UNIVERSITY OF TWENTE.

bam infra

WOOD, PLASTIC AND BIO-BASED COMPOSITES AS BUILDING MATERIALS

'Are plastic or bio-based composites more beneficial than wood as building material for the barrier on ecoduct Koekendaal considering sustainability and costs?'

ABSTRACT

In this research an analysis on wood, plastic and bio-based composites is done. All three building materials are compared to each other based on their sustainability and costs. These building materials are the three options for a barrier mounted on to ecoduct Koekendaal, so the advice and conclusion are specified to this project. A Life Cycle Costing and Multi-Criteria Analysis is done to compare the alternatives.

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1 Management Summary

Introduction & Problem Statement

Currently BAM Infra is doing maintenance on the highways in the region East of the Netherlands. The maintenance contract included the realization of two ecoducts. One of them is in the neighbourhood of Doetinchem, the Netherlands, named ecoduct Koekendaal. The ecoduct connects natural habitat of the local animals. To make sure the animals use this ecoduct, a barrier is constructed on to the ecoduct to provide shelter.

Rijkswaterstaat, the Ministry of Transports, Public works and Water management in the Netherlands, is responsible for these types of projects. Now Rijkswaterstaat focusses a lot on sustainability and wants this to be integrated in their projects, due to the high demand of a sustainable building industry. BAM Infra has the challenge to integrate it in this project.

One of the objects of the ecoduct is the barrier. This barrier should be made out of wood according to the contract, but in later conversation both parties agreed it could be made out of wood-like materials. So in this research an analysis on the sustainability and cost-effectiveness of wood, bamboo, plastic composites and bio-based composites is carried out, specified to the barrier on the ecoduct. This results in the main question:

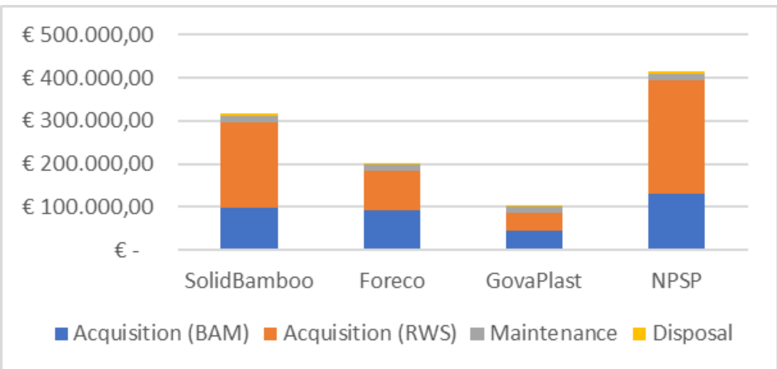
Are plastic or bio-based composites more beneficial than wood as building material for the barrier on ecoduct Koekendaal considering sustainability and costs?

Method

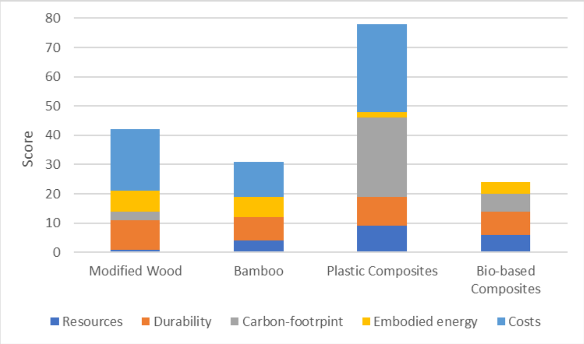
To answer this question a research methodology is needed. First of all literature on the sustainability aspects of the building materials is studied and interviews with material suppliers are conducted. Furthermore, offers are asked to the suppliers to get to know the costs of the materials. The information is gathered and compared to each other. With this input data two analysis are carried out. First of all a Life Cycle Costing (LCC) is done to get to know the costs per alternative of the barrier over the lifetime of the ecoduct. Secondly a Multi-Criteria Analysis (MCA) is carried out to compare the alternatives on sustainability criteria and costs. To check the robustness of the analysis a sensitivity analysis is carried out as well. Future perspectives of the alternatives are taken into considerations into the eventual advice.

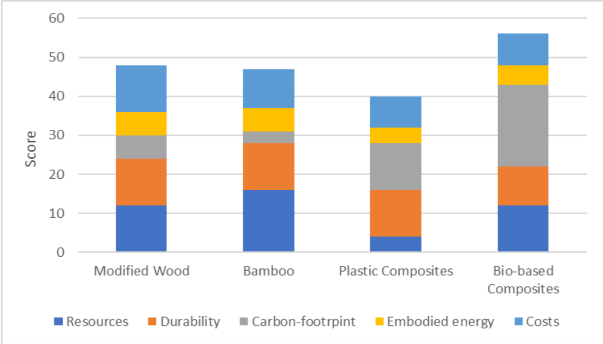
Results

The results of the LCC show that the plastic composite from GovaPlast is the most cost-effective one of the materials considered. The reason for these low costs over the lifetime of the ecoduct is mainly the low acquisition costs. All other materials are way more expensive in acquisition.



The results of the MCA are given on the next page. There is a difference in the current (left) and future (right) perspective. The analysis clearly shows that plastic composites are way more sustainable than the other materials nowadays. The long durability, low costs and low carbon-footprint cause this advantage. However, future developments can cause this to change in a negative way for plastic composites due to new policies and scarcity of the virgin resources. According to the literature bio-based composites will become much more sustainable due to more knowledge and better processing. Wood and bamboo remain constant and reliable building materials in the future.





Conclusion
Both analyses show that the plastic composite (from the company GovaPlast) has the best characteristics on sustainability and cost-effectiveness. However this may change in the future, because plastic can become scarce, and developments in bio-based composites look very promising. The modified wood of Foreco scores second in the LCC and the MCA. Bamboo and bio-based composites score the lowest in both the analyses.

Recommendations
The best choice for BAM Infra is to make the barrier from a plastic composite. It has the best material characteristics and is the most cost-effective one nowadays. But when the material of the barrier is up to replacement it is important to consider all materials again because the values in the LCC and the MCA can change in the future.

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2 Introduction

During the last decennia the Netherlands has built a lot of infrastructure, form railroads to highways. These infrastructures shredded the nature in the country, making it hardly impossible for some animals to move to other areas. Therefore, Rijkswaterstaat started ‘het meer-jarenprogramma ontsnippering’, or MJPO (‘more-years program de-shredding’). Ecoducts, ecotunnels and faunatunnels are realized to recover the mobility of animals in nature (Rijksoverheid, over MJPO, 2019).

Rijkswaterstaat is the executive agency of the Ministry of Transports, Public works and Water management in the Netherlands. They are responsible for building and maintaining state highways and waters in the Netherlands (Rijksoverheid, Rijkswaterstaat, 2019). Currently large maintenance on highways in the Eastern region of the Netherlands (Integraal Groot Onderhoud Oost, IGOO) has to be done. The contract not only includes maintenance on the highways but also includes designing, building and realizing two new ecoducts, keeping the MJPO in mind. Rijkswaterstaat wrote out a tender for this project directed to building contractors.

BAM Infra got the contract and started working in January 2018. As said before the contract includes the realization of two new ecoducts. One of those ecoducts is in the neighbourhood of Doetinchem, named ecoduct Koekendaal, crossing the highway A18. This ecoduct connects the natural areas of ‘de Slangenburg’, ‘de Wrange’ and ‘Montferland’ (Rijksoverheid, over MJPO, 2019). A lot of animals like deer, badgers and tree frogs can advance from this ecoduct. (see Figure 1)

Figure 1 - Ecoduct Koekendaal and its surroundings (Pols, 2018)

At this moments the abutments and the middle pillar are constructed. Furthermore preparation of the further realization of the ecoduct is being done. In the final stages of construction, a barrier has to be mounted on to the ecoduct, providing shelter for the crossing animals. The end result should look like Figure 2.

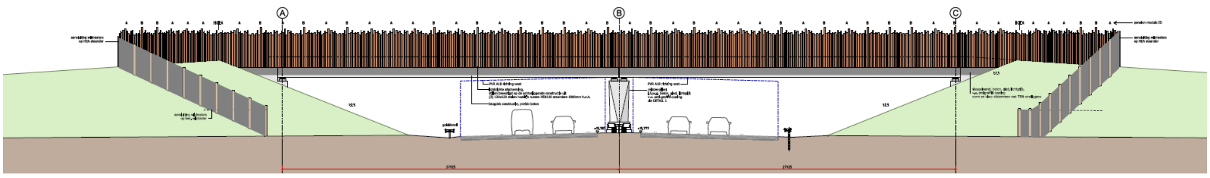

Figure 2 - Design ecoduct Koekendaal (Wurck)

The focus in this research will lay on the barrier of the ecoduct. The drawings for the barrier are already made (Figure 3, for technical drawings see Appendix A).

Figure 3 - Design of the barrier (Wurck)

2.1 Problem statement

Since the existence of human life humans have to live in harmony with nature. A lot of ancient civilizations did this by showing respect for nature, but currently the human impact is associated with serious problems concerning the environment. The idea of sustainability has taken an unprecedented significance, and the problem only seems to grow by day (Banon Gomis, Parra, Hoffman, & McNulty, 2011).

This unprecedented significance of sustainability can also be seen in Civil Engineering. Sustainability is a key concept nowadays. Because Rijkswaterstaat wants sustainability to be integrated in their products (according to the basic agreement of IGOO (Rijkswaterstaat, Basisovereenkomst, 2017)), BAM Infra has to integrate it in this project. According to the basic agreement with Rijkswaterstaat the works during IGOO should be done in such a way that it is not harmful, or when inevitable least harmful, for the environment. This means that production- and construction-processes and material use should not be damaging for the environment.

Now BAM Infra already has the idea of replacing the old 'standard' material for a barrier, wood, for a plastic composite, possibly from the company 'GovaPlast', but no thorough research is done before making this choice. This plastic composite is supposedly better for the environment, costs less over its lifetime and is low in maintenance (Calkins, 2009). But the acquisition costs of plastic composites can be higher than they are for wood. BAM Infra has therefore the question if this investment in a new building material, plastic composites, is worth the effort. Bio-based composites are taken into consideration as well to get a good comparison.

2.2 Research aim

Sustainability and cost-effectiveness are key concepts in the design of the barrier. These concepts can be divided into four themes; resources and carbon- and energy-footprint are important aspects of sustainability (Calkins, 2009). Furthermore, durability and costs are included on request of BAM Infra. These four themes will be present throughout the whole research.

The aim of this research is to find out whether using plastic or bio-based composites as a building material for the barrier at ecoduct Koekendaal is actually a better choice than using wood. This will be done by investigating if plastic and bio-based composites are more durable, less energy consuming, less carbon emitting and less costly than wood. Eventually an advice is given to BAM Infra, so they can make a deliberate choice for the material of the barrier on ecoduct Koekendaal.

2.3 Scope

In this research the focus lays on wood, plastic and bio-based composites. Materials like concrete, glass or steel are not taken into consideration because one of the demands in the contract with Rijkswaterstaat is that the barrier should be made out of wood. In later discussions between BAM Infra and Rijkswaterstaat they came to an agreement that it could also be made out of materials that look like wood, plastic composites for example.

The research is done for the lifetime of the ecoduct. Sustainability- and costs-aspects are taken over the functional lifespan of the ecoduct, so not over the lifespan of a certain building material.

2.4 Main Question

To be able to reach the aim of this research the following main question must be answered:

Are plastic or bio-based composites more beneficial than wood as building material for the barrier on ecoduct Koekendaal considering sustainability and costs?

2.5 Sub-questions

The main question can be answered by answering the following sub-questions. These sub-questions are answered by means of the literature, interviews and the analyses done in this research.

What are characteristics of wood as a building material?

- *How sustainable is wood as a building material?*
  - *What are the resources for wood?*
  - *How durable is wood as a building material?*
  - *What is the energy- and carbon-footprint of wood?*
- *What are the lifetime costs of a wooden barrier on ecoduct Koekendaal?*

Wat are the characteristics of plastic and bio-based composites as a building material?

- *How sustainable are plastic and bio-based composites?*
  - *What are the resources for plastic and bio-based composites?*
  - *How durable are plastic and bio-based composites?*
  - *What are the energy- and carbon-footprint of plastic and bio-based composites?*
- *What are the lifetime costs of a plastic or bio-based compostie barrier on ecoduct Koekendaal?*

2.6 Reader Manual

In the next chapter the theoretical framework will be given. Theories, research methodologies and the data collection plan are explained. In chapter 4 a literature study is done on the four building materials. Chapter 5 elaborates on the conducted interviews and this is compared to the literature. Chapter 6 includes the LCC and chapter 7 gives the MCA with its criteria's, values and weights. In the last three chapters the discussion, conclusion and recommendations are given. Hereafter the references and appendices are stated.

3 Theoretical framework

In the theoretical framework first some important theory that is used during the research is explained. Second the data collection plan is given. Furthermore the research methodologies will be explained, which are needed for answering the sub-questions and eventually the main question. Three methodologies are used in this research.

3.1 Theories

First of all a general description of sustainability of building materials is given, because this word is used in such a broad way. Hereafter the meaning of the themes of sustainability are explained.

3.1.1 Sustainability in general

Sustainability has a lot of interpretations, for instance environmental-, economical- or social sustainability. First of all, economical sustainability could be described as maintenance of capital. But this could be extrapolated to sustained economic growth (Goodland, 1995). This means that a business is sustainably managed when it allows exploitation over an indefinitely prolonged time (Mora, 2005).

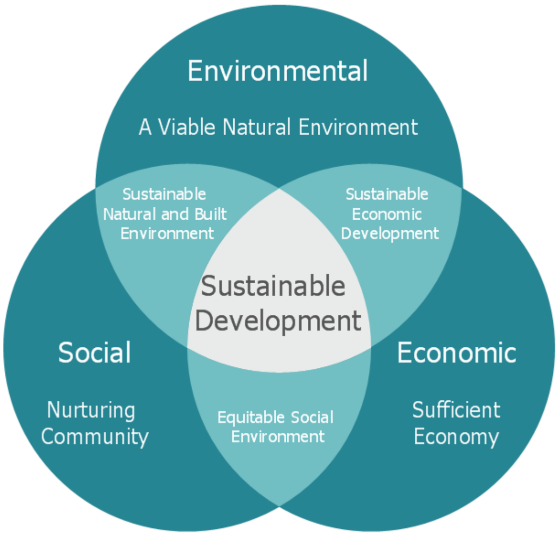

Figure 4 - Economic, social and environmental sustainability (HLMS, 2016)

This economic concept of sustainability overlaps the environmental concept of sustainability, but differs as well. This can be seen in Figure 4. According to *Goodland (1995)* environmental sustainability does not allow sustained economic growth. It implies sustainable levels of both production and consumption, so there is no growth. Environmental sustainability is therefore focussed on maintaining natural capital. So environmental sustainability implies that there is an endless source (production) that can be mined (consumption) at the same rate. It counts all services of the recourses like carbon balance, biodiversity or energy-consumption.

The main difference between the two concepts of sustainability is that economic sustainability is more focussed on sustained growth while environmental sustainability is focussed on sustained recourses and consumption. Environmental sustainability can be seen as qualitative development instead of quantitative growth, which is desired in economic sustainability.

Social sustainability is another concept of sustainability. It specifies to sustaining a society, by reducing poverty and improve environmental quality (Goodland, 1995). Together with economic and environmental sustainability, they form the basics of sustainable development.

In this research the focus will lay on environmental sustainability, considering resources and their energy- and carbon-footprint. Economic sustainability will be taken into account, but will only be a small part.

3.1.2 Themes of sustainability

The themes of sustainability can be coupled to the 'trias energetica' (sustainable use of energy) or 'trias hylica' (sustainable use of materials). The three steps in both concepts look like each other. For the trias energetica, the first step implies less use of energy, while the first step of trias hylica implies prevention of unnecessary use of materials (Brouwers & Entrop, 2005). The second step in both concepts implies the use of local and sustainable (energy) sources. The last step implies that, when it is inevitable, non-sustainable resources should be used in the most effective way.

Resources

There are a few different ways to obtain the resources for a building material. The 'old-fashioned' way of obtaining resources is using virgin resources. Virgin resources are raw materials which are used for the first time for its purpose. Fossil fuels or wood from a cut tree are examples of virgin resources.

Another way to obtain resources is from recycled material. Recycling turns waste materials into resources. So recycled materials are waste materials that are turned into resources, which would otherwise be landfilled or incinerated (Mills, 2012).

Besides recycling products, one may also reuse a product. By reusing materials the material is again used for its intended purpose. The difference with recycling is that reusing a material leaves the materials with its intended purpose and form while recycling gives a new purpose and form to a material or product (Mills, 2012).

Repurposing a material is a combination of recycling and reusing it. Repurposing gives a materials, as the name says, a new purpose but it keeps its intended form. This use of resources requires a little bit of creativity, but is very environmental friendly because the product does not need to be changed.

The last way of handling resources is reducing. This literally means using less resources. This can be done by increasing the effectiveness of a process and reducing waste materials.

According to the concept of trias hylica resources should be locally obtained and unnecessary use of material should be prevented (Brouwers & Entrop, 2005). So the concepts of recycling, reusing, repurposing and reducing are very much in line with the concept of trias hylica.

Durability

The durability of a material can be described as the lifespan of the material. The lifespan of a material is based on the characteristics of the raw materials, processing and maintenance. The raw materials are discussed in the resources part and the process will be discussed in the energy- and carbon-footprint. So for the durability the lifespan of a material and the amount of maintenance are taken into account.

According to the third step of the trias hylica materials from non-sustainable resources should be used in the most effective way (Brouwers & Entrop, 2005). A long durability is a way of effectivity of the material. Building materials from sustainable resources can be made more sustainable as well when they have a great robustness or long durability.

Energy- and carbon-footprint

The energy-footprint of a material can be described as the embodied energy. Embodied energy is the amount of energy that is used to obtain, process and manufacture a material (Falk, 2009). A lower embodied energy of a building material is a positive aspect.

The carbon-footprint is the amount of CO2 that is released during the lifetime of a building material. Materials that are based on non-fossil fuel-based renewable energy resources can contribute to a better environment (Calkins, 2009). In this research the carbon-footprint of the material is taken over its lifetime, meaning cradle-to-grave.

Both the energy- and carbon-footprint are in line with the trias energetica. The first step of the trias energetica is using less energy, which is called the embodied energy in this research. The second step is the use of sustainable energy which lowers the carbon-footprint of a material. The same goes for the third step; using the least possible amount of non-sustainable resources in the most effective way causing a lower carbon-footprint (Brouwers & Entrop, 2005).

3.2 Research methodology

3.2.1 Life Cycle Costing

To calculate the cost-effectiveness of the materials a Life Cycle Costing (LCC) is done. It considers the costs of a product or project over its whole lifetime. Acquisition-, maintenance- and disposal-costs are considered during the analysis. This analysis is carried out to come to a clear advice considering costs and durability. Durability is included due to the amount maintenance and lifespan of a material.

Since BAM Infra is a contractor it wants to make money, and therefore the costs of the project has to be as low as possible, but keeping the work at high quality. The LCC is carried out so the eventual lifetime costs can be assessed for both the wood as the plastic or bio-composite alternatives showing the eventual cost effectiveness of the alternatives.

3.2.2 Multi-criteria analysis

For the sub-question that consider resources, durability, energy- and carbon-footprint and the costs a Multi-Criteria Analyses (MCA) can be used. In a MCA multiple parameters or criteria are taken into account. These parameters can have an added or negative value to the objective. Each criteria gets a rating and weight. A view alternatives of the objective are composed and each of criteria gets a score per alternative. The weights per criteria will stay the same in each alternative. By taking the sum of the multiplications (criteria x weight), you get the eventual score per alternative. For comparing building materials on its sustainability and costs the following criteria will be used:

- Recourses;
- Durability;
- Embodied energy;
- Carbon emission;
- Costs

These criteria are chosen based on the research aim and questions. The resources are important, because this shows whether the raw materials are recyclable or are from an endless recourse. The material has to be durable as well. The durability can be divided into two aspects; replacement and maintenance. Less maintenance and a higher lifespan are positive for this criteria. The embodied energy is the energy which is needed during production. Less energy use during production is a positive aspect. Carbon emissions are known to be bad for the environment. It is a greenhouse gas, and to stop global warming these emissions need to be reduced. The last criterium is the cost-effectiveness. Lower costs are preferable for this project.

The criteria are scored, based on the answers of the sub-questions. When all criteria are scored the eventual main question can be answered by comparing the alternatives of various types of wood and plastic- and bio-based composites. Dependent on the weights of certain criteria, which BAM Infra can set for themselves, an advice can be given.

3.2.3 Semi-structured interviews

The information from the external companies for the two analyses is gathered by conducting a semi-structured interview. These interviews are conducted by calling. The aim of the interview is to get to know the characteristics of the materials from the companies. The interview scheme can be seen in Appendix B. The question about the costs of the material is left out due to the complexity of a cost estimation for such a project.

3.2.4 Alternative methodologies

The MCA is not the only analysis for assessing alternatives. Life-Cycle Assessment (LCA) for example could be used as well for examining building materials. The reason this methodology is not used in this research is because LCA only examines the environmental stress of a materials through its lifetime. Economic arguments or costs are not taken into account, while this is an important aspect as well according to the question of BAM Infra.

A SWOT-analysis could also be considered for comparing multiple alternatives. A SWOT-analysis sums up the Strengths, Weaknesses, Opportunities and Threats. But this type of analysis is more focussed on alternatives of marketing strategies instead of alternatives of building materials. Internal (strengths and weaknesses) and external (opportunities and threats) factors are more applicable to marketing strategies than to materials. Therefore this type of analysis is not chosen for this research.

Another analysis is a Cost-Benefit Analysis (CBA). This analysis considers all costs and benefits of a product or project. The outcome of this analysis is the amount of money earned or spent after a certain lifespan of the product or project. In this research an analysis is done on a barrier. A CBA is not very applicable to this research since there are no monetary benefits of the barrier. Life Cycle Costing focusses more on the costs of a product or project making it more applicable than a CBA.

4 Literature study

In this research the focus mostly lays on the four themes (resources, durability, energy- and carbon-footprint and costs) of the building materials wood, plastic and bio-based composites. These materials will be specified to resources, durability and energy- and carbon-footprint, giving their advantages and disadvantages. In the durability parts, a clear division is made between preplacing and maintaining the material. For the estimation of costs real-life data is provided by asking offers or looking back to previous acquisitions and maintenance. Therefore, literature about costs is not significant in this study.

4.1 Wood as a building material

Wood is one of the most versatile and ancient used materials in human history (Asif, 2009). Even now when new developments evolved, wood is still one of the main materials used in construction. Half of the wood that is harvested in the forests of the USA is used in construction (Falk, 2009). So how does wood perform when looking at its resources, durability and energy- and carbon-footprint?

Resources

Wood is in the environmental sustainable eyes a good building material. It is a renewable resource, because it can be restored in a relatively short period (Trindade, 2019). Wood is widely available, and environmentally friendly. It can be supplemented continuously through sustainable forest management (Asif, 2009). This means that the extraction of wood is compensated for by planting new trees. This is unlike the case of most other materials. The only thing that humans have to do when a large part of forest is harvested, is replanting new trees to allow fast regrowth of wood.

When you look at economic sustainability, wood is not that sustainable at all. It cannot give sustained economic growth. A lot of wood is needed in construction but wood takes long to grow. An estimation is made in the decrease of the world's forests, implying a decrease from six billion hectares to 3,6 billion hectares. Approximately 75% of this decrease happened in the last hundred years (Buchanan & Levine, 1999). Trees simply cannot produce the amount of wood that is needed (Calkins, 2009). Although wood remains a source for exploitation for an indefinitely prolonged time, the production process is too slow.

Durability

Durability has always been one of the main disadvantages of wood. The cause of low durability of wood could be bad processing (Foilente, Leicester, Wang, Mackenzie, & Cole, 2002). The main issues of wood and its durability as construction material is decay, termite attack and corrosion of 'connectors' according to *Foilente et al.,* (2019).

Decay is a natural process of wood where bacteria convert the wood into carbon-dioxides. It can be seen as the opposite process of photosynthesis. This can be described as 'fungal attack'. The decay of wood depends on multiple variables like location of the construction, natural durability, type of wood, paint and thickness of the wood (Foilente et al., 2002). It is imaginable that a moist surrounding is beneficial for fungi and this can cause a faster decay of wood. Paint or other impregnating substances (maintaining the wood) can make it harder for fungi to grow, causing less decay. After a while wood decayed so much it has to be replaced with new wood.

The strength of a wooden construction is dependent on metal connectors as well. For example nails, bolts or other metal connectors could lose strength due to corrosion of the material. The amount of corrosion depends on the building location, place of the connector (within the wood or on the wood), type of metal and natural pH of the wood (Foilente et al., 2002). Acidity and moist can corrode the metals very badly, and thus weaken them. Metal connectors have to be replaced when they eroded too much.

Another variable in the durability of wood are termites, but termites do not occur in the Netherlands (Sander, 2017) and therefore termite attacks will not be included in this research.

Due to this low durability it is possible that wood could lose its market share, because it does not meet new durability issues. However, a lot of promising research is done to make wood more durable, and to choose the right type of wood for the right purpose.

In Europe various types of wood are classified in five different durability classes. These durability classes are determined based on fungal decay, so termite- or other insect attacks are not considered. The types of wood with their durability classes and lifetime are shown in Appendix C (Vandenbussche, 2011).

Energy- and carbon-footprint

First of all, wood has the positive characteristic of low embodied energy. This means that the energy required to harvest, mine, manufacture and transport the wood is very low (Falk, 2009). The sun provides energy for the trees to grow. On top of that, in the USA over half of the energy in wood processing is consumed by biomass, which is obtained from wood products itself. For other building materials like steel and concrete, fossil fuels are primarily used during manufacturing. Most of the carbon emissions related to building materials results from burning fossil fuels for energy in the manufacturing process (Buchanan & Levine, 1999). This embodied energy is much lower for wood than for other products such as concrete, steel or plastic.

Furthermore, *Falk (2009)* states that wood plays a large role in carbon-dioxide storage. Due to photosynthesis a tree is able to convert carbon-dioxide (and other substances) to glucose and oxygen. glucose is one of the main building materials for a tree to grow. Therefore, a tree can store a lot of carbon-dioxide, which is in fact a greenhouse gas. All this carbon-dioxide that is stored in the wood will be released ones the wood is burned or while it deteriorates. So using wood in construction, and thus not burning it immediately, keeps the carbon-dioxide out of the air for a large period of time. The carbon-dioxide is sequestered for the lifetime of the wood.

Conclusion

In conclusion, wood still is and probably will remain one of the main building materials for the coming years. It is a building material with a low energy- and carbon-footprint and it is a renewable resource. The durability of wood is a problem, but a lot of promising research is done to make wood more durable.

4.2 Plastic composites as building materials

Plastic composites are a new and upcoming building material. The characteristics are promising for construction considering sustainability and costs. But the lack of understanding of the properties of recycled plastic wastes continues to limit their usage as a civil engineering construction material (Arulrajah, Yaghoubi, Choy Wong, & Horpibulsuk, 2017). The developments over the past years of these new construction materials are therefore very important, not only for the construction industry but also for the plastic recycling industries. The material should be stronger, more durable and more effective than the conventional building materials like wood, steel and concrete (Rebeiz & Craft, 1995).

Resources

There are a lot of different types of plastic composites. PVC (Polyvinyl Chloride) is one of the most well-known plastic. PVC can be used in construction for example for pipes, decking and fencing among other things, but is not very recyclable due to additives that give the PVC certain characteristics. (Calkins, 2009). Another plastic, HDPE (High-density polyethylene) is created by the polymerization of ethylene. This plastic has a high tensile strength and density making it applicable for construction. Furthermore is it safer for human health risks than PVC, because PVC makes use of additives which can harm human beings. HDPE is mostly used for plastic lumber or sewer pipes and it is easily recyclable. Other plastics like LDPE (Low-density polyethylene) or PP (Polypropylene) are very widely used for other applications than construction.

The raw material of almost all of these plastics is derived from petroleum (Calkins, 2009). Petroleum is the virgin resource of plastic composites. Petroleum is not a renewable resource and the natural capital will not be sustained. This is not environmentally and economical sustainable at all.

As said before HDPE is easily recyclable and this can conserve the virgin resources, which are in this case fossil fuels. The plastic can be recycled multiple times. To make sure this actually happens the EU set up a protocol for construction and demolishment waste management. The protocol establishes a target of 70% of the construction and demolishment waste to be recycled (European Commission, 2016). If this is the case for plastic construction materials, which can be recycled over and over again, a circular concept can arise where no new building materials are needed.

Durability

Different kinds of plastics can have a lifespan from 10 years up to a lifetime (Calkins, 2009). It will not splinter or peel. The high durability of plastic even leads to problems during disposal. In the following paragraphs the durability is specified to wood-plastic components, because of the amount of researches in this material. The outer layer of wood-plastic composites is made out of plastic, giving this materials almost the same characteristics as plastic itself.

Wood-plastic composites (WPC) exist out of wood components and plastic components. As seen in the previous literature, concerning wood, wood can be vulnerable to fungal decay. The plastic matrix in a WPC can act like a barrier layer that excludes moist and fungal attack (Pendleton, Hoffard, Adcock, Woodward, & Wolcott, 2002). In the research of *Pendleton et al (2002)* the resistance of WPC formulations to fungal decay and biocide leaching was evaluated using laboratory procedures. The result of this research is that fungi can attack the wood if it is not well-dispersed. A WPC with a well-dispersed wood component has less to no signs of fungal attack, because the (thermo)plastic seems to act like a barrier. This means that hardly no maintenance has to be carried out to the WPC and it can last for a really long time, so replacement is scarce.

The durability of WPC in a structure is, just like wood, dependent on metal connectors as well. The same rules apply to connectors that are exposed to open air and weather, which most of them are. But internal connectors do not suffer from moist or weather at all if the wood component in the WPC is well-dispersed. The connector will not suffer from corrosion. And thus does not have to be replaced

The layer of thermoplastic also acts as a barrier for termite attack. According to research (Ibach, Clemons, & Schumann, 2007) no cracking, decay or termite attack has been found after two years of testing. This is a positive aspect of WPC, but not very applicable in this case because there are no termites in the Netherlands (Sander, 2017).

From these researches it can be concluded that WPCs and plastic composites are very durable and therefore low in maintenance. Replacement of the material itself is exceptional due to its long lifespan.

Energy- and carbon-footprint

There is much to say about plastic when looking at its recourses and durability. Now the question remains if it is energy- and carbon-friendly as well.

The embodied energy of plastic varies among the different types of plastic. When the embodied energy of plastic is compared to metal for example, it turns out that plastic has a relatively low embodied energy (Calkins, 2009). However a research of Hammond and Jones (2008) show that the embodied energy of plastic relative to its weight is much higher than other materials like steel and concrete (Hammond & Jones, 2008). This can be confirmed by multiple other researches and investigations; The embodied energy of plastic can be much higher than the embodied energy of steel and concrete (Menzies, Turan, & Banfill, 2007), and according to *Falk (2009)* the embodied energy of wood is even less. In the research of Hammond and Jones the various types of plastics are investigated as well. It shows that high-density polyethylene has the lowest embodied energy relative to its weight compared to for example PVC or LDPE.

Making plastic composites from petroleum costs energy, causing the release of carbon-dioxide into the air, which supports global warming. But the largest amount of CO_2 during the lifetime of plastic is released during combustion of the material (Calkins, 2009). Before combustion the CO_2 is assimilated in the material itself.

Conclusion
In conclusion plastic composites are promising building materials. More development in this field is necessary to make it an applicable building material, not only in construction but in more fields as well. Some types are highly recyclable, and will not lose any structural characteristics when they are recycled. This makes the material highly durable as well. The main downside of the material is the high embodied energy and the problems during disposal, but recycling regulation can help solve these problems.

4.3 Bio-based composites as building materials

Bio-based composites are widely used materials for different applications. The car industry and construction industry are an example of these applications. A bio-composite is formed by natural fibres like jute or bamboo. These materials supposed to be environmental friendly during production, processing and waste (Balaji, Karthikeyan, & Sundar Raj, 2015). The bio-based composites could replace the petroleum-based composites. The challenge in replacing conventional plastics by biodegradable materials is to design materials that exhibit structural and functional stability during storage and use, yet are susceptible to microbial and environmental degradation upon disposal (Mohanty, Misra, & Drzal, 2012).

Resources
Natural polymers are the main resources for bio-based composites. These polymers are obtained from biomass, but humans are currently using only 3-4% of the biomass capital (Zia, Noreen, Zuber, Tabasum, & Mujahid, 2016). Since there is such an excess of biomass and since it is a renewable resource, natural polymers are considered to be a promising material for the future. But the high price is still a burden for wide application (Avella, Buzarovska, Erricom, Gentile, & Grozdanov, 2009).

One of the resources of bio-composites could be bagasse. Bagasse is a residual waste of the production of sugarcane. Together with resin it can form a natural bio-based composite. Since there is an excess of bagasse due to the extensive sugarcane cultivation, it makes this material a perfect resource for material use (Balaji, Karthikeyan, & Sundar Raj, 2015). When bagasse is used for construction materials this means that it will not be burned or landfilled, keeping the environment untouched. The bagasse is an agricultural waste from sugarcane which can be cultivated in European countries. This can cause low energy consumption during transport if the bagasse is obtained from sugarcane from Europe.

A lot of other resources are possible for making bio-based composites. Agricultural wastes from corn, rice, coconut or maize are possible resource fibres for bio-based composites (Ashori & Nourbakhsh, 2009). Other resources of bio-based composites could be synthetic fibres, like poly lactic fibres. These are biodegradable, human made fibres (Rasal, Jnorkar, & Hirt, 2009). All types of fibres have different characteristics and give different material properties to the composites.

Durability
Natural fibres or polymers have the drawback of absorbing moisture. This high moisture absorption can lead to microcracking of the composite and degradation of the mechanical properties (Bogoeva-Gaceva, et al., 2007). Moisture can also affect metal connectors and cause erosion. To solve this problem the materials can be treated with chemicals, which lowers the moisture absorption. The initial rate of absorption depends on many variables of the composite itself; the kind of fibre and matrix, temperature conditions and other variables (Biogiotti, Puglia, & Kenny, 2004).

Furthermore, fungi are a major concern for bio-based composites. Multiple studies show fungus development on the surface after a short period (Dittenber & GangaRao, 2011). The fungi are able to grow due to the biodegradation (decay) and moisture retention. Besides the fungal attack the material can reduce in strength as well, especially in outdoor conditions. Due to this degradation the material should be replaced and it cannot be recycled.

Energy- and carbon-footprint

Since the main resources of bio-based composites, natural fibres, grow naturally it could be said that bio-based composites have a low embodied energy and assimilate carbon-dioxide. However, cultivation and processing of natural plant fibres consumes more water, may use synthetic fertilizers and pesticides, and results in emissions of greenhouse gases in some processing stages (Rana, Pichandi, Parveen, & Fangueiro, 2014).

Studies show that the embodied energy of bio-based composites is lower than the embodied energy of glass fibre composites (which are fossil based products) for example. Natural fibres are produced by solar-energy on the contrary of man-made fibres (Mohanty, Misra, & Drzal, 2012). The study of Mohanty *et al., (2012)* shows that the amount of energy needed to grow flax fibres is about one fourth of the amount of energy needed to create glass fibre. A life cycle energy assessment shows that 40-60% less energy was consumed during the lifespan of natural fibre reinforced polymers in comparison to glass reinforced polymers (Mutnuri, Aktas, Marriott, Bilec, & GangaRao, 2010).

According to Dittember *et al., (2012)* natural composites provide a minimal carbon-footprint due to their assimilation of CO2 of the natural resources. Another research compares the carbon footprint of hemp mats made with bio-based resin with glass fibre made with petroleum based resin. According to this research the CO2 footprint of hemp mats is approximately 6 times lower than the carbon footprint of glass fibres and the bio-based resin has a significantly lower carbon footprint in comparison to the petroleum based resin on a cradle to manufacturer scale (La Rosa, et al., 2014).

Conclusion

Bio-based composites are promising materials because they can replace petroleum-based composites. But the benefits of these material could also be drawbacks. The biodegradability is good for disposal, but shortens the possible lifespan. The resources of the product are environmental friendly, due to the excess in agricultural waste. So this material has high potential when it is designed and processed in the right way, causing high durability and good processing and keeping low environmental stress.

5 Data collection

In the data collection, all necessary data from literature and interviews is gathered and compared to each other. First of all the demands in the contract is elaborated to see what the requirements and constraints for the barrier are. Then the specifications of wood, plastic and bio-based composites are given. The data that will be used in the MCA are marked bold for clearance. In the following chapters the two analyses can be done based on the collected data.

5.1 Demands contract

Based on the basic agreement with Rijkswaterstaat, BAM Infra came up with a 'Vraagspecificatie eisen' (VSE, Demand-Specification Requirements). In this VSE document the requirements for the whole project are listed. All requirements are listed per object and divided into themes. For ecoduct Koekendaal these themes can be bearing, design, lifetime or connect habitats for target species for example. Important themes for this research are design, lifetime, sustainability and maintenance. All the demands can be seen in Appendix D (Dutch).

There are two demand specific requirements for sustainability. These demands are focussed on the durability of its building materials. The demands require a good preparation of the steel structure and other building materials against damage mechanisms.

The lifetime of the ecoduct has two requirements as well. One is specified to the ecoduct as a whole, the other is specified to components of the ecoduct. The first requirement states that during the period of hundred years after realization, the ecoduct must be functional. The second requirement states that the technical lifetime for the components must be at least 25 years.

The maintenance of the ecoduct requires three demands. The first one is specified to vandalism resistance against graffiti, meaning all concrete that could be vandalized with graffiti should be provided with anti-graffiti protection. The other two requirements state that the ecoduct and components with a lifetime less than hundred years, should be easy in maintenance, inspection and replacement on an acceptable level based on the guidelines for inspection and maintenance facilities (Rijkswaterstaat, Richtlijnen ontwerp kunstwerken, 2015).

The last requirement is about the design of the ecoduct. The only requirement states that barrier should be made out of wood in combination with a concrete substructure, keeping wood the dominant building material. But as said in the introduction BAM Infra had some discussions about this with Rijkswaterstaat, finally agreeing the barrier could be made of wood-like material as well.

5.2 Specifics of wood

For the specifications and characteristics of wood as the building material for the barrier on ecoduct Koekendaal various types of wood are considered. The suppliers of the wooden components are chosen based on previous projects of BAM. One of the companies is Foreco. Foreco is specialised in modified, fast-growing softwood. The modifications give the wood the lifetime and appearance of tropical hardwood. Another company, SolidBamboo, is contacted as well. SolidBamboo makes two kinds of bamboo-based materials. One is laminated bamboo, and the other is pressed bamboo fibres (Figure 5). In the following paragraphs the summarised outcomes of the interviews with these companies are given, and they are compared to the literature studied in the previous chapter. The real outcomes (not summarised) of the interviews are given in Appendix E.

Figure 5 - Strandwoven Bamboo (left) and Solid Bamboo (right) (SolidBamboo, 2018)

5.2.1 Outcomes interview

Bamboo

In the interview with SolidBamboo the characteristics and production process of bamboo as a building material were discussed. The bamboo is retrieved from China, out of bamboo forests which are being maintained. Bamboo does not need to be replanted in contrast to trees. Trees need to be replanted every time when they are cut, but bamboo simply regrows from its remaining.

SolidBamboo has two kinds of bamboo as building material. The first is Strandwoven bamboo (SWB) and the other is Solid bamboo. Strandwoven bamboo is made from pressed bamboo-fibres. Solid bamboo is made from laminated bamboo strips. The lifespan of both can be compared to the lifespan of the wood type Accoya (a type of modified wood), but SWB has a higher chance on a longer lifespan and is more applicable for outdoor use. Both the bamboo as Accoya should last for a 'lifetime', but scientifically this can only be 'more than 25 years' (Stichting Porbos, 2009). The durability of the bamboo is dependent on the drying process as well. If wood or bamboo is not dried well and long enough, it can shift and warp, making the material useless.

SolidBamboo guarantees the product for 15 years. The most chance of failure of the material is in the first year after acquisition (probably due to bad processing). When there is nothing wrong after this first year the material could last for **30 years or more** for example.

As said the bamboo can be compared to the wood type Accoya when considering durability, and the same goes for maintenance. For both the Solid bamboo as Accoya it cannot be excluded for hundred percent that fungi forms on the surface of the material. For SWB this is hundred percent excluded. Both of the bamboo types are tested against internal rot, and it turns out the bamboo is not affected by it. The surface fungi only have a bad influence on the aesthetics of the material and this can be easily corrected.

During the production process residual waste is used to produce the heat that is necessary for the production of the bamboo. A Life Cycle Assessment (LCA) is carried out by INBAR (International Network for Bamboo And Rattan) in combination with a few fabricants. This LCA shows that the bamboo is in fact CO_2-negative meaning it assimilates more CO_2 than it releases. The production and shipment of the bamboo was taken into account while doing the LCA.

Modified wood

To get to know the characteristics of the modified wood (NobelWood) from Foreco an interview was conducted. The resources for the modified wood are softwood and biopolymers. The wood is retrieved from New-Zealand from the wood-type Radiata Pine and is being cut there. The biopolymers are residual waste from sugar cane harvest (bagasse), which is obtained from several countries. The wood and biopolymers are gathered in Belgium. The wood is transported by ship which has equivalent emissions as transportation by road.

During the interview more alternatives came up. For instance SoundWood. This is a commonly used material for sound barriers along highways. This wood is made from WaxedWood, which is basically waxed wood. The process of this wood only strengthens the surface, while the process of NobelWood gives the wood another structure.

Another alternative is FaunaWood. This is a relatively new sort of material. The resources are slightly different from NobelWood. The basis of FaunaWood is Radiata Pine as well, but it is strengthened with pyrolysis oil instead of biopolymers. The pyrolysis oil is obtained from residual wood. The wood can be obtained from the construction site for instance, making it a more circular process.

The approximated lifespan of NobelWood wood is **50 years**. This is based on experiences with previous projects. The guarantee is 25 years. Algae or dust can form on the surface of the wood dependent on the weather and rain. To keep the aesthetics of the material it is necessary to maintain the wood ones in the ten years approximately, by treating it with a high pressure sprayer.

The energy used during production process is mostly sustainable energy. The production process takes mostly place in New-Zealand. According to the interview a lot of sustainable energy is used here, because of the large amount of natural energy resources.

5.2.2 Interview compared to literature

Bamboo

When the outcomes of the interview are compared with the literature studied it can be seen that there are a few similarities and differences for bamboo in specific and wood in general. One difference is the durability. According to the company SolidBamboo bamboo has a lifespan of over 25 years and they expect even longer. Replacement is probably needed after approximately 30 to 50 years. The bamboo is only affected by fungi on the surface level, but this chance is very small. This means that the bamboo will not rot or decay from the inside during its lifespan. There still is a small chance of surface fungi and this requires maintenance with a high pressure sprayer.

The bamboo is according to INBAR CO2-negative throughout its lifetime. This International Network can be seen as a trustworthy source. The literature shows that wood assimilates carbon-dioxide as well (Falk, 2009), but they do not say that it can be CO2-negative. When more literature is studied it turns out that due to the low amount of heat that is needed in the production process and the amount of carbon-dioxide assimilated, bamboo is in fact 'CO2 neutral or better' meaning CO2-negative, as seen in Figure 6 (van der Lugt, Vogtländer, & Brezet, 2015). In this research strandwoven bamboo for outdoor application is considered, taking carbon sequestration, transport (from China to Europe), processing, gluing, internal transport and end of life (bioenergy) into account. The research of *Van der Lugt et al., (2015)* shows a carbon footprint of **-0,05 kg CO2-eq / kg** for this type of bamboo.

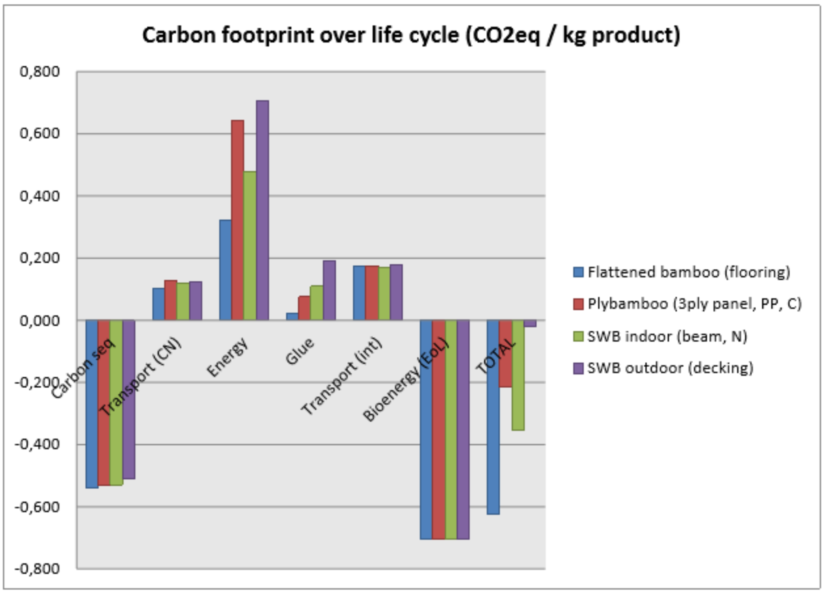

Figure 6 - Life Cycle Assessment on carbon footprint with different bamboo types (van der Lugt, Vogtländer, & Brezet, 2015)

This LCA is done with the scope of cradle-to-gate, meaning the analysis is done from the growth of the bamboo till it leaves the warehouse/manufacturer. The research of *van der Lugt et al., (2015)* also includes an end-of-life calculation (making it cradle-to-grave) where they state that approximately 90% of the bamboo in most Western Europe countries ends up in an electrical powerplant. So the carbon-dioxide released during this process is mostly (due to the efficiency of the powerplant) converted into (bio)energy.

The energy footprint of the bamboo is low as well due to the use of residual waste for production and processing. Now you might say that burning this residual waste releases carbon-dioxide as well. In fact this is true, but the way these CO2-emissions are approached in a LCA is different. The reason for this different approach is that the burned bamboo replaces the burned fossil fuels, which have high CO2-emissions as well. Because the emissions from bamboo, which would happen either way, replace the emissions of fossil fuels it is considered as CO2-negative (van der Lugt, Vogtländer, & Brezet, 2015).

Bamboo as a resource is a little different from wood as a resource. As stated in the literature wood does not grow fast enough for the demand and humans already deforested almost half of the world's forests in the last hundred years (Buchanan & Levine, 1999). Bamboo on the contrary regrows really fast and does not need to be replanted. Bamboo-forests are easily maintained due to the characteristic of bamboo that it regrows fast and under various conditions. The high growing rate allows it to have a 25 times greater yield than timber (Dethier, et al., 2000). Bamboo regenerates itself by sending up culms from its perennial subterranean rhizomes (Maoyi & Banik, 1996).

Modified wood

The raw material of this wood type is Radiata Pine. This wood type is a fast-growing wood type and can grow up to two meters a year (Centrum Hout, 2014). One of the downsides of wood, and especially tropical hardwood, as a building material is the long production period, but the Radiata Pine is fast-growing. Therefore, when looking at the resources-aspect, this type of wood is very beneficial, under the condition that it will be processed well. The other resources for NobelWood are sustainable as well. They are residual wastes of other production processes and these are widely available. So this specific type of wood has the same characteristics, but other more beneficial resources than tropical hardwood which is needed for construction.

According to the literature one of the main problems of wood is its durability. But wood can be made more durable when processed right. Radiate Pine, the raw material of the processed wood, is a soft wood and has a durability class of 4-5 (Stichting Porbos, 2009). But after processing, the wood gets a durability class of 1 and will last for 50 years according to the website of Foreco BV. The well processed wood has the highest durability-class which wood can get, but the maximum lifespan of this durability class is 'more the 25 years', which is in contrast with the 50 years.

Due to furfurylation (the process of impregnating wood with furfuryl alcohol, obtained from agricultural waste) only surface areas can be affected by algae, and internal rot is averted (Mantanis, 2017). Algae can form on the surface, but this is easily corrected and does not affect the structural strength of the material.

The Radiata Pine assimilates a lot of CO2 as well according to the website of Foreco. They state that one cubic meter of pine can assimilate up to 600 kg CO2. In a research of *Vogtländer (2013)* an LCA for Accoya wood is done. This LCA shows the global warming potential (kg CO2-eq / kg) or carbon footprint. For Accoya Radiata Pine a carbon footprint of -7.49 kg CO2-eq / window frame is calculated (Vogtländer, 2013). In this research the window frame weighs 34,9kg resulting in a carbon footprint of **-0.21 kg CO2-eq / kg** product. Since the process of making Accoya (acetylation) is comparable to the process of Nobelwood (furfurylation) (Mantanis, 2017), the carbon footprints are assumed to be comparable as well.

Furthermore is the embodied energy for this wood low. The energy used during production is partly obtained from residual waste and partly from other energy resources. Most of the production process takes place in New Zealand, and according to the interview this country uses a lot of sustainable energy resources. The literature shows that this is true. New Zealand already had a high proportion (29%) of renewable energy generation in 2007 (Kelly, 2007). This overall low embodied energy of wood can also be obtained from the literature.

Foreco participated in a research in the biodiversity footprint of multiple companies. Further details of this research are given in Appendix F.

5.3 Specifics of plastic composites

Plastic composites come in various types with all different production processes. In the literature the focus lay mostly on wood-plastic composites. In these interviews the focus will be more specific by considering normal plastic composites. The first company that will be contacted is GovaPlast. This company is already mentioned before because BAM Infra has a preference towards this company. Furthermore another company specialised in plastic composites, Lankhorst Recycling Products, is approached to get a good comparison between them and GovaPlast.

5.3.1 Outcomes interview

Lankhorst Recycling Products

The company Lankhorst Recycling Products uses recycled plastic for their products and has therefore some sort of 'endless' resource because ones this plastic is made, it does not decay and can be recycled. Furthermore the raw materials do not need to be imported from overseas countries. The plastic waste availability in Europe is high enough. They expect that the material will last for **fifty years** and it will not need any maintenance, only cleaning with a high pressure sprayer once in the three years or so. During the production process the main influencing factor on the environment is the heating of the product. Furthermore there are no big incriminating factors. The residual heat from the process is used to keep the factory on the right temperature.

Lankhorst had a CO2-footprint analysis for their material carried out by Tauw (Kupfernagel, 2018). In this report an analysis of the carbon emissions is done over the whole lifespan of the KLP (Kunststof Lankhorst Product). The analysis shows that the production phase has the biggest impact on the carbon emissions. When environmental benefits (recycling and not burning resources) are taken into account the CO2-footprint becomes negative. Figure 7 (next page) clearly shows that the negative carbon emissions outnumber the positive emissions making this material CO2-negative over its lifetime **(-1,7 kg CO2-eq / kg)**.

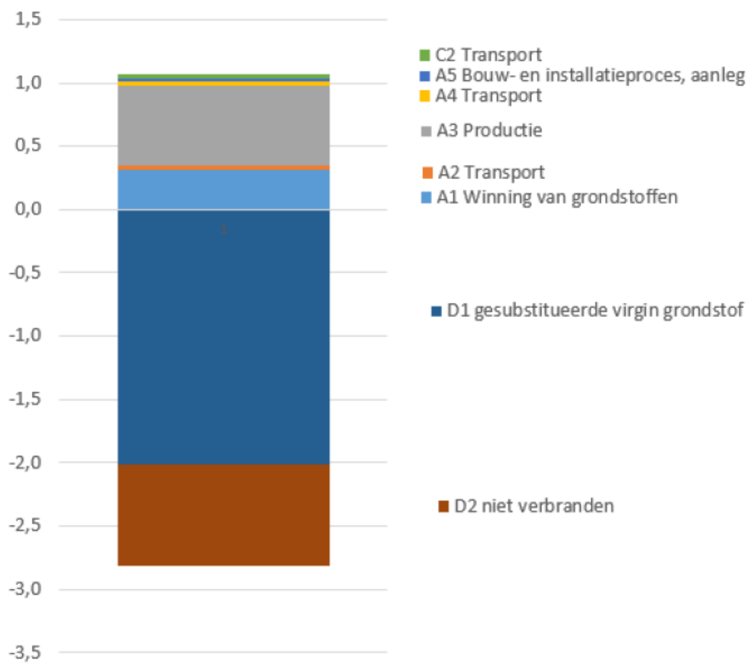

Figure 7 - CO2 emissions of KLP through its lifetime cradle-to-grave (Kupfernagel, 2018)

The biggest positive emissions are during production of the product. The biggest impact is the use of electricity (96%) according to the report. Lankhorst Recycling Products works mostly with 'grey energy' meaning it is derived from fossil fuels. When the company starts using green energy the CO2 impact can decrease by half according to the sensitivity analysis (Kupfernagel, 2018).

GovaPlast

The main resource of the GovaPlast material is recycled plastic. Additives and dyes are added to give the materials the required characteristics. De types of plastics in the product are polyethylene (PE) and polypropylene (PP) and is gathered in Western Europe.

The lifespan of the material is at least thirty years. The first projects started thirty years ago and they still last. The expected lifespan of the material is even longer, due to the characteristics of plastic. The long durability is a problem for disposed plastic but an advantage for our products. The guarantee is ten years. Besides that, the material is low in maintenance. A low water absorption rate causes less chance on algae. Only the shadow side of the material has a small chance on algae on the surface. The maintenance that has to be done is not more than on wood, on this material algae can form as well but this is easily fixed with a high pressure sprayer.

The energy which is used during the production process is presumably green energy, but this is not certain. A LCA is not carried out because there is no demand for it. It is very clear that the materials used are recycled plastics. The only energy consuming process is the heating of the plastic to press it into moulds. The plastic materials can be send back for free after the lifespan of the material.

5.3.2 Interview compared to literature

Lankhorst Recycling Products & GovaPlast

The literature shows some positive and negative aspects for plastic as a building material. Plastic has a non-renewable resource (petroleum) and a high embodied energy and carbon emissions. On the other hand plastic is very durable and once it is made it can be recycled over and over again.

The interview is mostly in compliance with the literature. The durability for example is very high, and no extra maintenance is needed. The material does not rot or decay. The use of recycled plastics gives the material more environmental benefits.

The energy-footprint of the material is, as expected, high. The product needs heat to form it in the right way. In the case of Lankhorst, this heat is obtained from fossil-based energy, making the carbon-footprint of the material higher. But the LCA shows that the material has a negative carbon footprint on the scale of cradle-to-cradle. When the scope of cradle-to-gate is used (excluding the environmental benefits) it becomes clear that the material has a carbon-footprint of around 1 kg CO2-eq / kg. This number can be reduced when the company starts using green energy, like GovaPlast supposedly does. GovaPlast on the other hand did not carry out a LCA making it hard to say what the carbon- or energy-footprint of the material is.

Furthermore, the products are made out of recycled plastics, so no new petroleum is used to create this material. After the expected lifetime (of 50 years for Lankhorst and more than 30 years for GovaPlast) the product itself is still recyclable which is in compliance with the literature. GovaPlast even takes the material back for free.

5.4 Specifics of bio-based composites

One company which is specialised in nature based composites is contacted to get to know the characteristics of these materials. The name of this company is NPSP. It uses nature based fibres which are reinforced with (partly) natural resin.

5.4.1 Outcomes interview

The product of NPSP is a bio-composite which is made from residuals of biological waste. The plant fibres origin from agricultural waste from cane, flax or cotton. The residuals are normally burned which releases CO2 in the air. On the contrary of wooden trees the plant fibres regrow very fast. Cane for example only needs two years to regrow. The bio-composite consists for 80% of these biological materials, the other resource is a resin which is obtained from petroleum.

The expected lifetime of the material is **more than thirty years**. It does not decay and only needs cleansing on the surface. The lifetime is based on endurance tests and comparison with other materials. Further maintenance is not needed, and is not possible. Paint for example does not stick to the material.

During the process heat is needed to form the composite. It is uncertain whether green energy is used or not, but presumably not. However residual products of the process are reused for new materials.

5.4.2 Interview compared to literature

According to the interview the resources of bio-based composites are highly renewable and sustainable. The literature shows that there is an excess in bio-mass and that agricultural fibres renew in a short period of time (Zia, Noreen, Zuber, Tabasum, & Mujahid, 2016).

The problems in the literature with durability of the bio-composite does not stand out in the interview. The cause of the long durability of the nature-based composite of NPSP could be the addition of fossil fuel-based resin. This resin can give the composite a longer lifespan but can make it harder to recycle the material as well.

The interview does not say that much about the energy- and carbon-footprint. Some literature shows CO2-negative carbon emissions over the lifetime of the product. A research in hemp-lime walls show a carbon-footprint of **-0,44 kg CO2-eq / kg** (Ip & Miller, 2012). But more research in the literature shows that the carbon footprint of bio-based composites may not be that good after all. The cradle-to-manufacturer scope shows a low carbon footprint, but due to processing (cradle-to-gate) this footprint can increase significantly. The high amount of carbon emissions also suggests a high amount of added embodied energy during the production process. *Hottle et al., (2013)* states that the benefits of biopolymers will not be realized until the energy- and carbon footprint of the material are reduced.

The carbon-footprint of the hemp-lime material is taken into account in this study. the hemp-lime material has the most similarities with the material of NPSP. Despite not being representative for all bio-based composites, this value is sufficient in this study.

6 Life Cycle Costing

A life cycle costing is carried out to give a good advice to BAM Infra on which material is the most cost-effective one over the whole lifespan of the ecoduct. This lifespan must be a hundred years according to the VSE (Demand-specification requirements) document. But BAM Infra will not be responsible for the ecoduct after completion. Rijkswaterstaat is responsible for maintenance and disposal, so the life cycle costing could be of more interest to Rijkswaterstaat than BAM Infra. The analysis can show to Rijkswaterstaat what the most cost-effective alternative is, although this might not be the one with the lowest acquisition costs. So by choosing the material with the lowest life cycle costs BAM Infra can get a lot of good will from Rijkswaterstaat which may lead to more future cooperation.

The following paragraphs elaborate on the costs of the barrier. Hereafter the LCC itself is carried out and a conclusion to this analysis is given.

6.1 LCC

To carry out the LCC a lot of information has to be provided. Dimensions of the barrier, costs of the materials and material characteristics are used to calculate the eventual costs of the barrier over the lifetime of the ecoduct. The main costs of the barrier can be divided into three subjects; acquisition, maintenance and disposal. In these subjects multiple variables are taken into account to give a good representation of the costs of the barrier.

Acquisition

The acquisition costs of the materials are the costs of the procurement of new materials. The initial costs of this expense is for BAM Infra, because they are building the ecoduct. The acquisition costs will go to Rijkswaterstaat when new material is needed due to degradation of the former material, probably at the end of its expected lifetime. Therefore, the acquisition costs in the LCC are divided into the acquisition of BAM Infra and the acquisition of Rijkswaterstaat (RWS).

The initial acquisition costs for BAM Infra are either taken directly from offers of the suppliers or calculated by the hand of previous offers. The total acquisition costs for Rijkswaterstaat are calculated by multiplying the initial acquisition costs with the amount of times the material has to be replaced. These calculations can be found in Appendix G.

Maintenance

The material of the barrier has to be maintained to keep the barrier aesthetically appealing and in good shape. These costs can be cleansing on the surface or regular check-ups. Replacement costs do not fall under maintenance costs, but under acquisition costs.

The maintenance costs are calculated by the amount of maintenance needed over the whole lifespan of the ecoduct and the costs per maintenance service, including cleaning, rent of equipment and personnel. The specific calculations can be found in Appendix G.

Disposal

The costs of disposal depend on to what extend the material is recyclable or useful for another purpose. For example, rotten wood is not recyclable and can only be landfilled or combusted, so it has no valuable properties anymore. Other materials, like plastic, are recyclable giving it value, but the questions remains whether or not people want to invest money in it. Still the disposal costs differ for recyclable materials and non-recyclable materials. GovaPlast for example is willing to receive the used materials for free. Non-recyclables have landfilling-costs.

The disposal costs are calculated by the hand of transportation costs, landfill- or recycling-costs and the amount of the material that has to be disposed of. The specific calculation can be found in Appendix G.

The LCC is carried out by calculating all the costs named above and sum them up to get the eventual life cycle costs. This sum gives an approximation of the total costs of the material used for the barrier on ecoduct Koekendaal.

Most certainly not all costs are included specifically. The steelwork for the bearing construction for example is not taken into account as well as the staff costs for new acquisitions and roadblock costs during maintenance. The main reason for omitting these costs is the low expected influence of them and the uncertainty of these costs. The steelwork can be manufactured by an external supplier, assuming the same structure for all materials and the staff will have to put approximately the same effort in the new acquisitions, resulting in the same costs for all alternatives. Roadblock costs can vary a lot per project and time and are therefore not included as well. Furthermore, inflation is not taken into account, because the aim of this analysis is to make a comparison and inflation will only rise all costs equally. A summary and overview of the LCC are given in Table 1 and Figure 8.

Alternative	**SolidBamboo**	**Foreco**	**GovaPlast**	**NPSP**
Acquisition (BAM)	€ 99.180,00	€ 91.741,50	€ 43.444,80	€ 131.868,00
Acquisition (RWS)	€ 198.360,00	€ 91.741,50	€ 43.444,80	€ 263.736,00
Maintenance	€ 14.000,00	€ 14.000,00	€ 14.000,00	€ 14.000,00
Disposal	€ 5.250,00	€ 4.200,00	€ 3.780,00	€ 5.250,00
Life cycle costs	**€ 317.840,00**	**€ 201.683,00**	**€ 104.669,60**	**€ 415.904,00**

Table 1 - LCC of four different materials for the barrier on ecoduct Koekendaal

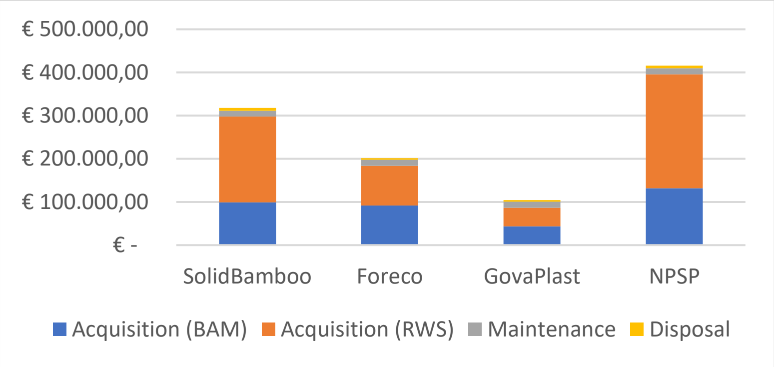

Figure 8 - Overview of the LCC for the barrier on ecoduct Koekendaal

6.2 Conclusion

In conclusion the material of GovaPlast scores the best, having the lowest costs over its lifetime. GovaPlast has the lowest initial costs, is comparable in maintenance costs and has low disposal costs. The low disposal costs are due to free material retrieval, so no landfilling costs are included during disposal, only transportation to GovaPlast is considered here.

The bio-based composites of NPSP have very high acquisition costs. The literature shows as well that this is a problem of bio-based composites. The production process is too expensive in comparison to the competing materials.

The bamboo of SolidBamboo has comparable acquisition costs to Foreco's NobelWood but the lifetime of this material is slightly lower. According to the interview the material can last longer than thirty years, and approximately thirty to fifty years. The literature shows a wide variety of expected lifespans of processed bamboo products. Therefore, an average of the interview is taken, which is forty years. A lifetime of forty years results in three acquisitions of the bamboo in a hundred year lifetime of the ecoduct. The acquisition costs of the new bamboo makes the bamboo more expensive in comparison to the modified wood over the whole lifetime of the ecoduct.

So in the end, after hundred years, the plastic materials of GovaPlast are expected to be the most cost-effective ones in comparison to wood, bamboo and bio-based composites. The plastic has low acquisition and disposal costs and is comparable in maintenance, this results in the low life cycle costs of the plastic composite.

7 Multi-Criteria Analysis

7.1 Values

The criteria for the multi-criteria analysis (MCA) are already described in chapter 3 'Theoretical framework'. In this paragraph the criteria are scored per alternative based on the literature and interviews. The minimum score is zero and the maximum score is ten. To make sure that the scores can be added all criteria should be formulated in the same way, so either positive or negative. In the research all criteria are formulated positive, so materials with *environmentally and economical friendly resources, long durability, low carbon footprint and low embodied energy* score high.

First of all the resources are scored. The resources should be economical and environmentally friendly. According to the collected information wood is environmentally friendly, but in comparison to the other building materials not economical sustainable. It takes a long time to regrow. Bamboo scores better on this aspect. It grows naturally just like wood, but has a lower recovery period. Bio-based composites have resources with comparable characteristics as bamboo. Both are very renewable and grow in excess, but the resources for bio-based composites can grow in Western Europe which is advantageous. Plastic composites on the other hand are in the first place not environmentally and economical friendly at all. It is not a renewable resource, but the positive aspect of this material is the recyclability. There is an excess of waste plastic which is highly recyclable and currently harming the environment. A solution is needed to get rid of this waste and using it in construction is very promising. Therefore, recycled plastic scores very high at this moment, because of the excess of waste plastic. A matrix is used to compare the materials relative to each other. Based on this matrix the alternatives for this criterium of the MCA are scored. The matrix can be found in Appendix H. The scores are as follows:

- Modified wood: 1
- Bamboo: 4
- Plastic composites: 9
- Bio-based composites: 6

Secondly the durability of the material is scored. Long durability is a good characteristic for construction building materials. Plastic for example is very durable. It can last very long and is not that influenceable by weather. On the other hand, due to improvement in material knowledge, modified wood, bamboo and bio-based composites have high durability levels as well. According to the literature and interviews all materials have a comparable lifetime and they are all low in maintenance, but the modified wood and plastic composites have a bigger chance on a longer functional lifetime. The stated lifetimes for modified wood, bamboo, plastic composite and bio-composites are respectively fifty years, forty years, fifty years, forty years. The maximum score can be given to the material which lasts as long as the ecoduct, meaning hundred years, so every ten years adds one to the value. This results in the following scores:

- Modified wood: 5
- Bamboo: 4
- Plastic composites: 5
- Bio-based composites: 4

Thirdly the carbon-footprint of the building materials is scored. This criteria scores high when the carbon-footprint is low. Data from LCA's of the materials are used to compare this criteria. A cradle-to-grave/cradle-to-cradle scope is taken for the carbon-footprint, because this scope gives realistic environmental impacts of a product over its whole lifetime. The carbon-footprints of the materials are given in Figure 14 in Appendix H.

The LCA's show that plastic composites have a high CO2-negative footprint, followed by lower CO2-negative footprints of bio-based composites, wood and bamboo. The carbon-footprint of bio-based composites is hard to quantify with certainty since it is such a new material. The literature shows high variations in carbon-footprints with the current processing techniques. But the process which results in this carbon-footprint comes closest to the process of the bio-based composite considered in this research. The maximum score in this criteria is 10 for a -2,0 kg CO2-equivalent. The scores of the materials are given below (See Appendix H for calculations):

- Modified wood: 1
- Bamboo: 0
- Plastic composites: 9
- Bio-based composites: 2

Second-last the embodied energy is scored. As for the carbon-footprint, the embodied energy scores higher with a lower value. Since the embodied energy is very process specific and hard to quantify (even more than carbon-footprint), general scores are given, mostly based on literature. As said before bio-based composites do not have an effective production process giving it a high embodied energy. Wood- and bamboo-processing have similar energy consumption which is approximately lower than the amount of energy needed for plastic production due to the amount of heat. For this criterium a matrix is used again to compare and score the materials. This matrix can be found in Appendix H as well. The materials are scored as follows:

- Modified wood: 7
- Bamboo: 7
- Plastic composites: 2
- Bio-based composites: 4

Finally the costs of the materials are scored as well. The outcomes of the LCC in the previous chapter are used to score this criterium. Including the costs makes this MCA project-specific. An project-exceeding MCA is given in Appendix I to give a more general analysis on the sustainability of the building materials without their project related costs. For the project of ecoduct Koekendaal the scores for the costs are as follows, based on the LCC (Table 1, the value-calculations can be found in Appendix H):

- Modified wood: 7
- Bamboo: 4
- Plastic composites: 10
- Bio-based composites: 0

7.2 MCA

Besides the scores of the alternatives the weight per criteria must be set as well. The sum of the weights is set to be ten, so the maximum score for the alternatives will be hundred (ten times ten). For this research the sustainability visions of Rijkswaterstaat (Rijkswaterstaat, Duurzaamheid en Leefomgeving, sd) and Royal BAM group (BAM, sd). The carbon-footprint is considered the most important in these visions. Furthermore the costs are important to BAM Infra as a contractor and to Rijkswaterstaat as a client, so both of them get a weight of three. The durability is important due to the amount of maintenance and replacement that has to be carried out, but this is not mentioned in the durability visions. However, long durability saves time, money and production of new materials, so this criteria gets a weight of two. The resources and embodied energy are considered least important because these criteria influence the environment the least and get a weight of one for now.

These criteria can become more relevant when the problems around CO2 emissions and durability become lower.

The multi-criteria analysis is carried out in Excel. The scores or values of the alternatives are multiplied with the weights of the criteria. The weighted values are summed to get to the final score per alternative. The MCA can be seen in Table 2 and Figure 9.

Criteria	**Weight**	**Modified Wood**		**Bamboo**		**Plastic Composites**		**Bio-based Composites**	
		value	weighted value	value	weighted value	value	weighted value	value	weighted value
Resources	**1**	1	1	4	4	9	9	6	6
Durability	**2**	5	10	4	8	5	10	4	8
Carbon-footprint	**3**	1	3	0	0	9	27	2	6
Embodied energy	**1**	7	7	7	7	2	2	4	4
Costs	**3**	7	21	4	12	10	30	0	0
	Score		**42**		**31**		**78**		**24**

Table 2 - Multi-criteria analyse on four types of building materials on durability and costs

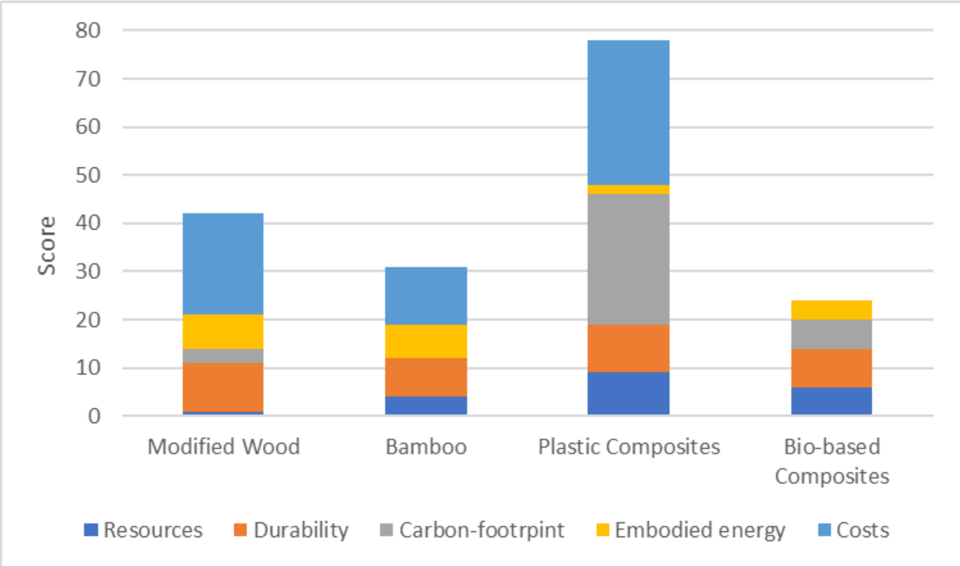

Figure 9 - Overview MCA on four types of building materials

7.3 Sensitivity Analysis

To give a convincing advise to BAM Infra and Rijkswaterstaat on the sustainability and cost-effectiveness of the materials the outcomes of the analysis must also be robust. This means that the outcome of the analysis should stay approximately the same when minor changes are made in the input. The input of the MCA mainly consists out of the values to the alternatives and the weights of the criteria. An analyses on the sensitivity will be done on both of them.

Weights of the criteria

The criteria have different weights resulting in more and less important criteria. The choice of weights is dependent on multiple variables like time, situation, location, policy, etc., or in one word; context. If a company wants to invest in sustainable building materials to get a 'green image', costs can be less important, for example. Or if a project only has a lifespan of ten years than the durability will not matter that much.

There could be plenty of scenario's where the criteria differ in importance, therefore it is important to check which material scores best with different weights. To check this the different weights are picked, while the sum of the weights remains ten. The top left diagram in Figure 10 shows the standard weights taken in the MCA. The top right diagram shows low weights at high scoring values for plastic composites. The bottom left diagram shows all equal weights of two. The bottom right diagram has random weights.

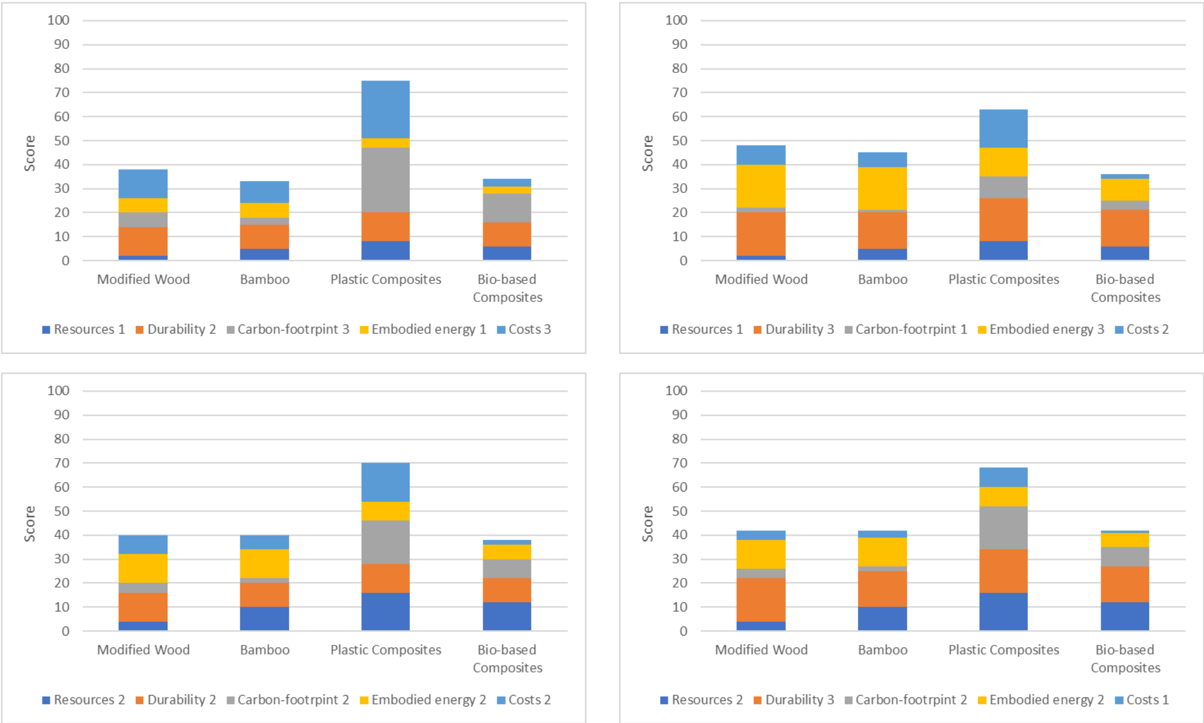

Figure 10 - Random sensitivity analysis on the weights of the criteria of the MCA (weights shown per criteria)

The sensitivity analysis clearly shows that it does not matter what weights are applied, the plastic composites remains the best option. However, there is a difference for modified wood, bamboo and bio-based composites. The low embodied energy and slightly lower costs make the bamboo and modified wood a better option when these criteria are considered important.

In the end the analysis shows that the outcome of the MCA about plastic composites is very robust. It does not really matter which weights are applied, plastic composites remain the best choice with the values it has.

Values of the alternatives

The way a MCA calculates the best alternatives logically implies that the sensitivity of the values of the alternatives is dependent on the weight of the criteria. For example, a change in value of plus or minus one in a criterium with weight three, will result in a change of plus or minus three in the weighted value. When the weight of the criterium is one and the value of this criterium drops or increases by one, than the weighted value will also drop or increase by one. The simplicity of these calculations in the MCA clearly show that the sensitivity of the values is dependent on the weights of its criterium. To get an idea on how this looks like a sensitivity analysis on the values of plastic composites is done. All values are either lowered or increased by 50%. Figure 11 clearly shows that the criteria with higher weights (costs and carbon-footprint in this case) have a higher sensitivity due to the steepness of this line. The graph also shows that higher values have a slightly higher sensitivity as well. This can be logically explained, because a percentage of the initial value is taken. An initial value of eight results in a range from four to twelve (+/- 50%, with a maximum difference of eight), while an initial value of four results in a range from two to six (with a maximum difference of four). The table with all the values are shown in Appendix J.

So it can be said that the sensitivity of the values is mostly dependent on the weights of the criteria and slightly dependent on the magnitude of the value itself. The weights of the criteria itself can vary, but this shows no big changes in the eventual outcome of the MCA, making it a robust analysis.

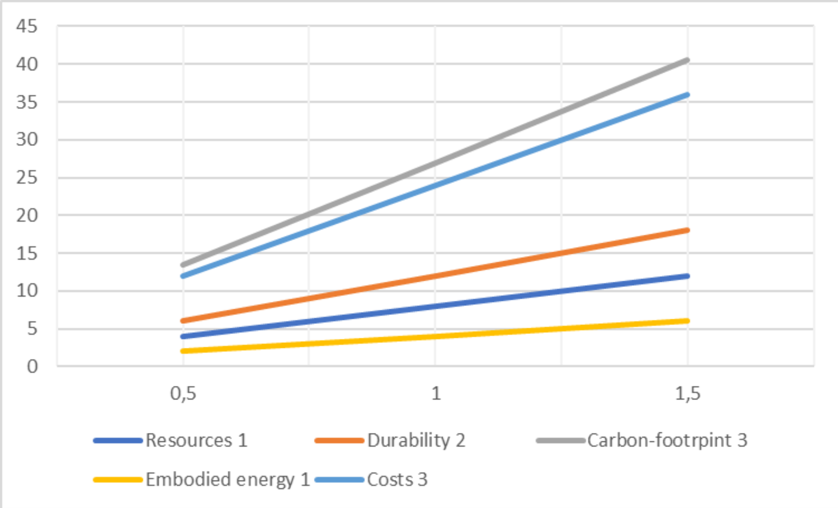

Figure 11 - Sensitivity analysis on the values of plastic composites

7.4 Future perspectives

This MCA is done based on the context of modern day problems and solutions. This may change in the future due to new developments. A lot can change in the availability of resources, processing techniques or sustainability visions. To make sure that the advice will also be applicable in the future, it is important to take these changes into consideration.

First of all the problem of waste plastic is a variable that will most certain change in the future. In this research plastic composites score high on resources due to the availability of waste plastic. Plastic composites retrieve this waste out of the environment and put it into useful attributes. But new developments and policies can cause less plastic waste, and the scarcity of petroleum can cause the stagnation of plastic production. So in the future this material may score low on resources and costs due to the scarcity.

Secondly sustainable forest management is developing in more and more countries over the world. Sustainable forest management causes less to no environmental harm to forests, leaving natural habitats in peace and preventing deforestation. This may cause a good supply of certified wood or bamboo with high quality. This will give wood and bamboo higher scores at resources.

At third, new developments in processing techniques can cause lower carbon emissions and less energy usage. A lot of research is done to optimise processing techniques, especially in new, promising materials like bio-based composites. One of the biggest problems of these kind of composites is the production process and the price. The literature says that these developments in better processing techniques can cause lower carbon-emissions, energy usage and prices.

When all values are changed according to these arguments the results of the MCA looks like Figure 12 (score table inAppendix K). The result clearly shows a big loss for plastic composites. Bio-based composites on the other hand can become very appealing due to the future developments. Modified wood and bamboo increase in score as well, and remain a reliable building material for the coming years.

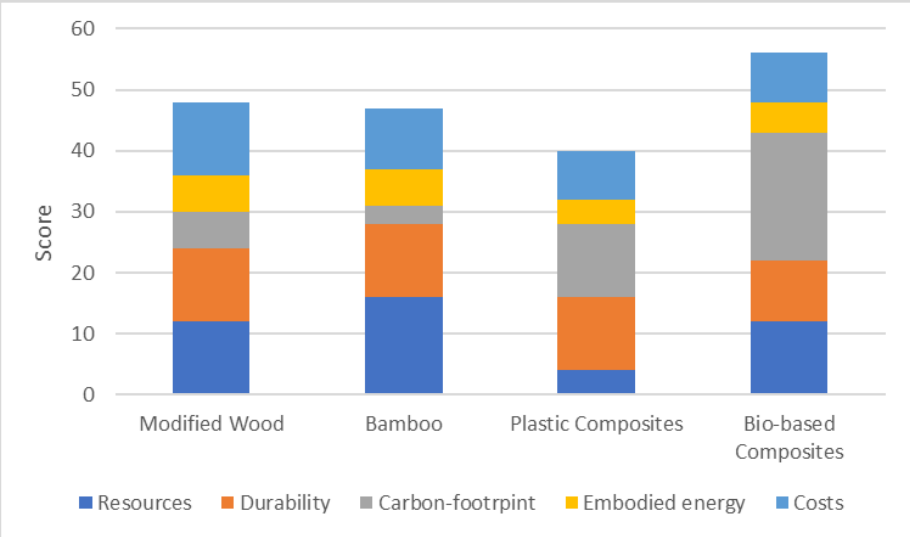

Figure 12 - MCA on four types of building materials with future perspectives

7.5 Conclusion

A conclusion can be derived from this MCA. Table 2 clearly shows that plastic composites have the highest overall score. This high score is due to the good material characteristics and cost-effectiveness. Modified wood comes second followed by bamboo. In the last place are bio-based composites. Bio-based composites score least due to low scores at high weighing criteria. The LCC in the previous chapter shows that bio-based composites are a very expensive building material over its lifetime. Besides that it has a low negative carbon-footprint. But this does not mean that bio-based composites are an unsustainable and expensive building material in general. The score in this MCA is based on comparison with the other materials and the costs are project-specific. So the outcome of the MCA only shows which material is better in comparison to the others for the project of ecoduct Koekendaal.

The sensitivity analysis shows a high robustness for the outcome of the MCA. Plastic composites remain the best alternative when the weights of the criteria are changed. The values of the alternative are more sensitive when the value is for a certain criterium with a high weight. This can be logically implied by the simplicity of the analysis.

An estimation for the future values of the alternatives shows that plastic composites will lose their value due to new developments and policies. Bio-based composites on the other hand will increase in value and will become a good alternative for current building materials. Wood and bamboo remain reliable resources.

So for the barrier on ecoduct Koekendaal it can be said that plastic composites are currently the most sustainable and cost-effective materials. The long durability, excess in resources, relatively low carbon- and energy-footprint and the low costs cause this high score for plastic composites. The future perspectives can lead to a different outcome with bio-based composites as the eventual winner.

8 Discussion

This research is done in a certain context and with a few assumptions. It is important to point them out and consider what the consequences are. In general, the outcome of this research is specified to a barrier on an ecoduct. So the advice cannot be used in a very broad way, for bearing structures for example. The literature that is studied in this research could be helpful for other applications, but the advice is only sufficient for wood-like barriers.

The location of this research is important to the context to start with. This research is carried out in the Netherlands, where ecoduct Koekendaal is made. Some of the inputs of both the analyses are based upon this fact. For example the values for the resources are based on the origin of the resources. Building materials with recourses from other countries or continents do not support circularity and may cause environmental harm. When this research was conducted in New-Zealand for example, the modified wood would score much higher on resources since most of this wood origins from New-Zealand. The LCA would also be different because CO2 emissions during transportation would be negligible. Furthermore prices in the LCC are based upon Dutch (and Belgian) suppliers. These costs can differ in other countries. In short, resource-values, carbon-footprints and prices can differ a lot in other countries, especially outside Western Europe.

Furthermore, as said in the conclusion of the MCA, this research is very time dependent. The values given to the criteria in the MCA and the arguments they are based upon are based on the current problems, solutions and policies in the world. At the same time this is also the case for the literature studied in this research. Most of the articles which are time dependent are recently published, but could already be slightly outdated. Therefore, it is important to check if arguments are still valid if this research is used in the future.

Besides the literature, the data is based on interviews with the suppliers as well. The information from these interviews can be biased because suppliers may give information which delineates their products in an advantageous way. The interviews are compared to the literature to filter out these biases. Luckily no major differences stood out in the comparisons.

Another important contextual aspect of this research is the LCC. The costs of the barrier over the lifetime of the ecoduct are based specifically on the offers of suppliers. Therefore this information cannot be used for any other application than the barrier. The costs are project specific and are not representable for any other barrier.

At last there is one important aspect to point out in the setup of this research; the criteria for the analysis on sustainability. These criteria are different from each other but not all of them are independent. The embodied energy and carbon-footprint can have a strong correlation during production processes because the energy used during production is most of the time originated from fossil fuels. So a lot of embodied energy can cause more carbon emissions in this way. Another example, which is already mentioned a little bit before, is the carbon-footprint and resources. The values for the resources are based on the availability and the origin of the resources. The carbon-footprint is based on LCA's, which takes carbon emissions during transportation into account. So resources which origin from a country far away can score less on resources, but also on the carbon-footprint. These interdependencies can have an influence on the outcome of the analysis. It can cause more variation in the results than there actually should be, because negative aspects can be counted double. On the other hand it is almost impossible to avoid interdependencies in a MCA. So it is more important to be aware of them and take them into account than trying to avoid them.

9 Conclusion

The analyses show insights in the characteristics, sustainability and cost-effectiveness of the building materials. With these insights the sub-questions and eventually the main question (Chapter 2.4 and 2.5) can be answered.

First of all the questions concerning the cost-effectiveness of the building materials can be answered based on the LCC. This analysis is pretty straightforward, because the costs are taken from offers. The results clearly show a difference in cost-effectiveness of the building materials over the lifetime of the ecoduct. Plastic-composites have the lowest costs, followed by modified wood and bamboo. Bio-based composites are the least cost-effective. So when these building materials are compared on the basis of cost-effectiveness, plastic composites score the best.

Secondly the materials are analysed on their sustainability, which is divided into resources, durability, carbon-footprint and energy-footprint. In the MCA these criteria (and costs) are taken into account and they are given a weight to prioritise them. The values in this analysis are based upon literature and interviews with suppliers. The results of the MCA show high scores for plastic composites. Plastic composites score high due to the context of the modern day problems and solutions. These problems and solutions may change in the future due to new developments. Another MCA is carried out to check what the best outcome will be in the future. This MCA shows that plastic composites score way lower due to the future scarcity of waste plastic and petroleum. Bio-based composites score much higher because a lot of promising research is done in this materials. Modified wood and bamboo also score a bit higher in the future but remain more or less constant. These materials stay reliable in the future.

Than the materials can be compared to each other in general. Modified wood and bamboo are both show mediate outcomes in comparison to plastic composites. Plastic composites outweigh the other materials on all surfaces. They are more cost-effective and sustainable and make the perfect building material for a barrier. On the other hand plastic composites may not be the best option for the future, making modified wood and bamboo a more reliable alternative in comparison. Bio-based composites can score even higher than modified wood and bamboo in the future.

Finally it can be said that plastic composites are the best option for the barrier on ecoduct Koekendaal for now. It shows the highest score on sustainability and is the most cost-effective. The other alternatives are only in comparison to plastic composites less sustainable and cost-effective, so this does not mean that they are bad alternatives. They may be even better than plastic composites in the future.

10 Recommendations

A recommendation on the type of building materials can be made based on the conclusion of this research. It is evident that a plastic composite is by far the best choice of building material for the barrier on ecoduct Koekendaal. Nowadays it has the best material characteristics and it is the most cost-effective. However, when the material has to be replaced in approximately fifty years the other alternatives should seriously be taken into consideration. For now it is hard to predict what developments occur, but the current trends in society can lead to worse scores for plastic composites and better scores for the other alternatives. Whether these scores already apply in fifty years is unknown, but the changes will happen sometime, and therefore it is necessary to reanalyse the sustainability and cost-effectiveness of the barrier when it is replaced.

It is recommended that in the future more research has to be done in different aspects of this research. Bio-based composites are taken very general in this research, but there are a lot of different types of composites that are applicable to the building industry. Furthermore, it is recommended that more LCA's are studied to get a more precise approach of the carbon- and energy-footprint. These LCA's can only be used and compared when they are done with the same goal and scope using the same standardization.

Besides a more precise approach of the carbon- and energy-footprint, other criteria must be taken into account as well. An extended LCA also takes other environmentally harmful gases into account. Acidification, eutrophication and fresh water ecotoxicity, could also be taken into account while doing a sustainability assessment, for example.

Furthermore a general study in sustainable engineering is recommended, since sustainability is such a dynamic concept and a lot of developments change the way we treat our environment. The fast growth of awareness of sustainability will only go faster and this leads to new alternatives in building materials, new production processes of building materials, and new resources for building materials. In short, the developments in sustainable engineering keep on going and research in the actual sustainability of the materials is needed to maintain the state of the art materials in the field of civil engineering.

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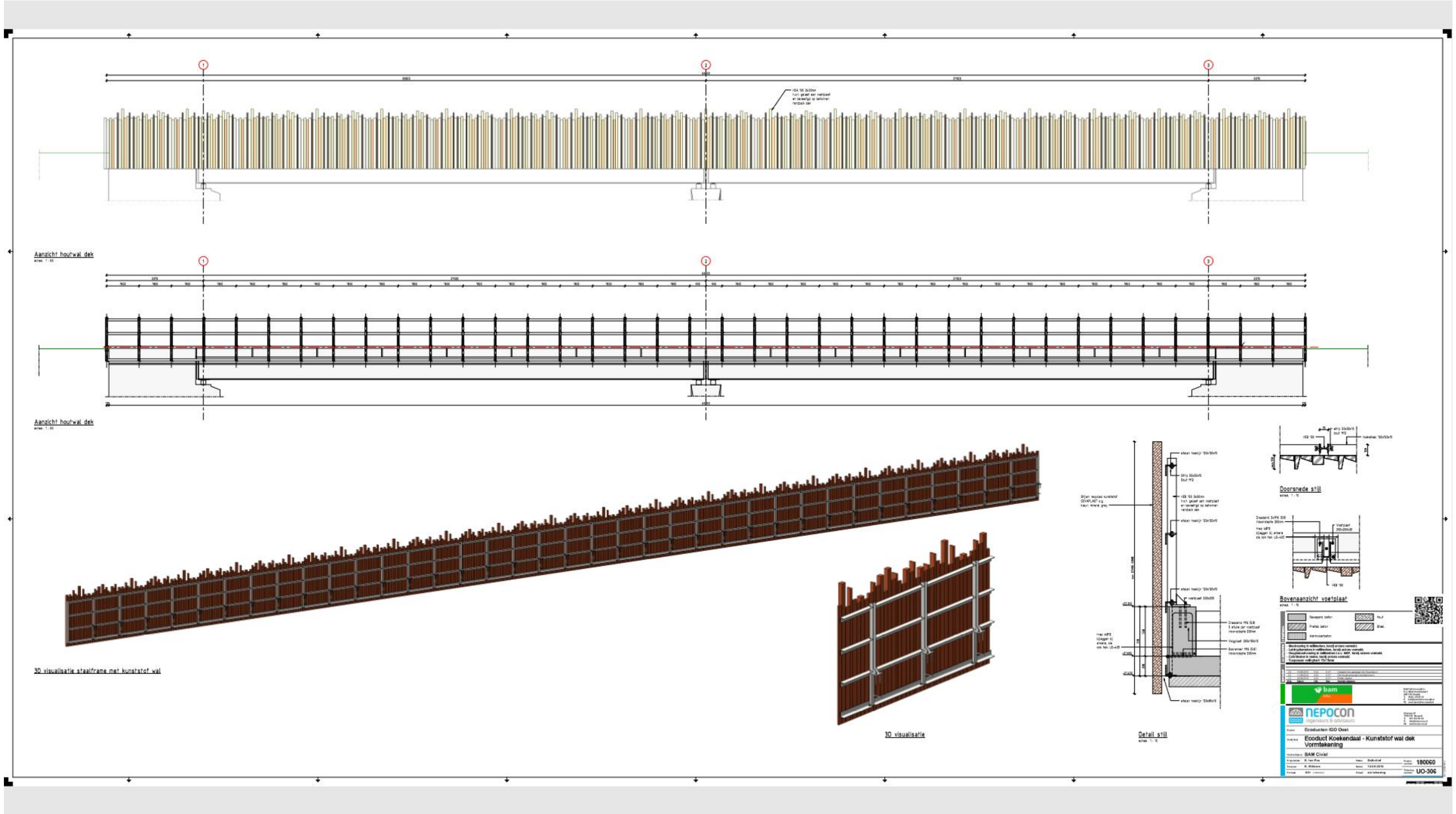
12 Appendices

12.1 Appendix A

Technical drawings of the barrier on ecoduct Koekendaal.



12.2 Appendix B

Semi-structured interview scheme (Dutch, see English below)

Beste ….,
Op dit moment ben ik bezit met een onderzoek naar de materiaalkeuze voor een hekwerk op een ecoduct. Daarbij kijk ik vooral naar duurzaamheid en kosten. Ik heb daarvoor een paar vragen die ik u zou willen stellen over het bouwmateriaal dat u verkoopt. Het duurt ongeveer 20 minuten.

- Van welke grondstof wordt het bouwmateriaal gemaakt?
    - Waar komen deze grondstoffen vandaan?
- Wat is de levensduur van het materiaal?
    - Geeft u zo lang ook garantie?
- Wat zijn de mogelijkheden voor het verlengen van de levensduur?
    - Wat zijn de kosten hiervan?
- Wat zijn de aanschaffingskosten van het materiaal?
    - Gebruikt u mallen? En zijn deze herbruikbaar?
- Gebruikt u duurzaam opgewekte stroom tijdens het productieproces?

Bedankt voor uw tijd! Had u de antwoorden die ik heb opgeschreven nog opgestuurd willen krijgen?
Fijne dag nog.

(English)

Hello…,
At this moment I'm doing a research on the type of building material that will be used for a barrier on an ecoduct. During this research I will be looking at sustainability and costs. I have a few questions on the building material that you supply. It will take about 20 minutes.

- What is the resource for this building material?
    - What is the origin of the resource?
- What is the lifespan of the building material?
    - Do you guarantee the building material for so long?
- What are the possibilities for expanding the lifespan?
    - What does this cost?
- What are the acquisition costs of the building material?
    - Do you use moulds? Are they re-usable?
- Do you use sustainable generated power during the production?

Thanks for your time. Do you want me to send the answers that I documented?
Have a nice day.

12.3 Appendix C

Durability classes wood (Vandenbussche, 2011)

Klasse	Duurzaamheid	Levensduur *	Voorbeelden
I	zeer duurzaam	minimaal 25 jaar	massaranduba, cumaru, ipé, robinia (I-II), angelim vermelho, pau amaralo
II	duurzaam	15 - 25 jaar	louro gamela, robinia (I-II), piquia, purperhart, sapupira, Europees eiken
III	matig duurzaam	10 - 15 jaar	guariuba, douglas, lariks (III-IV), noords grenen
IV	weinig duurzaam	5 - 10 jaar	lariks (III-IV), inlands grenen, vuren
V	niet duurzaam	maximaal 5 jaar	alle spinthout, beuken, elzen, berken

* Gemiddelde levensduur van een paaltje met afmetingen van 50 x 50 mm in grondcontact

12.4 Appendix D

Demand-specifications requirements (Rijkswaterstaat, Vraagspecificatie Eisen, 2017)

Sustainability

SYS-0302	**Voorkomen aantasting stalen onderdelen**	Geldigheids-periode(s):	G
Generiek	Aantastingsmechanismen die de restlevensduur van stalen onderdelen van Ecoduct kunnen verkorten dienen te zijn voorkomen dan wel te zijn bestreden.		
Bovenliggende:	SYS-0368	Onderliggende:	
Verificatie:	Fase: Realisatiefase; ontwerpen Methode: Analyse Criterium: ontwerp in overeenstemming met eisen Fase: Realisatiefase; uitvoeren Methode: Inspectie Criterium: uitvoering in overeenstemming met ontwerp; meting		
Stakeholder(s):	Rijkswaterstaat	Bron:	RTD Richtlijnen Ontwerp Kunstwerken (ROK) / versie 1.4 RTD 1001:2017

SYS-0308	**Voorkomen aantastingsmechanismen**	Geldigheids-periode(s):	G
Generiek	Aantastingsmechanismen die de restlevensduur van onderdelen van Ecoduct kunnen verkorten dienen te zijn voorkomen dan wel te zijn bestreden conform de ROK [DOC-0141], RTD 1002 [DOC-0228] eis 8.8 (9) t/m (11) en RTD 1009: Richtlijn ontwerp van asfalt wegverhardingen op betonnen en stalen brugdekken [DOC-0157].		
Bovenliggende:	SYS-0368	Onderliggende:	
Verificatie:	Fase: Realisatiefase; ontwerpen Methode: Document beoordeling Criterium: ROK [DOC-0141], RTD1002 [DOC-0228] eis 8.8. (9) t/m (11) en RTD 1009 [DOC-0157] Fase: Realisatiefase; uitvoeren Methode: Inspectie Criterium: Uitvoering in overeenstemming met ontwerp en verwerkingsvoorschriften		
Stakeholder(s):	Rijkswaterstaat	Bron:	

Lifetime

SYS-0313	**Technische levensduur Ecoduct**	Geldigheids-periode(s):	G
Generiek	Ecoduct dient gedurende ten minste 100 jaar zijn functies te vervullen.		
Bovenliggende:	SYS-0368	Onderliggende:	SYS-0319
Verificatie:	Fase: Realisatiefase; ontwerpen Methode: Analyse Criterium: voldoen aan ROK [DOC-0141] / RBK [DOC-0140]		
Stakeholder(s):	Rijkswaterstaat	Bron:	

SYS-0319	**Technische levensduur componenten**	Geldigheids-periode(s):	G
Generiek	De technische levensduur dient, voor Opleggingen, ten minste te voldoen aan 25 jaar		
Bovenliggende:	SYS-0313	Onderliggende:	
Verificatie:	Fase: Realisatiefase; ontwerpen Methode: Analyse Criterium: voldoen aan ROK/RTD 1007: Eisen voor voegovergangen [DOC-0159] Toelichting: Analyse ontwerpdocumenten waarmee aangetoond wordt dat het betreffende onderdeel de minimale technische levensduur heeft.		
Stakeholder(s):	Rijkswaterstaat	Bron:	

Maintenance

SYS-0323	**Vandalismebestendigheid graffity**	Geldigheids-periode(s):	G
Generiek	Alle voor graffiti bereikbare beton oppervlakken van Ecoduct dienen voorzien te worden van antigraffiti bescherming.		
Bovenliggende:	SYS-0368	Onderliggende:	
Verificatie:	Fase: Realisatiefase; ontwerpen Methode: Analyse Criterium: aantoonbaarheid Toelichting: Analyse ontwerpdocumenten, waarmee wordt aangetoond dat op bereikbare betonoppervlakken een effectieve antigraffiti bescherming wordt aangebracht. Fase: Realisatiefase; uitvoeren Methode: Keuring Criterium: Anti-graffity aangebracht		
Stakeholder(s):	Rijkswaterstaat	Bron:	

SYS-0381	**Onderhoudsstrook Ecoduct**	Geldigheids-periode(s):	G
Generiek	Er dient een strook voor onderhoudsvoertuigen onder het Ecoduct, van 3 meter breed tussen het kunstwerk en de voertuigkering, aanwezig te zijn.		
Bovenliggende:	SYS-0368	Onderliggende:	
Verificatie:	Fase: - Methode: - Criterium: Keuze Opdrachtnemer		
Stakeholder(s):	Rijkswaterstaat	Bron:	

SYS-0299	**Onderhoud, wijze van onderhouden**	Geldigheids-periode(s):	G
Generiek	Ecoduct dient gedurende de levensduur op een veilige en acceptabele wijze geïnspecteerd en onderhouden te kunnen worden.		
Bovenliggende:	SYS-0368	Onderliggende:	SYS-0293
Verificatie:	Fase: Realisatiefase; ontwerpen Methode: Analyse Criterium: gefundeerde conclusie Toelichting: Analyse ontwerpdocumenten op basis waarvan geconcludeerd kan worden dat inspecties en onderhoud op een eenvoudige, veilige en ergonomisch verantwoorde en voor de beheerder acceptabele wijze kan plaatsvinden.		
Stakeholder(s):	Rijkswaterstaat	Bron:	Richtlijn Ontwerp Inspectie- en Onderhoudsvoorzieningen (concept)

SYS-0293	**Onderhoud onderdelen Ecoduct met een kortere levensduur dan 100 jaar**	Geldigheids-periode(s):	G
Generiek	Onderdelen van Ecoduct met een levensduur korter dan 100 jaar dienen eenvoudig inspecteerbaar, onderhoudbaar en vervangbaar te zijn.		
Bovenliggende:	SYS-0299	Onderliggende:	
Verificatie:	Fase: Realisatiefase; ontwerpen Methode: Analyse Criterium: aantonen van de eis Toelichting: Analyse ontwerpdocumenten, waarmee aangetoond wordt dat het betreffende onderdeel: - inspecteerbaar is waarbij de wegen in de vereiste mate beschikbaar zijn; - onderhoudbaar is waarbij de wegen in de vereiste mate beschikbaar zijn; - vervangbaar is zonder sloop van andere onderdelen.		
Stakeholder(s):	Rijkswaterstaat	Bron:	

Design

SYS-0396	**Vormgeving Koekendaal Doetinchem**	Geldigheids-periode(s):	G
	Voor de vormgeving/basis uitgangspunten geldt het volgende: - houten afscherming i.c.m. betonnen onderbouw, waarbij het hout dominant is met een slanke vorm van de onderbouw; - leidend thema bij de vormgeving: bos, d.w.z. struweel op de randen van het ecoduct en de doorsnijding van de rijksweg door bos.		
Bovenliggende:	SYS-0397	Onderliggende:	
Verificatie:	Fase: - Methode: - Criterium: Keuze Opdrachtnemer		
Stakeholder(s):	Rijkswaterstaat	Bron:	

12.5 Appendix E

Outcomes interviews (First Dutch, then English translated by Koen Burghouts)

The questions about costs are left out of the interview, because no direct answers could be given. The costs are dependent on various factors.

12.5.1 Solid Bamboo bv.

Beste Roeland de Korte, 22-4-2019

Op dit moment ben ik bezit met een onderzoek naar de materiaalkeuze voor een hekwerk op een ecoduct. Daarbij kijk ik vooral naar duurzaamheid en kosten. Ik heb daarvoor een paar vragen die ik u zou willen stellen over het bouwmateriaal dat u verkoopt. Het duurt ongeveer 20 minuten.

- Van welke grondstof wordt het bouwmateriaal gemaakt?
    - Waar komen deze grondstoffen vandaan?

De bamboe komt uit China en is afkomstig van de Phyllotachys pubescens. De reden dat het uit China gehaald wordt is de verfijnde techniek van de Chinezen, zij gebruiken het al jaren als bouwmateriaal. De bamboe is afkomstig van een bamboebos dat wordt onderhouden. Een plantage is niet toepasbaar omdat bamboe niet opnieuw geplant hoeft te worden na het afkappen. Houtbomen daarentegen worden gekapt en daarna rotten ze gewoon weg.

- Wat is de levensduur van het materiaal?
    - Geeft u zo lang ook garantie?

Wij hebben twee verschillende soorten bamboe materialen; strandwoven bamboo en solid bamboo. Strandwoven kan het makkelijkst omschreven worden als geperst bamboe. Het is een product dat redelijk exclusief uit China komt. Solid Bamboo kan omschreven worden als gelamineerd bamboe. Het bestaat uit allemaal latjes van precies dezelfde grootte die aan elkaar verlijmd zijn. Dit wordt voornamelijk gebruikt in interieur. In de afgelopen 10 jaar is dit soort bamboe ook meer in trek voor buitengebruik. Dit komt door meer kennis en goede behandeling van het bamboe.

Beide soorten bamboe zijn vergelijkbaar in levensduur met Accoya hout. Het gaat een leven lang mee. Om deze levensduur te bereiken is er voor zowel bamboe als Accoya een behandeling nodig. De levensduur van het materiaal is wetenschappelijk bepaald en is daardoor maar te beperken tot 'meer dan 25 jaar', echter is de verwachting dat het langer meegaat.

De garantie op ons product is 15 jaar. Dit heeft de simpele reden dat uit ervaring blijkt dat als er iets mis gaat dat het dan in het eerste jaar vaak misgaat. Er is dan iets mis gegaan in het productieproces waardoor het bamboe kan gaan verbuigen. Stel dat er na het eerste jaar niets mis is met het bamboe dan kan het ook zo makkelijk voor nog 30 jaar meegaan.

- Wat zijn de mogelijkheden voor het verlengen van de levensduur?
    - Wat zijn de kosten hiervan?

Accoya en GreenLine (Solid Bamboo) zijn vergelijkbaar in onderhoud. Je kan van beiden nooit met honderd procent zekerheid zeggen dat ze geen last krijgen van oppervlakte schimmel. Strandwoven Bamboo daarentegen heeft absoluut geen oppervlakte schimmel. Beide soorten zijn wel positief getest op houtrot, dit is een interne rotting en vreet het hout echt op. De oppervlakte schimmel is makkelijk te verhelpen en heeft alleen een negatief effect op de esthetiek van het hout, het verzwakt de constructie niet.

Verder moet zowel hout als bamboe drogen. Hout moet alleen relatief veel langer drogen. Dit kan wel oplopen tot een half jaar tot jaar. Bamboe hoeft maar veel korter te drogen omdat het versnipperd is en daardoor een relatief groter oppervlakte heeft. Het zal ongeveer 2 tot 3 weken duren. Fabrikanten die hun hout te snel leveren door het minder lang te laten drogen leveren kwalitatief mindere producten. Dit hout of bamboe gaat na een jaar al (datzelfde jaar als beschreven bij de garantie) sporen laten zien van krom trekken of torderen. Door het lang genoeg te laten drogen, gaat het hout langer mee.

Het bamboe voldoet tot en met gebruikersklasse drie. Dit houdt in dat het bamboe geschikt is voor buiten gebruik, blootgesteld aan weer en wind, maar niet in contact is met de grond.

- ~~Wat zijn de aanschaffingskosten van het materiaal?~~
    - ~~Gebruikt u mallen? En zijn deze herbruikbaar?~~

- Gebruikt u duurzaam opgewekte stroom tijdens het productieproces?

Tijdens het productieproces wordt gebruik gemaakt van afvalresten van het bamboe zelf. De hitte afkomstig van de verbranding van deze afvalresten wordt gebruikt bij het persen en lamineren. Dit gebeurd in bijna alle fabrieken.

Voor het bamboe zelf is ook een Life Cycle Assessment gedaan (LCA). Uit de LCA is gebleken dat het bamboe CO2-negatief is. Dit wil dus zeggen dat het voor het CO2 negatief is en positief voor het milieu dus. De LCA is gedaan door INBAR (International Network for Bamboo And Rattan) in combinatie met een aantal andere fabrikanten. In de LCA is niet alleen het productieproces meegenomen maar ook de verscheping. Zelfs dan blijkt het bamboe nog CO2-negatief te zijn.

Bedankt voor uw tijd! Had u de antwoorden die ik heb opgeschreven nog opgestuurd willen krijgen? Fijne dag nog.

(English, translated by Koen Burghouts)

Hello Roeland de Korte, 22-4-2019

At this moment I'm doing a research on the type of building material that will be used for a barrier on an ecoduct. During this research I will be looking at sustainability and costs. I have a few questions on the building material that you supply. It will take about 20 minutes.

- What is the resource for this building material?
    - What is the origin of the resource?

The bamboo grows in China and is retrieved from the Phyllotachys pabescens. The refined techniques from the Chinese is the reason from getting the bamboo out of China, they have used this building material for years. The bamboo is retrieved from a bamboo forest which is being maintained. A plantation is not needed because bamboo does not need to be replanted. Trees on the contrary are being cut and then rot away.

- What is the lifespan of the building material?
    - Do you guarantee the building material for so long?

We have two different bamboo materials: Strandwoven bamboo and Solid Bamboo. Stradnwoven can be described as pressed bamboo. It is a building materials that origins almost exclusively from China. Solid bamboo can be described as laminated bamboo. It consists of strips with exactly the same size which are clued together. This bamboo is mostly used for interior purposes. In the last decade this type of bamboo is also popular in outside construction. This development comes from more knowledge and better treatment of the bamboo.

Both types are comparable to the lifespan of the wood type Accoya. It will last a 'lifetime'. To get to this lifespan both the bamboo and Accoya should be treated. The lifespan of the materials is scientifically determined and therefore limited to 'more than 25 years', however the expectation is that it will last longer.

The guarantee for this product is 15 years. This has the simple reason that it seems , from experience, that if something goes wrong, it goes wrong in the first year after acquisition. Probably something did go wrong in the production process causing the bamboo to swift and warp. If nothing went wrong with the bamboo after the first year, it could for example last for 30 years.

- What are the possibilities for expanding the lifespan?
    - What does this cost?

Accoya and Greenline (Solid Bamboo) are comparable in maintenance. For both materials you cannot tell with a hundred percent certainty that fungi will form on the surface. Stradnwoven bamboo on the other hand has completely no surface fungi. However they are both tested positively against internal rot which really ‘eats’ the wood. The surface fungi are easily corrected and only have an effect on the aesthetics of the material, it does not weaken the construction.

Furthermore the bamboo and wood should have a long enough drying time. This is for wood relatively longer. It can take up to half a year till a year for it to dry properly. Bamboo does not need that long because it is shredded and has therefore a much higher surface area. The drying time will take two to three weeks. Fabricants who deliver their wood too fast, and let it try too short, deliver a product with low quality. This wood or bamboo can warp or shift already after one year (the same year described by the guarantee). By drying the wood long enough it becomes more durable.

The bamboo suffices till user class three. This means that is applicable for outside use, exposed to weather and wind, but not in contact with the ground.

- ~~What are the acquisition costs of the building material?~~
    - ~~Do you use moulds? Are they re-usable?~~

- Do you use sustainable generated power during the production?

During the production process residual waste from the bamboo itself is used. The heat derived from burning the waste is used for pressing and laminating the bamboo. This happens at almost all of the fabricants.

For the bamboo itself a Life Cycle Assessment (LCA) is carried out. The LCA shows that the production process of bamboo is CO2-negative. This means that it is negative for the CO2, which is positive for the environment. The LCA is carried out by INBAR (International Network for Bamboo And Rattan) in combination with a few other fabricants. Not only production is taken into account in the LCA, shipment is also taken into account. Even then the bamboo appears to be CO2-negative.

Thanks for your time. Do you want me to send the answers that I documented?
Have a nice day.

12.5.2 Foreco bv

Beste Klaas Jan Swager, 24-4-2019

Op dit moment ben ik bezit met een onderzoek naar de materiaalkeuze voor een hekwerk op een ecoduct. Daarbij kijk ik vooral naar duurzaamheid en kosten. Ik heb daarvoor een paar vragen die ik u zou willen stellen over het bouwmateriaal dat u verkoopt. Het duurt ongeveer 20 minuten.

- Van welke grondstof wordt het bouwmateriaal gemaakt?
    - Waar komen deze grondstoffen vandaan?

De grondstoffen komen van snelgroeiend naaldhout, Radiata Pine. Dit hout groeit in Nieuw-Zeeland en wordt hier ook gezaagd. De biopolymeren zijn afkomstig van bagasse, dit is een soort afvalbiomassa van suikerriet. De polymeren zijn afkomstig uit meerdere landen maar komen naar een fabriek in

België. In de fabriek wordt het hout verder verwerkt tot NobelWood. Dit proces is anders dan bij het maken van Accoya. Bij Accoya vindt acetylatie plaats, dit maakt het hout enigszins poreuzer. Nobelwood wordt geïmpregneerd door in water opgeloste biopolymeren.

Voor het gebruik van een schutting is het ook nog mogelijk om SoundWood te gebruiken. Dit hout heeft een ander proces ondervonden. Dit hout is gewaxt en dus oppervlakkig versterkt. Bij dit hout blijf je de houtsoort houden terwijl je bij NobelWood een hele andere houtsoort maakt.

Er kan daarnaast ook nog gekozen worden voor FaunaWood. Hierbij wordt het zachte hout versterkt door het impregneren met pyrolyseolie. Deze olie wordt vervaagd uit resthout dat bijvoorbeeld van de projectlocatie afkomstig is. De pyrolyse vervangt het biopolymeer en maakt het FaunaWood dus daardoor meer circulair omdat het van eigen locatie komt in plaats van de biopolymeren voor NobelWood die uit verschillende landen komt.

- Wat is de levensduur van het materiaal?
    - Geeft u zo lang ook garantie?

De levensduur van NobelWood is verwacht op 50 jaar. Dit is gebaseerd op vorige projecten die al zo'n 60/65 jaar staan. Dit hout ziet er nog steeds mooi uit. De garantie op het hout is 25 jaar. Verder is het voor de esthetiek van belang om het hout te onderhouden. Alg-aanslag of stof kan op het oppervlak van het hout blijven zitten afhankelijk van het weer en de regen. Dit zou ongeveer om de 10 jaar moeten gebeuren. De geluidswanden naast de snelweg die zijn gemaakt van WaxedWood staan ondertussen al een hele tijd zonder onderhoud.

- Wat zijn de mogelijkheden voor het verlengen van de levensduur?
    - Wat zijn de kosten hiervan?

De behandelingen van NobelWood en WaxedWood (SoundWood) verlengen de levensduur.

- ~~Wat zijn de aanschaffingskosten van het materiaal?~~
    - ~~Gebruikt u mallen? En zijn deze herbruikbaar?~~
- Gebruikt u duurzaam opgewekte stroom tijdens het productieproces?

Het productieproces vindt grotendeels in Nieuw-Zeeland plaats. Dit land maakt veel gebruik van duurzame energie en heeft veel natuurlijke energiebronnen. Zo wordt er daar ook gebruikt gemaakt van resthout voor processen waarbij hitte nodig is. Het verschepen van de producten heeft een equivalente uitstoot als het vervoeren over de weg.

Bedankt voor uw tijd! Had u de antwoorden die ik heb opgeschreven nog opgestuurd willen krijgen? Fijne dag nog.

(English, translated by Koen Burghouts)

Hello Klaas Jan Swager, 24-4-2019

At this moment I'm doing a research on the type of building material that will be used for a barrier on an ecoduct. During this research I will be looking at sustainability and costs. I have a few questions on the building material that you supply. It will take about 20 minutes.

- What is the resource for this building material?
    - What is the origin of the resource?

The resources origin from fast-growing pine wood, Radiata Pine. The wood grow in New Zealand and is being cut here is well. The biopolymers origin from bagasse, which is some sort of residual biomass from sugar canes. The polymers come from several countries, but are gathered in a factory in Belgium.

In the factory the wood is processed further to NobelWood. This is a different process to the process of making Accoya. Acetylation takes place during the process of Accoya, this makes the wood slightly porous. NobelWood is being impregnated by in water dissolved polymers.

For making a barrier it is possible to make use of SoundWood as well. This wood is processed in a different way. It is waxed and therefore only strengthened on its surface. With this wood the wood structure is remained, while with NobelWood you create a different type of wood.

Besides this type of wood, FaunaWood can be used as well. During this process the soft wood is strengthened by impregnating it with pyrolysis oil. The oil is obtained from residual wood, which can be found on building locations for example. The pyrolysis oil substitutes the biopolymers and makes FaunaWood therefore more circular, because the oil is obtained from the future construction site instead of biopolymers from NobelWood, which are obtained from several countries.

- What is the lifespan of the building material?
    - Do you guarantee the building material for so long?

The lifespan of NobelWood is expected to be 50 years. This is based on previous projects which are already there for 60/65 years. This wood still looks good. The guarantee on the wood is 25 years. For aesthetics it is important to do some maintenance on the wood. Algae and dust can stuck to the surface of the wood dependent on weather and rain. The maintenance should be done approximately every ten years. The sound barriers besides the highway from SoundWood are there for a while now without any maintenance.

- What are the possibilities for expanding the lifespan?
    - What does this cost?

The process of NobelWood and WaxedWood (SoundWood) expand the lifespan of the material.

- ~~What are the acquisition costs of the building material?~~
    - ~~Do you use moulds? Are they re-usable?~~

- Do you use sustainable generated power during the production?

The production process mostly takes place in New Zealand. This country uses a lot of sustainable energy and has a lot of natural energy resources. They use residual wood for the heat that is necessary during production. Shipping the product has equivalent emissions as transporting it by road.

Thanks for your time. Do you want me to send the answers that I documented?
Have a nice day.

12.5.3 Lankhorst Recycling Products

Beste Jurgen Groot Landeweer, 1-5-2019

Op dit moment ben ik bezit met een onderzoek naar de materiaalkeuze voor een hekwerk op een ecoduct. Daarbij kijk ik vooral naar duurzaamheid en kosten. Ik heb daarvoor een paar vragen die ik u zou willen stellen over het bouwmateriaal dat u verkoopt. Het duurt ongeveer 20 minuten.

- Van welke grondstof wordt het bouwmateriaal gemaakt?
    - Waar komen deze grondstoffen vandaan?

Het plastic is afkomstig van een ander bedrijf die de gerecyclede materialen verzamelt. Het plastic is dan al verwerkt tot gemaald plastic of korrels. Extra grondstoffen kunnen nodig zijn afhankelijk van het eindproduct dat wordt gemaakt. Verder zijn de producten een mix van bepaalde soorten kunststof die op maat worden gehaald. Het is dus niet één grote hoop van allemaal verschillende kunststof snippers.

- Wat is de levensduur van het materiaal?
    - Geeft u zo lang ook garantie?

De verwachte levensduur van het materiaal is 50 jaar. De garantie op het materiaal is afhankelijk van waar het product voor wordt gebruikt. Vaak is het product onderdeel van een eindproduct van een ander bedrijf. Afhankelijk van deze eindproducten wordt de garantie bepaald. Verder is het niet nodig om het materiaal te onderhouden of te vervangen. Het materiaal is glad en kan dus niet eens geschilderd worden. Dit maakt het ook makkelijk in onderhoud met betrekking tot graffiti. Algen kunnen zich wel vormen op het oppervlakte van het plastic maar dit is makkelijk te verhelpen en heeft geen invloed op het plastic. Het product zal dus structureel na 50 jaar nog steeds als nieuw zijn.

- Wat zijn de mogelijkheden voor het verlengen van de levensduur?
    - Wat zijn de kosten hiervan?

De levensduur kan niet verlengd worden door goed onderhoud aangezien dit onderhoud niet nodig is. Schilderen heeft geen zin, en het verwijderen van algen is alleen nodig voor de esthetiek.

- ~~Wat zijn de aanschaffingskosten van het materiaal?~~
    - ~~Gebruikt u mallen? En zijn deze herbruikbaar?~~

- Gebruikt u duurzaam opgewekte stroom tijdens het productieproces?

Tijdens het productieproces van het plastic moeten de grondstoffen verhit worden tot 180 graden. Dit is dan ook de grootste milieu belastende factor maar tevens ook de enige, aangezien er verder geen chemische reactie is. Tijdens het proces wordt duurzame energie gebruikt voor zover mogelijk. Op de werkplaatsen gaat men wel duurzaam om met de restenergie van het productieproces. Zo wordt de warmte afkomstig van de machines gebruikt om de werkplaats op te warmen voor de werknemers.

Bedankt voor uw tijd! Had u de antwoorden die ik heb opgeschreven nog opgestuurd willen krijgen?
Fijne dag nog.

(English, translated by Koen Burghouts)

Hello Jurgen Groot Landeweer, 1-5-2019
At this moment I'm doing a research on the type of building material that will be used for a barrier on an ecoduct. During this research I will be looking at sustainability and costs. I have a few questions on the building material that you supply. It will take about 20 minutes.

- What is the resource for this building material?
    - What is the origin of the resource?

The plastic is obtained from another company which gathers recycled plastics. The plastic is already processed to pulverized plastic and aggregates. Extra recourses may be necessary depending in what the end product should be. Furthermore the products are a mix of certain types of plastics which are bought in certain sizes. It is not one big pile of different shredded plastic pieces.

- What is the lifespan of the building material?
    - Do you guarantee the building material for so long?

The approximated lifespan of the material is 50 years. The guarantee of the material is dependent on the eventual usage of the product. Most of the time the product is a part of an end product of another company. The guarantee is determined dependent on this end use. Furthermore it is not necessary to maintain or replace the material during its lifespan. The surface is smooth and cannot be painted. This makes it easy in maintenance considering graffiti. Algae can get stuck on the surface of the materials but this can be easily redressed and does not have any influence on the internal structure of the material. So the structure of the product will be as new after 50 years.

- What are the possibilities for expanding the lifespan?
    - What does this cost?

The lifespan cannot be expended by good maintenance because the material needs no maintenance. Painting is not necessary, and algae only has to be removed for aesthetic purposes.

- ~~What are the acquisition costs of the building material?~~
    - ~~Do you use moulds? Are they re-usable?~~

- Do you use sustainable generated power during the production?

During the production process of the plastic products the raw materials has to be heated up to 180 degrees. This factor has the highest influence on the environment but is also the only influencing factor, since there is no further chemical reaction. During this process sustainable energy is used where it is possible. The residual energy during the process is sustainably managed on the work floor. The heat from the machines is used to heat the work floor for the workers.

Thanks for your time. Do you want me to send the answers that I documented?
Have a nice day.

12.5.4 NPSP

Beste Lody Klement, 2-5-2019

Op dit moment ben ik bezit met een onderzoek naar de materiaalkeuze voor een hekwerk op een ecoduct. Daarbij kijk ik vooral naar duurzaamheid en kosten. Ik heb daarvoor een paar vragen die ik u zou willen stellen over het bouwmateriaal dat u verkoopt. Het duurt ongeveer 20 minuten.

- Van welke grondstof wordt het bouwmateriaal gemaakt?
    - Waar komen deze grondstoffen vandaan?

Het product is een bio-composiet, dit is gemaakt van reststromen van biologisch afval. Dit zijn vaak plantenvezels afkomstig van riet, vlas of katoen. Op dit moment wordt er vooral met riet gewerkt. De resten die overblijven op landbouwgronden worden normaal verbrand en daardoor komt er dus CO_2 vrij in de lucht. Door dit te gebruiken in de composieten komt het CO_2 niet vrij maar is het opgeslagen. De plantenvezels hebben in tegenstelling tot bomen weinig tijd nodig om opnieuw te groeien. Planten als riet hebben meestal maar 1 of 2 jaar weer hernieuwd. Het product bestaat voor 80% uit deze biologische materialen. Het andere product is hars en om dit te verkrijgen zijn er nog wel producten uit aardolie nodig.

- Wat is de levensduur van het materiaal?
    - Geeft u zo lang ook garantie?

De verwachte levensduur van het materiaal is meer dan 30 jaar. Dit is gebaseerd op duurtests en vergelijkingen met andere natuurlijke composieten. Op het materiaal zelf zit in principe 10 jaar garantie maar die vervalt naarmate het ergens in verwerkt wordt. Het materiaal vergaat verder niet en heeft alleen oppervlakkig onderhoud nodig voor esthetiek.

- Wat zijn de mogelijkheden voor het verlengen van de levensduur?
  - Wat zijn de kosten hiervan?

Het materiaal heeft geen onderhoud nodig, en dit is ook niet mogelijk. Verf hecht bijvoorbeeld niet aan het materiaal

- ~~Wat zijn de aanschaffingskosten van het materiaal?~~
  - ~~Gebruikt u mallen? En zijn deze herbruikbaar?~~

- Gebruikt u duurzaam opgewekte stroom tijdens het productieproces?

Tijdens het productieproces is hitte nodig om het composiet te vormen. Dit gebeurt doorgaans nog niet met groen opgewekte energie. Dit is alleen niet zeker. Tijdens het proces worden restproducten wel hergebruikt voor nieuw materiaal.

Bedankt voor uw tijd! Had u de antwoorden die ik heb opgeschreven nog opgestuurd willen krijgen? Fijne dag nog.

(English, translated by Koen Burghouts)

Hello Lody Klement, 2-5-2019
At this moment I'm doing a research on the type of building material that will be used for a barrier on an ecoduct. During this research I will be looking at sustainability and costs. I have a few questions on the building material that you supply. It will take about 20 minutes.

- What is the resource for this building material?
  - What is the origin of the resource?

The product is a bio-composite, which is made from residuals of biological waste. Most of the time these are plant fibres from cane, flax or cotton. Currently they are mostly made of cane. The residuals of cane on agricultural lands are 'normally' burned and this releases CO2 in the air. By using the residual cane for composites this won't happen and the CO2 remains assimilated. The plant fibres do not need much time to regrow on the contrary of wooden trees. Plants like cane only need one or two years to regrow. The composite exists for about 80% out of these biological materials. The other resource is resin and to get this products from petroleum are needed.

- What is the lifespan of the building material?
  - Do you guarantee the building material for so long?

The expected lifetime of the material is more than 30 years. This is based on an endurance test and on comparisons with other nature based composites. On the material itself there is a 10 year guarantee, but this expires ones it is processed into something else. The material does not decay and only needs cleansing on the surface for aesthetics.

- What are the possibilities for expanding the lifespan?
  - What does this cost?

The material does not need maintenance, and this is not possible either. Paint does not stick to the material for instance.

- ~~What are the acquisition costs of the building material?~~
    - ~~Do you use moulds? Are they re-usable?~~

- Do you use sustainable generated power during the production?

During the production process heat is needed to form the composite. This is usually done without the use of green energy, but this is uncertain. During the process residual products are reused for new materials.

Thanks for your time. Do you want me to send the answers that I documented?
Have a nice day.

12.5.5 GovaPlast

Beste Robert Hempenius, (24-05-2019)
Op dit moment ben ik bezit met een onderzoek naar de materiaalkeuze voor een hekwerk op een ecoduct. Daarbij kijk ik vooral naar duurzaamheid en kosten. Ik heb daarvoor een paar vragen die ik u zou willen stellen over het bouwmateriaal dat u verkoopt. Het duurt ongeveer 20 minuten.

- Van welke grondstof wordt het bouwmateriaal gemaakt?
    - Waar komen deze grondstoffen vandaan?

Het product wordt gemaakt van plastic. De plasticsoorten die erin verwerkt zijn, zijn polyethyleen en polypropyleen. Dit plastic is gerecycled. Het komt vanuit West-Europa waar het ingezameld en gescheiden wordt. Zo komt het uiteindelijk bij ons terecht als korreltjes van verschillende soorten plastic. Additieven en kleurstoffen kunnen worden toegevoegd afhankelijk van de karakteristieken die het materiaal moet hebben.

- Wat is de levensduur van het materiaal?
    - Geeft u zo lang ook garantie?

Wij bestaan als bedrijf nu al 30 jaar en onze eerste projecten staan nog steeds. De levensduur is dus sowieso 30 jaar, maar langer wordt verwacht. Plastic is een materiaal waar we niet vanaf komen. Het is het spul dat jaren lang in de zee blijft drijven, dat blijft dus wel een tijd goed. De garantie op ons product is 10 jaar.

Verder is het materiaal laag in onderhoud. Het heeft een hele lage waterabsorptie waardoor het voor algen moeilijk is om op te groeien. Vooral op de schaduwkant is er nog wel een kans dat er algen ontstaan op het oppervlak. Dit tast het materiaal intern niet aan. Het onderhoud aan het plastic is niet meer dan dat je zou hebben aan hout, hierop kunnen zich ook algen vormen en die zijn er ook makkelijk af te halen met een hogedrukspuit.

- Wat zijn de mogelijkheden voor het verlengen van de levensduur?
    - Wat zijn de kosten hiervan?

Plastic heeft al een enorm lange levensduur. Dat is vaak ook het probleem van plastic. Voor ons is dit juist een voordeel.

- ~~Wat zijn de aanschaffingskosten van het materiaal?~~

- ~~Gebruikt u mallen? En zijn deze herbruikbaar?~~

- Gebruikt u duurzaam opgewekte stroom tijdens het productieproces?

Ik geloof van wel. Dit kan ik alleen niet met 100% zekerheid zeggen. Tijdens het productieproces moet het plastic verwarmd worden tot 200 graden Celsius om in de matrijzen te spuiten. Hiervoor wordt vermoedelijk wel groene stroom gebruikt. Een LCA is niet uitgevoerd met de reden dat het proces heel duidelijk is. Je kan duidelijk zien dat dit gerecycled materiaal is, daarom is de vraag naar een LCA voor dit plastic product niet hoog.

Bedankt voor uw tijd! Had u de antwoorden die ik heb opgeschreven nog opgestuurd willen krijgen? Fijne dag nog.

(English, translated by Koen Burghouts)

Hello Robert Hempenius, (24-05-2019)
At this moment I'm doing a research on the type of building material that will be used for a barrier on an ecoduct. During this research I will be looking at sustainability and costs. I have a few questions on the building material that you supply. It will take about 20 minutes.

- What is the resource for this building material?
  - What is the origin of the resource?

The product is made out of plastic. The types of products which are processed are mostly polyethylene and polypropylene. This is recycled plastic which origins from Western Europe where it is collected and separated. In this way it ends up at our factory as grains of different types of plastic. Dependent on the characteristics of the material, additives and paint can be added.

- What is the lifespan of the building material?
  - Do you guarantee the building material for so long?

Our company exists for 30 years and the projects from back than still function. The lifetime of the materials is at least 30 years, but we expect it to be longer. Plastic is the material where we cannot get rid of. This material floats in the sea for many years, so it will remain for a while. The guarantee on the product is 10 years.

The product does not need much maintenance. It has a low water absorption rate which makes it hard for algae to grow. But especially on the shadow side there is a chance of algae forming on the surface. This does not affect the material internally. The maintenance of the plastic is not more than you would have on wood. Algae can form on this material as well but this is easily corrected with a high pressure sprayer.

- What are the possibilities for expanding the lifespan?
  - What does this cost?

Plastic already has a long lifetime. Most of the time this is the problem with plastic. In our situation this is an advantage.

- ~~What are the acquisition costs of the building material?~~
  - ~~Do you use moulds? Are they re-usable?~~

- Do you use sustainable generated power during the production?

I believe we do, but I cannot say it with a hundred percent certainty. During the production process the plastic must be heated up to 200 degrees Celsius to press it in to the moulds. For this process green energy is used I suppose. A LCA is not conducted for out material because the process is very clear. It is obvious that this is recycled material, therefore the need for an LCA of this material is not necessary.

Thanks for your time. Do you want me to send the answers that I documented?
Have a nice day.

12.6 Appendix F

Biodiversity footprint Foreco

Foreco contributed in a research of the biodiversity footprint of several companies (van Rooij & Aerts, 2017). In this research the biodiversity footprint is calculated including land use, climate water abstraction and nitrogen and phosphorus emissions to water. The calculation is done based on the amount of land (ha) a company uses and the impact of the usage. The impact is calculated by the Mean Species Abundance (MSA). When the MSA is zero, the biodiversity footprint of the company is zero as well. Radiata Pine has one of the lowest biodiversity footprints, see Figure 13.

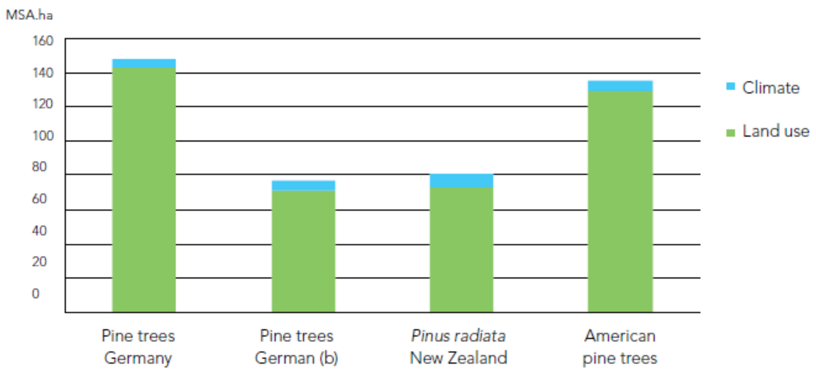


Figure 13 - Biodiversity footprint of different timber for NobelWood (van Rooij & Aerts, 2017)

12.7 Appendix G

Calculations LCC

For the cost calculations different types of information of the barrier is needed. First of all the dimensions are important. Other material characteristics like the lifespan are needed as well. The averaged dimensions and further information used in the LCC are given below:

Average thickness:	0.1 m
Average height:	3 m
Width:	66.6 m (133.2 m for both sides)
Amount of planks:	1073
Frontal surface:	3*133.2 = 399.6 m^2
Volume:	3*133.2*0.1 = 39.96 m^3
Lifespan ecoduct:	100 years
Lifespan SolidBamboo:	40 years
Lifespan Foreco:	50 years
Lifespan GovaPlast:	50 years
Lifespan NPSP:	40 years

Acquisition

The acquisition costs are determined based upon (previous) offers. For GovaPlast, SolidBamboo and NPSP the prices are based upon offers for this specific project and are taken directly from the offer in the LCC. The prices of Foreco is based on a former offer of another project. During this project SolidBamboo wrote out an offer as well. To calculate the acquisition costs of the modified wood from Foreco a percentage of the difference in the former project is taken. Foreco turned out to be 7,5% cheaper than SolidBamboo. So for the acquisition costs of Foreco in this project 92,5% of the offer from SolidBamboo is taken, resulting in the following acquisitions costs.

Input variables:

- Acquisition SolidBamboo: €99.180,-
- Foreco relative to SolidBamboo: 92.5%
- Acquisition GovaPlast: €43.444,80
- Price per m^2 NSPS: €330,-
- Frontal surface barrier: 399.6 m^2
- Replacements SolidBamboo: 1,5 (100/40 – 1)
- Replacements Foreco: 1 (100/50 – 1)
- Replacements GovaPlast: 1 (100/50 – 1)
- Replacements NPSP: 1,5 (100/40 – 1)

Costs:

- SolidBamboo: €99.180,-
- Foreco: 92.5% * €99.180,- = €91.741,50
- GovaPlast: €43.444,80
- NPSP: €330,-/m^2 * 399,6 m^2 = €131.868,- (price is given in price/m^2)

The acquisition costs for Rijkswaterstaat are calculated by multiplying the acquisition costs by the amount of times the material has to be replaced, which is for forty years 2 (1,5 actually) and for fifty years 1 time.

- SolidBamboo: 2 * €99.180,- = €198.360,-
- Foreco: 1 * €91.741,50 = €91.741,50
- GovaPlast: 1 * €43.444,80 = €43.444,80
- NPSP: 2 * €131.868,- = €263.736,-

Maintenance

Maintenance costs are based on multiple variables. First of all the amount of maintenance checks is determined. It is assumed that during these checks the barrier is cleaned with a high pressure sprayer. So the maintenance costs are the costs of the checks themselves times the amount of checks needed in the lifespan of the ecoduct. The costs of the maintenance check is determined by the costs of renting materials and hiring personnel.

Input variables:

- Costs cleaning = €400,- (1 euro / m^2, standard by 'ProNed reinigen beschermen & behouden')
- Costs hiring water tank = €300,- (based on the average of multiple lessors)
- Amount of maintenance checks: 20 (1/5 year over 100 years)

With these input variables the actual maintenance costs of the barrier over the lifetime of the ecoduct can be calculated.

Costs:

- SolidBamboo: (€400,- + 300,-) * 20 = €14.000,-
- Foreco: (€400,- + 300,-) * 20 = €14.000,-
- GovaPlast: (€400,- + 300,-) * 20 = €14.000,-
- NPSP: (€400,- + 300,-) * 20 = €14.000,-

Disposal:

The disposal costs are, dependent on the material, either for landfilling or recycling. Besides that transportation costs are considered as well. These costs are multiplied with the times the material is renewed.

The disposal costs of GovaPlast are null, because GovaPlast wants to receive their material for free. Transportation costs do need to be taken into account because GovaPlast does not account for that. The transportation costs are taken from the offer of GovaPlast, where they have the transportation costs determined. It is assumed that the costs for disposal transportation are the same.

The transportation and disposal costs of non-recyclables are based upon information on websites of dumpsites and transporters. The most plausible data is used for this analysis.

Input variables:

- Amount of disposal SolidBamboo: 2,5 (100/40)
- Amount of disposal Foreco: 2 (100/50)
- Amount of disposal GovaPlast: 2 (100/50)
- Amount of disposal NPSP: 2,5 (100/40)
- Transportation costs non-recyclables: €750,-
- Transportation costs recyclables: €1.890,-
- Disposal costs non-recyclables: €1.350,-
- Disposal costs recyclables: € -

Costs:

- SolidBamboo: (€750,- + €1.350,-) * 2,5 = €5.250,-
- Foreco: (€750,- + €1.350,-) * 2 = €4.200,-
- GovaPlast: (€1.890,- + €0,-) * 2 = €3.780,-
- NPSP: (€750,- + €1.350,-) * 2,5 = €5.250,-

12.8 Appendix H

Score matrices for the MCA

The calculations for the values of the alternatives are given below. The criteria which are scored with a score matrix are calculated in the following way: Each alternative starts with an average value of 5. Dependent on how good they are in comparison to each other values are added or subtracted from the average. So one minus sign is -1 and two plus signs is plus two. This results in the following score matrix for resources (Table 3).

Horizontal relative to vertical	Modified wood	Bamboo	Plastic composites	Bio-based composites
Modified wood		+	+ +	+
Bamboo	-		+	+
Plastic composites	- -	-		-
Bio-based composites	-	-	+	
5 +/-...	5-4 = 1	5+1-2 = 4	5+4 = 9	5+2-1 = 6

Table 3 - Score matrix for the MCA of resources

The calculations for the carbon footprint are calculated by dividing the carbon footprint by -0,2. The carbon footprint of the materials is given in Figure 14. This results in the following values:

- Modified wood: -0,21/-0,2 = ±1
- Bamboo: -0,05/-0,2 = ± 0
- Plastic composites: -1,7/-0,2 = ± 9
- Bio-based composites: -0,43/-0,2 = ± 2

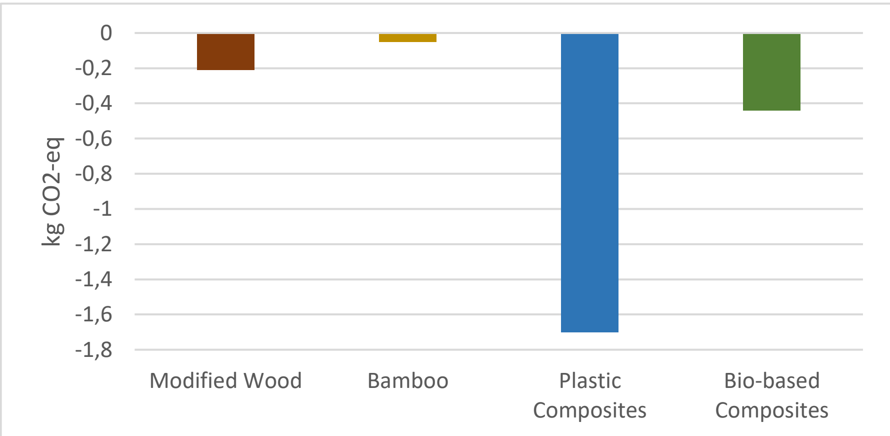


Figure 14 - CO2-footprint of different materials over its whole lifetime

The value-calculations for the embodied energy are done in the same way as for the resources. This gives the following results:

Horizontal relative to vertical	Modified wood	Bamboo	Plastic composites	Bio-based composites
Modified wood		+/-	-	-
Bamboo	+/-		-	-
Plastic composites	+	+		+
Bio-based composites	+	+	-	
5+/- …	5+2 = 7	5+2 = 7	5-3 = 2	5-2+1 = 4

Table 4 - Score matrix for the MCA of embodied energy

For the costs the highest costs gets the lowest value of 0 and the lowest costs gets the highest value of 10. The values in between are dependent on the linear line between the lowest and highest costs.

- Modified wood: € 201.683,-
- Bamboo: € 267.200,-
- Plastic composites: € 127.337,-
- Bio-based composites: € 348.920,-

So plastic composites will get a score of 10 and bio-based composites a score of 0. The difference in score is 10 and the difference in costs is € 221.583,-. This can be put in a ratio table leading to the other values.

Bio-based composites with	Plastic composites	Bamboo	Modified wood
Difference in costs	221.583	81.720	147.237
Difference in value	10	3,7	6,6

So the values for the costs are as follows:

- Modified wood: ±7
- Bamboo: ±4
- Plastic composites: 10
- Bio-based composites: 0

12.9 Appendix I

General multi-criteria analysis on the sustainability of certain building materials

Criteria	**Weight**	**Modified Wood**		**Bamboo**		**Plastic Composites**		**Bio-based Composites**	
		value	weighted value	value	weighted value	value	weighted value	value	weighted value
Resources	**1**	2	2	5	5	8	8	6	6
Durability	**2**	6	12	5	10	6	12	5	10
Carbon-footrpint	**3**	2	6	1	3	9	27	4	12
Embodied energy	**1**	6	6	6	6	4	4	3	3
	Score		**26**		**24**		**51**		**31**

Table 5 - Multi-criteria analysis on the sustainability of four building materials

12.10 Appendix J

Sensitivity analysis on the plastic composites in the MCA

Criteria	**Weight**	**Plastic Composites**		**Plastic Composites -50%**		**Plastic Composites +50%**	
		value	weighted value	value	weighted value	value	weighted value
Resources	**1**	8	8	4	4	12	12
Durability	**2**	6	12	3	6	9	18
Carbon-footrpint	**3**	9	27	4,5	13,5	13,5	40,5
Embodied energy	**1**	4	4	2	2	6	6
Costs	**3**	8	24	4	12	12	36
	Score		**75**		**37,5**		**112,5**

Table 6 - Sensitivity of the values of plastic composites with +/-50%

12.11 Appendix K

MCA with future perspectives taken into account

Criteria	**Weight**	**Modified Wood**		**Bamboo**		**Plastic Composites**		**Bio-based Composites**	
		value	weighted value	value	weighted value	value	weighted value	value	weighted value
Resources	**2**	6	12	8	16	2	4	6	12
Durability	**2**	6	12	6	12	6	12	5	10
Carbon-footrpint	**3**	2	6	1	3	4	12	7	21
Embodied energy	**1**	6	6	6	6	4	4	5	5
Costs	**2**	6	12	5	10	4	8	4	8
	Score		**48**		**47**		**40**		**56**

Table 7 - MCA on four types of materials with future perspectives