclude, it can be said that the Tangramhouse scores as one of the best houses with regards to the kg CO2 eq/year/m2. In that way, especially for a house framework which will be implemented a lot more to a standardised modules to build it more over the Eastern of the Netherlands, it is a really sustainable house in terms of CO2 emissions. Also compared to the single famlily house in Sweden and Slovakia which are designed for reducing the environmental impact, the tangramhouse results are quite similar so it can be said that the tangramhouse is very sustainable in terms of CO2 emissions.

8. LCC implementation

A Life Cycle Costs Analysis (LCCA or LCC) is an assessment in which the total costs of a product or structure are determined over its life cycle. This is done by combining all pieces of information regarding costs, from production process costs to waste processing and disposal costs. By comparing the total Net Present Value and total Life Cycle Costs of the Tangramhouse with that of other houses, decisions can be made and conclusions can be drawn up about the economic impact. In combination with the LCA, as conducted in section 6, conclusions and advices can be drawn up about how the environmental impact and economic impact influence each other.

The LCC for this study is, similarly as the LCA, divided into three main phases; Construction (& Investment) Phase, Use Phase and End-of-life Phase. In each phase certain expenses and costs have to be made and by stepwise investigating this, monetary values can be added to the products and processes.

8.1. Construction & Investment Phase

During the construction phase, most of the expenses come from all the materials which are required for building the house, together with the costs of design and assembly. To get a better knowledge of this, the following steps were performed to get insight into the whole costs process for construction:

<u>1. List material requirements and amounts.</u> By breaking down the design of the house in parts and subsystems, an overview in materials required could be made. This is done in 7.1. Geometric characteristics.

<u>2. Determine material processing costs.</u> The most data for this part is gotten from the available cost estimate for the Tangramhouse. The rest of the complementary works which was not budgeted are based on given prices of certain companies services or products. The calculations and estimations for these services and products are stated in Appendix B.

<u>3. Costs of Transportation.</u> In the LCC model, just as in reality, some parts of the house including the walls and the roof elements have been prefabricated in the company. The rest of the materials are brought on site to construct. However, everything will be transported to the site by truck. it is assumed that the bridge is partially constructed outside of the project location. The costs of fuel for fuel are calculated by determining the fuel usage per distance, multiplied by the distance itself. Also other transportation costs such as the crane and construction workers to get to the site are taken into account in this subsection.

<u>4. Costs of construction, design and assembly.</u> By using the average loan for a construction workers at a certain job and the estimated data in the budget, the costs of the personnel could be estimated.

8.2. Use Phase

The Use Phase or Operation Phase costs do mostly consist of reoccurring maintenance and yearly energy costs. During this phase it is assumed that only small maintenances or replacements will happen. Compared to the construction phase, this phase has more uncertainty since the speed of products or materials withering down can vary. The green roof and the solar PV panels including the system will be maintained and replaced in correspondence with the life spans. For this phase the following steps are taken:

<u>1. Assess Lifespans.</u> For each object or system on the house, a lifespan was attached. After this lifespan has passed, the object should be replaced in a replacement session.

<u>2. Reoccurring maintenance and actions.</u> Some actions are done on a more frequent rate, such as re-painting or re-lacquering, or the yearly inspection of the green roof.

3. Costs of living. When the house is in use, there are energy costs of all the devices and living apparatus. The calculations for the energy costs are further elaborated in Appendix B.

8.3. End-of-life Phase

During the end of life phase, no material costs are made, since the house will be deconstructed and the materials are brought elsewhere for either recycling, landfilling or incineration. The one and only step done in this phase was to assess the demolition costs since the wages, transport of waste and costs of recycling, landfilling or incinerating are all taken into account with the demolition costs.

8.4. LCC Results

All of the information and data processed in the excel model gives the following results. The overall Life Cycle Costs of the Tangramhouse over 100 years is rounded €507.168. This consists of €300.760 as present value and €206.408 as net present value. The parameters used in this case are a discount rate of 0,75% and a inflation rate of 2%.

In Figure 12 below the costs per life cycle is shown.

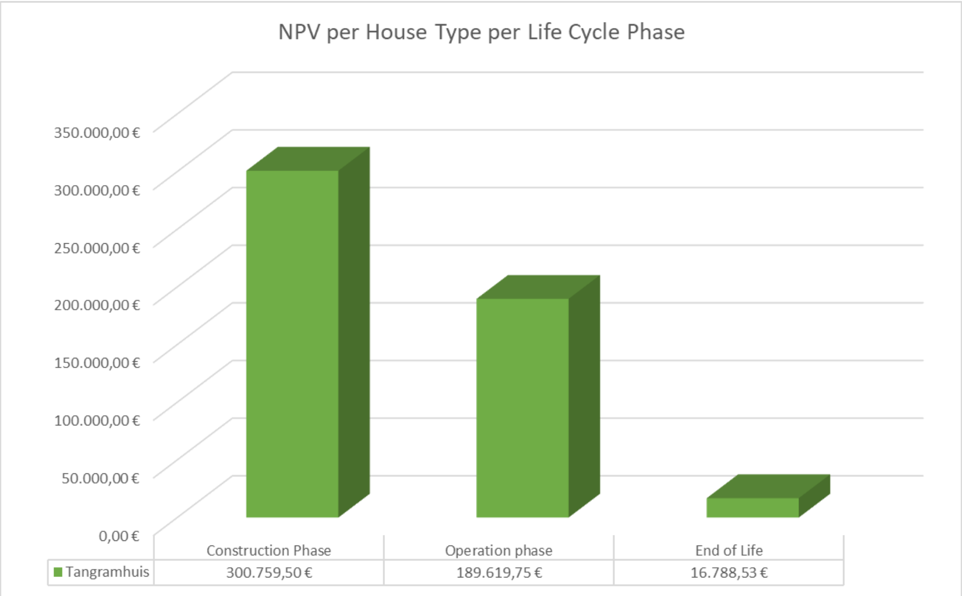

Figure 12: Total life cycle costs per life cycle phase

When comparing these results to other studies LCC, it can be seen that the proportions of each phase are quite similar. In order to compare the monetary values of the whole houses will be divided by its gross floor area. So for the Tangramhouse the construction phase costs are € 2.406,08 /m2 ; the use or operation phase costs are € 1.516,96 /m2 and the end-of-life costs are € 134,31 /m2.

The single family timber frame house in Sweden, Darnallas Villa, which was designed specifically to reduce the environmental impact had the following costs (Petrovic, Zhang, Eriksson, & Wallhagen, 2021). In converted currency, over 100 years with also an inflation rate of 2% and a discount rate of 3%, the construction phase € 3066,20 /m2. The use phase costs are € 1149,83 /m2 and the end-of-life costs are € 95,82 /m2.

Another residential building to compare is the case-study of a detached-house, a residential building composed by 3 residential units structured on three floors, with a total net-floor area of 350 m2. Different building styles have been evaluated in this study, here the timber frame construction alternative and the concrete alternative will be compared (Dejaco, et al., 2020).

Timber frame construction: The construction phase costs are € 1.171,43 /m2 ; the use or operation phase costs are € 971,43 /m2 and the end-of-life costs are € 157,14 /m2.

Concrete construction: The construction phase costs are € 1.228,57 /m2 ; the use or operation phase costs are € 1052,64 /m2 and the end-of-life costs are € 285,71 /m2.

It can be concluded that the Tangramhouse in terms of costs is in the construction phase is relatively cheap. The use phase costs are slightly more than the other houses and the end-of-life costs are almost similar in comparison with the other houses.

8.4.1. LCC Sensitivity Analysis

LCC: change in discount rate

The discount rate determines the rate of value loss of an object in the future. This important for calculating the total value of a structure in the future. The sensitivity analysis is performed by varying the discount rates from -0,25% to 1,75%, where 0,75% is the 'zero-change' reference number. It can be noticed that lower discount rates have an bigger influence on the relative value then higher discount rates, but the changes still seem to occur in a relative linear matter in Figure 13 below.

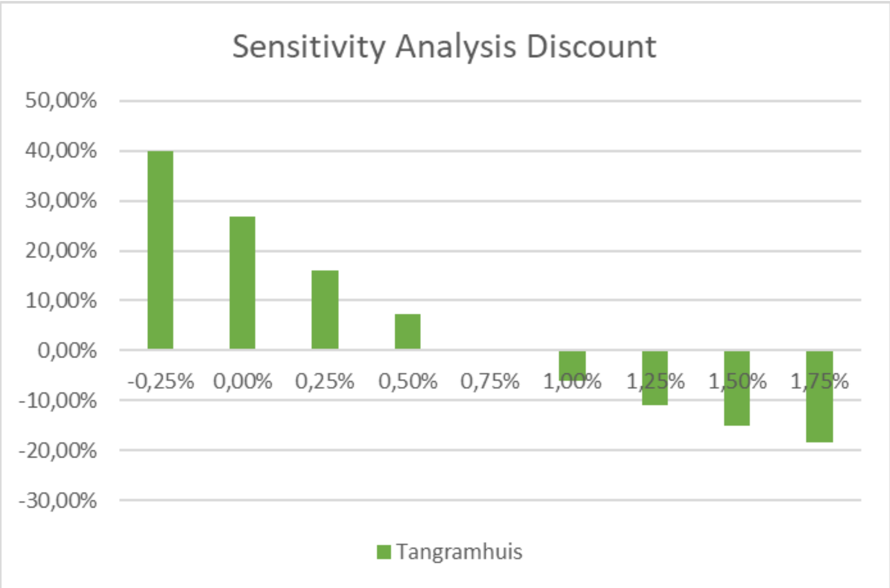

Figure 13: Sensitivity analysis results of the discount rate

It can be said that the discount rate does have a significant influence on the final monetary value of the LCC.

LCC: change in inflation rate

More interesting is the figure for the inflation rates, Figure 14. Inflation is an change in the value of money. This means that the same product can become more expensive over time, due the money getting worth less. Although, this seems like something which should be avoided, it should not. It belongs to a well-functioning economical system, and stimulates economic growth. Since inflation rates have been varying between -2% and 6% over the past couple of years, it is important to investigate how such percentage change influences the final monetary value of the LCC. In Figure 14 below, the relative change in LCC worth is plotted against an inflation percentage varying from -2% until 6%, with 2% as reference number:

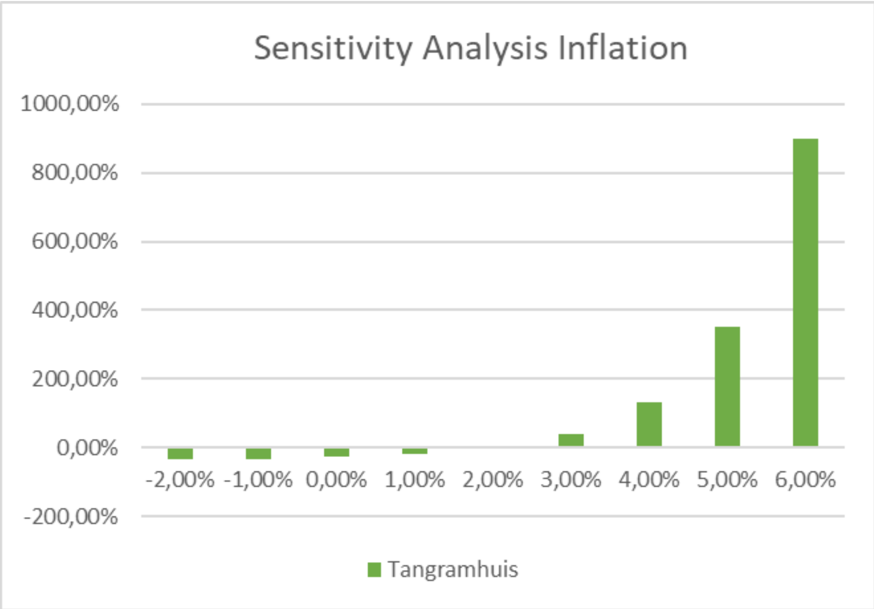

Figure 14: Sensitivity analysis results of inflation rate

It can be noticed that the graph follows an exponential growth when the inflation increases, with peaks of about 900% compared to the reference number.

9. House market research results

In the following section the house market research approach and its results will be discussed. In section 3 a problem statement was given that the Tangramhouse is a relatively ‘new’ type of zero-energy house on the market of which not much similar houses have been built and sold in the Eastern of the Netherlands. Therefore it is still unknown how the Tangramhouse as an innovative type of house, which is planning to upscale to also terraced houses, will sell on the current housing market.

In order to evaluate the current housing market and answer the question above an interview have been carried out. A couple of questions have been answered by estate agents in the region about sustainable housing, the current market towards sustainable houses and the Tangramhouse itself. The full interview answers can be found in Appendix D.

Amongst the interviewed estate agents sustainability in general is viewed as a very important topic which will become even more important in the near future in order to keep living on the planet. Within the real estate in the Netherlands there are currently more tightened rules and guidelines in coming from the government in order to stimulate the field to reach the Paris Agreement goals. Another measure implemented by the government is that applying sustainability will be rewarded in the form of being able to get a higher mortgage for a new building. Also there are certain terms which are now standard for newly built environment such as the BENG-norm, which is a norm for evaluating the energy consumption of a building towards almost energy neutral.

Sustainable measures in a house are nowadays standard up to a certain point. The houses in general become more expensive to build, but it is cheaper to live in. A higher energy label or more sustainability measures to reduce energy consumption or GHG emissions increases the value of the property.

Since 2015 there are standards for energy labels of all buildings (BusinessGovernment, sd). This energy label is a performance indication on energy efficiency. Within the current housing market a building that will be renovated and preserved often gets to energy label B, which means less than 1.3 gigajoules energy use per m2 per month. From label B to label A++ (less than 0,5 GJ/m2/month) is very expensive, since much complementary measures are required to reduce energy use.

The awareness around sustainability and wanting to help the climate amongst the house buyers is more present nowadays.

The estate agents also mentioned that zero-energy houses are being built and sold more now, but this is mainly due to the demand from individuals. The standard range of zero-energy houses is not yet present but it is predicted that these zero-energy houses will sell much faster in the near future.

There is a trend in the number of sustainable houses sold in the East of the Netherlands, but this is due to more supply than before. It is in that sense not demand driven. Sustainable measures or characteristics will not in itself lead to a higher demand for housing, but customers attach great value to it because of the rising energy prices and the long term environmental effect. In the current housing market basically everything sells because of the shortage. The tightness indicator is about 1.3 houses per potential buyer, and this means that there is in fact no choice.

Currently in the Netherlands the zero-energy houses and the passive houses do not sell very well. The reason for this according to the estate agents is awareness-related and financial-related. The consumers in general are not yet sufficiently aware of what such a house can mean for them. As mentioned before, the last step towards A++ or a zero energy house is very expensive. Most consumers would rather sit just below that level and invest the extra amount in luxury for example. Another financial reason is that the builders nowadays cannot fully give the warranty to the buyers that the house will perform consistently as a zero-energy house on the long term. However, there are developments that the sustainable parts become more affordable and the awareness of the consumers is getting better towards being more sustainable in housing. Buyers are taking the long term costs of a house more and more into account, part of this is also due to the financial advisors. The amount of money that can be saved becomes clear in the long run cost calculations.

To get more specific into the Tangramhouse in Bruinehaar itself, it also did not sell that good too. Bruinehaar is a very small village in the Northern of the Twente region. The village has not much facilities and there are no larger cities nearby which can compensate for that. Bruinehaar as a location is also a bit behind the rest of the Netherlands.

A Tangramhouse on a location closer to the larger cities of Twente would sell better in general. This of course also depends on the type of location and the total price. Also a Tangramhouse type which is flexible or modular would be an option to reach a broader target. Moveability, flexibility and adaptability could be something to investigate further in the future of this housing project.

The Tangramhouse in Bruinehaar is on the market for about 6 months now and up until now it had some interests but not people really wanting to buy it. Recently a very enthusiastic consumer would like to buy the house. That is a great development because after the contract is signed, the building of the house can start.

10. Conclusion

The goal of this study was to analyse the current Life-Cycle-Assessment and Life-Cycle-Costs of the ‘Tangramhouse’ and to evaluate the current housing market. Out of this, statements could be made about the environmental & economic impact and about the feasibility to sell the house in the current market with its high demand. The following research questions have been answered in this research.

1. **How cost-efficient and environmental friendly is the Tangramhouse?**

1.1. What are the CO_2 emissions from cradle to the end-of-life of the building and compare this with similar and traditional styles of building houses?

With the GaBi software the LCA has been modelled in three phases; production phase, use phase and end-of-life phase. The Climate Change Impact, or the Global Warming Potential, is the only impact category taken into account to assess the environmental impact. The results of the LCA were for the energy type ‘grid mix of 2020’ as follows: GWP: 8,88 kg CO2 eq. /year/m2. In comparison to a single family house in Sweden, Darnallas Villa, designed with the aim to reduce energy impact and achieving low environmental impact from life cycle perspective it is 5,7 kg CO2 eq. /year/m2.

1.2. What are the life cycle costs of the Tangramhouse?

The same three life cycle phases have been modelled in an Excel program to get results out of the LCC. The overall Life Cycle Costs of the Tangramhouse over 100 years is rounded €507.168. Breaking this down per phase gives the construction phase costs of € 2.406,08 /m2 ; the use or operation phase costs of € 1.516,96 /m2 and the end-of-life costs are € 134,31 /m2. In comparison to the same house in Sweden, Darnallas Villa, the construction phase costs are € 3066,20 /m2. The use phase costs are € 1149,83 /m2 and the end-of-life costs are € 95,82 /m2.

2. **How would the Tangramhouse sell on the current housing market in the East of The Netherlands?**

2.1. What are the developments on the housing market in the East of The Netherlands towards more sustainable houses and zero-energy houses?

The estate agents mentioned that zero-energy houses are being built and sold more now, but this is mainly due to the demand from individuals. The standard range of zero-energy houses is not yet present but it is predicted that these zero-energy houses will sell much faster in the near future. Sustainable measures or characteristics will not in itself lead to a higher demand for housing, but customers attach great value to it because of the rising energy prices and the long term environmental effect. In the current housing market basically everything sells because of the shortage. Buyers are taking the long term costs of a house more and more into account, part of this is also due to the financial advisors. The amount of money that can be saved becomes clear in the long run cost calculations.

It could be concluded that, compared to the single famlily house in Sweden which is designed for reducing the environmental impact, the Tangramhouse results are quite similar so it can be said that the Tangramhouse is very sustainable in terms of CO_2 emissions.

Furthermore, in terms of costs, the construction phase is relatively cheap. The use phase costs are slightly more than the other houses and the end-of-life costs are almost similar in comparison with the other houses. To reduce costs and GHG emissions, an alternative foundation with steel piles instead of concrete could be considered.

The estate agents mentioned that sustainable measures in a house are nowadays standard up to a certain point. The awareness around sustainability and wanting to help the climate amongst the house buyers is more present nowadays. A Tangramhouse on a location closer to the larger cities of Twente would sell better in general, since the facilities of a city are nearby. A Tangramhouse type which is flexible or modular would be an option to reach a broader target. Moveability, flexibility and adaptability could be something to investigate further in the future of this housing project.

11. Recommendations for further research

Within this thesis there are some aspects on which further research could be useful in order to improve decision making on certain topics. This research is set up broadly and gives general conclusions on the topics but when given more time and expertise, some aspects could be researched deeply.

Topics that potentially can be added to supplement this research or can be further elaborated:

- In the LCA more impact categories could be taken into account in the analysis, such as ozone depletion, or water usage. This will give a more complete picture of the environmental impact.
- The current LCA analysis is only done in GaBi, another analysis with another LCA software and thus another database could give a better overall view of the emissions.
- Getting more expert views on the cost estimations, since this research is quite various and depending on the parameters of the discount rate, inflation rate and energy prices for example.
- Another interesting topic to expand the research will be alternative renewable energy sources that could be applied on the house.
- The LCA and LCC could be combined in further research to evaluate in the future where to cut and reduce the costs and the emissions. In this way the relationship between materials with costs and emissions could be seen. Within this, certain ranges can be given to certain values in the house and its costs to conduct an optimization analysis for emissions and costs. To expand this even further within the building process, an integration with BIM modelling with costs and GHG emissions could be made to get a total view of the house in detail already before the construction starts.
- There will be both environmental and economic savings as parts from the building can be reused in other buildings or for other purposes. Following this idea, it would also be interesting to explore how to use secondary materials during the construction of the building. This could bring investment costs down, unless it will cost more labour, and also from an environmental point of view it will be advantageous as the carbon footprint for such materials will be less.

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Appendices

Appendix A

Calculation LCA appendices:

- Electricity use to produce 1 ton (1000kg) of wood fibre insulation is 20 million BTUs = 21101117052 Joule = 21.101,12 Megajoules (Shredding, 2013).

- Energy use of solar panels for calculating the CO2 eq. emissions. The energy requirements Tangramhouse is 61,00 kWh/m2, this house is 125 m2 living surface, so in total this is 7625 kWh, so with the 40 g CO2 eq./kWh /30 years this is 305.000 g CO2 eq., which is also 305 kg CO2 eq. X3.33 = 1015,65 kg CO2 eq (Laboratory, 2012).

- **CO2 eq. over lifetime of extensive green roofs:**

- 13,9 kg CO2 eq. / 90 years / m2 , so this will be **1544,44** kg CO2 eq. / 100m2 / 100 years (Alves, 2015).

- 15,1 kg CO2 eq. 1m2 for 50 years. This means **3020** kg CO2 eq. / 100m2 / 100 years (Oliveira & Alves, 2015).

- 50 years, 1340m2, 13000 kg CO2eq. global warming, calculating this for the Tangramhouse results in **1940,3** kg CO2 eq. / 100m2 / 100 years (Cubi, Zibin, Thompson, & Bergerson, 2015).

- The average of the three studies above is taken as value for the Tangramhouse green roof emissions, so **2168,25** kg CO2 eq. / 100m2 / 100 years.

Appendix B

LCC Appendices:

In this analysis all the costs will be assessed over its total life cycle. It starts with design costs, the architects who designed the house spend a couple working hours on it. Thereafter the design is ready, it is needed to evaluate what the rest of the costs are going to be.

The can be divided as follows:

Pre-construction costs:

- ground work, digging, equalling
- land measuring service

Construction costs:

- Foundation of the house
- Floor for the ground floor
- Sewerage system
    - Average price: 175 euros per meter, on average 11 meters of sewerage, so about 1925 euros for sewage (Werkspot, 2013).
- Exterior walls and roofs
- Timber frame construction building package, as delivered by Scana Bouw: ‘For the house as it is now, we think that our kit will cost € 135,000. We expect that there will still be additional costs of approximately € 3,000 for the interior wall finish in plywood sheets. The total construction kit would therefore cost approximately € 138,000. We have already taken into account a different roof element than standard (assuming a DSD element suitable for sedum and/or grass roofs.’
- Wooden cladding
- Façade and roof vegetation
    - Cost of green cladding roof 275 euros per square metre. So it is approximately 100 square meters of roof so the total price will be 27,500 euros (Farwick, sd).
    - A green roof as this will last for about 50 years, the replacement costs of a green roof / façade is according to this research in the Netherlands about 46,32 euro / m2 so this will be x100m2 so 4632 euro, including labor costs etc. (Kantor, 2017).
    - Maintenance costs green roof are 85 euro per year (Groendakcoach, sd).
- Interior walls
- Exterior frames, windows and doors
- Interior doors
- Mezzanine floor
- Loft
- Stairs and solar chimney
- Windowsill and skirting boards
- Water pipes
    - everything added together on average is 980 euros (Zoofy, 2022).
- Paint / lacquering work
    - two painters, 2 working days, 16 hours, so 32 hours x 35 euros = 1120.
- Solar panels
    - 10 large solar panels, 160 euros each. We need 10 to be fully 100% on EP3. This is the share of renewable energy in percentage (BlijMetZonnepanelen, sd).
    - Installation of solar panels costs 1250 euros (Homedeal, sd).
    - Solar water heater: 3000 euros.

- Inverter costs + installation costs: 1100 euros.
    - Inspect and clean solar panels once every 5 years: 100 euros.
    - Replace inverter once every 15 years: 1400 euros (Homedeal, sd).
    - Replace solar PV panels once every 30 years: 10 x 160 euro = 1600 euro + installation 1250 = 2850 euro.
    - Start-up costs: Solar panels + installation + solar boiler + inverter = 6950.
- Transportation costs of all the materials
    - Transportation for heavy loaded trucks fuel costs:
        - Diesel euro/L € 1,650
        - Diesel km/L 3,0
        - Diesel Euro/km € 0,55
    - From ScanaBouw to Bruinehaar and back: 220 km x 0,55 = 121 euro
    - From wilmink-oosterveld to bruinehaar and back: 60 km x 0,55 = 33 euro
    - Bouwkraan transport kosten: 50 euro

Use costs:

- Use costs
- Maintenance costs of house and replacement and maintenance of solar panels
- Energy costs will be the energy used besides the heating and cooling of the house, since that is covered by the solar panels. When we assume that the people who will live in the house will be average, so 2 to 3 persons, and also assume that they are quite economical in terms of energy use, the total estimation of energy use per year would be 2500 kWh (VergelijkEnergie, sd). So in total over 100 years this is 250.000 kwh, which is equal to 900.000 MJ (Milieucentraal, sd). The costs per kWh are now about 0,23 cents in the Netherlands (Overstappen, sd). So final price per year will be €575 per year.

End of life costs:

- transportation of waste
- demolition costs for fully demolition including the foundation
    - 50 euro per m2, the house is 125m2 so then 50 x 125 = 6250 euro for demolition including the transport of the waste (Viveen, 2021).
    - So this is including the demolition workers, and including the transport and so also including the wages of labour.

LCC assumptions and data from collaborating companies:

- The LCC only covers the house delivered as bare. So excluding kitchen furnishings, sanitary ware, wall finishing and floor finishing. Also the land acquisition is excluded.
- Then general inflation rate will average to about 2% in the coming future (DNB, sd).

Appendix C

Figure 15: Energy mix 2020 Use phase as modelled in GaBi

Figure 16: End-of-life phase of Tangramhouse as modelled in GaBi

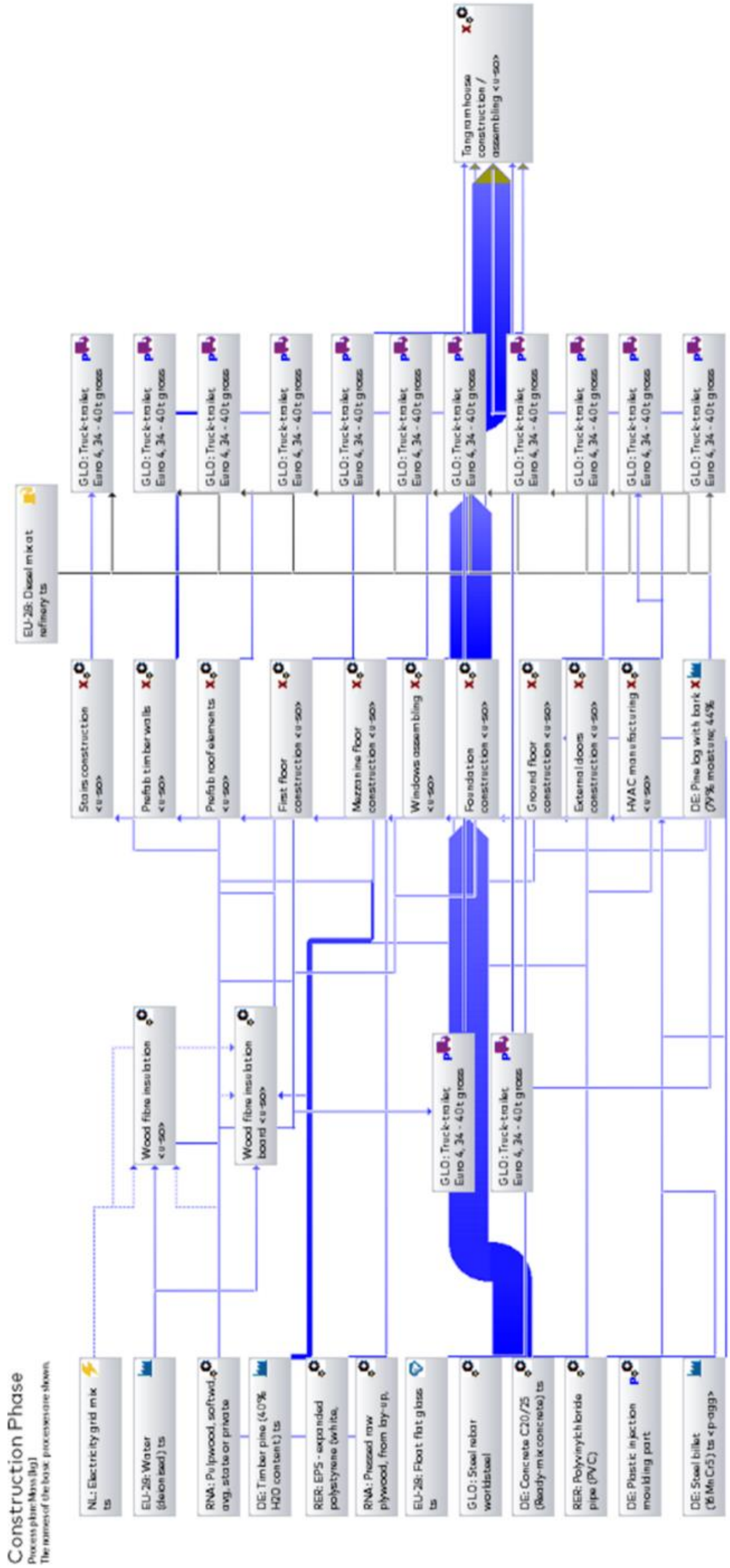

Figure 17: Construction phase of Tangramhouse as modelled in GaBi

Appendix D

Interview results of 3 estate agents:

In order to answer the second research question I will do a literature review and also do interviews with a couple estate agents. Below the interview questions which I will ask during the interview will be stated. It will be about sustainable houses in general but also about the Tangramhouse concept.

- **What would sustainability mean for you exactly, how do you see sustainability in general?**

Sustainability is necessary for the coming generations on this planet

This is an important part of real estate for us, both the government has tightened up the guidelines in this regard, but there are also many financial conditions to be achieved for property owners.

She's an appraiser, with construction influence. New living in twente, new living in Achterhoek, everything with new construction. That is actually quite sustainable in the sense of the BENG standard = sustainable. That's all good as a new-build broker. Air heat pump, not only mortgage costs but also housing costs. Homes are becoming more expensive, more investment means lower housing costs. People also notice that they have come up with more in that regard with regard to sustainability, expanding panels they get a lot of demand. Also with an eye to the future. Rijnmarkt has a look at it, making existing buildings more sustainable, comes from the rent on the market, that is mandatory. With package with panels, insulation, double glazing. driving market. It is rewarded for applying sustainability, you can also borrow more if you build new buildings sustainably

- **What is the influence of sustainability on the house price?**

houses often become more expensive to build but cheaper to live in

Sustainability increases the value of the property

Around 15 to 20 thousand in technology, system heat pump, underfloor heating. The market in Nieuwbow was more expensive, and so were houses. Due to market forces but also prices up and also with the bang standard

- **Do so-called zero-energy homes sell better and/or faster these days?**

these homes will sell much faster within a very short period of time.

No, real estate owners certainly want to pay extra for sustainability and are more willing to buy and will also decide more quickly, but this does not have to be Zero on the meter or a passive home.

Awareness has come and landed. Also important in existing construction, insulation, energy labels, the last step to label B to A+ is very expensive. That sells better compared to existing construction, they say better investment now also in the future. Also to the mortgage advisor and brokers to provide financial insight into housing costs. Triodos, HSN.

- **What influence does sustainability have on the demand for housing and to what extent?**

The rising energy costs mean that many consumers attach great value to this, in addition to the environmental effect in the later term.

This will not lead to more demand in the market! However, for sustainable homes compared to non-sustainable homes.

There is too little supply, the shortage is just there. 1.2 / 1.4 tightness indicator. Now everything sells. Then it really becomes important, in a market that is not tight. Then it is very important and influential.

- **Is there a trend in the number of sustainable houses sold in the East of the Netherlands?**

yes, but that is not demand driven but supply

No, of course more are being realized/sold, but this is also due to more supply than before.

The choice is no longer there, no, there is no more. So anything new is sustainable. With collective things, heat pump, district heating linked to the gas price, how do they deal with this. The awareness is there. The shortage in the market makes it more difficult.

- **What do you think is the reason why zero-energy homes or passive homes are not selling very well at the moment?**

consumers are not yet sufficiently aware of what this can mean for them.

For many, the investment and savings do not match the last step to zero on the meter. Then one would rather sit just below it and invest the extra amount in luxury (kitchen, etc.).

Not much on offer, actually. They don't want to give the warranty, the builders. From the light to on. The supply of warger homes is all zero on the meter, they believe epc 0, that doesn't differ much among people

- **To what extent do buyers today consider the long-term costs of a home? So with energy costs and maintenance costs.**

Increasingly

Buyers definitely take this into account! but this is also charged to them by their financial advisor

More and more, actually. People are really interested in that, how expensive will that be. What you can save is really becoming aware in the long run. Existing homes made more sustainable. This is reflected in the rental price.

- **What do you think that is the reason the Tangramhouse in Bruinehaar is still not sold after 5 months?**

can be location, or price, or marketing

Given that it is offered in Bruinehaar and that is always more difficult and perhaps Bruinehaar is also a bit behind the rest of the Netherlands.

The increasing price can also be the problem (they don't want to pay that extra).

I am very honest, robert ten oever. And I think it has more to do with brown hair and the place. Nikkelsweg 9 is running, let's take a look at Robert van 't oeve:

Call with Robert: op dit moment hebben ze een serieusze klant, morgen. Het is vooral de locatie die het lastig maakte, er zijn daar gewoon weinig faciliteiten in de buurt, met ook andere vrijstaande woningen in de buurt.

- **Would a Tangramhouse closer to the larger cities of Twente (Almelo, Hengelo, Enschede) sell better?**

Probably in the right location.

I think so.

Idea about given in the price. A little survey from gosh would you like this. I think there is definitely a market for that. Then you should conduct a survey. With house to start, novito sold to a belligerent. In Almelo on indie terrain. So there's some good in that. Also the roof, and water drainage, and everything will get better, and so will the market as a result. And more decreased in price, the durability. Reducing the footprint is now much more important, and that is certainly no longer the case

- **What suggestions could you make to have the house to sell the house itself, the Tangramhouse?**

I would like to be in touch with a sales order.

Trying to keep the starting price as low as possible and let interested parties choose for themselves the extra sustainable adjustments to zero on the meter/passive home.

You have to look at location level and market level. Also depends on the target audience. A life-long home would then be much nicer. The flexibility is very important, different modules, with bath and sleeping downstairs. Adapting to the homes, being able to think flexible living because of the shortage. Movable homes, adaptability and flexibility. There is also a great need for flexibility from municipalities.