Preface

As a designer you put products in the world, which makes you responsible for them. From the beginning of my bachelor I knew I didn’t want to be a designer of just more and more consumer goods serving human needs that weren’t even there before the product existed, without realizing the consequences.

In my bachelor, and even more so during my masters I took every opportunity to learn about all aspects of sustainability design. It encourages me to meet more and more students with similar visions that want to contribute to a more sustainable way of living.

In this graduation project everything fell in place. It gave me the opportunity contribute to a direct design problem with direct results and with a bigger vision of re-evaluating the whole civil sector behind it.

I want to thank the people at IGWR, especially Leon Dijk and William Schutte, for giving me input and being my sparring partner when needed; and for introducing me to the right people, giving me the opportunity to broaden my knowledge and make this project into a success.

My supervisory team, Joost Vogtländer and Anton Heidweiler: thanks for the detailed feedback on the process and for sharing the great expert knowledge on sustainable materials and civil engineering.

Thanks to my parents and brothers, friends and family; for just being there and letting me know I always had your support. Wouter, for staying supportive even if I wasn’t the nicest person to live with in stressful situations - you know I love you.

Meike van den Broek
September 2012

Abstract

In the upcoming years a few hundreds of pedestrian bridges in Rotterdam have to be replaced. At Agentschap NL and at Ingenieursbureau Gemeente-werken Rotterdam (IGWR) there is the desire to take sustainability into account when replacing pedestrian's bridges. There was however not much information available yet about the criteria that make a bridge sustainable, and how to incorporate sustainability in the civil design process.

During this graduation project a manual is designed that gives practical guidelines specifically targeted at the sustainable design of pedestrian's bridges.

The manual has two goals: To introduce a new design process, in which sustainability is an integrated criterium; and to give visual information on what makes a bridge sustainable.

Part 1 of this report describes the research done to come up with a new design process, integrating sustainability with respect to the habits, ways of working and thinking of civil engineers. The requirements for the manual are set based on this research.

Part 2 describes the research to the sustainability of the pedestrians bridges. Different materializations are investigated, based on rules of thumb used by the civil engineers in their process. The graphs given in the manual are based on this research.

The content of the manual, which is based on the outcomes of the research described in parts 1 and 2, is described in part 3.

To test and evaluate the manual, and to provide the readers of the manual with an example on how to use it in practice; a case from practice at IGWR is investigated using the manual. This is described in part 4.

Part 5 is the evaluation of the manual and the project.
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Part 1
Design process analysis
1. Introduction

Commissioned by Agentschap NL, within the program ‘Groene Performance Chemie’, research is done to sustainable materials for bridges. In cooperation with Ingenieursbureau Gemeentewerken Rotterdam (IGWR) the research focuses on how the sustainability performance of a pedestrian’s bridge can be influenced by the design process. To design a sustainable bridge a practical manual is needed, combining civil-technical and sustainability criteria. The manual will include: 1) guidelines for controlling the design process itself, and 2) information and rules of thumb for making the right decisions during the design process. For the IGWR this manual will be valuable, since many of the 775 pedestrian’s bridges will be replaced in the upcoming years and the IGWR has the desire to do this in a sustainable way. To end with a sustainable design, it is important to take this criterium into account early in the design process.

Early in the design process, little is fixed and no big investments are made, therefore there is still a lot of freedom to change the design. A downside of this is that there is not much information available about the design. On the other hand, at the end of the design process the total design is already fixed, a lot of time and money is spend, and to change things is costly. There is however a lot of information available about the design. This dilemma is made visible in figure 1.

To make a full LCA much information is needed about the design. For that reason a LCA is made at the end of the design process, when the design is finished. However, when the design doesn’t score well on the LCA, not much can be improved.

To make really innovative improvements it is needed to take sustainability into account during the whole design process. The manual will for that reason take the design process as a starting point, and focuses in particular on the first phases of this design process: the initiation phase and the preliminary design phase.

To be able to make a manual which fits in the design process of the engineers at the Ingenieursbureau, their process needed to be analyzed. The research goals and questions of this analysis, the methods used and the results of the research will be explained in the next chapters.

2. Problem statement and goals

2.1 Problem statement
At Agentschap NL and at Ingenieursbureau Gemeentewerken Rotterdam there is the desire to...
take sustainability into account when replacing pedestrian’s bridges. There is however not much information available about what criteria make a bridge sustainable, and what the influence of the material choice and other design choices are on the sustainability value.

Thus, there is a need for a manual which gives practical guidelines specifically targeted at the design of pedestrian’s bridges. These guidelines have to make sure that, if implemented well in the design process, the resulting bridge is optimally sustainable.

A pedestrian’s bridge, when referred to in this report, means a bridge suitable for pedestrians and bikers and, if the bridge is big enough, for an incidental emergency vehicle. The scope of this project is limited to bridges up to 25 meters long and 5 meters broad. If this report or other documentation about this project talks about a pedestrian’s bridge, or a bridge, a bridge within these limits is referred to.

2.2 Goals
The graduation assignment can be split in three goals:
1. To include sustainability in the current design process of pedestrian bridges.
2. To research what is a sustainable bridge, and how to make a responsible material choice.
3. To apply these in an example bridge to evaluate the results.

3. Research goals, questions and methods

3.1 Goals of the research
One of the goals of this graduation is to alter the design process in such a way sustainability is taken into account as a logic and natural thing to do during the whole process. To be able to find out how this can be done, the current design process needs to be analyzed. Parallel to that, other design processes, from both civil and product design and with and without sustainability taken into account, are analyzed. This will make clear what differences in approach there are and in what way sustainability is already integrated in other design processes.

3.2 Research questions
1. How is the current design process at Ingenieursbureau Rotterdam structured?
2. What are the reasons this is the structure followed?
3. What are problems and gaps in this design process?
4. How does the design process in practice differ from a theoretical design process?
5. How does the design process in civil engineering differ from a process in product design where sustainability already is integrated?
6. What would be the ideal design process and how is sustainability integrated?
7. Would this design process be likely to work in the practical situation at IGWR?

3.3 Methods
To analyse the different design processes, a combination of interviews and literature research are done.

To answer the first three research questions, interviews are done with one of the project team leaders and one of the overseers after which the results are validated with other civil engineers and overseers.

To analyse the standard method at TU Delft an interview is combined with literature research. To analyse other processes literature research is done.
Designing Sustainable Bridges

Figure 2: Current Design Process at IGWR
4. Analysis of the current design process

4.1 Scheme
Figure 2 shows the design process at IGWR. This figure is based on an interview done with William Schutte, who is civil engineer of bridges the IGWR. The outcomes of this interview are schematized. Feedback on this scheme is gathered from other civil engineers and overseers, and included in the final scheme and described in the following paragraphs.

It has to be noticed that in practice the design process is not very explicit. Many steps and crucial decisions (like the material choice) are made implicit, in the heads of people.

4.2 Phases
4.2.1 Initiation
The bridges are managed by an overseer, who is responsible for the maintenance of the bridge. If the bridge has to be replaced, the overseer gives instruction to the IGWR. A Requirements Plan (Plan van Eisen) is made with the requirements for the new bridge. These are technical requirements (length, capacity) but also easy to maintain is an important requirement and the costs during the whole lifecycle are taken into account.

The requirements used to be very restrictive, often even including material already. Nowadays the requirements are based on function and not specifying how this function has to be fulfilled (for example: 'make it possible for people to go to the other side of the water', instead of 'place a bridge with steel beams, composite deck and wooden railings').

4.2.2 Architect
Sometimes but not always an architect is involved in the process. One-on-one replacements until now are usually done without an architect. At the moment many bridges are about to be replaced in clusters. Per cluster there is a design by an architect, this will create a unity in the city. These designs stay available to use for replacements of bridges later on. Only on special occasions an architect is involved for a one-on-one replacement, for example for a one-of-a-kind innovative type of bridge in the city center, which gives charisma to the city.

If an architect is involved, this is someone from an outside company. At the IGWR this architect is mainly responsible for the outside shape of the bridge. After delivering the concept for the exterior of the bridge, he or she is not further involved in the design process. Other engineering offices have often own architects, who play a bigger role in the whole design process.

The architect is contracted by the client. If the architect has to take sustainability into account, the client, being overseer or dS+V needs to know how to communicate this to the architect and how to evaluate the design.

4.2.3 Preliminary Design
The Preliminary Design is the phase in which demands and wishes are translated into a design, a product. Contradicting requirements (including costs) are weighted, choices are made, which leads to a preliminary design. Because this is the phase in the process where the ideas and requirements are materialized, where the crucial decisions are made, this phase is researched more thoroughly. In figure 3 the details of this process are visualized.

Although visualized as linear, it is in fact an iterative process. Different possibilities and variations are formed, which are evaluated with the requirements of the different stakeholders. Usually this process is not very explicit. The decisions are made based on previous experience and 'gut feeling'.
A bridge has a lot of properties, like length, mass, material, kind of railing, etcetera. These properties are set during the preliminary design. The
properties influence each other, if one dimension changes, others automatically have to change too. How these influences are is visualized in figure 4. Designing a bridge means choosing the optimal properties for the situation.

Because this gives a rather complicated diagram, it is researched if there could be identified a hierarchy in the properties. Which requirements are regarded most important by the designers and decided upon first, and which ones automatically follow from there. This hierarchy is visualized in figure 5.

This diagram makes clear which properties are dealt with first, and which follow. The further on in the process, the more is properties are fixed, so the less freedom there is for the remaining properties. Note that there is a difference between basic (mechanical) properties (blue) and deductions (red). Costs, maintenance, sustainability and building time follow from the pure mechanical properties like material and geometrics.

Traditionally these deducted properties are last in the hierarchy. Because life cycle costs and maintenance are considered very important by overseer, these are put high in the hierarchy. The mechanical properties are decided upon with costs and maintenance in mind. This way, a low-cost, low maintenance product can be reached. The purpose of the manual is to give a guideline to bring also sustainability issues higher in the hierarchy.

4.2.4 Final design
In the final design phase more details are added to the design. Not much can be changed anymore to the core properties. Traditionally this phase is done by the IGWR, but nowadays a lot of detailing is done by the contractor.

4.2.5 Statement of work
The writing of the statement of work is an important phase because now the responsibility goes from the IGWR to the contractor. Traditionally the procedure of contracting is based on lowest price. Sustainability requirements can be stated, but there is no motivation for the contractor to be more sustainable than asked for, although he might have the skills to do so. More and more often different forms are used. This opens up possibilities for contracting based on best sustainability value,
Requirements related to each other

Figure 4: Properties influencing each other

Properties in the design process

1. A bridge is meant to make a certain traffic capacity able to cross water or an obstacle. This leads to fixed properties.

2. The slope will determine the accessibility (in the building code), the span influences the free space under the bridge (water board). These are conflicting requirements that lead to a compromise. Low in maintenance and costs are important requirements set by the overseer.

3. Because of the compromise between span and slope the overall shape is set. Material and geometry are chosen based on the primary and secondary requirements.

4. The height follows from the material combined with the span (rules of thumb). The mass and the statical system are set.

5. The mass (and statical system) determines the foundation. The length profile except for the handrail is now complete.

6. Detailing like handrail and colour are decided upon in the end. These refine the properties of the length profile but haven't much influence on the properties of the bridge.

7. The kind of material, the way of construction and the needed foundation will set the construction time / nuance and the sustainability generally. Because these are not (yet) weighty requirements that are included from the beginning these are properties that automatically follow. This is also the stage in which maintenance and LCC are definately set.

Figure 5: Properties of the design hierarchical
4.2.6 Use phase and end-of-life phase

In the use phase the bridge is the overseer’s responsibility. The overseer decides which maintenance is needed and when the bridge has to be replaced. There are three main reasons to replace a bridge:

1. Technical value. The technical lifetime has exceeded, the bridge is not safe anymore and maintenance is no longer profitable.

2. Use value. The functional requirements have changed, so the bridge is no longer sufficient, for example: the bridge has to be broader due to increase in traffic load, or a separate road for bikers is needed. Because technically the bridge is still valuable, it would be desirable to be able to move the bridge to another location. The current bridges aren’t suitable for this.

3. This counts for the now existing wooden bridges. When the bridges were placed, financing was determined for the theoretical technical lifetime. For a wooden bridge this is 25 years. After this 25 years there is no financing for maintenance anymore causing the bridge to degrade fast and a replacement will be needed soon.

Besides these reasons politics play an important role. Every new alderman has new plans with the public space, influencing the functional lifetime of bridges. A political lifetime so too say. Overseer has to take into account the objectives of the board of alderman. These objectives are for example about the traffic flow in the city center, overseer is then responsible for fast maintenance with new techniques to ensure this.

4.3 Stakeholders analysis

In the design of pedestrian’s bridges the engineers have the end responsibility. They have to take into account the requirements and wishes of other stakeholders involved. Some stakeholders are people who receive instructions from the engineers, for example the drawer of the technical drawings and the statement of work writer. Other stakeholders are not directly involved but have requirements and wishes, for example the users of the bridge and the Water Board. Besides the stakeholders there are also other influences on the design, for
example the building code and the landscape. In figure 6 the stakeholders and their relation to the design team are visualized. The stakeholders and influences have requirements and wishes for the bridge and therefore influence different aspects the design, as shown in table 1. The requirements for the stakeholders have to be taken into account when making decisions on the aspects that are influenced.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>is responsible for</th>
<th>Demands/wishes</th>
<th>Has influence on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineer</td>
<td>usefulness /feasibility /repairability /foundation /contracting</td>
<td>not much maintenance / cheap (life cycle) / easy to maintain / easy to inspect</td>
<td>maintenance, lifecycle costs, maximum load, building time/ annoyance, sustainability span, material, length profile building time/ annoyance building time/ annoyance</td>
</tr>
<tr>
<td>Overseer</td>
<td>maintenance /inspection /request for replacement /financing</td>
<td>maximum load, with, shape shape, thickness, length profile, material, color, handrail maximum load, foundation, handrail, sustainability</td>
<td></td>
</tr>
<tr>
<td>Water board</td>
<td>water</td>
<td>maximum load, with, shape shape, thickness, length profile, material, color, handrail maximum load, foundation, handrail, sustainability</td>
<td></td>
</tr>
<tr>
<td>Residents</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Werf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DStV</td>
<td>shape /aesthetics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Architect</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building code</td>
<td>strength /sustainability /general</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landscape</td>
<td>environment influences</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Stakeholders, their requirements and influences

5. Analysis of other design processes

5.1 Introduction
A few other design processes are analyzed. The goal of this further analysis is on one hand to get a broader scope of the civil design process, and on the other hand to get a better idea on how sustainability already is integrated in other design processes (product design). The broader view is necessary because the manual should not only be useful for Rotterdam, but also for other engineers. Also the design process in Rotterdam is rather implicit, while the method as taught at TU Delft Civil Engineering is explicit. The analysis of the product design process is to gain awareness on how sustainability can be integrated in an existing design process.

5.2 TU Delft Civil Engineering
At the Civil Engineering department of TU Delft a process it taught which has more explicit steps than the process in Rotterdam. This theoretical civil design process is analyzed by interviewing Shahid Suddle, teacher of design processes at Civil Engineering, TU Delft and conducting a literature research on dictations of design courses from the faculty of Civil Engineering at TU Delft [2],[3],[4],[5]. This method is again summarized in a scheme and evaluated at TU Delft. In figure 7 the resulting scheme is shown. This process is compared with the process at the IGWR to gain a better understanding on why the process is the way it is and where the opportunities for improvement are.
Designing Sustainable bridges

Figure 7: Design process TU Delft Civil Engineering
Notable is that especially the feasibility study is more explicit in the scheme. At the IGWR this is partly done by the client in the initiative phase and partly in the preliminary design phase. Also the phases in Rotterdam are gone through more quickly due to deadlines, there is no time to do everything as thorough as prescribed by TU Delft. Another remarkable thing is the role of the architect, which isn’t mentioned explicitly in the TU Delft process (because in the student projects there is no collaboration with architects). In Rotterdam there is sometimes an architect from outside, whose role is restricted to the beginning of the design process.

5.3 CROW (sustainable)
The CROW, a knowledge platform for civil engineering, recently published the ’handboek specificeren’, a manual about system engineering (CROW, 2011, 1) [6]. Included was information about sustainability (CROW, 2011, 2) [7]. This is an attempt to create awareness and knowledge about sustainability in civil engineering, from another viewpoint. Figure 8 shows the scheme distilled from this ‘handboek specificeren’ and the information about specifying sustainability.

Remarkable in this design process is that after every phase a report is composed which looks back on the previous phase and forward to the next phase. This way of evaluating makes information about the design process and the results explicit and checkable. Information doesn’t get lost during the design process. Previous projects can be used as an example, so the process and the results can be improved in an iterative way. Also requirements concerning sustainability are evaluated in this way.

5.4 Design for Sustainability
In other design fields, like product design, there are already methods available to integrate sustainability. In the search for such methods for civil design, it is a good starting point to analyze these existing methods and see if they can be of use in these processes as well.

With the use of literature these methods are analyzed both theoretically -for which the UNEP Design for Sustainability manual (CRUL & Diehl, 2009) [8] is taken as a base- and in practice -by analyzing graduation reports from Industrial Design Engineering [9-14] for aspects of sustainability integrated in the process. These processes are put in the same scheme format as the civil engineering processes to be able to compare. (figure 9).

In the first phase the company’s drivers and concerns are identified, based on which a project is defined, for example a product to redesign. For this project the internal and external drivers identified, based on which objectives are set. The sustainability impact of the current product is assessed, which gives a focus for improvement. Strategies are chosen based on both analyzes and ideas are generated based on the strategies. The feasible ideas are worked out to concepts and evaluated using the set objectives. The final product is evaluated by comparing it to the previous version.

6 Principles as a result of the design processes

6.1 Develop a practical definition for sustainability
‘Sustainability’ is a very general concept. A definition for sustainability widely used is ‘a sustainable development is a development that meets present needs without compromising the ability of the future generations to meet their needs’ (WECD, 1987) [15]. This definition is complete and correct, but it isn’t a definition that is practical to use in a design process.

In the civil sector there is awareness about sustainability, but not known is how to make sustainable choices and how to integrate sustainability in the
Design process CROW

**Figure 8: Design process according to CROW, following the principles of functional specification, applied on sustainability issues**
Design process CROW sustainable

**Input**
- client requirements specification - chose sustainability theme

**Activities:**
- what is the goal for sustainability?
- balance people/planet/profit with most chances and least costs
- look beyond project framework

**Translate requirements to design**
- also evaluate People aspects
- in the V&V report requirements are evaluated; also evaluate sustainability, for example in DuboCalc.
- don't oversize

Extra attention for phase transitions like contracting and delivery. These are the weak points in the process where often much knowledge and ambition concerning sustainability is lost. The Systems Engineering process makes sure knowledge about the design is better maintained during the lifetime by means of the V&V report; also sustainability information needs to be transferred.
Figure 9: Sustainable product design process, based on the UNEP D4S manual and graduation reports from TU Delft
D4S strategy and design brief
- choose strategies from the strategy wheel based on D4S drivers (2) and D4S impact assessment (2)
- write a final evaluation
- write a design brief including results and conclusions from previous steps

Idea generation and selection
- generate ideas applying earlier documentation and creative techniques
- select and develop ideas
- cluster the improvement options to D4S strategies

Concept development
- generate concepts from ideas using morphological chart or other techniques
- assess feasibility of concepts
- evaluate concepts using product specification (design brief)
- develop production and marketing plan

D4S evaluation
- compare new design to previous product
- estimate sustainability merits as quantitative as possible
- use drivers and goals defined in step 2

Implementation and follow up
- prepare a communication strategy
- keep evaluating sustainability performance of product:
  - prototyping: test actual sustainability
  - marketing: test customer reaction
daily work situation. Sustainability is often regarded as durability only: a bridge with a long lifetime. There is no time to do an elaborate sustainability evaluation for every project separately, to take every aspect into account; so clear guidelines are needed.

The definition needs to make sustainability measurable for bridges, to be able to evaluate the sustainability of an idea or product. This will help to make substantiated choices early in the design process.

In the building sector there are already more guidelines, but much focus is on minimizing the energy consumption in the use period. For housing and utility this phase has the most impact. In civil constructions the energy consumption in the use phase is almost zero, and energy and material usage in the construction phase are more important. Awareness should not only be created in the IGWR, all the stakeholders need to be informed, so sustainable decisions are made through the whole lifecycle of the bridge. An important phase is when the construction of the bridge is contracted. The measurable definition should be used to be able to contract on sustainability grounds instead of on lowest price only.

6.2 Make the design process explicit and checkable

The design process as used is very diffuse. Decisions made are often not explicit, the reasoning happens in the head of the engineers. From outside it is not possible to evaluate on which ground the decisions are made. By making this process explicit, it is checkable which will improve the overall quality and the sustainability of the result in an

Figure 10: Design processes compared
iterative way.

6.3 Make information about materials explicit
This principle is comparable to the last one. Decisions, for example about materials, are based on information known to the engineer. The engineer often has a favorite material because he knows the properties and possibilities of this material. Making this information -about properties and possibilities of the materials- explicit, will lead to a product that is better suitable for the situation and is more sustainable. This could be done by making LCA's.

6.4 Make information about the design explicit
A lot of information, for example about sustainability, gets lost during the design- and realization processes. This is because the information is implicit and isn't transferred to the next phase (with different people responsible). For example: the contractor doesn't know on which base decisions are made and will make changes to them (especially with small bridges, because much of the detailing is left to be done by the contractor). (Parts of) modern concepts which make information explicit (for example the Bouw Informatie Model [16] or the Living Buildings Concept (de Ridder, 2006)[17]) can be used to make sure this information is kept, which leads to a more sustainable end result.

Specifically talking about sustainability, this process is called the erosion of sustainability. The ambition in the beginning of the project is high, but degrades if the criteria are not evaluated and refreshed in the mind after every step in the design process.

A lot of pedestrian's bridges are comparable. However, barely can be learned from previous design processes and results because these aren’t explicit and documented. By using standardized ways to document, an iterative improvement can be done using earlier projects, which results in a more and more sustainable result.

6.5 Budgets
Budgets allocated to (departments within) the municipality (like budgets for the replacement of bridges), are usually based on expenses the year before. This causes receivers wanting to spend the money and secure their budget for the year after. Money which isn't spend is apparently not needed and will be reduced next year. If money is left, projects are started (for example replacement of bridges) even though it isn't really needed yet, simply because the budget has to be spent. The project has to be finished within the calendar year

(because the budget can’t be taken to the next year), which causes time pressure. Decisions (for example about the design and material usage) are made hastily, there is no time for a solid design process.

A solution would be not to plan in the current

\[ \text{Figure 11: Erosion of sustainability ambition, prevented by evaluation and planning} \]
calendar year, but see what projects have to be planned for the next year, with next year’s budget. This gives time to think about how these projects have to be done, and sustainability can be taken into account.

7. New design process, as proposed in the manual

Based on the research of the current design process and other design processes, a new design process is proposed in the manual. Sustainability is part of the new design process from the early beginning. To prevent loss of information and erosion of sustainability, evaluation steps are included. Described in the manual is what these evaluation steps should entail and example documentation strategies are offered. After every design phase the goals set on beforehand should be checked and goals should be made for the next design phase, and decisions made should be documented. In figure 12 this process is visualized.

8. Requirements for the manual

Based on research on the design process and the life cycle analysis of bridges, the following list of requirements is set for the manual:

• The manual should explain sustainability, the need for sustainable design and the benefits of it.
• The manual should propose a new design process, explaining the necessity of involving sustainability from the start.
• The sustainability ambition loss and the way to prevent this, by evaluation and documentation, should be explained.
• The manual should be practical: it should not ask a lot of extra time or effort, and should not have a steep learning curve for understanding how to apply it. It should be directly usable in the design process.
• The results of the life cycle analysis should be visualized in a clear way, providing direct information fitting in the different steps of the design process.
• The manual should give information about methods that can be used in the design process of a sustainable bridge, besides the material choice.
• For the discussed materializations, the manual should give advice on how these bridges could be made more sustainable. This by providing information about the biggest contributors to ecocosts (lifetime phase or part) and methods to improve the ecocosts of the biggest contributor.
• The manual should provide with information on how to design a sustainable bridge which differs from the standard bridges in the LCA’s: what is the direction to go and things to keep in mind during the process.

The graphs included in the manual should contain:

• Ecocosts of the materializations compared, for different lengths and widths.
• Ecocosts compared to lifecycle costs.
• Ecocosts of the different phases (materials, maintenance, construction) of the lifetime of a bridge.
• Ecocosts of the different parts of the bridge.
• Ecocosts of other materials that might be interesting for bridges, in relation to their strength and costs.
Figure 12: Design process as proposed in the manual

### Design process - proposal for the manual

**Initiation**
- The client notices a demand for a new bridge (new or replacement).
- Gives instruction to start the design process.
- Output: Program of Wishes

**Team and planning**
- Team is composed and division of roles is determined.
- A planning is made for the time and budget.
- Output: Planning

**Client requirement specification sustainability drivers en impact**
- A Program of Requirements is made with:
  - Stakeholders analysis
  - Environmental analysis
  - Sustainability opportunity analysis
  - Consideration conflicting wishes
- Output: Program of Requirements (PvE)

**Idea generation (preliminary design phase)**
- Brainstorm about possible (partial) solutions
- With tools like the morphological chart concepts are composed
- These are checked with the PvE
- Output: preliminary design

**Concept development (final design, statement of work)**
- Chosen concept is further developed and detailed
- (Details concerning contracting are set)
- Work plan is composed
- Checked with the PvE
- Output: final design, statement of work

**Realisation**
- Bridge is build according to work plan
- Overseer plan is composed
- Divisions from the design are recorded in the overseer plan
- Checked with PvE and work plan
- Output: bridge, overseer manual

**Use and overseer**
- In the overseer manual guidelines are given for maintenance
- The overseer manual is kept up to date if there are changes in maintenance and use
- Output: end functional lifetime of bridge

**End of life phase**
- If there is still technical lifetime: adjustment (broadening) or replacement to prolong lifetime
- If not possible: discard as in overseer plan or on the most sustainable way.
- Output: rest material, evaluation

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**Meike van den Broek**
Part 2
Sustainability
9. Principles for sustainability

9.1 Practical definition sustainability

A sustainable bridge (or product in general) has -of course- low ecocosts; but this is not the only criterium to define sustainability. If the low-ecocost version of the product has for example a much shorter lifetime and thus has to be replaced more often, the total ecocosts can be much higher than that of the higher-ecocost version. Another example: if no one wants to buy the low-ecocost version; because it is much more expensive or less attractive compared to the higher-ecocost version, it doesn’t solve anything. A more elaborate definition is required:

A sustainable bridge is a bridge that, within the functional and technical requirements during a functional lifetime, favorable ratio between costs, value and ecocosts; as shown in figure 13. In other words: the ‘value-for-(money+ecocosts)’ has to be as high as possible. It is important that the share of the ecocosts in the total costs is low. Value is the total value, specified by the use value, the experience value and the technical value (Explanation in chapter 9.1.1). Ecocosts are explained in chapter 9.2.

In the manual the focus is on reducing the ecocosts, for example in material choice, to increase the difference between total costs and the value. The ecocosts, costs and value are not independent to each other. If reducing the ecocosts results in a strong increase of the costs, the design will not be feasible and therefore will not be sustainable. ‘Profit’ is therefore an important part of sustainability. A way to reduce the ecocost, measured for the lifetime of the object, is to prolong the functional lifetime. This means: preserve the use-, experience- and technical value over a longer time.

9.1.1 Value

The definition of value used in the definition of sustainability as described in this report comes from (de Ridder, 2006) [17]. According to this book there are 3 types of value: use value, experience value and technical value. These will be explained shortly below:

Use value: the degree to which a building is used; this is determined by the functionality. In case of a pedestrians bridge the use value is for example that people can cross the water at that location

Experience value: the degree to which a building is appreciated. In case of a bridge this is in the aesthetics. A beautiful bridge is appreciated apart from its function. The aesthetics of a bridge are significantly determined by the architect (if involved).

Technical value, often called future value: the degree to which a building is ‘fit for purpose’ and ‘up to date. It is related to the (technical) properties. In case of a bridge, this includes safety and maintain-
ability, but also space for changing requirements in the future. These values can theoretically be expressed in money, this makes it easier to compare. In practice this is however difficult because the value of the bridge is subjective. For the end user the value is in definition not expressed in money because the value is consumed. Important is that the (sense of) total value is higher than the total costs. The total value is not the sum of the three value types, it is the sum of the weighted value types. For a pedestrians bridge the technical value and the use value are usually dominant, where the technical value partly defines the use value, and the use value answers the question if the bridge stays or is demolished. A distinct bridge has besides that a high experience value, that determines if (with maintenance) the technical and use value are lengthened, instead of demolishing the bridge.

9.2 Ecocosts
9.2.1 Ecocosts
In the data for the manual, the Eco Value Ratio (EVR) model [18] is used. Ecocosts are used as an indicator for environmental burden. These ecocosts are calculated by the sum of so called marginal prevention costs, which are toxic emissions, materials depletion and energy consumption. It indicates the costs required to bring back the environmental burden to a sustainable level.

A sustainable level means that the estimated carrying capacity of the earth is not exceeded. The carrying capacity is the number of individuals an environment can support without significant negative impacts to the given organism and its environment. This is called the ‘no-effect-level’.

Figure 14: The main structure of ecocosts as a single indicator of LCA
To keep the environmental burden in control a society (the government) has to take measures. For a car, examples of measures would be particulate filter, a cleaner engine, use biofuels, or even electricity or hydrogen. More than one measure will be needed to reach the goals for sustainability (the no-effect-level). The effect of these measures, plotted against their costs give a curve, as depicted in figure 15. The measures will be executed in order, the cheapest (in euro/kg) first, followed by more expensive measures. On a certain point the measures will have enough effect to reach the no-effect-level. The measures are virtual costs. Since our society is yet far from sustainable, the needed measures to bring pollution and material depletion back to the earth’s carrying capacity aren’t actually taken. The measures are formed by the costs/kg at that point (the tangent of the curve). The measures are therefore estimated based on a ‘what if’ scenario. In other words: the measures indicate to what extend a product or service is not yet environmentally sustainable.

All ecocosts of a product should be added “from cradle to grave”, ecocosts for raw materials, production, use, maintenance and recycling should be summed. The calculation model includes both direct and indirect components, examples of indirect components are the environmental impacts of labour (office heating and lighting, computers, commuting, etcetera) and production assets (equipment, buildings, transport vehicles, etcetera).

9.2.2 Other methods of calculating the environmental burden [19]

Indicators for LCA can be divided in three categories: single issue, damage based and prevention based.

The EVR model is a prevention based method. Calculated are the costs it takes to prevent the damage (exceeding the earth’s carrying capacity) from happening.

The carbon footprint is an example of a single issue indicator. Only the total emissions of kg CO2 are calculated. The advantage is that no complex assumptions are made, it is transparent and easy to communicate to the public. Disadvantage is that problems caused by other pollutants and by material depletion are not taken into account.

The third category is that of the damage based methods. These methods calculate the costs it takes to undo the environmental damage done by a certain product or service. It raises awareness in people and companies to consume less and produce cleaner. Calculations however are very complex and not transparent at all. The system is based on many assumptions and suffers from a subjective weighting procedure. (E.g. how do you calculate the value of a human life, or a piece of nature?) Communication of these systems is not easy; since the results are expressed in points instead of money.
Besides EVR, there are other prevention based systems, for example the ‘shadow prices’ system developed in 2004 by TNO/MEP. This is a local Dutch method which is based on the costs of the most expensive prevention measure required by the Dutch government for each midpoint. Because these costs are no longer virtual, this is relevant for Dutch companies. However, it is based on political decisions instead of the ‘no-effect-level’, which makes it less universal. Outside the Netherlands it doesn’t have any meaning.

9.3 Lifetime

In civil engineering, often is designed for the technical lifetime (how long will the bridge last, regarding the mechanical properties of the materials). A high technical lifetime is seen as sustainable, the higher the technical lifetime the better (de Rieder, 2006) [17]. The situation in Rotterdam is that a bridge is that a lifetime of 50 to 100 years is always dictated by the overseer, although in many cases the expected functional lifetime is much shorter. It is often better to take into account the functional lifetime (how long will a bridge really be satisfying in practice). A technical lifetime that is (much) higher than the functional lifetime is not sustainable. Premature demolishing will cause waste material which didn’t reach the technical lifetime and will thus last for a long time. Designed should be for the (expected) functional lifetime, and this is what should be crucial in the decision for materials. Ecocosts have to be specified to functional lifetime.

In practice it is however difficult to design for functional lifetime. The functional lifetime is determined by different outside influencers, including politics which can change drastically every four years. Therefore overseers will generally ask for a technical lifetime which is as long as possible, just to be sure.

Another approach is to prolong the functional lifetime to make this more in line with the technical lifetime. For example by re-use. Downside is that bridges and other civil buildings are always specific for the environment, and environments are unique. For taking a bridge apart and rebuild it elsewhere by hand, a lot of manpower is needed, and manpower is expensive. Designs are influenced by time, trends are more and more important, and the preference will be a modern bridge, instead of an old-fashioned 20 years old bridge.

Standardized and modular design could be an interesting view. A bridge could be made suitable for the specific circumstances. For example by adding elements or slide elements a bridge can be made...
longer to fit on another location. And, when broken only one part has to be replaced. A disadvantage of building in a standardized way is however that the bridge is not specially tailored at the situation, so more material then strictly needed might be used. The same holds for a modular bridge, extra parts or overdimensioned parts might be needed (to make it extendable for example). This strategy should only be chosen if benifiting from the added functionality is very likely to happen.

10. Life Cycle Analysis

10.1 Introduction
To compare the different materializations of a pedestrians bridge, standard pedestrians bridges of different materializations are compared. These are bridges are similar to the ones currently built in Rotterdam.

As explained in chapter 4.2 the manual will mainly focus on the preliminary design phase, because the choice for a material and geometry is made in this phase. As explained in chapter 1 the freedom to change the design in this early phase is still high, but there is not much information about the design yet in this phase. Therefore LCA’s in this stage are not very detailed and only give an indication about the ecocosts, it are so called fast track LCA’s. If needed a conventional LCA should be made further on in the design process.

10.2 Rules of thumb
In the preliminary design phase engineers at the IGWR use rules of thumb to estimate the sizes of the bridge. These rules of thumb are based on experience with the material and the type of bridge. In the final design phase the exact calculations are made. To calculate ecocosts early in the design process, these rules of thumb are used as a starting point. This method resembles the way engineers are used to work.

- The first of these rules of thumb is used to calculate the construction height, the ‘thickness of the bridge’, which has a linear relation with the span. The formula is: \( h = \frac{l}{C} \); in which \( h \) is the construction height, \( l \) is the span and \( C \) is a constant that is dependent on the bridge type and material.

- Another rule of thumb is the range of spans in which a type of bridge is used: the maximum span without piers or fixed bearing.

- Normally calculations on the foundation are based on the properties of the soil at the specific location (obtained by a cone penetration test) and the properties of the used poles. A rule of thumb is used to be able to give generic information per bridge type on how many poles are used. This rule of thumb is based on the average situation in Rotterdam; and gives the maximum bridge surface area per pole per bridge side. Calculations are based on the mostly used type of foundation for that bridge type.

The bridge is divided in parts, which are calculated separately: the main bearing construction, which for many types consists of beams and a deck; the foundation; the piers and the handrail. The wear layer is left out of the scope of the LCA because it is the same for every bridge. Most types of bridges can be built statically determinate (roller bearing) and statically indeterminate (fixed bearing), statically indeterminate bridges usually being applied for longer spans.

The ecocosts of the handrails are calculated, but were found not very significant compared to the ecocosts of the rest of the bridge. Besides, every handrail can be applied on every bridge. Therefore these are not taken into account when calculating the ecocosts of the bridges.

10.3 Materialisations
Below the different materializations are shortly described. The extended versions are in attachment A.

### 10.3.1 Wood
A wooden bridge is made of wood with minimum strength D50. In the manual azobé is assumed. Also Accoya wood [20] is taken into account. This is European softwood which is treated to increase the durability and strength; the ecocosts are much lower than of tropical hardwood, but the strength and durability is comparable. Wood used to be the prevailing material for pedestrian’s bridges and most bridges in Rotterdam are of this type. Nowadays wood is no longer applied much because of its high maintenance.

The bridge consists of beams, a deck, piers and handrails, all made of the same material, and fir poles for foundation. Only statically determinate wooden bridges are built.

### 10.3.2 Steel
A steel bridge is made of steel beams. For the manual IPE beams are used, and HEM beams for bigger construction heights (longer span). The deck can be made of different materials, wood and composite are calculated. The handrails are made of steel.

The bridge consists of steel beams, a wooden or composite (see composite BIJL) deck, steel handrails and concrete piers. Shallow foundations are applied for statically determinate bridges, concrete poles for statistically indeterminate bridges.

### 10.3.3 Composite BIJL
Composite is a material consisting of glass fiber and polyester resin. Also carbon composite can be applied for bridges but this is left out of the scope of the manual. There are different types of composite materials (the amount of glass fiber and the way it is oriented in the resin differs) and types of bridges. The bridges in the manual are composite bridges as designed by the companies BIJL [21] and Fibercore [22]. The BIJL design consists of standard elements for the beams, deck, handrails, etcetera.

A composite bridge as designed by BIJL consists of beams, a deck and handrails, all made of the same material, and concrete piers. Shallow foundations are applied for statically determinate bridges, fir
poles for statistically indeterminate bridges.

Figu re 19: Composite bridge according to the BIJL principle, with wooden handrail (www.damsteegtwaterwerken.nl)

10.3.4 Composite Fibercore

A composite bridge as designed by Fibercore doesn’t consist of beams and a deck. A mesh is made with composite lamellae between two composite layers. The holes are filled up with PUR foam.

Figure 20: Spaanse Bocht, Rotterdam: Fibercore composite bridge

A plate of this material forms the substructure of the bridge.

This type of bridge consists of a substructure made of the composite materials, the same handrail as the BIJL bridge, and concrete piers. Shallow foundations are applied for statically determinate bridges, fir poles for statistically indeterminate bridges.

10.3.5 Concrete plate bridge

Different types of plate bridges are applied, of which the plate bridge is the most common for pedestrian’s bridges. Conventional steel reinforcement is used.

The concrete plate bridge consists of a massive concrete plate and concrete piers. Different handrails can be applied, usually steel is used. Concrete poles are used for the foundation of both statistically determinate and statistically indeterminate bridges.

Figure 21: Hoevebrug, Spoorsingel, Provenierswijk, Rotterdam: Concrete plate bridge with steel and wooden handrail

10.3.6 Concrete prestressed

Prestressing of the reinforcement steel is a method to increase the strength of the material. A pedestri-
an’s bridge is made of prestressed material consists of prefab elements with high strength prestressing cables and conventional steel reinforcement.

The prestressed concrete bridge consists of horizontally aligned prefab elements filled with conventional reinforced concrete. Only statistically determinate prestressed bridges are applied in Rotterdam. The handrail, piers and foundation are the same as for the concrete plate bridge.

10.3.7 Concrete bearing handrail
The concrete bridge with a bearing handrail is an innovative type of bridge. Not the beams or deck are bearing the forces on the bridge, but the handrail. Normally a concrete handrail is way too heavy and plump to consider seriously. In the future a concrete handrail might become interesting because of the development of new concrete types. For now concrete handrails are only applied as bearing element. Besides as handrail, these elements also apply for bearing the deck, which makes very thin decks possible. The bridge is made with ultra-high strength concrete, reinforced with steel fibers and where needed conventional reinforcement. The handrails are built of prefab elements which are connected with 4 prestressing tendons.

The bearing handrail concrete bridge consists of prefab handrail elements and a very thin (6 centimeters) deck. The foundation and piers are the same as for other concrete bridges. Only statistically determined bridges are applied at the moment.

10.4 Scope
To compare the LCA’s for the different types of bridges, first the scope of the LCA needs to be set. Naturally, this scope needs to be the same for every bridge type to make them comparable.

The lifecycle of the bridge is taken as the starting point for setting the scope. For every phase is described what is happening at that point in the lifetime in terms of ecocosts being generated.

For the production phase the ecocosts of the materials are taken into account, as are the ecocosts of the production processes. For wood this means a 5-15% (depending on the part) addition to the amount of material, because this material is lost in the shaving process.

Because there were no data for the production of composite in the EVR sheets, there were taken from (Song, Youn & Gutowski, 2009) [25]. The energy intensities of the manufacturing techniques are converted from MJ to ecocosts in the ratio 1 MJ = 0,026 ecocosts according to [23]. BIJL profiles are made with a pultrusion process. Fibercore composite materials are manufactured with a vacuum assisted resin infusion (VARI) process.

To produce the steel beams a rolling process is used.

Transport from the production facility to the
construction site is considered negligible, all the production facilities are in or near Rotterdam, and it is difficult to give general data applicable for every bridge without knowing the exact construction site. Transport of the tropical wood to the harbor of Rotterdam is already taken into account in the ecocosts of the material.

To calculate the ecocosts made during construction and during the demolition or disassembling of the bridge, fuel use of the machinery is used as a guide. This fuel use is based on the estimated hours the machines need to build the bridge and the estimated fuel use of the machines. The machines (cranes, excavators, mixers, etcetera) themselves are left out of the scope of the LCA. Only data of bridges with a size of 12*2 meters were available.

Wood if used in bridges has a lifetime of approximately 25 years, bridges of other materials usually have a lifetime of 50-100 years. For the manual the average of 75 years is assumed. For wood both a lifetime of 25 years and a lifetime of 75 years (including 3 times replacement) are included. Steel with a wooden deck is hot-dip galvanized every 25 years. This includes taking the bridge apart and taking the beams back to the factory, and putting the bridge together again. A composite deck protects the steel better from humidity, so this maintenance will be needed less often. For all steel and wooden parts painting every 5 years is taken into account. Composite and concrete are free of maintenance.

In the building industry recycling of materials after demolition is in practice well arranged; 95-99% of the materials that can be recycled or burned for energy find their way to the best possible waste scenario. For wood and composite this is waste incineration (if the composite bridge cannot be re-used directly), for concrete this is grinding it and using it as underlayment for roads. Steel is part of a closed-loop cycle and is melted into new products.

10.5 Methods
The size of the bridge is determined by the length and the width of the bridge. The height of the bridge is calculated using rules of thumb, as explained in chapter 2.2. If these measures are known, and the design of the bridge is known, the amount of material used for the bridge can be calculated. The ecocosts concerning materials are based on these figures.

To compose the graphs in the manual these calculations are made for every materialization, for lengths between 1 and 25 meters and widths between 0,5 and 5 meters. In fact (25*10=) 250 micro-LCA’s are made for every bridge type.

The bridge consists of different parts: the substructure, which for many types consists of beams and a deck; the foundation; the supports and the handrail. The ecocosts for these parts are first calculated separately and then added. Graphs comparing the influences of each part on the total ecocosts are made.
For bridges with a length of 12 meters and a width of 2 meters more data were available; about building and demolishing the bridges and about life-cycle costs of the bridges. Comparisons including these variables were made based on the information for this size.

11. Results

11.1 Graphs
The results are visualized in the graphs in attachment B.

11.2 Wood
The ecocosts of azobe are high, mainly because the material has a lower lifetime than the others. Accoya scores very good compared to the other materialisations. With a lifetime of 25 years it is the best scoring materialization, and even with a lifetime of 75 years (including two replacements) it still scores well on all spans and widths. For a bridge of 12*2, the difference between azobe and Accoya is a factor 6.

For azobe, the bridge itself generates most of the ecocosts, the influence of construction and foundation is low. Because those factors stay the same for Accoya, while the material factor is much lower, those have bigger influence. For an Accoya bridge of 12*2, construction is responsible for almost half of the ecocosts.

Wood needs maintenance (paint), but this doesn’t contribute to the ecocosts much.

11.3 Steel
The curve for all types of steel bridges is steep. For big spans the ecocosts are very high, especially after the breakpoint where IPE beams are no longer suitable and HEM beams are used. For small spans however, up to approximately 7 meters, a statically determined bridge with a composite deck would be a very good option.

Steel be executed with a wooden or a composite deck. A composite deck scores better in all cases. The ecocosts of steel bridges are mainly caused by the material of the bridge itself: foundation, construction and maintenance have relatively lower ecocosts. The wooden deck is the main contributor, except for high spans when the HEM beams become the biggest influence. The composite deck has lower ecocosts, for steel bridges with a composite deck the beams have the biggest influence.

Steel needs maintenance. This isn’t a big contribution to the ecocosts when a composite deck is applied. For a wooden deck the contribution is bigger, because interim hot dip galvanization is required every 25 years and to do this the bridge has to be taken apart.

11.4 Composite
This material scores especially well on lower spans, but on the whole it scores quite average. When the two producers -Fibercore and BIJL- are compared, the conclusion is that in general Fibercore scores better for shorter spans and BIJL for longer spans. The breaking point differs per width but lies around 11 meters.

Because there is barely a foundation needed, the ecocosts of the foundation are negligible.

11.5 Concrete
Concrete scores excellent on middle and long spans, especially if the bridge is also wide. For a bridge of 12*2 the construction has a contribution of more than 50% in the total ecocosts, this has to be taken into account when interpreting the data.

Because of its weight, concrete needs a lot of foundation. Of all of its parts, the foundation of a concrete bridge has by far the biggest influence. Compared to the ecocosts of the foundation, those of the bridge itself are negligible.
For bearing handrail bridges this holds too, however the contribution of construction is a bit lower (40%) and contribution of the main bearing construction increases for bigger bridges at the expense of the contribution of the foundation.

12. Design strategies

The UNEP Design for sustainability manual (CRUL & Diehl, 2009) [8], 7 design strategies for sustainability innovation are given:

1. Selection of low-impact materials
2. Reduction of materials usage
3. Optimisation of production techniques
4. Optimisation of distribution system
5. Reduction of impact during use
6. Optimisation of initial lifetime
7. Optimisation of end-of-life system

Some of these strategies to reduce the ecocosts could be relevant for bridges. Dependent on the properties of the material and the scores of the materialization in the LCA’s a different strategy would be recommendable.

1. To reduce the ecocosts of the material
   a. Selection of low-impact materials
      From the options available (wood, steel, composite, concrete) a material with a low impact should be chosen, this is what the manual is about in the first place. Besides that, there are also different options within the material categories. Innovative new materials have become available, for example Accoya wood and ultra strong concrete.
   b. Reduction of material usage
      Because it is perceived as beautiful and modern, bridges are getting thinner and thinner. This is a form of reduction of material usage; less material is used for the bridge and the foundation. Therefore this is a good trend, as long as there are no materials needed with higher ecocosts to make bridges that thin, for example carbon instead of glass fiber in composite.

2. Reduce the ecocosts during production / construction
   a. Reduce machine hours / use of fuel during construction
      The ‘optimization of production techniques’ and ‘optimization of distribution system’ strategies are related to bridges interpreted as optimization of the construction phase. This means the reduction of machine hours and therefore liters of fuel.
   b. Adapt the material to the lifetime
      From the interview with the overseer followed that it wouldn’t be accepted by the overseers to contract for a shorter lifetime. Even if it is 99% sure the lifetime will not be longer than 25 years, still a bridge with a minimum lifetime of 50 to 100 years is asked for because of the 1% chance. For most materials it would barely mean less material can be used, because of the building act demanding a high strength and guaranteed durability. The only material that could be suitable for this strategy is wood. Wood has a lifetime of only 25 years, and when a long lifetime is not required this could be an interesting option.

3. Optimization of the initial lifetime
   a. Make the lifetime longer
      By ‘making the lifetime longer’ especially the functional lifetime is meant. Bridges have a long technical lifetime but are often demolished before that, because they lose their function. Reasons can be that the flow of the water changes, the traffic intensity changes, the plans with the location change and the style of all the civil art has to be adapted, etcetera.
   b. Adapt the material to the lifetime
      From the interview with the overseer followed that it wouldn’t be accepted by the overseers to contract for a shorter lifetime. Even if it is 99% sure the lifetime will not be longer than 25 years, still a bridge with a minimum lifetime of 50 to 100 years is asked for because of the 1% chance. For most materials it would barely mean less material can be used, because of the building act demanding a high strength and guaranteed durability. The only material that could be suitable for this strategy is wood. Wood has a lifetime of only 25 years, and when a long lifetime is not required this could be an interesting option.

Other design strategies

The strategies ‘Reduction of impact during use’ and ‘Optimisation of end-of-life system’ are not relevant for bridges. The impact during use would be maintenance. Maintenance doesn’t have a significant
impact on the total ecocosts. The end-of-life system in the building and civil industry is already well controlled. Materials are separated and for at least 95% the end-of-life system with the least impact is chosen. bron

13. Design strategies for materializations

13.1 Wood
Azobe wood has high ecocosts, especially when a lifetime of 75 years has to be assumed. These ecocosts are caused by the material itself. Accoya wood has good potential. Replacement of azobe (and other tropical hardwood) by Accoya would therefore be an interesting option to look into (strategy 1a).

In Rotterdam there is no experience with the Accoya material. Accoya is less strong than azobe. Most of its properties fall in the D40 category instead of the D50 category, which is currently the standard for pedestrian’s bridges and the category on which the rules of thumb are based. The data in the graphs are based on the assumption that 15% extra material would be enough to cover this, but more research on what an Accoya bridge would look like is necessary. The data so far look promising enough to do so.

Accoya would not be recommended for modular building, because of the influence of construction and foundation. It would be highly recommended to use this material if the functional lifetime of the bridge is low, up to 25 years, because then there is no need for replacement which results in very low ecocosts (strategy 1b).

Another consideration if a 100% Accoya bridge is not an option could be to use combinations of different types of wood. Tropical hardwood for the parts of the bridge that need the higher strength and types of wood with lower ecocosts but still high durability (like European oak or chestwood, or Accoya) for the rest of the bridge. This is for example demonstrated in part 5 of this report, one of the variants for the Kerkbrug is to reconstruct a similar bridge of partly azobe, partly oak.

13.2 Steel
Steel bridges used to have wooden decks, but for new steel bridges often a composite bridge is used (strategy 1a). The data show this is a good development: the wooden deck is the main contributor to the ecocosts (except for long spans). Therefore it is not surprising the ecocosts for a steel bridge with a composite deck are significantly lower. Not only are the ecocosts of the material itself lower when composite is used, also the ecocosts of maintenance will be lower. A wooden deck has cracks which let rainwater and other substances reach the steel beams. This causes a lot of necessary maintenance on the steel: it needs to be painted and once in 25 years the bridge has to be taken apart for the beams to be hot-dip galvanized. Because a composite deck doesn’t have this problem the steel beams are much better protected, and need much less maintenance (strategy 2a).

Steel is used a lot in temporary bridges, such as Bailey bridges and bridges that are used for events and during roadwork. In most cases these are modular bridges, their dimensions are adaptable to the situation. Because most of the ecocosts are in the material itself, and not in the construction or the foundation, this could be an interesting view. If the expected functional lifetime of the bridge is low, a temporary bridge could be used (semi) permanent, and adapted to the new situation or replaced to another location. This would lengthen the functional lifetime of the bridge (strategy 3a).

13.3 Composite
Composite scores quite average on the whole range. It has however quite a few advantages over the other materializations. It is very light weight,
which keeps the ecocosts of the construction and foundation very low. This is especially an advantage compared to concrete, which has high construction and foundation costs.

Although there is no practice example yet, it is claimed about composite bridges that they are reusable. They can be lift up and put down on a different location, if they become superfluous on their first location. Of course this is not possible with concrete, but even if it was, it wouldn’t be recommendable because of the high foundation and construction ecocosts compared to those of the bridge itself. For composite it would be recommendable. This measure would lengthen the lifetime of the bridge (strategy 3a).

The arguments against replacement of bridges involve that bridges are often tailor-made for the specific location / environment; and that bridges can get old fashioned. “Nobody wants a 30 years old second hand 80’s style bridge if they can get a brand new modern tailor-made one.” To make reuse of bridges possible, they have to be standardized in size. The handrail is the most striking part of the bridge, it determines the style of the bridge the most. It should be detachable, so it can easily be replaced with a handrail of a matching style for the location.

A lot of bridge replacements involve the need of a wider bridge due to the increase of traffic. It would be interesting to investigate if a composite bridge can be designed in such a way that two of the same (standardized) bridges next to each other could together form one wide bridge.

13.4 Concrete
Construction has a big impact on the ecocosts. Possible solutions to decrease the ecocosts (strategy 2a) could be to use more prefab elements, which reduces the need for in situ mixing and depositing concrete. Because foundation also has a big impact (and foundation also has a big impact on the ecocosts of the construction, a lot of piles are required), it would be a good idea to have another view on this too. Only one type of foundation is calculated now, maybe more efficient solutions are available already, or can be invented.

Because of the soil in Rotterdam, a lot of foundation is needed in general. Concrete would be interesting for locations with firmer soil: less foundation is needed which would reduce the ecocosts.

Reducing the total weight of the bridge isn’t really necessary for the ecocosts of the bridge itself, because they are already pretty low. This would however mean a reduction in the foundation material (strategy 1b) and the transportation costs during construction (strategy 2a). Therefore the research in new, stronger composite types and thinner constructions is of use.
14. Content

The manual consists of four parts. In the first part the purpose of the manual is described. In the second part general guidelines in sustainable design are explained, in the third part the different phases of the design process are described and explained is how sustainability can be integrated in that phase, in the last part an example is given.

14.1 Chapter 1: Introduction
In this chapter the who-what-why questions are answered: What is this manual? Why is it written? Who can use this manual? For what kind of problems can the manual offer a solution? What questions of the reader are going to be answered? How should this manual be read?

14.2 Chapter 2: The power of sustainability design
The definition of sustainability is explained (as in chapter 9 of this report) in this chapter. Ecocosts are introduced, and explained is why this system is chosen to calculate the environmental burden. The reasons to integrate sustainability in the design process from early on are revealed. The principle of ambition erosion (in this report: chapter 6.4) is described to emphasize the need to evaluate sustainability thorough the design.

This leads to the new design process, on which the manual is based. This new process includes sustainability in all phases and prevents ambition erosion.

14.3 Chapter 3: Before you start… the initiation phase
In chapter 3 of the manual the design process is elaborated. The properties of the bridge are related to the design process.

During this design phase the design team is formed and the stakeholders analysis is made.

The width and length of the bridge are the first properties of the bridge that are set, as shown in figure 5 in part 1. This is the reason the first graphs compare the ecocosts by these properties. The engineer can easily find what would be the recommended material choice for the situation. This does not give much information yet, just a top 3 to have a slight indication but no information about what the ecocosts of the bridges are and much difference there is between the materials. Nevertheless it can help to form the design team. If steel scores best, you might want to involve a steel expert in the team, while if composite scores better the composition of the team should be different.

Also the results of the stakeholders analysis are shown in this part of the manual, and how the properties of the bridge are related to the stakeholder. This is important when starting up a project, because this is the phase when stakeholders are brought together to share their demands, wishes and ideas. Recommendations are given on how to compose a team.

Then this chapter looks forward to the rest of the design process: how do you plan the rest of the design process, how do you set demands for sustainability, and how do you chose a contracting type to make sure sustainability criteria are met after the responsibility goes to the contractor.

14.4 Chapter 4: Preliminary design
The chapter about the preliminary design phase is the most elaborate in the manual, because this is the phase where the LCA’s come in. First the base of the LCA’s is explained: the rules of thumb. It is important for the reader to know on what bridge types the LCA’s are based, especially when changes have to be made for future versions if the bridge types that are used in Rotterdam change.

Next to the rules of thumb about the bridges themselves, similar to Attachment B in this report, a rule of thumb is given about how the construction costs are calculated for a bridge of 12*2. While testing the manual with an example bridge (part
4 of this report), it became clear that the combination of such a graph and data for fuel use of construction machinery can help to estimate the construction costs of bridges of other sizes.

Then the graphs are displayed and explained how to use them. There are graphs that compare the ecocosts of the different materializations for different widths and spans. There are also graphs that show what percentage of the ecocosts are caused by what part of the bridge (beams, deck, foundation, etcetera) and by what phase in the lifecycle of the bridge (construction, materials, use, demolishing, etcetera).

The graphs for widths and spans in this chapter are more elaborate compared to the ones in the initiation phase chapter. Like the design process, the graphs go from less to more detailed information, based on the information available about the bridge. Material choice is not only dependent on ecocosts. There are more, probably conflicting, requirements. To make a choice for a materialization, it is not enough to know only which material scores best, but it’s also interesting to know which other materials score well and how much the difference is between the materials. Not always is the materialization with the lowest ecocosts also the best choice. If the other material for example is only slightly more expensive, but has many advantages regarding other requirements, this is probably the best choice because the value of the bridge will be higher. As explained by picture 13 in part 2, the most sustainable bridge is the one with the biggest difference between value and (eco)costs.

The graphs that compare the different parts of the bridge and their share in the total ecocosts should be used to find out where improvements would be most beneficial. The same holds for the graph about the lifecycle phases and their share in the total ecocosts. If for example the foundation has by far the biggest share in the ecocosts, it does make more sense to look for a different type of foundation; than to waste time improving the ecocosts of the handrail which has only a small share.

Based on these results, recommendations are given for each material type (report chapter 10.6). Depending on the ecocosts and the distribution of the ecocosts, different strategies become interesting. For example investing in making a bridge movable would only make sense if the ecocosts of removing the bridge and placing it on another location are not exceeding the ecocosts of the materials. Aimed is for measures which have high benefits for low costs.

14.5 Chapter 5: Final design
In the final design the detailing of the bridge is done. This is the point where the rules of thumb are often not sufficient anymore, for example if a totally different type of handail is designed, or if the bridge has a non-standard length/height ratio, foundation or configuration of beams. A table of different materials, parts, processes and their ecocosts (both per kg and per m$^3$) is given. With this table the engineer can make adaptations to the calculations done in the preliminary design to get a more detailed idea of the ecocosts.

The statement of work and the contracting is also done in this phase. Referred is to the ambition erosion theory (figure 11 in part 1) and how to prevent erosion from happening in this crucial phase with recommendations for the statement of work and the type of contracting.

14.6 Chapter 6: Practice example
In part 4 of this manual a bridge is proposal is made using the manual. This bridge is also referred to in the manual itself as an example on how to use the manual in practice.

This particular example is chosen because it is a typical design question for which this manual is designed. A bridge needs to be replaced, there are different options, which one is preferrable from a sustainability point of view, how are the scores compared to the other variants, what should the
designer be aware of from a sustainability point of view if a choice for a certain material is made.

This chapter explains how answers to that sort of questions derive from the use of the manual.

14.7 Chapter 7: Sources of inspiration
In this chapter a literature and website list is given where more information and inspiration on sustainable bridge design can be found. Mainly sources used in the research for this report and the manual are given. For example the EVR website is given [18], the LCA guide [1], and the CROW booklets [6],[7] used for chapter 5.3.

The evaluation of the manual can be found in part 5 of this report. First the use of the manual in a case study is described.
Design of Sustainable Bridges

manual for civil engineers

Figure 25: Cover of the manual
Part 4

Design of a bridge using the manual
15. Introduction

To evaluate the manual, and to have an example on how the manual can be used in practice, a real life case study is done. This case study is about the replacement of the Kerkbrug. There are a few different variants that are considered. All have all kinds of advantages and disadvantages that are taken into account, but the IGWR also wants to take sustainability into account. Therefore they want to know the ecocosts of the various variants. The manual calculate and compare these ecocosts, by going through the design process as proposed and do the calculations for each step. The results will be recommendations about which variant to choose concerning ecocosts.

Figure 25: Kerkbrug. From top to bottom: Drawing from the Statement of Work from 1896; Pictures from 1910-1933; Drawing from the Statement of Work from 1982; Picture from 2009 of the current bridge
16. Example bridge

The Kerkbrug at the Povenierssingel in Rotterdam is at the end of its technical lifetime. This bridge, built in Romantic style, is built in the 19th century, and has a monumental status. This status complicates the simple replacement of the bridge with a modern one, as would be usual with a wooden bridge at the end of its lifetime. The monument committee has a preference for renovation or otherwise replacement with a bridge which is exactly the same.

Because this is a wooden bridge, and wood only has a lifetime of approximately 25 years, the current bridge obviously isn’t the original one. The current bridge is built in 1982. The design is similar to the original bridge from 1896, but there are differences, as can be seen in the picture on the previous page. The piers are different, and also the pattern in the handrail and the end of the handrail are not the same. Funny anecdote is that during the WW II the bridge did not have handrails at all, because of the desperate need for firewood. If the bridge would be replaced with the same bridge -as the monument committee wishes- the goal would be to approximate the original design and material of the bridge as close as possible.

Another approach would be to replace the bridge by a different one. The most logical choice would be to use the same design as the new Hoevebrug, which is just completed. This bridge is located nearby the Kerkbrug and is especially designed for its environment, which is the same environment as the Kerkbrug. The Hoevebrug is a concrete plate bridge with handrails which are made out of steel combined with wood. Another variant would be to use the handrails of the Hoevebrug on a composite construction.

17. Variants

There are different possibilities for the Kerkbrug, the sustainability aspects of these variants need to be compared.

17.1 Variant 1: Renovation of the current bridge

TNO did research to the quality of the wood. Ac-
According to this research, for renovation of the current bridge the following needs to be done:

- The poles of the piers need to be shortened, and a steel pin has to be inserted
- Some of the buttresses need to be replaced
- The deck has to be partly replaced
- The upper part of the handrail needs replacement
- The uprights of the handrail need to be shaved
- Parts of the detailing in the handrail has to be replaced

To shorten the poles of the piers and replace the buttresses, the bridge has to be dismantled. To replace the detailing similar branches need to be found. This variant is not preferred by the IGWR because of the big effort, limited prolongation of the lifetime and limited benefits for the monumental status.

In total about 40-50% of the material needs to be replaced.

17.2 Variant 2: Reconstruction of the original bridge
The span of the bridge is approximately 23 meters, the width is 2,5 meters. The bridge is painted and has a wear layer.

According to the statement of work from 1896 (no. 176), in total around 12,3 m$^3$ of shaved oak wood is used for the bridge (excluding the foundation).

Meanwhile the building code, concerning surface load and the strength of the handrail, has become stricter. Exception is made for renovation. Question is if total demolishing and rebuilding of the bridge is still seen as renovation.

17.3 Variant 3a: Replacement with a concrete bridge, according the design of the Hoevebrug
The Hoevebrug is a concrete plate bridge. The wished thickness of the new Kerkbrug, resembling the Hoevebrug, is a length/height ratio of 1:43, with a span of 23 meters this is 540mm.

The mass of the handrail is 1,0 kN/m. About 10% of this is tropical hardwood, the rest is steel.

17.4 Variant 3b: Replacement with a composite bridge, with the handrails according to the design of the Hoevebrug.
A glassfiber bridge with the same thickness as the Hoevebrug (with a length/height ratio of 1:43) is possible, but would be very flexible. Solution could be to include carbon fibers or to make the bridge thicker. A bridge with a ratio of 1:35 is still flexible, but 35% stiffer than 1:43. A bridge with a ratio of 1:25 – 1:27 would be ideal concerning the flexibility but would give a thick bridge.

18. Initiation phase
The initiation phase is about involving the people in the project. This includes the team at the IGWR, but also the environment: the stakeholders.

18.1 Team
In this project the team has already been composed, and there are already different variants. Normally this would be done in the initiation phase.

With a quick look on the graphs the top 3 bridges with the least sustainability impact for a bridge of 23 by 2,5 meters is:
1. Prestressed concrete bridge
2. Concrete plate bridge
3. Accoya wood bridge

Based on this top 3 a concrete bridge is most likely. It could be a consideration in composing the team to involve a concrete expert.

18.2 Stakeholders
The stakeholders and influences involved in the process and their demands, wishes and influences are:
**Overseer**
The overseer wishes low life cycle costs and low maintenance. Renovation would mean big effort and limited prolongation of the lifetime. Also reconstructing a wooden bridge would mean a high maintenance and relatively short lifetime. Both concrete and composite are free of maintenance and will be preferred by the overseer.

**Water board**
The water board has requirements about the free space under the bridge. The height of the current bridge above the water is 1.70, unclear if this is the minimum required by the waterboard. The current bridge has piers in the water, which shouldn’t be problematic for the new bridge as well.

The water board has concerns about the water quality as well. This is important in this area. Originally canal was actually made to improve the water quality and prevent cholera. Of course cholera is not an issue anymore but water quality is, nowadays more focussed on the amount of fish in the water. With replacement of the timbering which is already done this was taken into account. With the materialisations that are proposed, water quality is not likely to be affected.

**Residents / Werf**
The bridge is frequently used by people in the neighborhood. Although they can use the nearby Hoevebrug or walk around the canal, they of course prefer the construction work to be finished fast.

The bridge is closeby buildings. For the people living there, short construction time and as less noise as possible would be preferable.

It is not clear if the residents prefer a renovation or reconstruction of the current wooden bridge, or would prefer a modern concrete or composite bridge.

**Ds+V**
In this stadium it is unclear what the wishes of the Ds+V are.

**Architect**
If the design of the Hoevebrug (by Marja Haring) is chosen for the Kerkbrug, the architect would prefer to follow her design as closely as possible. This gives requirements for the thickness of the bridge, preferred is 1:43. For concrete this is feasible. For composite it is more thin than normally would be constructed and presumably 1:35 would be the best attainable.

**Building code**
The building code gives strict rules about the strength of the handrail, it needs to be investigated if this is required for renovation and/or reconstruction.

The building code gives requirements for stiffness of the bridge. This influences the thickness. For composite, the rules in the building code are considered too strict. They are based on deflection. Because composite is strong but flexible, more material needs to be used than strictly necessary for safety. A bridge with a ratio of 1:43 would be safe for example, despite of the big deflection. This is why usually 1:25-1:28 is obtained, which gives a bridge that is 5-10 times stronger than necessary. New guidelines for composite are composed at the moment, providing more freedom for the architects and constructors. This is why 1:35 becomes an option.

**Environment / Landscape**
The neighborhood of the bridge has a lot of small streets. Investigation is needed to see if for example a composite bridge could reach the site on a truck in one piece. The same holds for the big machines necessary for concrete.

The quality of the soil has to be measured by a cone penetration test. Also the quality of the foundation of the current bridge is unclear. It might be
still usable for a new (wooden) bridge.

Monument committee
Because the Kerkbrug has a monumental status, an extra stakeholder is involved: the monument committee. The monument committee would prefer renovation or reconstruction of the current wooden bridge. Their first thought was to prefer renovation above reconstruction. Recently however, it became clear that the current bridge looks different than the original 1896 one. With reconstruction, the appearance of the bridge would go back to the original design. It is not yet clear what option (renovation or reconstruction) the monument committee would prefer based on this new information.

19. Preliminary design phase
In this phase the ecocosts of the variants are calculated using the graphs in the manual.

19.1 Variant 1: Renovation of the current bridge
According to the statement of work, the bridge consists of around 12,3m³ of wood, to be precisely oak wood. If approximately half of it needs to be replaced, this would be around 6m³. Oak wood is not one of the materialisations taken into account for the graphs, so we look in the tables to find that the ecocosts of european oak are 28,2 euro per m³, an average of 10% has to be added for shaving. This means 186,12 euro for the material.

The surface of the bridge is about 27,3m². The ecocosts for paint (waterbased) are 0,0715 euro per m². The total ecocosts for the per painting will be 1,95 euro. This is neglectible.

19.2 Variant 2: Reconstruction of the original bridge
The ecocosts of a normal wooden bridge (without handrail) with a span of 23 meter and a width of 2,5 meter would be, according to the graph: 11293,47 euro for a lifetime of 25 years.

Because this is a far from standard wooden bridge it is wise to calculate it seperately using the tables. The amount of wood needed would be around 12,3m³. A combination would be made of azobe for the non-visible parts and the deck (5,94m³) and oak for al the round parts (6,37m³) of the bridge. The ecocosts of azobe are 907,36 euro per m³, those of oak 28,2 euro per m³, and for shaving 10% has to be added, which brings the total to 11041,088; for a lifetime of 25 years.

Unclear is whether new foundation is needed, or the old foundation suffices. If new foundation is needed this would have ecocosts of 307 euro according to the graphs.

19.3 Variant 3a: Replacement with a concrete bridge, according the design of the Hoevebrug
The ecocosts of a concrete plate bridge (without handrail, with fixed bearing) with a span of 23 meter and a width of 2,5 meter would be, according to the graph: 2621,815 euro.

The handrail differs from a normal steel handrail and needs to be calculated seperately. The mass of the handrail is 1,0kN/m per side; the weight is 102 kg/m. The length of the handrail is (2 times 23 meter) 46 meter, the total weight is 4692 kg. Approximately 10% of that is wood: 469,2 kg; 4222,8 kg is steel. The ecocosts of the steel, rolling included are 0,701 euro/kg according to the table, of the wood is 0,848 euro/kg. The ecocosts of the handrail are 3358,064. The handrail needs to be painted, but the exact surface is unknown and ecocosts of the paint is considered to be neglectible.

In total the ecocosts of the material are 5979,879 euro.

19.4 Variant 3b: Replacement with a composite bridge, with the handrails according to the design of the Hoevebrug.
A composite bridge with fixed bearing is not yet build in practice. Also this bridge will be a bridge with roller bearings.

According to the manual a composite bridge (FiberCore) with a span of 23 meter and a width of 2,5 meter would be: 9510,901 euro, excluding handrail. This however is calculated for a height/length ratio of 1:28 instead of 1:35 or even 1:43.

Since FiberCore bridges are quite homogenous in composition, the ecocosts of the bridge itself (without foundation) can be calculated using the ecocosts of a 1:28 bridge without foundation. The ecocosts of the foundation are 132,2754; they have to be subtracted first and added in the end.

An option is to use piers to be able to construct a thinner bridge. If piers are used they are 478,86 euro each.

### 19.5 Other materializations to consider

**Prestressed concrete**

According to the manual, a prestressed concrete bridge, instead of a concrete plate bridge would be even better regarding ecocosts. This ecocosts would be, excluding the handrail: 2213,488 euro. With the handrails of the Hoevebrug design this would be 5571,552.

Technically there would be no objections to such a construction, but aesthetically there will. The bulging which characterizes the design of the Hoevebrug would not be possible with prestressed concrete.

**Accoya**

Accoya is the third best choice regarding ecocost according to the graphs. Because there is no experience at all with Accoya in Rotterdam, and because the monumental committee prefers to use the original material (oak), this option will likely not be taken in consideration.

Accoya has ecocosts of 82,308 euro/m³, plus approximately an average of 10% extra for shaving. If the Kerkbrug design would be made totally out of Accoya it would give ecocosts of 1113,627 euro; 1280,671326 euro if 15% extra material is assumed.

If the beams and deck would be made out of azobe and only the round parts with Accoya, the ecocosts would be 6505,422 euro; and 6591,9322194 if 15% extra material for the Accoya parts is assumed.

### 16.6 Construction

For a brige of 12*2 the ecocosts for construction of a wooden and composite bridge are comparable. (around 600 euro). The ecocosts of a concrete bridge are twice as much (around 1200). There are no exact data on construction of bridges of another size, so they have to be estimated. For wood they stay approximately the same, because the width is about the same and the amount of poles for foundation stay the same. A concrete bridge of this size would need at least four wooden foundation poles, which raises the construction costs a bit, but they’re still around 600 euro. For concrete the costs for the mixer and pump double with the size of the bridge, and the costs for deep foundation are higher because more poles are needed. In total this will come to around 1600 euro.

### 17.7 Results

In the table on the next page visualises the results. In green are the ecocosts for material and production, excluding construction and demolition. In blue are the ecocosts including the estimated ecocosts for those (600 and 1600). If the estimated construction costs are added, the order of preference concerning ecocosts does not change.
19.8 Conclusions
The renovation option (variant 1) does have by far the lowest ecocosts. Only half of the bridge needs to be replaced and this is done with oak, a material with relatively low ecocosts. However, it has to be taken into account that this is only a solution for a very limited period, after which the other half of the bridge is at the end of it’s lifetime and again a decision like this has to be made. Likely renovation is not an option anymore by then. The renovated bridge is vulnerable and needs a lot of maintenance. At least it has to be painted every year to keep it in good condition. Painting does however have a neglectable influence on the ecocosts.

Reconstruction of the Kerkbrug has far bigger ecocosts, especially because Azobe wood is used which has significantly higher ecocosts than oak. The displayed ecocosts are only for 25 years, the estimated lifetime of a wooden bridge. The estimated lifetime of concrete and composite is much higher: 50 to 100 years. Regarding ecocosts only, reconstruction would therefore not be a good idea.

Concrete has significantly lower ecocosts than composite, even if higher construction costs are taken into account. This would therefore be the recommended option regarding ecocosts.

If composite is chosen, there is no significant difference between a thin (1:43) bridge with two piers or a thicker (1:35) bridge with no piers. They can both be taken into consideration. Noting these calculations assume that only glassfiber and no carbon is used. The ecocosts of carbon are considerably higher.

The ecocosts for prestressed concrete are a bit (around 10%) lower than those of a plate bridge. It is not likely that this is enough to convince the stakeholders to step away from the typical bulging design of the Hoevebrug.

Making the visible parts of Accoya in stead of oak would lower the ecocosts significantly. It is however not likely that the monument committee will accept such a change in material. It is also questionable if deviating from the building code will be possible if the material changes. The ecocosts of the partly Accoya bridge would resemble those of concrete, however the lifetime would be shorter.

19.9 Recommendation
Conclusion is that the concrete bridge, resembling the Hoevebrug would be the best option regarding ecocosts. The next best option, composite (1:35 or 1:43 with piers) has around 80% higher ecocosts.

The ecocosts for renovation are low enough to consider, but renovation is only putting off the evil
hour. In a few years this very same decision has to be made anyway. Regarding ecocosts reconstruction is not a recommendable option, by then the preferred option would still be concrete.

20. Final design phase

In the preliminary design phase, after the final choice for a material would be made, more details would be added to the design. For example the exact amount of foundation and reinforcement steel needed. In the final design then calculations are done on the exact height of the bridge and details like bolts and screws would be added. After this, a more detailed LCA can be made to know the exact ecocosts. Not enough details are yet known about this bridge to make these calculations.

Another important part of the final design phase is the contracting phase following it. In the initiation phase a way of contracting is chosen. In the final design phase the statement of work needs to be written and the contractor has to be chosen following the contracting method chosen in the initiation phase. With the information available now, not more can be said than is in the recommendations in the manual.

21. Evaluation

This design case is not only used as an example of the use of the manual for the readers, it is also used as a test case if the manual indeed provides the right information needed in a bridge design project.

A small adaptation which is done to the manual during this test phase is to add the table on which the ecocosts for construcion are based. This is a table with the different machines (cranes, trucks, pumps, etcetera), the time they need to build each type of bridge and the estimated use of fuel per hour. This graph, in combination with the ecocosts for fuel per liter or hour of machine use; estimations of the ecocosts for building a bridge of a different size can be made. Known is for example how many foundation poles there are needed for a 12*2 bridge of a certain type. If more or less poles are needed this influences the use of a deep foundation machine in a lineair way.

The other graphs and information given were helpful to at least lead the designer through the initiation - and preliminary design phase. Since there is not enough information available to simulate the final design phase, not much can be said about that. Because 80% of the ecocosts are set in the preliminary design phase [, it is expected that if the right choices are made in the beginning of the design process, the influence of the final design phase will be neglectible.
Part 5
Overall evaluation
22. Evaluation of the calculations and graphs

The basis of the manual are the rules of thumbs provided by the IGWR. These rules of thumb are not fully objective, but since they are thoroughly discussed within the IGWR there is a shared vision behind them. Although exact data can not be given, most of the bridges designed at IGWR are according to the rules of thumb. The results given by the graphs are not exact because the rules of thumb they are based on are not exact and based on estimations; but that is not the purpose in this phase of the design process. Exact LCA’s will be made at the end of the design process. Since the difference in ecocosts between the materializations is high, the results are relevant in the sense that they give the designers direction in what materializations to take into consideration.

The difference in ecocosts between the materializations is significant. For small spans (1 meter) the difference between the ecocosts of the materialization with the lowest ecocosts and those with the highest ecocosts are a factor 10 approximately. For spans of 25 meter this goes up to a factor of 15 to 20. The theoretical improvement that in ecocosts that could be achieved is therefore a factor 10 to 20.

In practice not all materializations are seriously considered. In the practical example the factor between the lowest - and highest scoring materialization was a factor 2. Considerably less but still significant, especially when taking into account that what the civil engineers taught was the least sustainable materialization (concrete), turns out to be the most sustainable.

23. Evaluation of the manual

In chapter 8 a list of requirements for the manual was given. This list is repeated here to check if the requirements are met.

✓ The manual should explain sustainability, the need for sustainable design and the benefits of it.
   Chapter 2

✓ The manual should propose a new design process, explaining the necessity of involving sustainability from the start.
   Chapter 2

✓ The sustainability ambition loss and the way to prevent this, by evaluation and documentation, should be explained.
   Chapter 2

✓ The manual should be practical: it should not ask a lot of extra time or effort, and should not have a steep learning curve for understanding how to apply it. It should be directly usable in the design process.
   This is proven by the practice example, part 4 of this report.

✓ The results of the life cycle analysis should be visualized in a clear way, providing direct information fitting in the different steps of the design process.
   It is visualized in the graphs, the practical example proves the graphs are usable in a design process.

✓ The manual should give information about methods that can be used in the design process of a sustainable bridge, besides the material choice.
   Chapter 3 and 5

✓ For the discussed materializations, the manual should give advice on how these bridges could be made more sustainable. This by providing information about the biggest contributors to ecocosts (lifetime phase or part) and methods to improve the ecocosts of the biggest contributor.
   Chapter 4

✓ The manual should provide with information on how to design a sustainable bridge which
differs from the standard bridges in the LCA's:
what is the direction to go and things to keep
in mind during the process.

Chapter 2 and 5

The graphs included in the manual should contain:
✓ Ecocosts of the materializations compared, for
different lengths and widths.
✗ Ecocosts compared to lifecyclecosts.

There was not enough data available about
the lifecycle costs of the materializations
to make this graph. Information should be
made available and this graph should be
added, to make sure the lifecyclecosts and
the ecocosts are calculated based on the
same information (rules of thumb).
✓ Ecocosts of the different phases (materials,
maintenance, construction) of the lifetime of a
bridge.
✓ Ecocosts of the different parts of the bridge.
✓ Ecocosts of other materials that might be inter-
esting for bridges, in relation to their strength
and costs.

24. Relevance of
the manual for
IGWR

For standard bridges that are similar to the materi-
alizations on which the manual is based, the eco-
costs can be found in a minute. This holds for most
bridges.

As can be seen in the practice example, in reality
the situation is sometimes different from the rules
of thumb. Downside of this system is that there are
always materializations not included. For example
for the sake of clarity only one type of founda-
tion per bridge type is discussed. The height of the
bridge can differ from the rules of thumb, like in
the composite variant of the Kerkbrug. Handrails
can differ even more. Idea for further improvement

25. Suggestions
for improvement
of the manual

To make the manual more universal, to make it
more relevent outside Rotterdam, the rules of
thumb should be checked with the rules of thumb
of other cities and adaptations to the calculations
should be made. Expected is that especially the
foundation will be different in other cities, due to
differences in soil quality throughout the country.

There were not much data available about con-
struction and (life cycle) costs. Data about con-
struction were only available for a bridge sized
12x2, data for costs were only available for that size
and only for a few types of bridges. This is why the
graphs in the manual are for material and mainte-
nance only.

Ecocosts for construction should now be estimated
seperately. It would be easier for the user if con-
struction data for all bridge sizes were available
and already added in the graphs.

Life cycle costs are an important requirement for
the bridge. It would be an addition to the manual
if life cycle costs and ecocosts of different bridge
types could be compared. The graph would look like the costs/ecocosts graph in the attachment (but would include all materializations of course).

An idea that went through my mind a few times (but requires an extra graduation period and some programming skills) is to put variables -like materials of the bridge, length/height ratio, type of foundation, weight and material of the handrail, etcetera- in a computer program. This could be done in different levels: only width, span and force in the initiation phase; specific (combinations of) materials and geometries in the preliminary design phase and details in the final design phase. The program then would automatically calculate the ecocosts for that materialization and gives you the main contributing factors in the ecocosts; based on pre-programmed data. Next to this program, the manual would then give advise on what to do with certain outcomes. For example ideas on improving the sustainability of the construction phase if that is the main contributor. This method would give even faster results, and changes can be made instantly.
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[24] Granta CES selector software 2012 (data for material density)
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Attachments
Designing Sustainable Bridges

**Wooden Bridge**
Attachment A: Rules of thumb

The rules of thumb are gathered by William Schutte, mechanical engineer at IGWR, in cooperation with his colleagues. The figures in this attachment are owned by the IGWR and taken from statements of work, documents from producers or other documentation. They depict examples of the type of bridge described.

In all the formulas:
- \( h \) = construction height
- \( l \) = length
- \( b \) = width

Wooden bridge

Material:
Beams, deck, piers, handrails:
Wood with a strength class of at least D50, tropical hardwood like, Azobé, Agelim Vermelo, etcetera. The manual is based on Azobé. Besides Azobé, Accoya is taken into account (http://www.accoya.com). Accoya is European softwood which is treated to give it properties of hardwood; and is an eco-friendly alternative for tropical hardwood. However it doesn’t totally meet the demands for strength class D50, therefore 15% material addition is taken into account in respect to Azobé.

Beams:
The beams are shaved. Because for the ecocosts crude beams have to be taken, 5% material for the beams and 15% for the decks, piers and handrails is added to resemble the shaved off part.

Parts:
Beams:
1 beam per 60 cm plus 1; width of the beam is 5 cm; height is the construction height.
Deck:
5 cm thick

Foundation:
Fir poles, size 250 mm diameter, 15 m long. For narrow bridges (up to 2 meters) 2 m², for broad bridges (from 2,5 meters) 5 m² deck per pole per edge.

Piers:
One on each side and one for every 6 meters of length. Consists of 2 bearing beams of 100*300*b; 2 buttresses of 200*200*0,74b; 1 undershot beam of 250*200*b (sizes in mm)

Construction height:
Statically determined: \( h = l/20 \)

Limits:
Maximum span of 6m, so per 6m a pier is needed.

Construction:
Ground work is needed for the construction of every bridge. Deep foundation is needed for a wooden bridge, for which a light pile driver is used, and a truck for supply. For demolition a demolition crane and a truck are used.
Composite bridge (Bijl)
Composite bridge (BIJL)

Material:
Beams, deck, handrails:
Composite material consisting of polyester resin and glass fibre, produced with a pultrusion process. Bridge consists of beams and a deck, with handrails of the same material. The volume percentage of fibers in the beams is 50%, in the deck it’s 45%. The formula to calculate the mass percentage from the volume percentage is:

\[ M_t = \frac{\rho_t \cdot V_t}{\rho_m + (\rho_t - \rho_m) \cdot V_t} \]

\( M_t \) = mass percentage fibers
\( \rho_t \) = density fibers
\( \rho_m \) = density matrix (resin)
\( V_t \) = volume percentage fibers

Parts:
Beams:
Two beams per 150cm width; mass of the beams is calculated by the total weight of the bridge, minus the weight of the deck. Per beam per meter this is 67,3kg for a statically determined and 36,7kg for a statically indetermined bridge.

Deck:
The weight of the deck is 22,4kg per m³.

Foundation
A statically determined bridge has a shallow foundation, this means 0,5 meters of soil is excavated, clean sand is deposited, with on that a concrete beam of 300*300*b and a concrete plate of 1500*(1+b). A statically indetermined bridge is founded on fir poles: up to 3,5 meters width 3 poles per abutment; from 4 meters width 4 poles per abutment; with on that a concrete beam of 300*300*b.

Piers:
Inapplicable, used from 25 meters length. See steel bridge.

Construction height:
Statically determined: \( h = l / 25 \)
Statically indetermined: \( h = l / 45 \)

However, in the manual the mass is calculated differently, because the mass per meter for the beams couldn’t be discovered otherwise. For a statically determined bridge the mass is 1,1kN/m² and for a statically indetermined bridge it’s 0,7kN/m².

Limits:
Statically determined bridges are applied up to 15 meter, statically indetermined bridges from 15 meter. From 25 meter a pier is applied.

Construction:
Ground work is needed for the construction of every bridge. No deep foundation is needed for a composite bridge. A truck and a crane place the bridge. For demolition a demolition crane and a truck are used.
Composite bridge (Fibercore)
Composite bridge (Fibercore)

Material:
Main bearing construction:
Composite material of polyester resin and glass fiber, combined in a sandwich construction with PUR foam. Produced in a vacuum form process. Hand rails of composite or steel are applied. The volume percentage of fibers in the upper and bottom layer is 45%, in the lamella it’s 30%. The formula to calculate the mass percentage from the volume percentage is:

\[
M_r = \frac{\rho_r \cdot V_r}{\rho_m + (\rho_r - \rho_m) \cdot V_r}
\]

- \(M_r\): mass percentage fibers
- \(\rho_r\): density fibers
- \(\rho_m\): density matrix (resin)
- \(V_r\): volume percentage fibers

Parts:
Main bearing construction:
Sandwich construction consisting of composite material and PUR foam.

Foundation:
A statically determined bridge has a shallow foundation, this means 0.5 meters of soil is excavated, clean sand is deposited, with on that a concrete beam of 300*300*b and a concrete plate of 1500*(1+b). A statically indetermined bridge is founded on fir poles: up to 3.5 meters width 3 poles per abutment; from 4 meters width 4 poles per abutment; with on that a concrete beam of 300*300*b.

Piers:
Inapplicable, used from 25 meters length. See steel bridge.

Construction height:
Statically determined: \(h = l/28\)
Statically indetermined: \(h = l/50\)

Limits:
Statically determined bridges are applied up to 15 meter, statically indetermined bridges from 15 meter. From 25 meter a pier is applied.

Construction:
Ground work is needed for the construction of every bridge. No deep foundation is needed for a composite bridge. A truck and a crane place the bridge. For demolition a demolition crane and a truck are used.
Designing Sustainable bridges

Steel bridge
Steel bridge

Material:
Beams:
For the beams IPE beams are assumed. When these weren’t available in sufficient height, HEM beams are assumed.

Deck:
For the deck wood or composite (BIJL) can be chosen. This is the same deck as used in wooden and composite bridges.

Parts:
Beams:
1 layer per 80 cm plus 1; height is the construction height rounded to the next standard sized beam.

Deck:
See wood / composite (BIJL)

Foundation:
A statically determined bridge up to 15 meters has a shallow foundation, this means 0,5 meters of soil is excavated, clean sand is deposited, with on that a concrete beam of 300*300*b and a concrete plate of 1500*(1+b). Above 15 meters a statically indetermined bridge is applied, by using fixed bearings or piers. Prefab concrete poles (300*300mm; 20m long) are then used, with on that a concrete beam of (h+300)*600*b. For bridges with piers (and a roller bearing) 17m² per pole per side is assumed, for bridges with fixed bearings it’s 11,5m² per pole per side (with a minimum of 2 poles per side).

Piers:
Applied from 15 meters. Consist of 2 concrete poles (see foundation) and a concrete beam of300*300*b (mm).

Construction height:
Statically determined: h=l/27,5
Statically indetermined: h=l/33

Limits:
Statically determined bridges are applied up to 15 meter, statically indetermined bridges from 15 meter; being with fixed bearings or with piers.

Construction:
Ground work is needed for the construction of every bridge. Deep foundation is needed for a steel bridge, for which a light pile driver is used, and a truck for supply. For demolition a demolition crane and a truck are used.
Concrete bridge, plate bridge

Material:
A massive concrete plate with conventional soft steel reinforcing bars in the draw zone. For a statically determined bridge 150 kg/m$^3$ steel is assumed, for a statically indetermined bridge it’s kg/m$^3$, for deck and abutment. For the concrete foundation poles, 150 kg/m$^3$ is assumed. The concrete type is C28/35, the reinforcement steel type is FeB 500. For calculating the ecocosts, the data for reinforced concrete are used.

Parts:
Main bearing construction:
Massive concrete plate with conventional soft steel reinforcing bars in the draw zone.

Foundation:
The bridge is founded on a concrete pole foundation. Prefab concrete poles (300*300mm; 20m long) are used, with on that a concrete beam of (h+300)*600*b. For statically determined bridges 17$m^2$ per pole per side is assumed, for statically indetermined bridges it’s 11.5$m^2$ per pole per side (with a minimum of 2 poles per side).

Piers:
Applied from 20 meters. Consist of 2 concrete poles (see foundation) and a concrete beam of300*300*b (mm).

Construction height:
Statically determined: $h=\frac{l}{27}$
Statically indetermined: $h=\frac{l}{45}$

Limits:
Statically determined bridges are applied up to 15 meter, statically indetermined bridges from 15 meter; being with fixed bearings or with piers (applied from 20 meters).

Construction:
Ground work is needed for the construction of every bridge. Deep foundation is needed for a concrete bridge, for which a light pile driver is used, and a truck for supply. The depositing of the concrete is done with a crane, mixer and pump. For demolition a demolition crane and a truck are used.
Concrete prestressed bridge
Concrete bridge, prestressed

Material:
The bridge consists of prefab concrete elements with very high strength steel prestression bars. The prestression bars serve to create as much pressure in the concrete that occurring draw is compensated for. To withstand the high pressure, usually a higher concrete class with a higher density is used, so corroding substances can penetrate less well. These beams are overlayed with a conventional concrete deck.

The prestressed concrete is C53/65, the conventional concrete is C28/35, the span bars are FeP1860. For calculating the ecocosts, the data for reinforced concrete are used.

Parts:
Main bearing construction:
Consists of prefab concrete elements and at site deposited conventional concrete. Assumed is 80 kg/m$^3$ of steel, except for the upper 8 cm deck, there 150 kg/m$^3$ is assumed.

Foundation:
The bridge is founded on a concrete pole foundation. Prefab concrete poles (300*300mm; 20m long) are used, with on that a concrete beam of (h+300)*600*b. Assumed is 17m$^3$ per pole per side (with a minimum of 2 poles per side).

Piers:
Inapplicable, used from 25 meters length. See steel bridge.

Construction height:
Statically determined: $h=\frac{l}{30}$, excluding deck layer.

Limits:
It is not recommended to use prestressed concrete in statically indeterminate constructions. These bridges have an application scope of 6 to 25 meters. Above 25 meters piers can be used.

Construction:
Ground work is needed for the construction of every bridge. Deep foundation is needed for a concrete bridge, for which a light pile driver is used, and a truck for supply. To place the prefab parts a crane and truck are needed. The depositing of the concrete (for the deck layer) is done with a crane, mixer and pump. For demolition a demolition crane and a truck are used.
Concrete bearing handrail bridge
Concrete bridge, bearing handrail bridge

Material:
Normally a concrete handrail is not applied, because of the high own mass and the inert sizes. (In the future this might become possible, because of new concrete types.) Concrete handrails are for now limited to bearing elements, which besides as handrail also function as main bearing construction. The deck therefore doesn’t need to be bearing in the length direction but only span in the width direction, therefore the deck can be lighter. The bridge is constructed with very high strength concrete, reinforced with steel fibers. On places where steel fibers aren’t considered sufficient, conventional reinforcement steel is used. The concept consists of prefab elements that are laced together with 4 prestression bars. The concrete for the deck and handrail is C170/200, the steel for the reinforcement is FeB 500. For calculating the ecocosts, the data for reinforced concrete are used.

Parts:

Handrail:
The handrail consists of a network of concrete bars. The mass of the handrail is 5,82 kN/m.

Deck:
The deck is 6 cm high.

Foundation:
Two prefab concrete poles (300*300mm; 20 meter long) are used per abutment are used. With that a concrete pole of (h+300)*600*b (mm).

Piers:
Applied from 15 meters. Consist of 2 concrete poles (see foundation) and a concrete beam of300*300*b (mm).

Construction height:
Statically determined: h=1400 mm

Limits:
The current generation of bearing handrail bridges is not suitable for statically indeterminate applications. The scope of this bridge type is 4-15 meters. Above 15 meters piers can be applied.

Construction:
Ground work is needed for the construction of every bridge. Deep foundation is needed for a concrete bridge, for which a light pile driver is used, and a truck for supply. To place the prefab parts a crane and truck are needed. The depositing of the concrete is done with a crane, mixer and pump. For demolition a demolition crane and a truck are used.
Attachment B: Graphs

The following three graphs have span on the x and width on the y axes and give the top 3 materializations with lowest ecocosts. They are in chapter 2 of the manual (initiation phase).
The following 10 graphs have span on the x and ecocosts on the y axes and give the ecocosts for 18 materializations. There is a graph for every width between 0.5 and 5 meters. They are in chapter 3 of the manual (preliminary design phase). The ecocosts are based on material and maintenance.
Designing Sustainable bridges

Width: 1.0 m

- Wood Azobe - 25 years lifetime
- Wood Azobe - 75 years lifetime
- Wood Accoya - 25 years lifetime
- Wood Accoya - 75 years lifetime
- Steel/Wood - statically determined
- Steel/Wood - statically indetermined - roller bearing
- Steel/Wood - statically indetermined - fixed bearing
- Steel/Composite - statically determined
- Steel/Composite - statically indetermined - roller bearing
- Steel/Composite - statically indetermined - fixed bearing
- Composite BUL - statically determined
- Composite BUL - statically indetermined
- Composite Fibercore - statically determined
- Composite Fibercore - statically indetermined
- Concrete Plate Bridge - statically determinate
- Concrete Plate Bridge - statically indeterminate
- Concrete Prestressed
- Concrete Bearing Handrail
Designing Sustainable bridges
Width: 3,0 m
Width: 4.5 m

[Graph showing cost analysis for various materials and spans]
The following 8 graphs (from next page on) give information about the distribution of ecocosts. First 2 are about the distribution over the phases in lifetime for a bridge of 12*2, other 6 about distribution over parts of the bridge for 3 different sizes. These graphs are in chapter 3 (preliminary design phase) of the manual.
<table>
<thead>
<tr>
<th>Material Description</th>
<th>Materials</th>
<th>Construction &amp; demolition</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete bearing handrail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete prestressed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete plate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite Fibercore</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite BiIL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel + composite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel + wood</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood Accoya</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood Azobe</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Ecocost - per phase - 12*2*
Designing Sustainable bridges
Ecocosts - per part - 25*5

- Concrete Bearing Handrail
- Concrete Prestressed
- Concrete Plate Bridge - with piers
- Concrete Plate Bridge - fixed bearing
- Composite Fibercore
- Composite BUL
- Steel/Composite - with piers
- Steel/Composite - fixed bearing
- Steel/Wood with piers
- Steel/Wood fixed bearing
- Wood Accoya
- Wood Azobe

Legend:
- Beams
- Main-bearing construction
- Deck
- Foundation
- Piers
The following graph is about the ecocosts of the handrail, displaying the average costs and the spread for different handrail weights. Ecocosts are per meter of handrail. In chapter 3 (preliminary design phase) of the manual.

![Handrail Graph]

The following graph has costs on the x and ecocosts on the y axe. For 5 bridge types, size 12*2 the costs are compared to the ecocosts.

![Costs vs Ecocosts Graph]
The following table shows the ecocosts per kg and per m³ (for diesel per liter, for paint per m²) for diverse materials. The graph can be used to make calculations on bridges that differ from the standard bridges. In chapter 4 (final design phase) of the manual.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ecocosts per kg</th>
<th>Ecocosts per m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azobe</td>
<td>0,848</td>
<td>907,36</td>
</tr>
<tr>
<td>Accoya</td>
<td>0,16075716</td>
<td>82,30766592</td>
</tr>
<tr>
<td>Oak (European)</td>
<td>0,03</td>
<td>26,2</td>
</tr>
<tr>
<td><strong>Composites</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite glass 30%[4]</td>
<td>0,74907635</td>
<td>1230,554773</td>
</tr>
<tr>
<td>Composite glass 35%</td>
<td>0,678350104</td>
<td>1161,751461</td>
</tr>
<tr>
<td>Composite glass 45%</td>
<td>0,552900083</td>
<td>1024,144837</td>
</tr>
<tr>
<td>Composite glass 50%</td>
<td>0,497013263</td>
<td>955,3415257</td>
</tr>
<tr>
<td>Composite carbon 30%</td>
<td>2,555943897</td>
<td>3634,754454</td>
</tr>
<tr>
<td>Composite carbon 35%</td>
<td>2,616123202</td>
<td>3798,996029</td>
</tr>
<tr>
<td>Composite carbon 45%</td>
<td>2,727255868</td>
<td>4127,479181</td>
</tr>
<tr>
<td>Composite carbon 50%</td>
<td>2,778668942</td>
<td>4291,720756</td>
</tr>
<tr>
<td><strong>Steel and Concrete</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>0,571</td>
<td>4482,35</td>
</tr>
<tr>
<td>Concrete (standard)</td>
<td>0,05</td>
<td>120</td>
</tr>
<tr>
<td>Concrete (reinforced)</td>
<td>0,28</td>
<td>714</td>
</tr>
<tr>
<td><strong>Materials for foundation, construction, wear layer, maintenance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fir</td>
<td>0,039</td>
<td>17,355</td>
</tr>
<tr>
<td>Sand</td>
<td>0,0066</td>
<td>9,1</td>
</tr>
<tr>
<td>Diesel (per kg-per liter)</td>
<td>1,271</td>
<td>1,06764</td>
</tr>
<tr>
<td>Crane, Truck or light pile driver (based on 20l/hour)</td>
<td>-</td>
<td>21,3528</td>
</tr>
<tr>
<td>Telescopic crane per hour (based on 30l/hour)</td>
<td>-</td>
<td>32,0292</td>
</tr>
<tr>
<td>Epoxy resin (wear layer)</td>
<td>2,111</td>
<td></td>
</tr>
<tr>
<td>Gravel (wear layer)[6]</td>
<td>0,0066</td>
<td>14,3</td>
</tr>
<tr>
<td>Hot dip galvanizing</td>
<td>0,571</td>
<td>4482,35</td>
</tr>
<tr>
<td>Paint, transparent, water based (per kg-per m³, 6m³ per kg)</td>
<td>0,429</td>
<td>0,0715</td>
</tr>
<tr>
<td>Paint Verf (transparant, oil based, including emissions) (per kg-per m³, 6m³ per kg)</td>
<td>1,646</td>
<td>0,274333</td>
</tr>
<tr>
<td><strong>Other materials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass fiber</td>
<td>0,102</td>
<td>267,3084073</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td>3,18</td>
<td>9334,136512</td>
</tr>
<tr>
<td>Resin (polyester, for glass)</td>
<td>1,343</td>
<td>1643,374654</td>
</tr>
<tr>
<td>Resin (epoxy, for carbon)</td>
<td>2,111</td>
<td>2649,305</td>
</tr>
<tr>
<td>PUR foam</td>
<td>1,382</td>
<td>62,19</td>
</tr>
<tr>
<td>Chestnut</td>
<td>0,025</td>
<td>12</td>
</tr>
<tr>
<td>Larch</td>
<td>0,048</td>
<td>27,84</td>
</tr>
<tr>
<td>Bamboo</td>
<td>0,009</td>
<td>2,1</td>
</tr>
<tr>
<td>Incl transport [3]</td>
<td>0,093</td>
<td>65,1</td>
</tr>
<tr>
<td>Bamboo-Composite (60% bamboo, 40% recycled)</td>
<td>0,1318</td>
<td>105,44</td>
</tr>
<tr>
<td>Aluminium (trade mix)</td>
<td>1,123</td>
<td>3032,1</td>
</tr>
<tr>
<td>Glass (recycled paper and)</td>
<td>0,215</td>
<td>0,529975</td>
</tr>
<tr>
<td>Cardboard</td>
<td>0,181</td>
<td>121,27</td>
</tr>
</tbody>
</table>
The following table shows the machine hours that are needed to construct a bridge of 12*2 and the estimated fuel consumption of the machines used. It can be used to estimate the ecocosts of construction for other bridge sizes and types, as described in chapter 16.6 of this report. It can be found in chapter 4 (final design phase) of the manual.

<table>
<thead>
<tr>
<th>work</th>
<th>machines</th>
<th>consumption (L/diesel/hour):</th>
<th>work in hours:</th>
<th>wood</th>
<th>steel</th>
<th>composite</th>
<th>concrete plate</th>
<th>concrete prestressed</th>
<th>concrete bearing handrail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>groundwork:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hydraulic crane</td>
<td>20</td>
<td>8</td>
<td>8</td>
<td>8</td>
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