Biobased construction of bridges

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1. Introduction

1.1 Background

There are currently several ongoing research about biobased materials, as this is a relatively new area to be explored with little long-term data available. To approach this, many companies and universities have begun collaborating to design, construct, and realize biobased materials and structures. To create a connection between companies and universities, the Dutch Ministry of Education, Culture, and Science has established the so called "centres of expertise".

The Centre of Expertise Biobased Economy (CoE BBE) is a specific example of this. This is a partnership between Avans University of Applied Sciences and HZ University of Applied Sciences, whereby the purpose of this partnership is to create a central knowledge point for biobased education, research, and facilitation. The final purpose is to support and shape the transition from 'fossil based' to 'bio based'. In recent years, one of the focus points of the CoE BBE is the design and realization of biobased bridges.

Commonly, bridges are made of steel and/or concrete. Steel is commonly used due to its high strength in both tension and compression, as well as being a ductile material, but is an expensive option. Alternatively, concrete is used due to having a high compressive strength whilst also being a cheaper option than steel. It is most common that a combination of the two is used so that it will compensate for the low tensile strength of concrete alone whilst being cheaper than using entirely steel only. (BuilderSpace.com, 2021)

However, concrete production causes large CO2 emissions up to 4-8% of the World's CO2, according to an article by the Guardian. And while steel is a suitable material for being recycled, it is also as concrete a finite fossil resource, which can eventually run out and are therefore not sustainable. (Guardian, 2021)

Using biobased construction materials can help to tackle these issues, as it supports the transition into a circular economy which can potentially be less damaging to the environment. This can also potentially allow for no material to be wasted, for a reduction in the depletion of raw materials, and for the reusing of products and resources. (Leipold, and Petit-Boix, 2018)

There have been successful attempts at building fully biobased bridges. An example of this is in Eindhoven University of Technology where a fully biobased composite 14m pedestrian bridge was built in 2016 as seen in Image 1.1A. Another successful project was executed in Schiphol Logistics Park, where another fully biobased 15m footbridge was built in 2018 as seen in Image 1.1B. These two bridges will be further described in chapter '2.1 Current situation' and '2.3 Literature review'

Image 1.1A: Eindhoven bridge (4TU, 2016)

Image 1.1B: Amsterdam bridge (Basalt.Today, 2018)

The transition to biobased materials allows for new economic opportunities, energy independence, and a reduction of greenhouse gases which helps to combat the issue of solely using and relying on fossil-based materials.

However, it is uncertain which material is the 'best' alternative in terms of biobased construction of bridges. The term 'best' is based on a multi-criteria analysis which is further described throughout the report.

1.2 Problem statement

As previously mentioned, a fully biobased pedestrian bridge was built in 2016 in Eindhoven University of Technology, over the river Dommel. This was a 14m bridge made from hemp and flex-fibre base. The project was developed by multiple parties including CoE BBE.

The initiators of the project hoped that the bridge would show the potential of biobased composite as a sustainable alternative to existing environmentally harmful construction materials.

In order to develop the bio-based composite, the fibres were stuck to a biological PLA foam (polylactic acid) core and then a bio resin was sucked into the fibre layers using a vacuum, which produced a very strong girder when hardened. After installation the bridge load capacity was successfully tested for the municipality of Eindhoven, however the lifespan of the bridge and its durability is still unknown.

For this reason, the CoE BBE wants to analyse possible alternatives to the design realized in 2016 within the project 'Back to the material of the future', financed by SIA RAAK. The idea is to design a new pedestrian bridge using sustainable biomaterials in a regular building process. Particular attention should be paid to the compatibility of the materials selected and to their durability, based on the information that can be retrieved through literature. Some other points of attentions are high strength, the low energy requirement during construction, the low maintenance requirement, and the long service life, and of course safety.

This process will begin by acquiring relevant literature on various biobased materials that can potentially be used for the biobased construction of the bridge. There will be one biobased material that will be considered the 'best' (based on certain criteria) option which will be decided through executing a multi-criteria analysis (MCA) on the chosen materials. Following this, the design process will begin, starting with applying the decided biobased material as a structural component of the bridge.

The final product will be a detailed design of a pedestrian bridge using the winning biobased material as a structural component.

1.3 Research questions

The main research question of this study and the sub questions to assist in answering the main research question are shown in this chapter.

1.3.1 Main research question

What is the most optimal design for a pedestrian bridge made out of biobased materials in the Netherlands based on durability, strength, cost efficiency, and additional criteria to be determined?

1.3.2 Sub research questions

The main research question will be answered by the following sub questions:

1. What criteria should be used in the multi-criteria analysis?
2. What weighting should be given to each criterion and how will this be justified?
3. What bio-based materials will be considered for this research?
4. How many criteria should be used in the multi-criteria analysis?
5. What components of the bridge will be constructed with a bio-based material?
6. What other materials can be used for the non-structural components of the bridge?

1.4 Research Objectives

This research focuses heavily on exploring existing biobased materials in the field of construction through secondary research, specifically for a pedestrian bridge. The world is slowly transitioning into a more circular economy, and this also involves construction materials. However, the transition is still in the early stages, and so there is a lack of research and data on biobased materials and its long-term effects.

The research will consider four bio-based materials. An MCA will be designed to assist in deciding which bio-based material will be the most optimal choice. Some criteria to be included have already been decided by the CoE BBE, which are durability, strength, and cost efficiency. Other criteria to be considered will be explored in this research during the design of the MCA. The bio-based materials considered in this research are as follows:

1. Flax and hemp.
2. Sisal fibre reinforced polymer.
3. Jute fibre reinforced polymer.
4. Bamboo.

Following this, the selected bio-based material that is decided through the MCA will be used in the design of a pedestrian bridge as a structural component. Additionally, the design will be compared to the fully bio-based pedestrian bridge in Eindhoven from 2016.

This research aims to prove which of the mentioned biobased materials in the construction of bridges is the best option to use based on an MCA. This will then show the extent of the transition to circular options for the construction of bridges.

2. Theoretical framework

2.1 Current situation

Research area

The research area will be over the Dommel river at TU/e campus Eindhoven. The exact location of where the bridge will be installed can be seen in Figure 2.1A (indicated by a red circle).

Figure 2.1A: Bridge installation location

The surrounding area of the bridge installation location is often well maintained as it is a University area, therefore the vegetation in the surrounding area only changes based on the season/weather conditions. Figure 2.1B shows a picture taken from 2020 of the research area.

Figure 2.1B: Picture of the research area (TU Eindhoven, 2020)

Fully Bio-based bridge (Eindhoven)

As previously stated, this fully biobased bridge was built in 2016 and was the first successful construction of a fully biobased bridge. The process of the entire bridge project itself took just under one year to complete. Eindhoven University of Technology themselves stated on their Facebook page on December 2020 that the bridge was intended to be in place for just one year, it was dismantled after almost four years. Note that all the following information regarding this fully bio-based bridge in Eindhoven is taken from the study on this bridge specifically by Blok, Smits, Gkaidatzis, and Teuffel (2019).

Materials used

The bridge design used a specific bio-composite material that is known as natural fibre reinforced biopolymer (NFRBP). The bridge design itself was based on the selected material, which were partially hemp fibres and partially flax fibres combined with an epoxy resin that has a 56% bio-content. The epoxy resin used was from a company called SR Greenpoxy56. During the design of the bridge, this resin was combined with a non-bio-based hardener called SD 4770, which was produced by the same company too. However, due to the hardener used, the bio-based content drops from 56% to 43%. The non-structural core of the bridge was made of polylactide (PLA), which is an aliphatic thermoplastic polyester produced from renewable resources.

Flax and hemp were chosen for sustainability reasons according to the study, but nothing more than this was specified. The availability of the materials varied. The flax fibres were available in directionally woven fibre mats, whereas hemp was available in a non-woven version, which makes it cheaper as it is non-woven.

The flax and hemp composite can be recycled, however the process for this is still currently under development as it is still relatively new. The process itself is a chemical recycling method that focuses on detaching and reusing the resin and the fibres. The materials will however be downcycled since some of their initial properties are lost during the chemical process.

The bridge itself was a thin shell construction that is placed in tension by the two abutments on either side of the bridge. This utilizes the flax fibres as these fibres are better at absorbing tensile forces than compressive forces. And so, the design focuses on reducing the compression stresses and keeping the tension zone slender.

Parts of the bridge deck was made of non-woven hemp. The corners at the bridge deck and underside of the bridge deck were made of stronger and stiffer woven flax and also a small amount of uni-directional flax. The sides of the bridge beam with low shear stresses have been designed using low-cost non-woven hemp fibres.

The final design (before determining the geometry of the bridge) was optimised based on the following criteria (however these criteria were undefined in the study by Blok et al. (2019)):

- Structural efficiency
- Safety
- Aesthetic
- Functionality

- Feasibility and cost efficient production

Cost

The cost is based on a life cycle assessment (LCA) of the materials. However, the LCA data is not available for Greenpoxy56. The study by Blok et al. (2019) considered a different biobased epoxy called SuperSap, which has a 37% biobased content and has LCA data. When comparing all the costs, the largest cost is the biobased epoxy SuperSap as this is the largest amount of material needed in comparison to the other materials for the construction of the bridge. The epoxy SuperSap cost approximately €285 in total for the entire bridge. The painting for the bridge had the highest relative costs per kg, however the exact value per kg was not specified and only the total cost of painting was given which was approximately €10.

Maintenance

The maintenance of the bridge is based on a service life of 50 years, and therefore will only be considered in the use phase. The maintenance needed for the bridge is for the coating which is done every 12.5 years for local surface deterioration, and this coating is fully renewed every 25 years. This cost totals up to €11.42. Additionally, there is a maintenance for the anti-slip layer, and this is assumed to be renewed just once in the 50-year lifetime. This is a new layer of grains mixed with an epoxy resin which will be applied on the original walking surface after it has been cleaned from the old first layer. The cost for this new layer totals to €13.94. Therefore annually, the cost will be approximately €0.51 (excluding labour costs).

Bridge data

During the construction of the bridge, optical fibre glass strands were integrated within the structure to measure deformations and changes in elasticity over time. The collection of data from the bridge continued for two years after the installation of the bridge. This meant more data could be measured for the bridge as during this time period, the bridge was still open to the public for use and also exposed to Dutch weather conditions.

Initial tests were done before installing the bridge. The moisture content was tested at 7.5% and showed no decrease in tensile strength but showed a large increase in strains. Overall, testing on the moisture content shows that the strain increases with increased water content and will require protection from water. The test for creep shows that the stress levels due to the permanent load must be kept ideally lower than 5MPa based on testing. Based on the samples that were tested in the full-scale production test, the compressive strength was calculated. The characteristic 5% limit value of the material compressive strength was 60 MPa. The tensile strength for the Uni-directional fibres was 244 MPa, and the Young’s modulus was 21,600 MPa, which was the highest in comparison to non-woven fibres and woven, bi-directional fibres.

A load test was done after the production of the bridge, but before the installation. A water loading testing took place where a gradual increase of $0kN/m^2$ to $5kN/m^2$. The results showed that the bridge follows the test models and so it is deemed safe to carry the maximum design load. The peak values are as follows:

- Deflection = 32.8mm
- Compression stress = -5.2MPa
- Tension stress = +7.8MPa
- Strains = ranging from -520µm/m to +780µm/m

After installation of the bridge, a static test was carried out in 2018, similarly to before, a gradual increase of a water load on specific areas of the bridge. The peak values are as follows:

- Deflection = 14.6mm
- Compression stress = -2.4MPa
- Tension stress = +3.5MPa
- Strains = ranging from -240µm/m to +350µm/m

Additionally, the long-term behaviour was measured from the sensors that were installed in the construction of the bridge. Over a period of 20.6 months, the expected creep value was approximated at 15mm, however the deflection at the centre of the bridge after 20.6 months estimated to be 51mm. Based on the data obtained, the creep process has not yet reached its end, but additional testing would be needed to confirm this.

2.2 Schedule of requirements

2.2.1 Functional requirements

- Both bridge designs will be for bicycles and pedestrians.
- The balustrade will provide support and safety for the pedestrians and cyclists.

2.2.2 Technical requirements

- The structural component of the bridge is the bridge slab and bridge deck.
- The dimensions of the bridge slab are as follows:
  - The length of the bridge slab is 14m.
  - The width of the bridge slab is 1.6m.
  - The thickness of the bridge slab is 0.25m.
- The concrete class used will be C20/25.
- The weight of concrete used is 2400kg/m^3.
- The density of sisal fibres used is 1450kg/m^3.
- The composition of concrete and sisal fibre is as follows:
  - Sisal fibres = 15.5%.
  - Concrete = 84.5%.
- The distribution of the sisal fibres that makes the FRP concrete is assumed to be equal throughout the entire slab.
- The bridge deck will be made out of azobé wood, and the dimensions are as follows:
  - The length of the bridge deck is 14m.
  - The width of the bridge deck is 1.2m.
  - The thickness of the bridge deck is 0.05m.
- The density of azobé wood is 1050kg/m^3.

- In accordance with the Eurocode NEN-EN 19931-1 regulations, the balustrade must have a minimum height of 1.1m.
- The balustrade will be a non-structural component of the bridge.
- The balustrade will be made out of oakwood.
- The density of the oakwood used is 897kg/m³.
- The bridge will be designed for a service life of 50 years.
- The exposure class is XC-4 cyclic wet and dry as the bridge is exposed to alternate wetting and drying. This is in accordance with EN 206-1. However, since the material used is a new material that does not have any proper set standards, the exposure class was taken from the standards for concrete as a reference since the material used is a concrete fibre reinforced polymer.
- The natural frequency of the bridge will be neglected due to time constraints.
- The substructure of the bridge will not be considered as this research will focus on main bridge design only (the superstructure).
- The safety factor to be used for the permanent load and variable load is 1.35 (for ULS loads).
- The magnitude of permanent and variable loads and de-load combinations should be determined on the basis of Eurocode NEN-EN 1990 and NEN-EN 1991 (Eurocode 0 and 1).
- The distributed load that will be used for the bridge is 5kN/m².

2.3 Literature review

The literature review will be divided into two parts. The first part will discuss the potential bridge materials that can be used for the construction of the bridge, and the second part will be about the criteria to be considered for the MCA.

2.3.1 Bridge materials

The costs of flax and hemp were found from an association called European Industrial Hemp Association (EIHA). This is an association that represents the common interests of industrial hemp farmers and producers. According to the EIHA (2017), the average price of technical flax and hemp short fibres was €0.80/kg and €1.00/kg respectively in 2017. This is based on the supply of 100 tonnes per year to a factory gate in central Europe.

A study by nova-Institute (2019) in Germany evaluated the carbon footprint of important natural fibres that were used in the automotive and insulation industry. The fibres evaluated in this study were flax, hemp, and jute. Two allocation methods were used in the life cycle analysis of these materials to discuss the impacts, which were economic allocation and mass allocation. However, to simplify the outcome, mass-based allocation was considered in this research as it is more stable than economic allocation due to the fluctuation of the prices of the materials (ranging from agricultural yields to fashion trends). The data obtained for greenhouse gas emissions are as follows:

- Flax fibre – 349 kg CO2-eq/tonne.
- Hemp fibre – 364 kg CO2-eq/tonne.
- Jute fibre – 479 kg CO2-eq/tonne.

These greenhouse gas emissions are of one tonne of fibre from the cultivation in Europe to the factory gate of the non-woven producer in Germany.

A study by Sen and Paul (2015) looked at confining concrete with sisal and jute fibre reinforced polymers (FRP) as alternatives for carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP). The sisal and jute FRP's went through mechanical testing and a summary of the useful data obtained is shown:

- Heat treated jute FRP.
  - Average tensile strength = 223.367 N/mm².
  - Peak deflection = 10.89 mm.
  - Average flexural stress = 350.034 N/mm².
- Heat treated sisal FRP.
  - Average tensile strength = 189.479 N/mm².
  - Peak deflection = 4.66 mm.
  - Average flexural stress = 208.705 N/mm².

The durability was also tested in the study by Sen and Paul (2015). The study looked at moisture content and thermal aging. The moisture content was tested by measuring and analysing the percentage of the moisture content, as well as the thickness welling and how the tensile strength is affected. The thermal aging looks at how much the material has expanded after being exposed to an increase in temperature.

- Sisal FRP
  - Moisture content = 2.7%.
  - Tensile strength increase based on moisture content = 6%.
  - Thermal aging = tensile strength decreased by 14%.

- Jute FRP
  - Moisture content = 8.9%.
  - Tensile strength increase based on moisture content = 8%.
  - Thermal aging = tensile strength decreased by 12%.

The study by Sen and Paul (2015) also tested the Sisal FRP and Jute FRP to check their confinement modulus and strength properties. Additionally, they also executed an axial compressive test. The relevant data is taken and shown below:

- Sisal FRP
  - Modulus of elasticity = 42.5 kN/mm².
  - Average ultimate axial load = 196.52 kN.
- Jute FRP
  - Modulus of elasticity = 32.5 kN/mm².
  - Average ultimate axial load = 175.64 kN.

The maintenance of sisal and jute FRP is similar to that of concrete as the outside of the material is just concrete and the sisal and jute are used instead of steel as a reinforcement. Therefore, the maintenance procedure and maintenance cost of the sisal and jute FRP would be the same as standard concrete. There are several factors to consider for the maintenance of concrete, and the various types of damage that can occur will have its own maintenance procedure. Some common maintenance practices are shown below for concrete bridges. The information here is obtained from a report by American Concrete Institute (ACI) Committee 345 (2006):

- Washing and cleaning of the entire bridge including the bridge deck, joints, and drains. This is often done once every one to two years and can slow down the concrete from deteriorating.
- Sealing cracks on the concrete when seen during maintenance checks, to protect the reinforcement inside. This is also often done every one to two years.
- Removal of debris as this may potentially contain chemicals that can damage the structural elements by blocking the water floor.
- Sealing deck joints which are leaking to assist with minimizing the deterioration of the bridge and any other elements beneath the joints. This is often checked and executed every three to five years.

The material cost of sisal and jute FRP varies as it depends on where it was produced and the delivery of the material itself. However, the cost of sisal and jute FRP could not be obtained, therefore the focus went to looking for the cost of the raw material itself as a fibre. The only source that had consistent availability was United Kingdom for sisal fibres and Bangladesh for jute fibres (found from Alibaba website). The approximate costs (varies with exchange rates) per kg of fibre are shown below (excluding shipping costs):

- Sisal fibre = €0.02 per kg.
- Jute fibre = €1.50 per kg.

A study by Broeren et al. (2017) explored the life cycle assessment of sisal fibre. Through this, the CO2 emissions for sisal fibres were found. The study looked at the cradle-to-port GHG emissions for Brazil and Tanzania. The obtained values are as follows:

- 1285 kg CO2 equivalent per tonne of sisal fibre for Brazil.
- 870 kg CO2 equivalent per tonne of sisal fibre for Tanzania.

Correia, Almeida, and Figueira (2011) conducted a study on recycling FRP composites, specifically glass fibre reinforced polymers (GFRP). It was found that GFRP cannot be remelted, and so the FRP waste is sent to a landfill, which is an unsustainable disposal method that creates environmental problems. There is a lack of research and information about how FRP composites can be recycled sustainably and in a more circular way. As time passes, the FRP industry will need to develop new recycling methods as the waste production from this industry will continue to grow. Although this is not exactly the same as sisal FRP and jute FRP, FRP's in general involve the material being mixed with concrete which results in a difficult to recycle or an unrecyclable material.

Awalluddin et al. (2017) looked at the mechanical properties of different bamboo species, which included testing of the different bamboo species moisture content. The study looked at four different species of bamboo and recorded the compressive strength and moisture content at a five-month interval so that they could determine the strength development of the different bamboo species. The highest average moisture content of each species of bamboo is shown below:

- Dendrocalamus Asper – 18.44%.
- Bambusa Vulgaris – 19.20%.

- Gigantochloa Scortechinii – 18.09%.
- Schizostachyum Grande – 19.63%.

In addition to this, an important mention of a limitation for using bamboo as a bridge material is that untreated bamboo has a design life of approximately 10 to 15 years if stored properly, whereas treated bamboo has a much longer design life (duration not specified but longer than 15 years).

Yadav and Mathur (2021) performed an overview of bamboo as a sustainable material in the construction industry. They found that bamboo as a construction material has twice the compressive strength on concrete and a tensile strength that is equal to steel. Additionally, the cost of bamboo is three times more cost effective than that of steel reinforcement. Based on this, the cost of bamboo can be calculated with reference to the price of steel (using Beonstaal.nl as a reference), whereby one kg of bamboo is approximately €0.43.

The study by Yadav and Mathur (2021) also found that the primary harvesting of bamboo takes between three to five years, whereas other types of wood forests which would roughly 25 years. Bamboo also produces more oxygen than other species of plants as well as trapping high quantities of CO2, which assists in combating the consequences of climate change.

Following this, a study done by Lugt, Vogtländer, Vegte, and Brezet (2015) looked at the environmental assessment of industrial bamboo products, focusing on the life cycle assessment and carbon sequestration. Through this, the carbon footprint per flattened bamboo board (Phyllostachys pubescens bamboo species) was calculated for cradle-to-gate, which totalled to approximately 1150 kg CO2eq.

Laroque (2007) executed a design of a low-cost bamboo footbridge, and in this study, an economic feasibility study was done to compare bamboo with other materials including azobé wood, concrete, steel and robinia. The purchasing cost of bamboo is affordable in the Netherlands as the material cost itself is the lowest in comparison to the other materials in their design and is only increased due to the cost of transportation from South America. However, when looking at the maintenance annual costs, the material costs are significantly higher due to the life span of bamboo being much shorter than other materials. A certain species of bamboo called Guadua was considered in a study by Lugt, Dobbelsteen, and Abrahams (2003), and it was stated that Guadua has a lifespan of 20 years. By having a shorter lifespan, the bridge has to be fully replaced instead of being maintained as although it grows quickly, the material tends to deteriorate quickly too. Lastly, the labour costs are very high as it is often difficult to assemble bamboo bridges due to its irregular dimensions and properties.

Candelaria and Hernandez (2019) conducted a study on determining the properties of a specific species of bamboo Bambusa Blumeana. In this study, a flexural strength test was carried out, and the following relevant values were obtained:

- Average deflection = 11.21mm.
- Average compressive stress = 50.36 MPa.
- Average tensile stress = 145.78 MPa.

An article by Eco & Beyond (2021) discusses the sustainability of bamboo, which also covers the topic of recycling used bamboo. The articles states that most bamboo can be composted unless chemicals have been added into the product. Additionally, some companies do purchase recycled bamboo, but whether this is applicable to the ones used in construction is still uncertain. In a different study by Lugt, Dobbelsteen, and Janssen (2005), there is a mention of a different preliminary study about the complete lifecycle of bamboo, which includes the retrieval of energy after incinerating the bamboo once it reaches its end of lifespan. It states that despite this end-of-life cycle process, it ended up having positive environmental costs. Unfortunately, this study is in Dutch and also cannot be accessed by the researcher.

2.3.2 Criteria for multi-criteria analysis

There can be various criteria to be considered when applying an MCA on bridge construction. Chaphalkar and Shirke (2013) conducted a multi-criteria analysis to decide which type of superstructure should be used for a proposed bridge. The main focus was on reducing traffic congestion, providing a new bridge to replace the old bridges, and the accessibility of maintenance of surrounding structures. A list of top 11 rated criteria was determined for deciding between three bridge design alternatives and was determined through using the Delphi technique. Following this, they determined an individual weighting for each criterion based on expert opinions. The weighting of the criteria is shown in order of highest weighting to lowest weighting:

1. Performance of particular type of bridge
2. Site selection and conditions
3. Hydraulic data
4. Safety
5. Environmental impact
6. Maintenance provisions
7. Money
8. Time
9. Traffic data
10. Labour availability
11. Shape

The study by Chaphalkar and Shirke (2013) does not offer a description of each criterion, therefore what may be interpreted by the reader may not be the actual intended meaning of that criteria. The 11 criteria selected here may not be fully applicable to the situation of this research as the study itself has a different scope, for example, site selection has already decided by the client and so it may potentially not be as useful as other criteria. However, the research by Chaphalkar and Shirke (2013) can provide guidance in deciding what criteria is considered useful in bridge construction.

A study done by Sierra, Yepes, and Pellicer (2018) focused on examining the treatment of social aspects in multi-criteria assessment methods of infrastructures. In doing this, the study also mentions a list of 23 social criteria that have been considered for a multi-criteria analysis from various studies in relation to infrastructure sustainability from the year 2001 to 2017. Since there are several criteria listed, the most frequent ones will be mentioned (in no particular order):

- Mobility and accessibility.
- Health.

- Safety of the environmental.

However, a notable mention is that the following criteria is strongly related to particularly transportation infrastructure, bridges, and tunnels (in no particular order):

- Health.
- Safety of the environmental.
- Identity and cohesion.
- Mobility and accessibility.
- Ground use.
- Distribution of the production benefits.
- Regional and local development.

The criterion mentioned above, and their respective descriptions can be found in Table 4, page 504 of the research by Sierra et al. (2018). There are various criteria to be considered in terms of social sustainability, but again, only certain criteria will be used in creating the MCA. The study will contain social aspects, but the depth of it may not be as specific as the study by Sierra et al. (2018) as environmental and economic aspects will be considered too.

The next study focuses on the life cycle sustainability assessment for multi-criteria decision making (MCDM) in bridge design and presents a systematic literature review on the use of MCDM techniques for the sustainability assessment of bridge projects (Navarro, Penadés-Plà, Martínez-Muñoz, Rempling, and Yepes, 2020). When the word sustainability is used here, what it means is that the focus is on the economic, social, and environmental aspects. Therefore, when executing an MCA, each aspect can be looked into individually although certain parts of these aspects overlap. The following impacts affects all three aspects of sustainability:

- Direct costs of construction.
- Maintenance along its service life.
- Demolition.

Economically, the direct costs are the costs during the construction phase itself. The maintenance is based on the service life and will also have an economic impact based on how regular maintenance is required, as well as if certain emergencies take place such as a natural disaster. The demolition will also incur economic costs when it takes place.

Environmentally, for all three impacts mentioned above, the most notable and reviewed problem is the emission of pollutants as it has the most studies being done on according to Navarro et al. (2020). Additional environmental impacts that are worth mentioning are energy consumption, material consumption, and solid waste generated.

Lastly, there are three social impacts that are mostly assessed when designing bridges which are the impact of the bridge maintenance on the users, the aesthetics of the bridge, and the health and safety of the workers.

All these factors can be strongly considered when conducting an MCA for the decision on the best alternative involving biobased bridges.

The next study discusses multiple criteria decision-making method and a graphical cross impact simulation model, which is then applied to comparing and evaluating three different bridge designs (Farkas, 2011). The selected design will be based on what satisfies the greatest number of stakeholders which can be seen through the MCA. Initially, there were some early considerations before conducting the MCA. The following was checked beforehand:

- Feasibility check.
- Economic analysis.
- Financial analysis.
- Environmental impact analysis.

Following this, the MCA was designed with six criteria, and each criteria had their own weighting which was determined through an extensive calculation that will not be discussed here, and so none were equally weighted. However, the difference between the weights between the criteria were minor (less than 0.05). The six criteria that was used in the MCA are as follows:

- Engineering feasibility
- Capital cost
- Maintenance
- Aesthetics
- Environmental impact
- Durability

Of these six criteria, the most heavily weighted criterion is the environmental impact, and the least weighted criteria was the capital cost. The criteria from the study by Farkas (2011) described above will be applicable for this research as it covers many aspects of bridge design within just six criteria.

A study by Plà, Yepes, García-Segura, and Martí-Albiñana (2017) was done by classifying and analysing the criteria used by different authors to evaluate the sustainability for each phase of the bridge life cycle. Therefore, the works shown in this study are a small sample of a larger review study.

Again, sustainability itself can be broken down into three different aspects, economic, social, and environmental. Four different phases were considered whereby each phase has criteria based on the three aspects of sustainability. Additionally, each phase has its own type of study. The phases considered and the most notable criteria for each one is shown below:

1. Planning and design phase
    - Economic – End of life cost, maintenance cost
    - Environmental – Area minimization
    - Social – Safety, durability
2. Construction phase
    - Economic – Construction cost, duration
    - Environmental – Environmental issues
    - Social – Safety, shape, durability, site condition
3. Operation and maintenance phase
    - Economic – Performance cost, material cost

- Environmental – Environmental impact
- Social – Safety

4. Demolition or recycling phase
    - Economic – Machinery, manpower
    - Environmental – Environmental impact
    - Social – Safety risk, proximity to adjacent structures

Although the MCA in this study will be used to decide which design is the best (planning and design phase), the other phases must be considered too as all the criteria listed above in the four phases are linked and therefore will affect each other at some point. These studies from the study by Plà et al. (2017) individually tackled issues at specific phases, however the criteria should attempt to assess the sustainability of the entirety of the bridge's useful life.

3. Methodology

3.1 Introduction

This chapter will provide an overview of the research methodology that will be used to answer the research questions, specifically focusing on two main areas of research which is the research of bridge materials, and the research of the criteria for the MCA. The research design that will be used will also be described in this chapter, 3.1 Introduction.

The research of bridge materials will be purely based on secondary research as the main and only research method, consisting of a mix of qualitative and quantitative data to ensure that the limitations of one type of data will be balanced by the strengths of the other type of data. This is due to the circumstances in which the research is being conducted whereby the researcher is executing all the activities outside of the Netherlands.

The research of the criteria will also consist of only one research method, being secondary research, which focuses on qualitative data. This research method is used to find what criteria should be considered for the MCA.

3.2 Research activities

This chapter will outline what activities need to be carried out to complete the research. This can be divided into separate steps. Each step will be described and justified to ensure that it will answer the research question. To further make this clearer, the chapter is divided in to two phases whereby the first phase is the research phase, and the second phase is the execution phase. Figure 3.2A and Figure 3.2B displays a flowchart of phase one and phase two respectively that summarizes all the main steps required to answer the research questions.

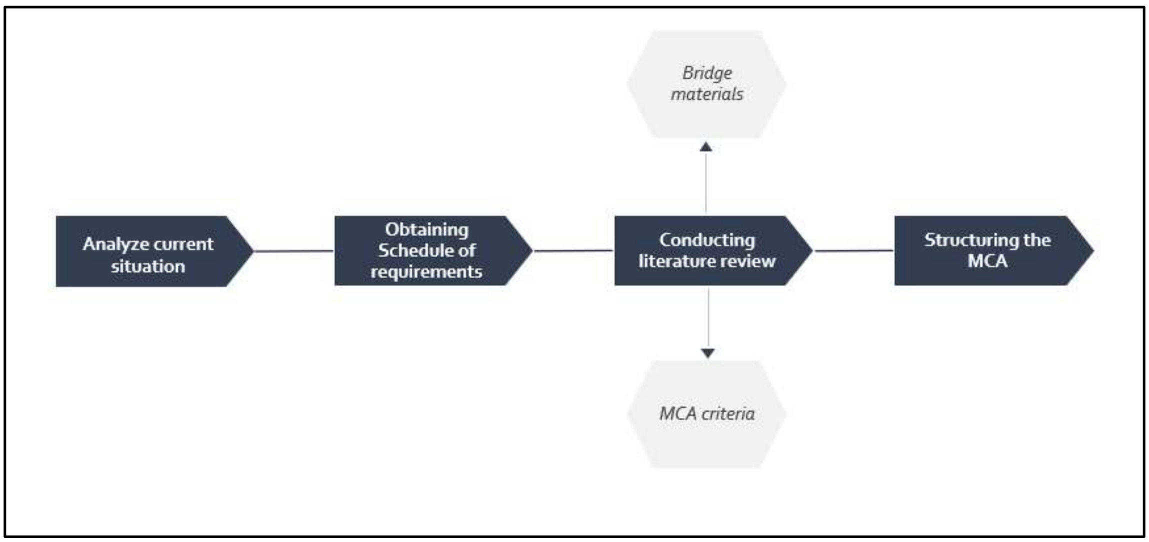


Figure 3.2A: Research phase (Phase one)

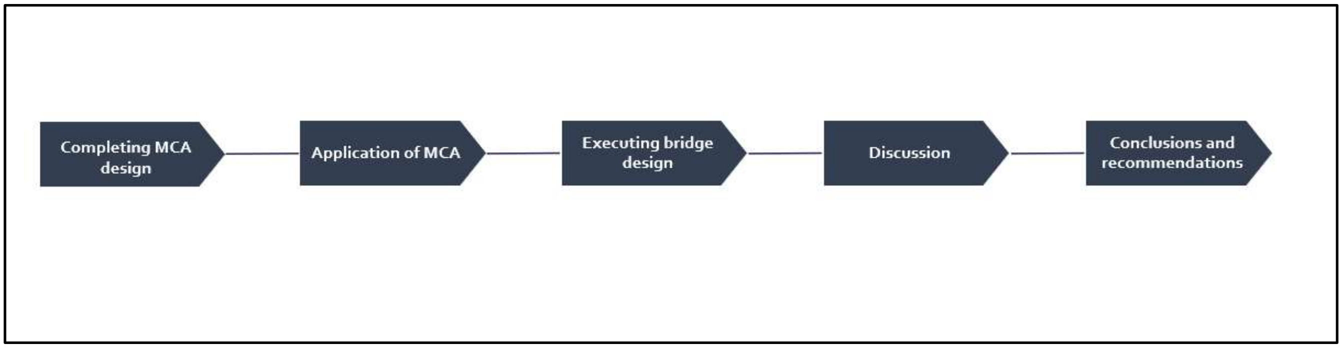


Figure 3.2B: Execution phase (Phase two)

<u>Phase one</u>

Analyse current situation

The first step is to analyse the current situation. This is where information on the fully biobased bridge in Eindhoven will be described. Since the bridge in Eindhoven is going to be compared to the bridge that will be designed later, there will be extensive research into the design of the Eindhoven bridge as well as any data obtained from after the bridge was installed (taking any information that is currently available). Additionally, a description should be given of the location and the surrounding area of where the bridge will be designed.

This description should outline what information will be needed in detail as it will act as a guide to determine what specific information is needed to obtain the schedule of requirements. The list below describes what information to look for in terms of the current situation:

- Fully biobased bridge in Eindhoven:
    - Materials used to construct the bridge.
    - Costs.
    - Maintenance.
    - Bridge data.
- Surrounding area:
    - The exact location of where the bridge will be constructed.
    - Vegetation surrounding the area.

To find information from the list above, the following sources of information were used:

- Eurocode 'EN 1991-1-4:2005+A1: Eurocode 1: Action on structures - part 1-4: General actions - Wind actions.
- Eurocode 'EN 1992-1-1 (2004) (English) : Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings.
- Eurocode 'NEN-EN 1991-1-4+A1+C2 (nl): Eurocode 1: Action on structures - part 1-4: General actions - Wind actions. (Netherland's norm).
- Bio-Based Composite Footbridge: Design, Production and In Situ Monitoring.

Obtaining schedule of requirements

The schedule of requirements will be the point of reference when designing the bridge, as this is direct detailed information about the location of where the bridge will be constructed and its surrounding area. The schedule of requirements will be divided in to two parts, functional requirements, and technical requirements. The functional requirements will provide information on what features are needed for the bridge to function, whereas the technical requirements will provide information on how the bridge will function. All the necessary schedule of requirements will be obtained from the Eurocodes that was previously listed, with the exception of the dimensions of the bridge which will be determined by the researcher.

Conducting literature review

The literature review will include all the secondary research about certain topics. There are two topics that will be covered. The first topic is bridge materials, and the second topic is MCA criteria.

<u>1. Bridge materials</u>

The first topic is biobased materials in construction of bridges. This will be research about what are the current or existing biobased materials that are being used in construction of bridges. There will be four bio-based materials that will be investigated in-depth through secondary research, although some of this research may be incomplete or lacking in certain areas. Therefore, when making the decision to investigate these chosen four materials, additional criteria was used to assist in discovering these four materials and whether it can be potential used for this research. The following criteria has been given by the client:

- Availability of materials
    - This refers to how easily can the material be obtained, considering the location of where the material comes from, how easily can it be produced, and how much of it can be produced.
- Costs
    - This refers to the cost of purchasing the material itself, as well as the delivery and maintenance costs.
- Difficulty of maintenance
    - This refers to how complicated is the process of maintaining the used material when applied in the construction of bridges.

<u>2. MCA criteria</u>

The second topic that will be covered is finding what criteria will be considered useful and relevant for conducting an MCA on the biobased construction of bridges. To begin with, three criteria have been deemed compulsory to be mentioned as given by the company which are as follows:

- Durability
- Strength
- Cost efficiency

These three criteria are explained in depth later in chapter 4.1.1 Final criteria. Even though these three criteria are provided, additional criteria that is relevant to bridge construction have been explored and considered to avoid missing certain aspects of the bridge. The final list of criteria and explanations will also be shown in chapter 4.1.1 Final criteria.

Structuring the MCA

Here, the focus will be on planning the structure of the MCA. This step is entirely decided by the researcher as it covers how the researcher wants to perform the MCA. In the literature review, the potential MCA criteria was researched, therefore an explanation of the rating structure itself is needed to show how the MCA will be carried out.

The rating structure will consist of a scoring factor to indicate which bridge design is considered desirable or undesirable, followed by a calculation and a formula that will be used to determine the best bridge design. This process itself will be shown in chapter 3.3 Developing a multi-criteria analysis.

Phase two

Completing MCA design

The first step in phase 2 is to complete the design of the MCA so that the MCA can be applied on the four bio-based materials that were have been explored and described in the literature review.

First, a final list of all the criteria that will be used will be determined. This is done through referring back to the chapter 2.3 Literature review, as all the criteria that will be found will be listed there. Therefore, the researcher must decide which criteria will be used, and which will not be used. This decision is done by first listing down all the criteria that have been found, followed by removing criteria that is not relevant to this research. Additionally, some criteria were combined to form a main criterion, and some were divided to form sub-criteria. This is shown and explained in chapter 4.1.1 Final criteria. Following this, a clear description has been given to each main and sub-criteria stating what that particular criterion means. Lastly, a weighting was assigned to each main and sub-criterion. The final list of criteria that have been chosen in the end and its necessary weighting was discussed and finalised with the client.

Application of MCA

Once the structure of the MCA has been completed, the application of the MCA can be carried out. This application of the MCA will consider the four bio-based materials that have been investigated:

1. Flax and hemp.
2. Sisal FRP
3. Jute FRP
4. Bamboo

The rating of these bio-based materials will be done by the researcher. Chapter 3.3 Developing a multi-criteria analysis will explain how the MCA will be applied without having bias.

Executing bridge designs

After applying the MCA, the bio-based material that has the highest rating will be used in executing the bridge design. The process for designing the bridge will use information from the current situation, the schedule of requirements, and the literature review.

The first step will be to decide the components and materials of the bridge. This mainly considers the following components:

1. Bridge slab
2. Bridge deck
3. Balustrade

Additionally, the dimensions of each of these must be determined in accordance with the schedule of requirements. The process up to now has involved the researcher to work closely with the client to discuss what design is most preferred by the client, and therefore will carry on until a final design has been decided.

Once the design was decided, a detailed drawing of the bridge was done through AutoCAD, showing the dimensions, materials, and bridge design and components. For the AutoCAD drawings, the following point of view has been considered:

- Top view
- Side view
- Longitudinal view
- Cross-sectional side view
- Detailed connections

Once a design is decided, certain calculations were be carried out to determine the starting points for the calculations and checks needed for the bridge design. This included determining the permanent and variable loads in accordance with the Eurocodes. Mechanical schemes were also be shown to allow for a clear visualisation of the different loads and situations that were be considered.

Discussion

The discussion will focus heavily on the winning bio-based material, which refers to the bio-based material that had the highest score from the MCA. This will breakdown why sisal FRP had the highest score and compare it with the other bio-based materials to see in detail how this material got the highest score. This will also consider the other criteria used and its weightings. Potential criteria that could be included but was not included in the MCA has also been discussed.

Conclusions and recommendations

The conclusion has summarized why sisal FRP was chosen (looking back at all the materials considered) and also mentioned the MCA itself. This was then linked back to the main research question and discusses whether the question has been answered.

The research ends with the recommendations chapter, whereby discussing what would be done different if the research were to be repeated, and what could be improved or further investigated if the research was continued. This has included any simplifications made throughout the project and any areas where there is a lack of information and research.

3.3 Developing a multi-criteria analysis

An MCA is a well-structured decision-making tool which can be used in situations where it is very difficult and complex for the researcher to make a decision that consists of multiple criteria. Previously in chapter 2.3 Literature review, several different criteria were researched and explained. This MCA will decide on which of the three bridge designs will be the most desirable design for the given area. The outcome of this MCA will be based on the assigned criteria and the weighting that will be assigned to each of these criteria. This chapter will explain the structure of the MCA.

In order to decide the which bio-based material is the most desirable material, a rating system will be used. For each main and sub-criterion, each material will be ranked in comparison to each other. However not every main criterion will have sub-criteria. Since there are four materials, the ranking order is as follows:

- Rank 1 = 4 points
- Rank 2 = 3 points
- Rank 3 = 2 points
- Rank 4 = 1 point

Rank 1 will be mean that the material is the best based on that particular criterion, whereas rank 4 will mean that that particular material is the worst based on that particular criterion. In total, there will be ten points to allocate for each criterion. Therefore, in the case where certain materials rank the same, the points will be equally divided to ensure that the total amount of points allocated is still equal to ten. To avoid bias in ranking the materials, all criteria have been either quantified, or clearly explained in such a way that the results cannot be biased. This will be clearer and further explained later in chapter 4.1 Final criteria and data.

After each criterion has been ranked and scored, it will then be multiplied by the weighting of that criteria. The weighting itself will total up to 100 and will be divided amongst the various criteria based on discussions between the researcher and the client. The weighting for each particular criteria was determined once all the criteria has been finalised.

This can be summarized by the given formula:

$$\text{Weighting} * \text{Rating} = \text{Scoring factor}$$

The final score is the final value and result which considers the scoring factor of all the criteria for a particular design. The final score is calculated by adding up all the scoring factors of each criterion. Therefore, the design with the highest final score will the most desirable design for the given area.

To display the results for each design, a table will be used. Table A shows an example of what the MCA rating table will look like, and this table will be applied to each design individually.

Criteria	Sub-criteria	Weighting	Rating	Scoring Factor
1	1.1	-	-	-
2	2.1	-	-	-
3	3.1	-	-	-
…	…	-	-	-
		100	**Final score**	-

Table 3.3A: MCA rating table example

4. Results

4.1 Final criteria and data

4.1.1 Final criteria

All the criteria and sub-criteria will be defined for a clear understanding below. This will also include assigning and justifying the given weighting. Sub-criteria are given for each criterion (where necessary) to aid with the explanation and justification of the weighting due to the complexity of certain factors that need to be considered in this project. Therefore, the total weighting will be shown in the main criteria, and the division of the weighting will be shown in the sub-criteria (if it is present). The weighting of each sub-criteria is equally divided based on the total weighting of its main criteria. All criteria and sub-criteria have been determined through internal discussions with the client and the weightings have been deemed acceptable in terms of value and distribution.

Durability – 20%

The chosen material should be able withstand the environmental conditions of the research area for its designed life span. This can be determined through looking at the environmental class (or exposure class) based on the research area, and to look at the existing information on the behaviour of the material in that particular condition. In this case, only the moisture content will be considered due to the exposure class XC-4 cyclic wet and dry. The durability refers to the ability for the material to last a long amount of time without significantly being damaged or deteriorating.

Strength – 20%

The criterion of strength refers to the ability of the material to withstand the applied load without failing or undergoing plastic deformation. However, the term strength is very broad and therefore three sub-criteria are listed below to allow for a more accurate analysis.

Compressive strength – 10%

This refers to the resistance of the material to breaking under a compressive load. Compressive strength has received a higher weighting than tensile strength and deflection as this will be the most decisive of the three when considering biobased materials in constructing a bridge.

Tensile strength – 5%

This refers to the resistance of the material to breaking under a tensile load.

Deflection – 5%

This refers to the degree to which the material is displaced under a load (whether externally applied or the self-weight) over a period of time. This displacement can refer to the angle or distance.

Cost efficiency – 20%

This factor is considered as the client will choose their design based on their budget and will attempt to cut costs where necessary. The material that is cheaper to use will be more cost efficient. The cost efficiency will be divided into two sub-criteria, maintenance cost and material cost.

Maintenance cost – 10%

Each material will have its own individual costs to bear in terms of maintenance and performance. The maintenance cost will be any cost incurred to ensure that the bridge is in good working condition. The costs that will be considered will be the annual costs.

Material cost – 10%

The material cost refers to the cost of the bio-based material used.

CO2 emissions – 10%

This criterion is focused on the production of the material itself as each material will have its own production process. The project aims to used bio-based materials which aims to combat the existing issues of high CO2 emissions from the production of concrete and steel. Therefore, this refers to the amount of CO2 emissions for the production of the raw material.

Difficulty of maintenance – 10%

The maintenance of using the material in a bridge design is considered as maintenance will be a major factor in the long term, and therefore the client will prefer a material that is simpler to maintain.

Each material will have a different process for the maintenance of it. Therefore, the difficulty of maintenance refers to how complicated or simple is the maintenance process. This involves what is the maintenance process itself and how often will the maintenance need to be carried out.

Availability of materials – 10%

This criterion was chosen as different materials will have a different location of where the material is produced. If the material is consistently available, the material will be more likely to be considered. And so, the availability of materials refers to how accessible will it be to obtain the material.

Circularity – 10%

The circularity is a criterion based on the idea of a circular economy. Following this, less material should be wasted and any possibility of reusing or recycling the material should be considered. Therefore, circularity refers to how complicated is the process of recycling the material, and whether the material can be recycled.

4.1.2 Data Rubric

The data rubric is a summary of all the information gathered from chapter 2.3 Literature review. Each material and each main criteria and sub-criteria have a brief summary for the information obtained for each part. The data rubric is shown below in Table 4.1A. The data rubric will be further explained later in this chapter.

Main criteria / sub-criteria	Flax and hemp	Sisal (FRP)	Jute (FRP)	Bamboo
Durability	Moisture content = 7.5%	Moisture content = 2.7% Thermal aging = tensile strength decreased by 14%	Moisture content = 8.9% Thermal aging = tensile strength decreased by 12%	Moisture content = 19.63%
Compressive strength (MPa)	60.000	196.520	175.640	50.360
Tensile strength (N/mm2)	244.000	223.367	189.479	145.780
Deflection (mm)	15.000	10.890	4.660	11.210
Maintenance cost (Euro per year)	0.507 (excluding labour)	Similar to concrete (large variations)	Similar to concrete (large variations)	Very high (read description)
Material cost (EURO)	Flax – 1/kg Hemp – 0.8/kg	0.02/kg	1.50/kg	0.43/kg
CO2 emissions	Flax – 349 kg CO2 -eq/tonne Hemp – 364 kg CO2 -eq/tonne Combined = 713 kg CO2-eq/tonne	Brazil's – 1285 kg CO2 -eq/tonne Tanzania's – 870 kg CO2 -eq/tonne	479 kg CO2 -eq/tonne	50x less than steel (energy production) OR approximately 1150 kg CO2 -eq
Difficulty of maintenance	Very simple	Same as standard concrete	Same as standard concrete	Very complicated (read description)
Availability of materials	Highly available in Netherlands (depends non/woven)	Can be easily accessed from various countries.	Can be easily accessed from various countries.	Can be easily accessed from various countries.
Circularity	Process is new	Difficult (due to usage of concrete)	Difficult (due to usage of concrete)	Can be recycled with certain conditions

Table 4.1A: Data rubric

Durability

The durability focused on moisture content as this was the data that was available for all the materials. Sisal FRP and jute FRP had thermal aging mentioned in their study, and so the information regarding thermal aging will be shown in the data rubric, however it will not be used in assessing the durability of the material when applying the MCA. The material that is rated the highest score will be the material with the lowest moisture content.

Compressive strength

The compressive strength are values that are taken from lab tests and so the values are not based on real life situations. An important mention here is that Bambusa Blumeana was the species of bamboo considered for the compressive strength as there was sufficient data on this species of bamboo for it to be considered. The material that is rated the highest score will be the material with the highest compressive stress.

Tensile strength

Similarly, to compressive strength, the values taken are from lab tests. And the species of bamboo considered was Bambusa Blumeana. The material that is rated the highest score will be the material with the highest tensile stress.

Deflection

Similarly, to compressive strength and tensile strength, the values taken are from lab tests. And the species of bamboo considered was Bambusa Blumeana. The material that is rated the highest score will be the material with the lowest deflection value.

Maintenance cost

The maintenance cost shown does not include labour costs. The maintenance cost for flax and hemp shown is calculated annually, based on the life span cost shown from the study by Blok et al. (2019). Sisal and jute FRP will be considered as the same material since they are both concrete FRP, therefore they will receive equal scoring. Sisal and jute FRP have no particular values given as this data could not be found. However, based on theoretical research, it is similar to that of concrete and therefore will have large variations depending on what maintenance is carried out. To simplify this, it is assumed that the maintenance cost of sisal and jute FRP is higher than that of flax and hemp due to the more maintenance activities being present. The maintenance cost for bamboo is considered to be very high as previously mentioned in the literature review, the life span of bamboo as a construction material is considered short, which means that it cannot meet the service life of 50 years unless the whole bridge is replaced with a new batch of bamboo which is the cause of the very high maintenance costs. The material that is rated the highest score will be the material with the lowest maintenance cost.

Material cost

The material cost for the different materials varies slightly. Starting with flax and hemp, the prices shown are based on the raw natural fibres only. The material cost of sisal and jute are the raw natural fibres itself and are both taken from the same website. The price of concrete that is used is not included. The material cost of bamboo is an estimated cost based on the price of steel as previously described in the literature review, therefore the actual cost of bamboo itself was not obtained. The material that is rated the highest score will be the material with the lowest material cost.

CO2 emissions

The CO2 emissions for flax, hemp, and jute were taken from the same source. However, since the material of flax and hemp are used together, their individual CO2 emissions will be added together, and the resulting CO2 emission will be used when applying the MCA. Sisal FRP has CO2 emissions of two locations where they are produced, Brazil and Tanzania, however the most extreme case will be considered to consider for the worst-case scenario. Therefore, the CO2 emission of Brazil will be considered for sisal FRP. Additionally, the CO2 emission of sisal FRP and jute FRP do not consider concrete. The CO2 emission shown for bamboo is measured in kg CO2 equivalent per flattened bamboo board, which is different from the others which are measured per tonne. This was the only source of CO_2 emission for bamboo that could be found and will be compared accordingly to simplify the application of the MCA. All the CO_2 emissions for each material except for bamboo is considered from cradle-to-gate. The material that is rated the highest score will be the material with the lowest CO_2 emissions. (Note that in Table 4.1A, the measurement of the values is in kg equivalent per ton with the exception of bamboo being in kg equivalent.)

Difficulty of maintenance

The difficulty of maintenance for flax and hemp is considered to be very simple in comparison to the others as their amount of maintenance works is very minor and is carried out in long intervals. The maintenance process for sisal FRP and jute FRP is similar to that of concrete, whereby when comparing the theoretical information, it is more complicated than that of flax and hemp. Lastly, bamboo has the highest difficulty of maintenance, due to its short life span in comparison to the other materials. Bamboo is the only material that cannot survive for a duration of the 50 years of service life and will require the reconstruction of the bridge with new bamboo materials to meet the service life of 50 years. Therefore, bamboo is considered to have a 'complicated' difficulty of maintenance. The material that is rated the highest score will be the material with the simplest difficulty of maintenance.

Availability of materials

The availability of flax and hemp is very high and consistent in the Netherlands; however, this depends on whether the material is ordered to be woven, non-woven, or uni directional. Furthermore, the arrangement of flax and hemp fibres that are used for construction are consistently available, unless new types are explored in the future. Sisal FRP, Jute FRP, and bamboo were not available in the Netherlands, however several countries offer consistent availability of the material that can also be delivered to the Netherlands and therefore will receive equal scoring. The material that is rated the highest score will be the material with the easiest accessibility and the most consistent availability of materials.

Circularity

Flax and hemp have the possibility of being recycled, but the process itself is relatively new and is still being explored, which is consider the most circular material in comparison to the others. Sisal and jute FRP are similar to reinforced concrete, however there are still no proper ways of recycling the material, and so the material is only dumped in a landfill. Sisal and jute FRP will be scored equally due to having the same end of life process and will receive the lowest score. Bamboo can be recycled in certain conditions by composting if no chemicals are used on the bamboo itself. However, it was mentioned even though the bamboo was incinerated, it still had positive environmental costs. Although incineration is used, this is not considered a recycling method since the material is being burned away. Therefore, the recycling of bamboo is considered situational, and will be scored better than sisal and jute FRP. The material that is rated the highest score will be the material that can be recycled with the easiest recycling process.

4.2 MCA results

This chapter shows the MCA results for each material, providing the breakdown of the scoring for each material and each criterion. This is shown in below in Table 4.2A.

			Rating			
Criteria	**Sub-criteria**	**Weighting**	**Flax and hemp**	**Sisal FRP**	**Jute FRP**	**Bamboo**
Durability	-	20	2	4	3	1
Strength	Compressive strength	10	2	4	3	1
	Tensile strength	5	4	3	2	1
	Deflection	5	1	3	4	2
Cost efficiency	Maintenance cost	10	4	2.5	2.5	1
	Material cost	10	2	4	1	3
CO2 emissions	-	10	3	1	4	2
Difficulty of maintenance	-	10	4	2	2	2
Availability of materials	-	10	4	2	2	2
Circularity	-	10	2	2	2	4
		Final score	**275**	**285**	**255**	**185**

Table 4.2A: MCA results table of all biobased materials considered

The highest final score will be the material that will be used for the bridge design, which in this case is sisal FRP with a final score of 285. A summary of the results of the final scores is shown ranking the biobased material with the highest final score first, and the biobased material with the lowest score last. This is shown below in Table 4.2B.

Ranking	**Material**	**Final Score**
1	Sisal FRP	285
2	Flax and hemp	275
3	Jute FRP	255
4	Bamboo	185

Table 4.2B: MCA results ranking table

4.3 Bridge design

The bridge design follows the result of the MCA and applies the winning biobased material (sisal FRP concrete) in the research area in Eindhoven University of Technology over the river Dommel. The sisal FRP concrete will be main structural component of the bridge and will be one single slab. In addition to this, the bridge design will include a bridge deck made out of azobé wood covering a certain area of the bridge which will be specified later in this chapter. Lastly, a balustrade will be designed as a non-structural component, being made out of oakwood. The weight of these materials was calculated (all detailed calculations and values can be found 'Appendix C (Hand calculations)') and shown below:

- Weight of sisal FRP concrete slab = 2252.75 kg/m³.

- Weight of oakwood balustrade (total from both sides) = 1543.288 kg/m³.
- Weight of azobé wood bride deck = 1050 kg/m³.

Additional values considered in the calculations:

- Flexural strength of the concrete = 350 N/mm²
- Modulus of elasticity = 42500 N/mm²

Following this, the bridge design was executed. The bridge design from various angles is shown in Figure 4.3A, 4.3B, and 4.3C. However, the drawings shown in this chapter is not to scale. The detailed dimensions can be found in the AutoCAD drawings in 'Appendix D (AutoCAD drawings)'.

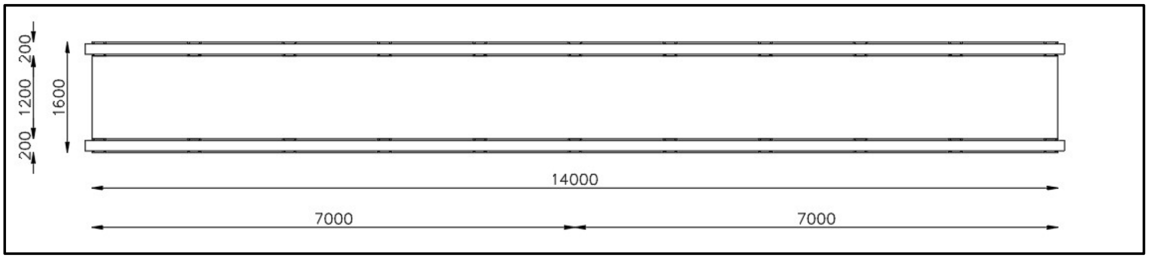


Figure 4.3A: Top view of the bridge design

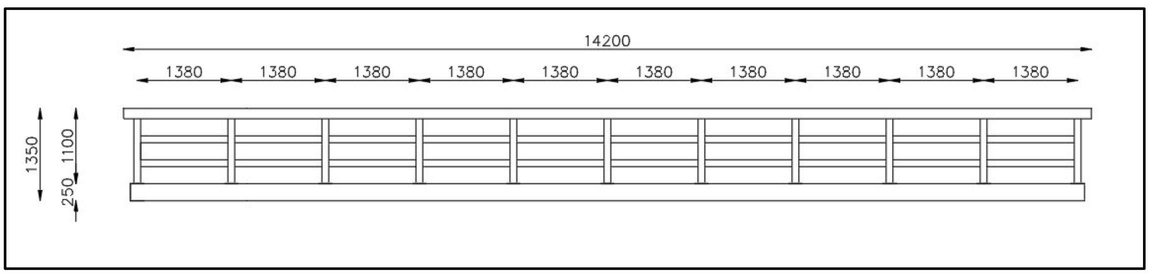


Figure 4.3B: Side view of the bridge design

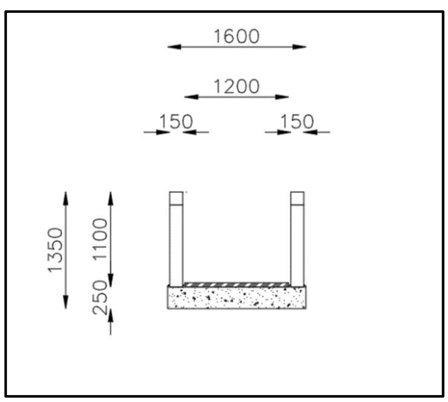


Figure 4.3C: Side view of the bridge design

Before considering the situations, the following should be referred to when looking at the different mechanical schemes for the different situations:

- Bridge slab is referred to as ‘B’.
- Bridge deck is referred to as ‘D’.
- Pedestrian load is referred to as ‘P’.
- Balustrade load is referred to as ‘F’.

Following this, a total of three situations was considered:

Situation 1 – Longitudinal direction (with balustrade)

The first situation focuses on the longitudinal direction, taking 0.4m of the bridge in the cross-sectional direction which considers the weight of the balustrade and the weight of the pedestrian load. The calculated permanent load and variable load is 62.92kN and 18.90kN respectively, totalling to 81.82kN (safety factor included). The area that will be calculated and focused on will be indicated in a red rectangle as shown in Figure 4.3D. The mechanical scheme for Situation 1 is shown in Figure 4.3E.

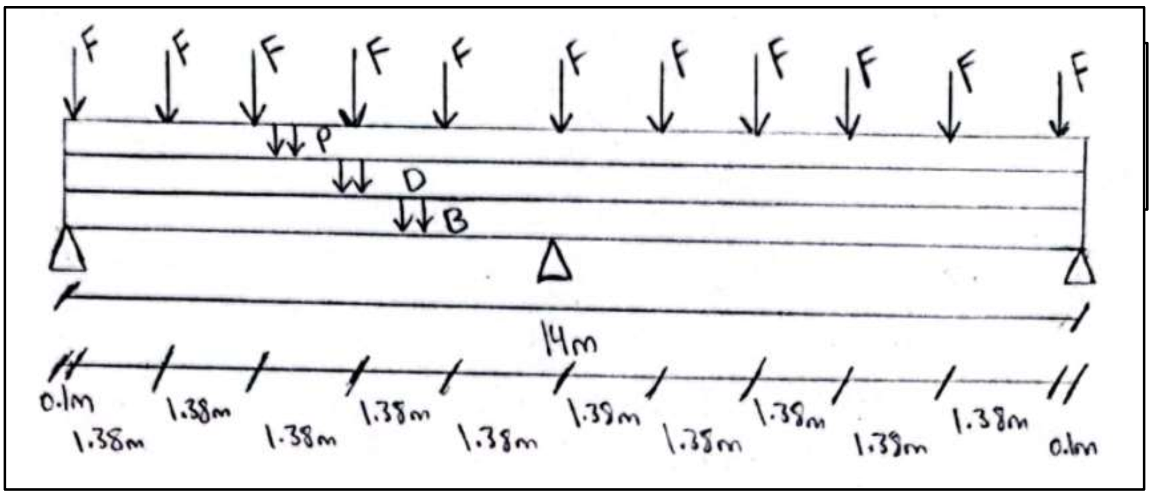


Figure 4.3E: Mechanical scheme of situation 1

Situation 2 – Longitudinal direction (without balustrade)

The second situation focuses on the longitudinal direction too but considers the middle section of the bridge where the pedestrian load becomes the focus (focusing on the area that situation one did not consider. This considers 0.8m of the bridge in the cross-sectional direction. The calculated permanent load and variable load is 124.85kN and 75.6kN respectively, totalling to 200.45kN (safety factor included). The area that will be calculated and focused on will be indicated in a red rectangle as shown in Figure 4.3F. The mechanical scheme for Situation 1 is shown in Figure 4.3G.

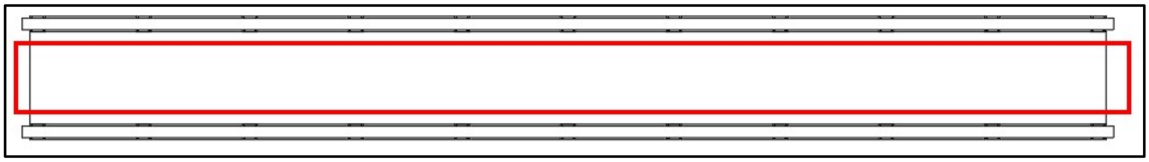


Figure 4.3F: Top view of the bridge

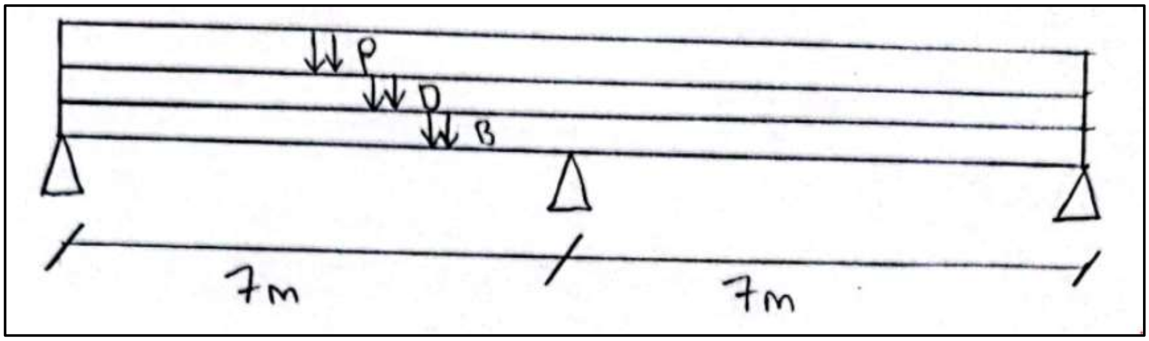


Figure 4.3G: Mechanical scheme for situation 2

Situation 3 – cross-sectional direction

The third situation focuses on the cross-sectional direction and considers all loads, however, the calculation for this will be done per metre of the bridge (in the longitudinal direction) to allow for a simpler calculation. The calculated permanent load and variable load is 13.56kN and 6kN respectively, totalling to 26.41kN (safety factor included). This is visually shown in Figure 4.3H. The mechanical scheme for Situation 1 is shown in Figure 4.3I.

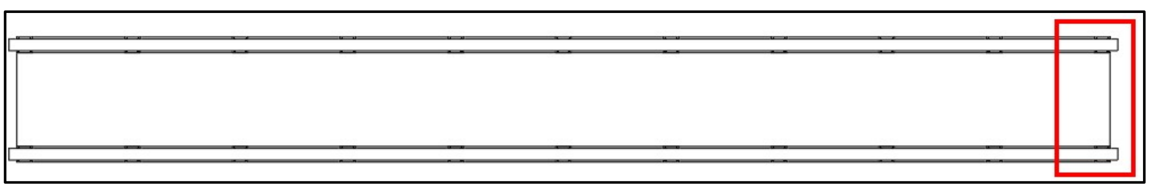


Figure 4.3H: Top view of the bridge

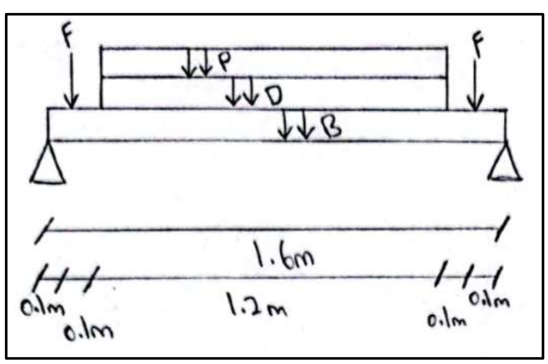


Figure 4.3I: Mechanical scheme for situation 3

5. Discussion and conclusion

5.1 Discussion

Criteria and materials

The results of the MCA show that sisal FRP was the most optimal biobased material to use for the construction of this pedestrian bridge. The key factors in the decision of this result of the MCA is based on the available research online, the criteria assigned, and the weightings of each criterion.

Durability

Durability is one of the three criteria to receive the highest weighting, and if comparing with the sub-criteria as well, the durability would be the highest weighting criterion. The durability focused on moisture content due to the exposure class being XC-4 cyclic wet and dry, therefore the condition for the bridge is very humid and is exposed to alternate wetting and drying, especially since it is close to the river water. Thermal aging should also be considered as due to the potential fluctuations in temperature which may cause irreversible changes in the structure. However, the data for thermal aging for flax and hemp, and bamboo was not available and therefore not considered in the MCA. Table 4.1A shows the thermal aging for sisal FRP and jute FRP for reference. This exposure has been assumed based on concrete (which is even more accurate when looking at the bridge design which is a FRP concrete) since all the biobased materials are still relatively new, and so there is still a lack of Eurocode regulations and standards available. As biobased materials become more popular and used, there may potentially be proper regulations for it, therefore allowing for a more accurate comparison between the materials.

Strength (compressive strength, tensile strength, and deflection)

The criteria for strength were divided into three sub criteria whereby compressive strength had the highest weighting of the three, whilst the remaining weighting was equally distributed amongst the tensile strength and deflection. The strength values of the biobased materials were obtained in different methods of testing, which may potentially lead to missing values or an unfair comparison. However, in this case, all values were present, although bamboo only focused specifically on one type of species. Flax and hemp were tested in a full-scale production test, which lead to the calculation of the compressive strength and tensile strength. The deformation was measured from when the bridge was installed, which approximated at 15mm in 20.6 months. Despite this short duration, the deflection has already reached approximately 15mm (Blok et al., 2019). This likely means that as time further continues, there will be more deflection of the material, however that extent of this deflection is still unknown and requires further testing. Additionally, the testing of flax and hemp also involves the hardener and resin used in the material.

Sisal FRP and jute FRP went through lab tests of confining concrete that was reinforced with sisal and jute fibres. All strength values were found through mechanical testing, therefore whether these values may be applicable in a bridge is still uncertain, especially as the test focused on confining fibre reinforced concrete rather than load testing. (Sen and Paul, 2015)

Bamboo has various species that can be used for construction, as previously mentioned by the study by Awalluddin et al. (2017) which looked at the moisture content of four different species of bamboo.

Bambusa Vulgaris was focused on when considering the strength values as this was the material with sufficient testing and results. The test conducted considered the flexural strength, tensile strength, and the compressive strength (Candelaria and Hernandez, 2019). This was a reliable study to use as the bamboo underwent several different tests and was analysed thoroughly, allowing for a good comparison with the other materials when conducting the MCA.

Cost efficiency (maintenance cost and material cost)

The cost efficiency was divided into maintenance cost and material cost. First the maintenance cost will be discussed. The maintenance procedure and activities are strongly linked to the maintenance costs in this study. These procedures itself and unclear explanations will be later clarified and discussed in this chapter in 'Difficulty of maintenance'. The maintenance costs for each material does not consider the direct labour cost but will discuss the present situation if labour costs were included. The labour cost will depend on the amount of maintenance that would need to be carried out and is therefore relative to the scale of the bridge.

Flax and hemp have the lowest maintenance cost due to its simplicity and little maintenance to be done. This was the only example that had a given total cost (annually) as it was taken from a practical example (Blok et al., 2019). Sisal FRP and jute FRP are considered to have similar maintenance procedures and therefore will have similar maintenance costs as both involve a large amount of concrete. Although there is no exact maintenance cost given, a comparison can be made with the other materials to gauge its rating. Bamboo is considered to have a very high maintenance cost due to its shorter lifespan and high labour costs from the difficulty of reassembling the entire bridge using this material (further explained later in this chapter in 'Difficulty of maintenance'). Therefore, bamboo will have the highest maintenance costs as the whole bridge has to be replaced as part of the maintenance. Flax and hemp will then be compared with sisal FRP and jute FRP, but flax and hemp have a very low maintenance cost in comparison to sisal FRP and jute FRP since the maintenance required for concrete is more often and work to do. (American Concrete Institute (ACI) Committee 345, 2006). However, the extent of this difference in maintenance costs between materials is unknown.

Next the material costs will be discussed. Only the price of the raw materials was considered in this criterion, and so the processing of the material once obtained is not considered. The issue in this case was that the sources of the costing may be unreliable. The price of flax and hemp was taken from directly from EIHA; therefore, the pricing is directly from the farmers and producers. Since flax and hemp will be used together for the construction of the bridge, the price of both raw materials was added to represent the material costs of flax and hemp. The price of bamboo was made on the assumption of a study by Yadav and Mathur (2021), where the cost of bamboo three times more cost effective than that of steel reinforcement, and therefore calculated based on the price of steel in the Netherlands from Beonstaal.nl. The price of sisal FRP and jute FRP is considered inaccurate as it only considered the price of the raw material, but not the price of concrete which is a major component to consider as sisal FRP and jute FRP will be used in conjunction with concrete when constructing the bridge.

CO2 emissions

The CO2 emissions part of the MCA faced a number of issues. The first was the combination of materials, which means that some of the biobased materials was not just one particular material but a combination. The materials that faced this problem was flax and hemp, sisal FRP, and jute FRP. When looking at the CO2 emissions of flax and hemp, the combined CO2 emission of the individual material of flax and hemp was added to give a total CO2 mission. However, for sisal FRP and jute FRP, only the CO2 emission of the raw material was considered, therefore concrete was not included. Therefore, this possibly gives an unfair advantage to sisal FRP and jute FRP as the CO2 emissions are less than they actually should be. The second issue faced was the units used for the CO2 emissions. For every other material except bamboo, the units used was 'kg CO2 equivalent per ton' or 'kg CO2 eq/ton' (both are the same units of measurement) however bamboo was measured in 'kg CO2 equivalent' or 'kg CO2 eq' (both are the same units of measurement). The issue here was that the study by Lught et al. (2015) used the aforementioned unit of measurement, which is not directly comparable to the other biobased materials as it is not per ton. This then offers an unfair comparison with the other materials as the units of measurement is different, therefore the values as a whole may potentially be different as well. The last issue would be what process is considered when measuring the CO2 emissions. Commonly, the term 'cradle-to-gate' is used, which means from the start of extracting the resource to the factory gate (or the stage before it is transported to the customer). The CO2 emissions for each material except for bamboo is considered from cradle-to-gate, there offering another unfair comparison between bamboo and the other biobased material. Overall, these three will impact the outcome of the MCA for CO2 emissions.

Difficulty of maintenance

When considering the maintenance of the biobased materials, each material had its own situation. Flax and hemp were taken from a study that had a practical example since they did construct the bridge with proper planning of the maintenance procedures. The maintenance was very simple and only involved coating for local surface deterioration (done a maximum of four times in its lifespan), and the reapplication of an anti-slip layer (done once in its lifespan) (Blok et al., 2019). Aside from this would be inspections checks which will be done for all bridges in any case as they are all relatively new materials to be used in bridge construction, and cleaning of the bridge. There is little maintenance to do and therefore received the highest rating in comparison to the other biobased materials.

Sisal and jute FRP are assumed to have the same maintenance procedure as they are both concrete FRP's using a plant fibre internally as a reinforcement. The assessment of this criteria was purely theoretical as practical studies were inaccessible. Therefore, the maintenance procedure that would be most similar would-be reinforced concrete. Since there is a lot of experience for the maintenance of reinforced concrete, there can be relatable practical examples to consider for a bridge made out of sisal and jute FRP (American Concrete Institute (ACI) Committee 345, 2006). Based on the amount of maintenance works that has to be done, (including examples such as cleaning or washing, sealing cracks on concrete to protect the reinforcement, or removal of debris that may contain chemicals that damages structural elements), there is more work to do in comparison to flax and hemp, and therefore will receive a lower rating than flax and hemp.

Bamboo was given the lowest rating as it had the highest level of difficulty for maintenance. This is because the material itself deteriorates quickly, in turn having a shorter lifespan. When considering a design lifespan of 50 years, a bamboo bridge will not be able to last long, for example Guadua has a lifespan of 20 years (Lugt et al., 2003). And another study states that untreated bamboo has a design life of approximately 10 to 15 years if stored properly, although treated bamboo has a much longer design life, the duration was not specified (Awalluddin et al., 2017). With a short lifespan, the whole bridge will need to be taken down and be replaced or rebuilt which will also involve a lot of labour. Additionally, bamboo bridges are difficult to assemble and therefore labour costs will rise accordingly (Laroque, 2007). Therefore, it is potentially best to use a bamboo bridge as a temporary structure to ease the maintenance difficulty which increases with time. This overall makes it more difficult to maintain over longer periods of time since the shorter lifespan means it will need to be maintained or replaced more often (Lugt et al., 2005). In comparison to the other materials, bamboo is much more difficult to maintain.

Availability of materials

The availability of the materials focuses on accessibility and consistency of availability. The import of materials was assumed to be less accessible than those that are locally obtained. There is a possibility that sisal and jute fibres are available in the Netherlands, however this needs further investigation as information on this could not be found. The materials accessibility was considered together with the pricing as it allows for a more accurate result, since a material is available for purchase with a set price, it will mean that this is a source to be considered. However, there may have been closer locations that were not considered with a similar consistency of availability, therefore further investigation is needed.

Circularity

The circularity focused specifically on the difficulty of recycling the material, but circularity is also related to reusability. The issue with considering reusability is due to the uniqueness of each situation, as it heavily depends on how the material is used in construction, and what chemicals have been mixed in together with the raw biobased material. Therefore, the difficulty of the recycling process was looked at as there was better availability of this information to allow for a fairer comparison between materials.

All the materials have a certain high level of difficulty when it comes to recycling. This is due to the materials being mixed with either certain chemicals or materials. The flax and hemp composite are used with resin to act as the binder between the materials. The separation process of this as discussed by Blok et al. (2019), is still under development as this combination of material is still relatively new. This recycling method is able to recycle and reuse the resin and the fibres, however these materials will be downcycled as their initial properties are lost in this chemical process. Additionally, overtime once the method is improved, the difficulty of recycling and reusing the material may potentially improve, allowing it to outperform the other materials even more in this criterion. (Blok et al., 2019)

The issue with the other materials is that they're usage is still relatively new, and so the recycling methods are either non-existent, or very underdeveloped. Bamboo is potentially one of the better materials, but only under the condition that chemicals have not been added to the bamboo Eco & Beyond (2021). However, chemicals are often added to the bamboo to protect the material from degrading, and so it will last longer. A study that was quoted by Lught et al. (2005) (which is inaccessible at the time) stated that the retrieval of energy after incinerating bamboo (at the end of its life span) in its complete lifecycle had positive environmental costs. This may potentially lead to bamboo being more circular than flax and hemp under the condition that flax and hemp results in any amount of negative environmental costs. This method for bamboo however does not directly consider reusability of recycling, due to the process of incineration.

Sisal FRP and jute FRP involves the usage of concrete which is where the problem begins when it comes to recycling. FRP's in general face the problem of circularity as there is little information and research about how FRP composites can be recycled. Due to this, the current method is sending the FRP to a landfill (Correia et al. 2011). Concrete that is reinforced with steel has been used for a long time, therefore there are already recycling methods that allow for the concrete and steel to be reusable despite it being energy intensive (The Concrete Centre, 2021) (Concrete Reinforcing Steel Institute, 2021).

Other alternative criteria

The results from the MCA for choosing a winning material that is supposedly the most optimal material for this pedestrian bridge in this specific situation is heavily reliant on what criteria was chosen. When deciding on what criteria should be used, there were criteria that were considered to be very important for the construction of bridges but was not fully applicable here due to the scope of this research. The other criteria that may be considered are shown below:

Construction duration

This is the total time taken for the construction of the bridge to be completed, therefore focusing purely on the construction phase. However, in the current situation, this is unapplicable as the focus is only on the design phase, and so the construction phase is excluded (Plà et al., 2017).

Demolition cost

This is the cost of demolishing the bridge when the bridge reaches the end of its service life. This has its own particular phase called the demolition phase and considers factors such as the environmental impact, cost of manpower, and cost machinery. In the current situation, the focus is only on the design phase, and so this is unapplicable as this is the final phase. Alternatively, the focus in this study goes towards recycling instead of demolishing (if possible) therefore the criteria 'circularity' is considered instead (Plà et al., 2017) (Navarro et al., 2020).

Land use

This refers to the efficiency and/or effect of the changes of the land to the surrounding area. Depending on the situation, there may be earthworks that involve excavation or piling (for example) and this will have an effect on the surrounding area. Alternatively, this can be defined as how well the construction of the bridge utilizes the given area, which focuses more on efficiency. In the case of this study, this was not considered as the bridge is only a potential design that was intended to be placed at the exact same location as the previous fully biobased bridge as previously mentioned in chapter '1.2 Problem statement' (Sierra et al., 2018).

User-oriented design

This refers to how beneficial is the implementation of the bridge to the people in the surrounding area. This would be an important criterion for deciding whether a bridge should be built in a specific location, whereby in this case, whether it benefits the pedestrians or cyclists in the surrounding area. However, the bridge will be built in the aforementioned location (from chapter '1.2 Problem statement) irregardless of how useful the bridge for the surrounding area is, and additionally, the MCA is focused on materials rather than social aspects (Sierra et al., 2018).

Accessibility

This refers to how accessible is the bridge for the intended users in the surrounding area, and/or what areas does the bridge give access to. In this case, the intended users are the pedestrians and cyclists, and the bridge gives access to Eindhoven University of Technology. However as previously mentioned when discussing 'user-oriented design', the focus of the MCA in this case is on the materials rather than social aspects (Sierra et al., 2018).

Engineering feasibility

This refers to the extent of how realistic or possible will it be to execute the design of the bridge. This is an important factor that should include the design and construction phase as the design of the bridge may possibly change due to certain conditions that do not allow the design or if the design is too complicated. In this study, the bridge design involved calculations to show the starting points for beginning a calculation of the bridge design. However, the bridge design still requires further calculations and testing of the material to check whether if it is a feasible design which can support the loads of the pedestrians and cyclists. This was not considered in the MCA since the focus of the MCA was in choosing biobased materials that could be used for bridge construction, however the materials that were considered in the first place were materials that have already been used in bridge construction, therefore the engineering feasibility of the biobased materials are possible in each case. This criterion would be useful if a preliminary design of the bridge was made using each material as each design can be analysed and compared (Farkas, 2011).

5.2 Conclusion

This research has gathered and summarized various studies and data of the four chosen biobased materials and has shown which biobased materials are the most optimal choice in the construction of bridges based on the criteria chosen and used in the MCA. This may assist in the transition to more circular options for the construction of bridges. Sisal FRP has the highest final score of 285. Therefore, based on the criteria chosen, sisal FRP was the most optimal biobased material for the construction of this pedestrian bridge over the Dommel river at TU/e campus Eindhoven. Flax and hemp, and jute FRP are also close competitors as they scored relatively close to sisal FRP, however bamboo scored significantly lower than the other materials. Whether this is either true or a lack of obtained data or execution of the MCA is something to look further into.

Sisal FRP was used as the bridge's primary structural component, with azobé wood as the bridge deck to be placed on top of this due to its suitability for the weather conditions of the area, having an exposure class of XC-4 cyclic wet and dry. The balustrade is designed and made out of oak wood as it is a strong and moisture resistant material. Therefore, there are three different biobased materials included in the final design of the bridge whereby one is a plant fibre and the other two are of different types of wood.

6. Recommendations

The study had several limitations which mainly included time restrictions, lack of availability of information, and lack of physical testing of materials.

The final score of the winning material sisal FRP was 285, whilst the second highest score was only flax and hemp with a final score of 275. And the third highest final score was 255 which was jute FRP. The difference between these final scores is at most only 30, which shows how close the result of this MCA is. A further study into reassigning the weighting of the criteria can cause a change in the final score for each material, and potentially also changing the winning material due to how close the final scores are to each other. This further study would be useful to see which criteria or sub-criteria would be decisive by receiving a higher or lower weighting in causing a change in the winning material.

Another factor that can heavily influence the outcome of the MCA is to redefine certain criteria instead of changing the weightings. Due to the lack of availability of data, some criteria were defined in a way that excluded certain factors that should be included in that criteria. An example of this would be durability. Durability in this study only considered moisture content but could have considered other factors too such as thermal aging. Another example is circularity. The definition of circularity in this case focused solely on recycling but can also include reusability.

One of the assumptions in this study was to not consider the natural frequency of the bridge as the calculation for this for each material can be time consuming, especially with the lack of available data online. However, this is still an important factor to consider for the comfort and safety of the pedestrians crossing the bridge. Therefore, this can be tested through making the material samples itself (since there was also no opportunity to do this) and testing each sample for its natural frequency.

Another factor that was not included in this study was the wind load. This may potentially have a large impact on the construction of the bridge as the other loads of the bridge are relatively small. A further investigation should be carried out to see the effect of the wind load on the bridge.

Previously in chapter '5.1 Discussion', it was mentioned that the criteria were the determining factor in deciding what was the most optimal material to be used for the pedestrian bridge in this situation. If the scope of the project was bigger, whereby potentially other phases such as the construction phase or demolition phase was considered instead of only the design phase, the outcome of the MCA will potentially be different. A further study into either one of these phases specifically, or a comparison or combination of the phases can allow for a more wholesome result as less factors are excluded, and potentially more criteria can be included (specifically the ones that were previously mentioned in chapter '5.1 Discussion'). Additionally, the criteria considered can also be different if the current situation itself was different, such as if the research area itself was yet to be chosen, then for example land use or accessibility will be a more relevant criteria to be considered for the study.

This study only considered four different biobased materials which were flax and hemp, sisal FRP, jute FRP, and bamboo. Therefore, the MCA only considers these four materials when deciding which material is the most optimal for this situation. Other materials may potentially be better for this situation if it was considered. A material that was initially considered was mycelium but due to the lack of available data on using mycelium in construction specifically, the material choice was dropped. This could be a potential material to consider if testing of this material can be done or if any further research is conducted in relation to construction.

The data for each material is based on certain studies that have already been done with their own tests and situations. Even then, the data available online is not complete and must be taken from various sources which leads to some inconsistent data as each source tests the material differently under different conditions (potentially having different results). Ideally a sample can be made of each material which can be tested for all the data required, however this is a very long process. Therefore, a possible approach is to do lab tests of missing measurements to make up for the data that could not be found.

The winning material from the MCA was sisal FRP and the bridge design used this material as its primary structural component. However, the bridge design is heavily based on the data obtained from other research papers, therefore the sisal FRP should be further investigated to see if the material is suitable for the bridge design and whether it is still feasible or realistic.

When looking at the material costs in the MCA, the costs only looked at the raw material costs. This causes an unfair comparison between the biobased materials as the price for sisal FRP and jute FRP will be significantly less without the cost of concrete considered. This is also the case for flax and hemp as in the study by Blok et al. (2019), the most significant cost in their bridge design was the epoxy resin, and the painting had the highest relative costs per kg. The outcome of the MCA would be different for the material costs if all the components and other materials involved in producing the final end product is considered, as the biobased material will not be the only material used in the construction of a bridge.

This study only compared biobased materials and provided starting points for the calculations of a bridge design using the winning material from the MCA. A further study should continue the calculations for the bridge to see if there is a possibility for this bridge to be constructed. These calculations can be further verified through Technosoft to obtain accurate results. Optimisation can potentially be made as well to reduce the costs or amount of material used for the final bridge design.

A comparison study could be done with the theoretical bridge design using sisal FRP concrete with the fully biobased bridge in Eindhoven that is made out of flax and hemp. Another MCA could be executed using similar criteria to see the difference between comparison of just materials, and a comparison of the actual application of the materials in bridge construction.

7. References

BuilderSpace.com. (2021). Why Concrete is Reinforced with Steel: The Complete Guide. https://www.builderspace.com/why-concrete-is-reinforced-with-steel-the-complete-guide

Guardian News & Media Limited. (2019). Concrete: the most destructive material on Earth. https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth

Sina Leipold, Anna Petit-Boix, The circular economy and the bio-based sector - Perspectives of European and German stakeholders, Journal of Cleaner Production, Volume 201, 2018, Pages 1125-1137, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2018.08.019.

Rijk Blok MSc, Joris Smits PhD, Rafail Gkaidatzis MSc & Patrick Teuffel

Prof. Dr-Ing (2019) Bio-Based Composite Footbridge: Design, Production and In Situ Monitoring,

Structural Engineering International, 29:3, 453-465, DOI: 10.1080/10168664.2019.1608137

European Industrial Hemp Association. (2017). Yearly average prices of technical flax and hemp short fibres in €-cent/kg (supply of 100 tonnes per year to factory gate in Central Europe).

Carbon Footprint and Sustainability of Different Natural Fibres for Biocomposites and Insulation Material, Niels de Beus (nova-Institute), Michael Carus (nova-Institute), Martha Barth (nova-Institute) March 2019, nova-Institut GmbH

Tara Sen, Ashim Paul, Confining concrete with sisal and jute FRP as alternatives for CFRP and GFRP, International Journal of Sustainable Built Environment, Volume 4, Issue 2, 2015, Pages 248-264, ISSN 2212-6090, https://doi.org/10.1016/j.ijsbe.2015.04.001.

Guide to Maintenance of Concrete Bridge Members Reported by ACI Committee 345, ACI 345.1R-16 September 2016, American Concrete Institute

https://www.alibaba.com/product-detail/Natural-Sisal-Fiber-Sisal-Fibre-BEST_1600122343745.html?spm=a2700.7724857.normal_offer.d_title.1f844a48Khcsiy

https://www.alibaba.com/product-detail/Best-Quality-Exportable-100-Natural-Raw_235644247.html?spm=a2700.7724857.normal_offer.d_title.1d4a7397SjDTt1

Martijn L.M. Broeren, Stijn N.C. Dellaert, Benjamin Cok, Martin K. Patel, Ernst Worrell, Li Shen, Life cycle assessment of sisal fibre – Exploring how local practices can influence environmental performance, Journal of Cleaner Production, Volume 149, 2017, Pages 818-827, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2017.02.073.

João R. Correia, Nuno M. Almeida, João R. Figueira, Recycling of FRP composites: reusing fine GFRP waste in concrete mixtures, Journal of Cleaner Production, Volume 19, Issue 15, 2011, Pages 1745-1753, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2011.05.018.

Awalluddin, Dinie & Ariffin, Mohd Azreen & Osman, Mohd & Hussin, M. & Ismail, Mohamed & Lee, Han-Seung & Abdul Shukor Lim, Nor Hasanah. (2017). Mechanical properties of different bamboo species. MATEC Web of Conferences. 138. 01024. 10.1051/matecconf/201713801024.

Madhura Yadav, Arushi Mathur, Bamboo as a sustainable material in the construction industry: An overview, Materials Today: Proceedings, Volume 43, Part 5, 2021, Pages 2872-2876, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2021.01.125.

Betonstaal.nl. (2021). Reinforcing bars 3 and 6 meters. https://www.betonstaal.nl/en/rebar/reinforcing-bars-3-and-6-meters/

Lugt, Pablo & Vogtlander, Joost & Vegte, J. & Brezet, J.. (2012). Life cycle assessment and carbon sequestration: the environmental impact of industrial bamboo products. Electronic Proceedings in Theoretical Computer Science.

Laroque, Paul. (2007). Design of a low cost bamboo footbridge.

Hernandez, Jr & Candelaria, Doreen. (2019). DETERMINATION OF THE PROPERTIES OF BAMBUSA BLUMEANA USING FULL-CULM COMPRESSION TESTS AND LAYERED TENSILE TESTS FOR FINITE ELEMENT MODEL SIMULATION USING ORTHOTROPIC MATERIAL MODELING. ASEAN Engineering Journal. 9. 10.11113/aej.v9.15508.

Bethany Carter. (2021). Truth or Trend: Is Bamboo Sustainable?. Eco & Beyond. https://www.ecoandbeyond.co/articles/is-bamboo-sustainable/

P. van der Lugt, A.A.J.F. van den Dobbelsteen, J.J.A. Janssen, An environmental, economic and practical assessment of bamboo as a building material for supporting structures, Construction and Building Materials, Volume 20, Issue 9, 2006, Pages 648-656, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2005.02.023.

P. VAN DER LUGT, A. VAN DEN DOBBELSTEEN, and R. ABRAHAMS. (2003). Bamboo as a building material alternative for Western Europe? A study of the environmental performance, costs and bottlenecks of the use of bamboo (products) in Western Europe.

Leonardo A. Sierra, Víctor Yepes, Eugenio Pellicer, A review of multi-criteria assessment of the social sustainability of infrastructures, Journal of Cleaner Production, Volume 187, 2018, Pages 496-513, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2018.03.022.

Navarro, I. J., Penadés-Plà, V., Martínez-Muñoz, D., Rempling, R., & Yepes, V. (2020). Life cycle sustainability assessment for multi-criteria decision making in bridge design: a review. Journal of Civil Engineering and Management, 26(7), 690-704. https://doi.org/10.3846/jcem.2020.13599

Farkas, András. (2011). Multi-Criteria Comparison of Bridge Designs. Acta Polytechnica Hungarica. 8.

Penadés Plà, Vicent & Yepes, Victor & García-Segura, Tatiana & Martí-Albiñana, José. (2017). STUDY OF CRITERIA USED TO OBTAIN A SUSTAINABLE BRIDGE. Proceedings of International Structural Engineering and Construction. 4. 10.14455/ISEC.res.2017.177.

The Concrete Centre. (2021). End of life recycling. https://www.concretecentre.com/Performance-Sustainability-(1)/Material-Effieciency/End-of-life-recycling.aspx

Concrete Reinforcing Steel Institute. (2021). Recycled materials. https://www.crsi.org/index.cfm/architecture/recycling

Everything-about-concrete.com. (2020). Density Of Concrete. https://www.everything-about-concrete.com/density-of-concrete.html

Matmatch. (2021). Density of wood in kg/m3, g/cm3, lb/ft3 – the ultimate guide. https://matmatch.com/learn/property/density-of-wood

GharPedia. (2020). 15 Popular Types of Wood used in the Construction Industry!. https://gharpedia.com/blog/types-of-wood-used-for-construction/

Omog Hardwood Consulting. 2002. Hardwood lumber species: very high density. http://www.omog-hardwood.com/english/speciesanduses_veryheavy.htm

Appendix A (MCA results)

Flax and hemp				
Criteria	**Sub-criteria**	**Weighting**	**Rating**	**Scoring factor**
Durability	-	20	2	40
Strength	Compressive strength	10	2	20
	Tensile strength	5	4	20
	Deflection	5	1	5
Cost efficiency	Maintenance cost	10	4	40
	Material cost	10	2	20
CO2 emissions	-	10	3	30
Difficulty of maintenance	-	10	4	40
Availability of materials	-	10	4	40
Circularity	-	10	2	20
			Final score	275

Table A1: MCA results table for flax and hemp

Sisal				
Criteria	**Sub-criteria**	**Weighting**	**Rating**	**Scoring factor**
Durability	-	20	4	80
Strength	Compressive strength	10	4	40
	Tensile strength	5	3	15
	Deflection	5	3	15
Cost efficiency	Maintenance cost	10	2.5	25
	Material cost	10	4	40
CO2 emissions	-	10	1	10
Difficulty of maintenance	-	10	2	20
Availability of materials	-	10	2	20
Circularity	-	10	2	20
			Final score	285

Table A2: MCA results table for sisal FRP

Jute				
Criteria	**Sub-criteria**	**Weighting**	**Rating**	**Scoring factor**
Durability	-	20	3	60
Strength	Compressive strength	10	3	30
	Tensile strength	5	2	10
	Deflection	5	4	20
Cost efficiency	Maintenance cost	10	2.5	25
	Material cost	10	1	10
CO2 emissions	-	10	4	40
Difficulty of maintenance	-	10	2	20
Availability of materials	-	10	2	20
Circularity	-	10	2	20
			Final score	255

Table A3: MCA results table for jute FRP

Bamboo				
Criteria	**Sub-criteria**	**Weighting**	**Rating**	**Scoring factor**
Durability	-	20	1	20
Strength	Compressive strength	10	1	10
	Tensile strength	5	1	5
	Deflection	5	2	10
Cost efficiency	Maintenance cost	10	1	10
	Material cost	10	3	30
CO2 emissions	-	10	2	20
Difficulty of maintenance	-	10	2	20
Availability of materials	-	10	2	20
Circularity	-	10	4	40
			Final score	185

Table A4: MCA results table for bamboo

Appendix B (Additional bridge materials information)

The normal weight of concrete is 2400kg/m³ (everything-about-concrete.com, 2020) and was used in the bridge design.

Oakwood is used for the balustrade as the material is strong and easy to work on. Additionally, it has good resistance to moisture and is often used in ships and boats, therefore this is suitable for the weather conditions of the research area and its exposure class of XC-4 cyclic wet and dry (Matmatch, 2021).

The density of oakwood ranges from 593kg/m³ to 897kg/m³, however a more conservative approach will be taken, therefore the density of oakwood used will be 897kg/m³ (GharPedia, 2020).

The bridge deck is made out of azobé wood. This is a common bridge deck material and therefore can be easily obtained. Additionally, this material is suitable for the exposure class of XC-5 cyclic wet and dry. The density of azobé wood is 1050kg/m³ and is very resistant to decay and wear (Omog Hardwood Consulting, 2002).

Appendix C (Hand calculations)

Starting points

Balustrade weight

Composed of 3 parts

① $14.2m \times 0.15m \times 0.15m = 0.3195 m^3$

② $1.28m \times 0.15m \times 0.1m = 0.0192 m^3$

③ $0.95m \times 0.15m \times 0.1m = 0.01425 m^3$

Total volume of balustrade (1 side)

① $\times 1 = 0.3195 m^3$

② $\times 20 = 0.384 m^3$

③ $\times 11 = 0.15675 m^3$

} Total $= 0.86025 m^3$

Weight of one balustrade

$0.86025 m^3 \times 897 kg/m^3 = 771.644 kg$

Sisal FRP concrete slab weight

Composition		Material density	
Concrete	84.5%	Concrete	2400 kg/m³
Sisal fibres	15.5%	Sisal fibres	1450 kg/m³

$84.5\% \times 2400 kg/m^3 = 2028 kg/m^3$

$15.5\% \times 1450 kg/m^3 = 224.75 kg/m^3$

} Total $= 2252.75 kg/m^3$

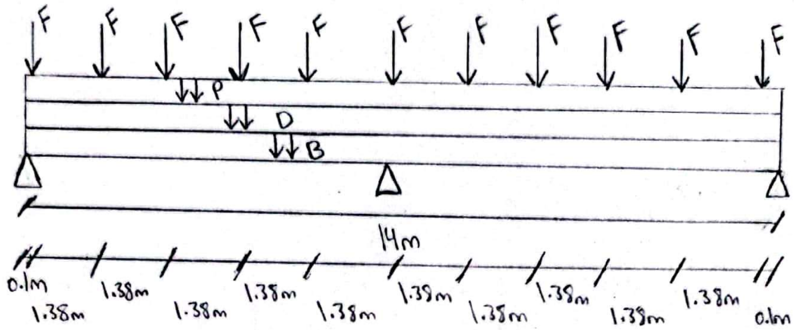
Weight of slab $= 2252.75 kg/m^3$

Other Info

Modulus of elasticity → $E = 42500 N/mm^2$

Flexural strength → $M_F = 350 N/mm^2$

Longitudinal direction (Situation D)



Bridge slab = B_1 = 2252.75 kg/m³ × 0.25m × 0.4m
= 225.275 kg/m → 2.253 kN/m

Bridge deck = D_1 = 1050 kg/m³ × 0.25m × 0.2m
= 52.5 kg/m → 0.525 kN/m

Pedestrian live load = P_1 = 5 kN/m² × 0.2m
= 1 kN/m

Balustrade = F_1 = $\frac{771.644 \text{ kg}}{11}$
= 70.149 kg → 0.701 kN

Loads

Permanent = B × 14m + D × 14m + F × 11
= 62.92 kN

Variable = P × 14m
= 18.9 kN

Total with S.F. = 81.82 kN

Safety factors (S.F.)

Permanent → 1.35

Variable → 1.35

Loads with S.F.

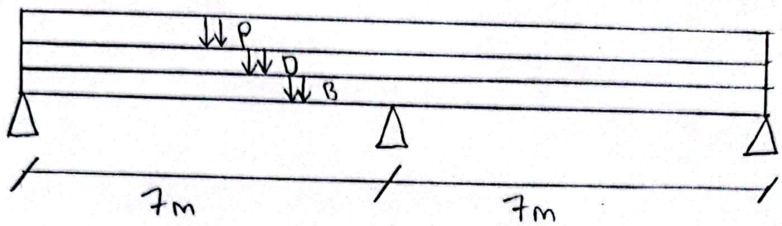
B = 3.042 kN/m

D = 0.709 kN/m

P = 1.35 kN/m

F = 0.946 kN

Longitudinal direction (situation 2)



Bridge slab = B_1 = 2252.75 kg/m³ × 0.25m × 0.8m
= 450.55 kg/m → 4.506 kN/m

Bridge deck = D_1 = 1050 kg/m³ × 0.25m × 0.8m
= 210 kg/m → 2.1 kN/m

Pedestrian live load = P_1 = 5 kN/m² × 0.8m
= 4 kN/m

Loads

Permanent = B × 14m + D × 14m
= 124.852 kN

Variable = P × 14m
= 75.6 kN

Total with S.F. = 200.452 kN

Safety factors (S.F.)

Permanent → 1.35

Variable → 1.35

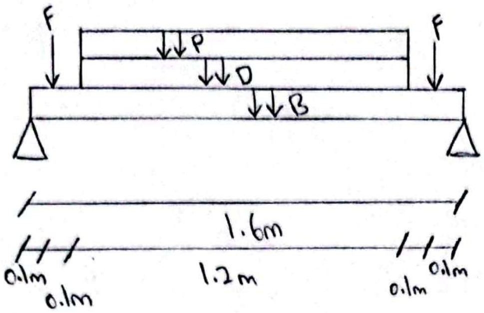
Loads with S.F.

B_1 = 6.083 kN/m

D = 2.835 kN/m

P = 5.4 kN/m

Cross-sectional direction



Bridge slab $= B_1 = 2252.75\,kg/m^3 \times 1m \times 0.25m$

$= 563.188\,kg/m \rightarrow 5.632\,kN/m$

Bridge deck $= D_1 = 1050\,kg/m^3 \times 1m \times 0.25m$

$= 262.5\,kg/m^3 \rightarrow 2.625\,kN/m$

Pedestrian live load $= P_1 = 5\,kN/m^2 \times 1m$

$= 5\,kN/m$

Balustrade $= F_1 = \dfrac{771.644\,kg}{11}$

$= 70.149\,kg \rightarrow 0.701\,kN$

Loads

Permanent $= B \times 1.6m + D \times 1.2m + F \times 2$

$= 13.563\,kN$

Variable $= P \times 1.2m$

$= 6\,kN$

Total with S.F. $= 26.410\,kN$

Safety factors (S.F.)

Permanent $\rightarrow 1.35$

Variable $\rightarrow 1.35$

Loads with S.F.

$B = 7.603\,kN/m$

$D = 3.544\,kN/m$

$P = 6.75\,kN/m$

$F = 0.946\,kN$

Appendix D (AutoCAD drawings)

The AutoCAD drawings have been attached in an external PDF file called 'AutoCAD drawings (bridge)'.