Arup Netherlands

CO2 Performance ladder

Value-chain analysis for two types of bridges

4.A.1 and 5.A.1, 5.A.2-1, 5.A.2-2

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ARUP

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1 Introduction

At Arup we strongly feel our responsibility to contribute to the transition towards a more sustainable future. We have adopted the CO_2 -performance ladder as a tool to map and reduce our CO_2-emissions. As Arup, we can have a positive influence on the CO_2 reduction of projects in the built environment through our design and consulting practice.

As part of level 5 of the CO_2 performance ladder, the requirement is to gain insight into downstream scope 3 emissions by executing two chain analyses. The chain analysis work is performed by our graduate intern Mark Gerritsen [1].

The main areas of influence for Arup b.v. are in buildings and infrastructure sectors. For this assessment, the environmental impacts are evaluated of two alternative bridge designs, executed in the most frequently used infrastructure construction materials: steel and concrete. The new bridge will replace an existing bridge to ensure the canal is accessible for Class Va and four-liner container ships. The bridge design has a total span of 193 meters.

The steel arch bridge proposal represents an architectural design, whereas the concrete bridge represents a more practical bridge span. The effects are calculated using the computing program DuboCalc [1], which uses data from the National Environmental database.

Objectives

The objectives of the chain analyses are:

- Determine the main CO2 emissions during the whole life cycle of a project;
- Identify the main areas of influence where carbon reduction can be achieved;

In this way, the analysis delivers input into the search for more sustainable design methods. The intention is not to compare the two construction materials concrete and steel, as the character of the bridge designs varies significantly. The steel bridge design has inefficiency in material use, due to the architectural ambition to extend the arch below the bridge deck.

Steel arch bridge

Concrete girder bridge

Figure 1: Alternative designs for the Zuidhorn railbridge ©ProRail & Arup.

[1] https://www.milieudatabase.nl/imgcms/Functionele_Specificatie_Dubocalc_rev_13.pdf

2 Scope of analysis

2.1 Scope bridge geometry

For the chain analysis the main construction elements are taken into account:

Steel bridge design	**Concrete bridge design**
Substructure	Substructure
Foundation piles Support points	Foundation piles Support points
Superstructure	Superstructure
Arch Longitudinal girder Cross-member girder Columns Transition plate Mounting plate Bridge deck Train rails Coating	Longitudinal girders Cross-member girders Tube Pillar Transition plate Mounting plate Bridge deck Train rails

2.2 Life cycle phases

A life cycle analysis is a method to determine the environmental impacts of a product's lifespan. The following life cycle phases are identified for our projects:

1. Design phase
2. Winning- and production phase
3. Transport phase
4. Building Phase
5. Maintenance and use phase
6. Demolition and processing phase

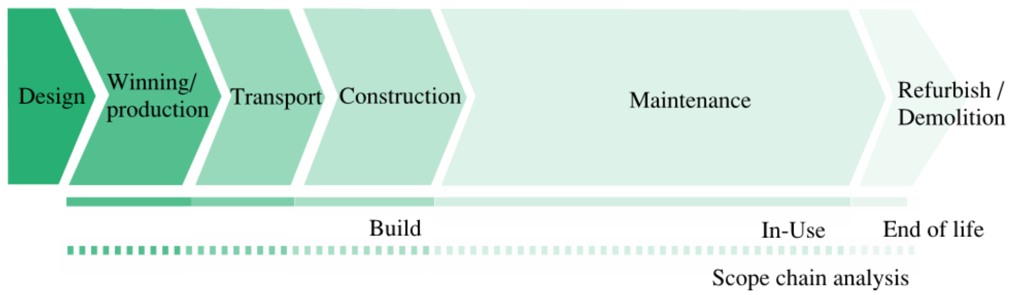


Figure 2 Main life cycle phases of a construction

In the chain analyses the emissions are assessed from the winning of materials up to demolition.

1. Design

The construction of a building or bridge is initiated by a client, after which a design is made by engineers. The activities of Arup lie mostly in this phase, ranging from feasibility studies to detailed designs. CO_2-emissions arise by:

- Energy use and transport by architects/planners/engineers
- Indirectly through design, which defines the amount and type of building materials, the construction activities and influences in-use emissions.

Via the design phase the engineer has indirect impact on emissions produced in subsequent phases.

2. Winning- and production phase

- Winning of the raw materials
- Processing and production of construction materials

3. Transportation phase

- Transport of building materials and people from production- towards construction site. CO_2-emission is due to fuel use of vehicles.

4. Construction

- On-site operations for assembly of the structure

5. Maintenance and usage phase

- The bridge has no in-use energy consumption. The emissions by the traffic on the bridge are not taken into account.
- Maintenance and repair of the bridge

6. Refurbishment / demolition

- Emissions arising from refurbishment.
- Indirect and direct emissions from demolition and waste removal and processing.

2.3 Partners in the chain

To achieve CO2-reduction in the chain of our projects it is important to have insight in the partners in our chain. The most important partners are:

- The client
- The architect
- The designer/ engineer
- Industry / Producer / Supplier building materials

- Transport companies
- Contractor / engineering in building phase, maintenance phase and demolition
- Manager use- and maintenance phase

3 Approach & database

In order to define the CO_2-emissions of the two alternative bridge designs, we have used calculation software and databases on material- and energy use in the construction sector.

Calculation method

The software program used for the chain analysis assessment is Dubocalc. The program is developed by Rijkswaterstaat to perform life-cycle analyses of projects in the GWW (soil, roads and hydraulic engineering). Dubocalc calculates the embodied energy for the whole life-cycle of the structure [2]. Material amounts are entered manually into the project documentation of the program.

Tally is a Revit-plugin which automatically extracts the material amounts from the Revit model. The tool is based on de GaBi database, which is developed in America. It is questioned how applicable their database is to the Dutch building industry, but it could provide a handy tool during design process as it is linked to the Revit Model. Tally calculations are not documented in this report.

Data collection

Data is preferably gained from primary sources, but as an engineering firm Arup does not have full control and information on all the steps in the chain. The determination of material consumption is deducted from the designs made by Arup. The other aspects concerning construction equipment, transportation and maintenance are deducted from comparable references in environmental databases.

- The Revit models of the (VO) bridge designs are used to extract the amount of materials used for the design of the bridges.

The DuboCalc library makes use of the National Environmental Database [3] and stores the following information:

- Environmental impacts and units
- Materials and processes
- Items containing materials and processes
- The calculation model, calculation the total MKI
- Material types
- The waste scenario's per material type.

The CO_2 conversion factors are deducted from:

https://co2emissiefactoren.nl/

MKI-value

DuboCalc calculates the environmental impact as an MKI value. The MKI-value is a fictional amount of money that would be needed to prevent or compensate the environmental impact.

The tool distinguishes 11 environmental impact categories:

Environmental impact	Equivalent unit	Weighing factor (€/kg equivalent)
Exhaustion of abiotic raw materials	Sb eq	€ 0,16
Depletion of fossil energy carriers	Sb eq	€ 0,16
Climate change	CO_2 eq	€ 0,05
Degradation of the ozone layer	CFK-11 eq	€ 30
Photochemical oxidant formation (smog)	C_2H_4 eq	€ 2
Acidification	SO_2 eq	€ 4
Eutrophication	PO	€ 9
Human toxicological effects	1,4-DCB eq	€ 0,09
Ecotoxicological effects, aquatic (freshwater)	1,4-DCB eq	€ 0,03
Ecotoxicological effects, aquatic (saltwater)	1,4-DCB eq	€ 0,0001
Ecotoxicological effects, terrestrial	1,4-DCB eq	€ 0,06

Table 1: Environmental impact and weighing factors used by DuboCalc. [4]

Assumptions

- The life-cycle analysis is performed according to standards ISO 14040 and ISO 14044.
- A lifecycle is assumed of 100 years
- Within this lifecycle the phases construction, maintenance and demolition are taken into account.
- For the choice of building components the most comparable elements are chosen in the databases.
- The distance for the transport activities is assumed at 20/50 km.

4 Analysis environmental impacts

4.1 Steel bridge design

The structural design under consideration is the tender design by Arup for the new Zuidhorn railbridge, which has not been built. The steel design contains a double arch with a hanging deck. The span of the arch is 160 m. The total height is 38 m. The bridge is a single-track railway bridge.

The deck consists of two longitudinal beams with cross members in between. Both beam types are executed as steel hollow section profiles. The longitudinal beams have a maximum height of 3m. The cross members are spaced 2,5 m apart and taper from 300 mm in height to 85 mm. The deck is made of concrete, with a built-in train track.

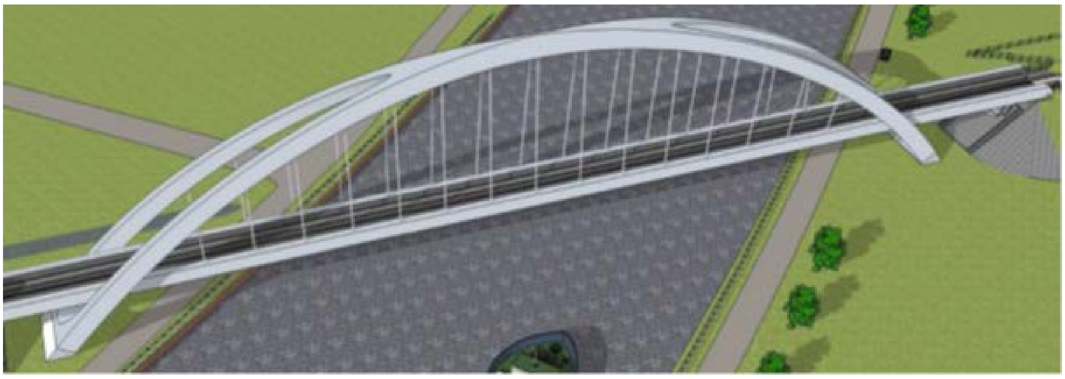


Figure 3: New steel design for the Zuidhorn railbridge. ©ProRail.

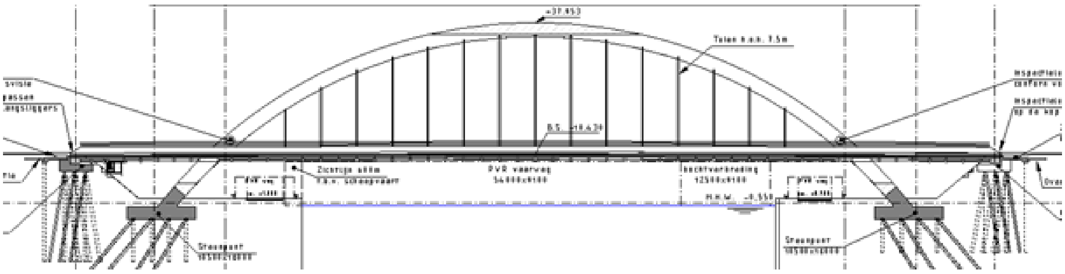


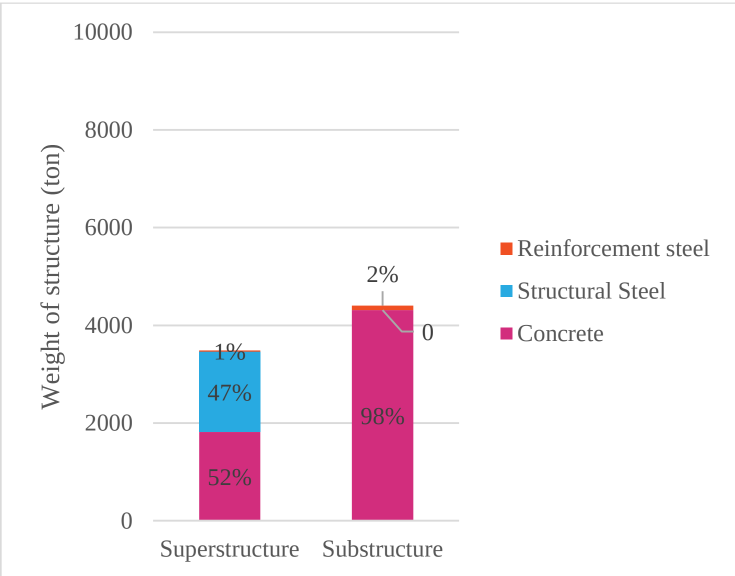
Figure 4: Section of the steel design for the Zuidhorn railbridge. ©ProRail.

4.1.1 Material distribution

The steel super structure is relatively light, with a total weight of 7887 ton. Due to the architectural ambition to extend the arch below the bridge deck, a heavy foundation is necessary to withstand the reaction forces in the foundation.

Structural part	**Weight (ton)**	**Percentage**
Super structure total	3485	44%
Substructure total	4402	56%
Total Structure	**7887**	

The arch bridge mass consists of 22% steel and 78% concrete.



4.1.2 Results DuboCalc calculation

The CO_2 contributions are calculated per life-phase of the bridge construction.

Construction phase	Total MKI-value (€)	CO_2 MKI-value (€)	Percentage
Build	147457	94959	85%
Maintenance	1360	596	1%
End of life	52350	16310	15%
Total	**201167**	**111865**	

The building phase represents the largest part of emissions for the steel bridge design. The contribution of the end-of-life phase is only 15%. For one, the steel material is easier to remove from building site than concrete (1 ton steel per hour vs. 1,5 ton concrete). And Secondly, the steel structure can be largely recycled into high-end steel.

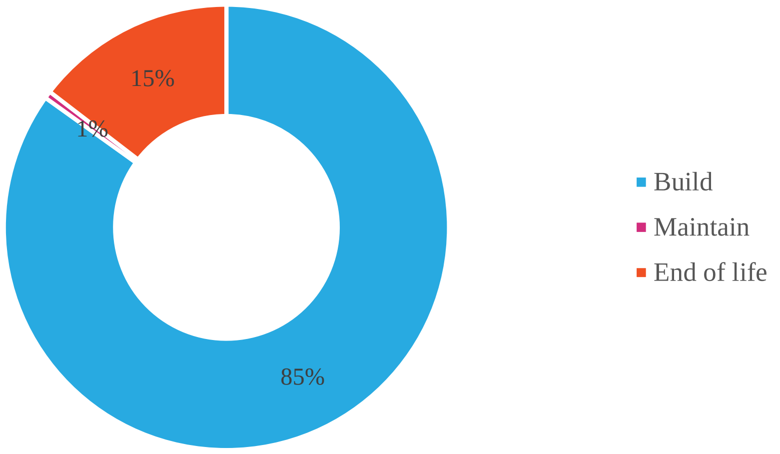


Figure 5 CO_2 MKI-value per life phase of the bridge

The following bridge elements have the most influence on the CO_2-emissions:

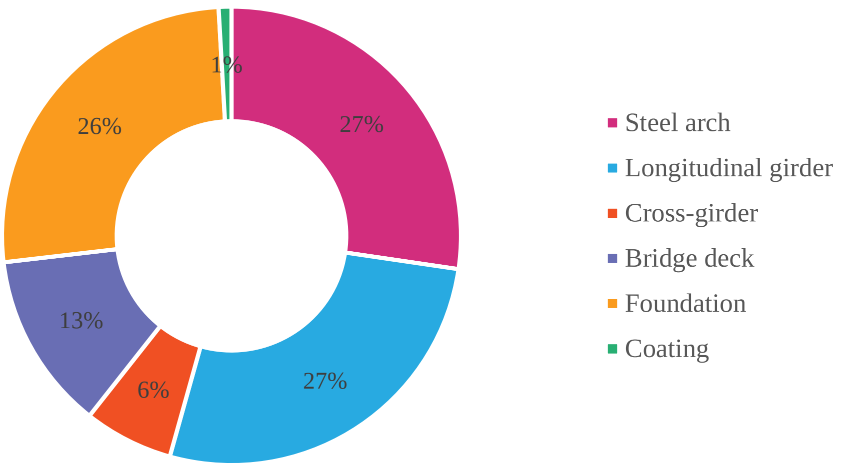


Figure 6 MKI-value contribution per structural component of the bridge

4.1.3 Optimization

The arch structure and longitudinal beams form the main cause of emissions. The embodied energy can be reduced by choosing to apply recycled steel for the arch structure and longitudinal beams. The embodied energy is then related to the amount of recycled steel used and the processes required for the sections (profile, tube or plate). An architectural feature (the extension of the arch below the bridgedeck) causes extra material use. The engineer could emphasize this issue towards the client and propose an elegant alternative.

4.2 Concrete bridge design

The concrete bridge is specifically designed for this chain analysis. The design is located at the same location and has the same span as the steel arch bridge. The bridge consists of 3 spans, of which the main span accounts for a distance of 112 m. The longitudinal beams are pre-stressed concrete with a height of 5m. The cross members are solid concrete, with a height of 1m and a spacing of 2,5m. The deck is made of concrete, with a built-in train track.

Figure 7 Alternative design for the Zuidhorn railbridge (Source: Arup)

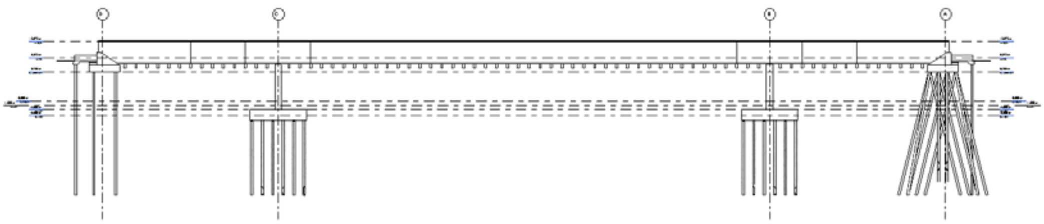


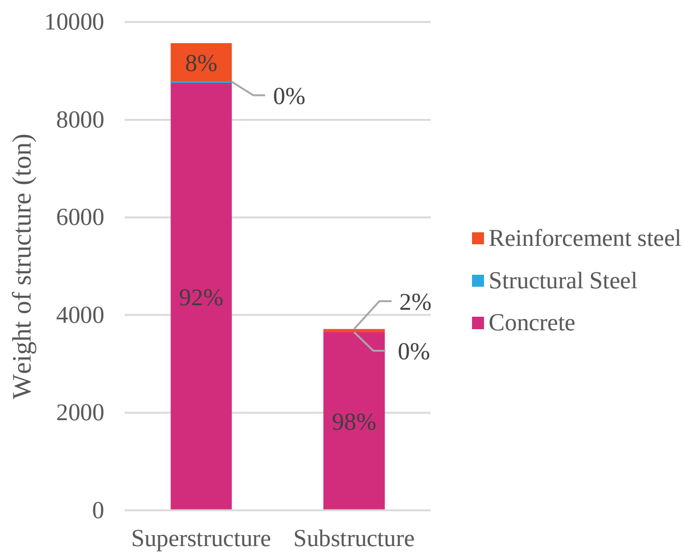
Figure 8 Section of the steel design for the Zuidhorn railbridge. ©ProRail.

4.2.1 Material distribution

The concrete bridge design weighs 70% more than the steel bridge design with a total of 13290 ton.

Structural part	Weight (ton)	Percentage
Super structure total	9573	72%
Substructure total	3717	28%
Total Structure	**13290**	

The material distribution is 93% of concrete and 7% of steel (including reinforcement steel.



4.2.2 Results DuboCalc calculation

The end-of-life phase represents almost half of the total emissions associated to the bridge. Reasons are that concrete takes more effort to remove from site (1 ton steel per hour vs. 1,5 ton concrete) and concrete can only be recycled to a low-grade aggregate.

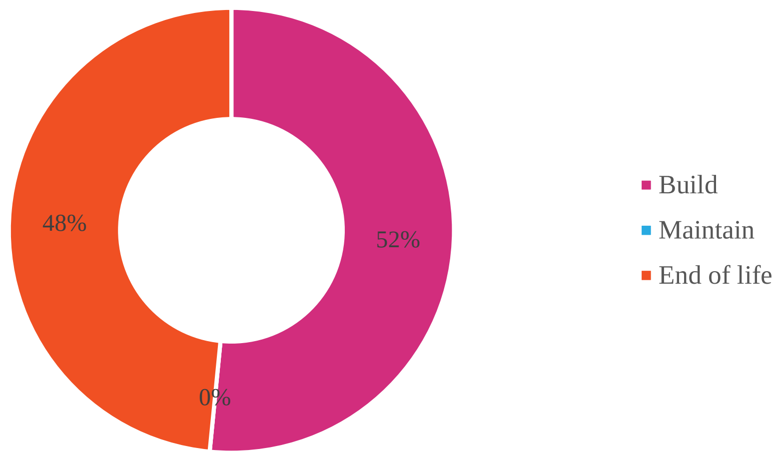


Figure 9 CO_2 MKI-value per life phase of the bridge

The following bridge elements have the most influence on the CO_2-emissions:

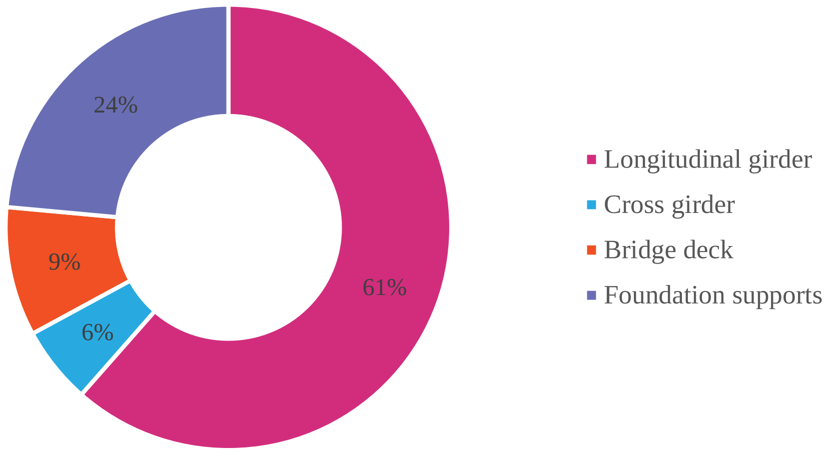


Figure 10 MKI-value contribution per structural component of the bridge

4.2.3 Optimization

The pre-stressed concrete longitudinal beams form the main cause of emissions. Consists largely of cement, additives (sand and gravel) and water. Possible optimisation strategies include [5]:

- The embodied energy increases for higher strength concrete. It is therefore advised not to pick higher concrete grades then necessary.
- The highest embodied energy lies in cement. Replace the usual Portland cement by types CEM III which contain either:
- Addition of blast furnace slag to concrete aggregate
- Addition of fly ash to concrete aggregate (min 25%, max 50%)

A comparison shows how the addition of the percentage fly ash can provide a reduction of 16% in emissions.

Environmental impact [tonCO2eq]	25% fly ash	50% fly ash	Reduction
Global warming	3821	3222	-16%

Table 2: Results optimization concrete design 25% and 50% fly ash.

5 Potential reduction strategies

The results of the DuboCalc chain analysis show that both for the steel arch bridge, as for the concrete girder bridge the winning- and production of materials and the demolition phase are governing in CO_2-contribution. For the steel bridge the contribution of the winning- and production phase of the material is almost 85% and only 15% to demolition, whereas for the concrete bridge 50% of emission contribution is associated to the demolition phase.

The concrete bridge has a lower demand for maintenance then the steel bridge, although the share of maintenance appears low (≥1%) for bridges compared to the total embodied carbon over the whole life cycle.

The main possibilities for reducing $_{CO2}$ emissions are therefore found in:

- Reduction of CO_2-emissions during materials or product manufacturing
  - Re-use and recycling of temporary building materials
  - Re-use and recycling of the demolished structure
- Material efficient structures
  - Using efficient building materials
  - Mixing the material with low-energy aggregates
  - Optimizing the structural design to decrease material use

An important part in the last exercise is to collaborate and advice the client and architect on material-efficient design solutions.

References

[1] M. Gerritsen, (2016) Thesis: environmental impact study on building materials for bridge engineers. Arup

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