

# Multi-objective design optimization applied to the structural design of a bridge with reused elements and recycled concrete aggregates

C. Braendstrup<sup>1</sup>, S.J. Wang<sup>1</sup>, M.W.F. Vullings<sup>1</sup>, S.L.A. Valcke<sup>1</sup>,  
J. Lennartz<sup>1</sup>, D.L. Allaix<sup>1</sup>, S. Groenia<sup>2</sup>, A.J. Bigaj-van Vliet<sup>1</sup>

<sup>1</sup> TNO, Delft, the Netherlands

<sup>2</sup> University of Twente, the Netherlands

Sustainable design of concrete structures may contribute significantly to reaching the European Union's ambitious targets regarding climate change and circularity. However, a sustainable structural design must meet multiple performance criteria simultaneously, making the design process more complex. To navigate complex design and decision processes, multi-objective design optimization is proposed in literature. This paper demonstrates the application of multi-objective design optimization to structural design, using the design of a bridge with reclaimed concrete girders and recycled concrete aggregate (RCA) as case study. First, a parametric model is defined for the design of the structure, including the relevant design variables, boundary conditions, and calculation models on material and structural level. Next, five design objectives are selected to optimize for in the case study, which reflect economic, environmental and circularity aspects. A multitude of optimal design solutions within the solution space are then generated using multi-objective design optimization algorithms and visualized in parallel coordinate plots. The advantages of multi-objective optimization in structural design are twofold: (1) the multitude of optimal design solutions gives insight into all possible interdependencies between design variables and performance criteria (objectives) and (2) it enables transparent decision-making. The results of the case study show how trade-offs are not the same for every solution and can be minimized, which is not always clear when considering only a few solutions. Also, it shows that generalizations about overall sustainability of structures based on one design exercise cannot be made easily. How much environmental impact or costs can be reduced, is dependent on how trade-offs are being made by stakeholders with respect to other criteria.

*Key words: Concrete structures, structural design, multi-objective design optimization, sustainability, circularity, reuse, recycling*

# 1 Introduction

The European Union has set ambitious targets regarding climate change and circularity in the European Green Deal (European Commission, 2019). A reduction of greenhouse gas emissions to at least 55% below 1990 levels by 2030 is proposed in the 2030 Climate Target Plan (European Commission, 2020b), while the Circular Economy Action Plan (European Commission, 2020a) aims to reduce primary raw material consumption. The construction sector is an important industry involved in reaching these targets in the Green Deal: the cement industry alone is responsible for about 7% of carbon dioxide (CO<sub>2</sub>) emissions globally (International Energy Agency, 2018) and concrete makes up more than 30% of construction and demolition waste (European Commission, 2020c). These high percentages demonstrate that innovations in the design of concrete structures may contribute significantly to reaching the Green Deal's ambitious targets.

One of the main strategies to reduce the footprint of concrete structures is to reduce the use of primary materials by reusing existing concrete structures (Fivet & Brütting, 2020). This can either be done by reusing entire concrete elements, such as prefabricated girders, or by crushing the concrete to obtain recycled concrete aggregate (RCA) for use in new structures. The first strategy of reusing entire elements has a higher potential of avoiding primary materials and CO<sub>2</sub> than recycling, notably by avoiding new cement. However, sometimes structural elements may not have sufficient quality and recycling these elements may be more advantageous. This is one of the trade-offs investigated in this study. The reuse of entire concrete elements in new building structures has already been put into practice in a number of projects in the past years (Küpfer et al., 2023). Considering reuse in infrastructure projects, various projects in The Netherlands have reported on the reuse of structural elements from existing bridges and viaducts to build new structures. Studies have shown the technical feasibility of the reclamation and reuse of existing prefabricated concrete girders in specific cases (Vergoossen et al., 2021) (Vergoossen et al., 2022b). This knowledge was put into practice in the new overpass Hoog Burel in the A1 highway near Apeldoorn in the Netherlands, in which existing concrete girders were integrated into the design (Vergoossen et al., 2022a). In these cases, the design is optimized in terms of capacity utilization and geometry to minimize cut-off waste. It appears, however, that deconstruction and reuse of structural elements from an existing structure currently costs (far) more than traditional demolition and production of new elements (Vergoossen et al., 2023). To reduce these costs, initiatives exist to further develop design and technologies for

deconstruction, such as the ReCreate project (Riuttala et al., 2024; Stenberg et al., 2022; Vullings et al., 2022) and to improve the supply chain efficiency of secondary construction materials, as stated in (*Samenwerkingsverklaring: Om in Gezamenlijkheid Toe Te Werken Naar Een Bouwmaterialenakkoord*, 2024). Furthermore, a market for reclaimed structural elements still has to be developed. In the end, the costs of deconstruction and reuse must be balanced with the environmental advantages of reusing structural elements in the design instead of using primary materials.

A sustainable structural design must meet a growing list of requirements. According to the sustainability framework in the *fib* Model Code for Concrete Structures 2020 (International Federation for Structural Concrete (*fib*), 2022), a sustainable structural design should include requirements related to the three pillars of sustainability, i.e. social performance, environmental performance and economic performance (Hajek, 2023). Social performance according to (Hajek, 2023) includes structural performance and other aspects of social performance, such as aesthetics and comfort. Additionally, following circularity principles (e.g., using objectives such as minimizing material use, or maximizing adaptability of a structure), may have an effect on multiple pillars of sustainability simultaneously. Every design solution affects multiple objectives and criteria simultaneously, in a positive or negative manner, often generating tension between them (Valcke et al., 2022). The need to consider multiple performance criteria simultaneously and the interdependencies between these criteria makes the design process more complex.

Decision support methods aid decision-makers to select the best solution in complex decision processes. Multi-Criteria Decision Analysis (MCDA) is a well-known decision-support method in the construction sector, as it enables actors to evaluate a set of alternatives on multiple criteria and select the best solution in various way (e.g. ranking, weighting, scoring, pairwise comparison) (Zhu et al., 2021). However, the MCDA method often takes into account a set of pre-defined limited alternative solutions, which are not yet optimized for all required criteria or objectives. Multi-objective design optimization generates multiple designs for which multiple objectives are optimized simultaneously (e.g. costs, safety and environmental objectives). Here, optimal or optimized means that a solution that is optimized for a given set of objectives, cannot be further improved with respect to one objective without compromising its performance on other objectives. Because there are many design variables as well as many objectives, the design optimization algorithm results in a multitude of optimal design solutions for which the

possible interdependencies between design variables and objectives become transparent (Purshouse et al., 2014). As a decision-support method, multi-objective optimization can be used by actors to select a balanced and well-performing design solution in construction projects (Dede et al., 2019). Currently, multi-objective design optimization is only used to a limited extent for structural design and decision-making, especially compared to the frequent use of MCDA methods (Chen et al., 2023).

The possibilities for multi-objective optimization in structural design have already been explored by Valcke et al. (2022), who provide a proof of concept of the multi-objective design optimization approach for the design of a single concrete floor slab with RCA. This paper builds further upon this proof of concept and demonstrates the application of multi-objective optimization in the structural design of an entire bridge with both reuse of entire concrete girders as well as the use of RCA in the parts where new concrete is still required. With this case study, this paper aims to illustrate the potential benefits of multi-objective optimization in structural design for supporting transparent decision-making.

The paper proceeds as follows. Chapter 2 describes the case study, including a description of the parametric models, the design objectives and the multi-objective design optimization framework used. Chapter 3 presents the results of the multi-objective design optimization and discusses these results. Chapter 4 concludes the paper.

## **2 Multi-objective design optimization approach**

The multi-objective design optimization approach used in this study is summarized in Figure 1. First, a parametric model is defined for the design of the structure, which includes the relevant parameters and boundary conditions, and calculation models on material and structural level. In this study, the multi-objective design optimization approach is tested for the design of a bridge with both reclaimed precast concrete girders as well as recycled concrete aggregate (RCA) in the new concrete in the design. Section 2.1 gives an outline of the parametric model used for this case study. In the second step of the multi-objective design optimization approach, design objectives are chosen for which the design is optimized. This choice is project-specific and should be made based on the specific requirements and needs of the client and stakeholders. From a mathematical point of view, the number of objectives can be as high as desired. However, through various workshops, it is experienced that the number of objectives that can efficiently be visualised

and discussed is limited. In this paper, 5 objectives are considered. Section 2.2 gives a description of the design objectives that are chosen as an illustration in this case study and their corresponding objective functions. Next, a multitude of optimal design solutions is generated by multi-objective design optimization, which is further described in Section 2.3.

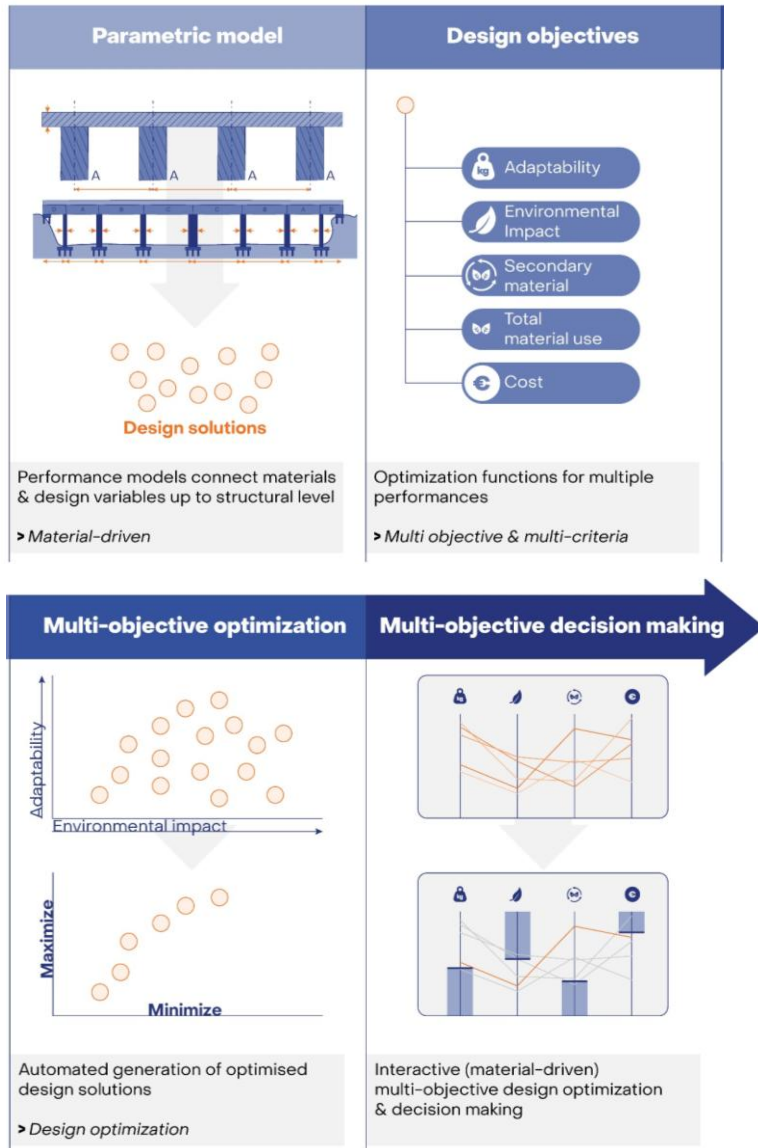


Figure 1. Steps in the multi-objective design optimization approach

Finally, a final solution is selected from the multitude of optimized solutions during an interactive decision making process. Section 2.4 gives a general description of multi-objective decision making given the generated optimal design solutions.

## 2.1 Parametric model

### 2.1.1 Case study introduction

The case study discussed in this paper concerns the structural design of a fictitious bridge with reclaimed precast concrete girders and RCA. Only reclaimed girders are used, no new girders are included. On top of the reclaimed precast concrete girders, a new concrete deck is applied with longitudinal and transverse reinforcement. For the in situ cast concrete of the deck, piers and foundation, a concrete mix with RCA is used. Figure 2 illustrates the cross-section and the longitudinal layout of the bridge used in the case study.

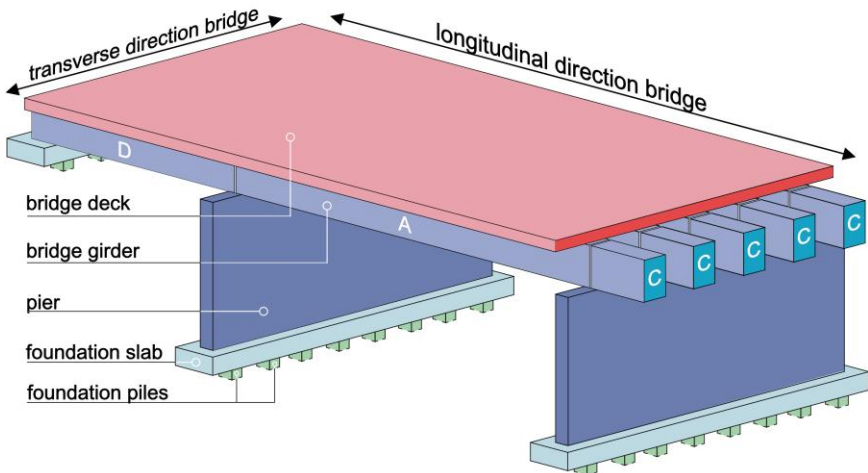


Figure 2. Schematic illustration of structural bridge design considered in the case study

In this case study, only specific design aspects are considered in the bridge design and analyses, which are deemed relevant for a comprehensive evaluation of the design process using a multi-objective optimization approach. The design considered in this study may not reflect the actual design practice in all respects, and only serves to illustrate the potential application of multi-objective design optimization to support decision making during a structural design process.

This section provides a concise description of the approach to structural design constrained to a stock of reclaimed elements (Section 2.1.2), followed by a description of the design variables and boundary conditions in the case study (Section 2.1.3) and loads considered (Section 2.1.4). Finally, the structural calculation models (Section 2.1.5) and material models (Section 2.1.6) are described.

### *2.1.2 Structural design based on availability of reclaimed girders*

In conventional structural design of overpasses or bridges, the structure is designed based on a set of requirements (e.g. road layout, length of the spans) after which the structural elements in the design are produced, tailor-made for that particular project (Vergoossen et al., 2023). When reusing structural elements, the dimensions and structural capacity of the available elements are fixed and must be integrated in the new structural design. This requires a different, stock-constrained design approach, in which the availability of elements is used as starting point, rather than designing with new, tailor-made elements with project-specific dimensions.

Stock-constrained structural optimization has previously been addressed by Brütting et al. (2020) and Van Lookeren Campagne et al. (2023) for steel structures. In order to efficiently utilize the available reclaimed elements in the design of steel truss and frame structures, the design process must be modified by taking the properties of the available elements as starting point in the design. In the case study, a similar approach is adopted: based on the available reclaimed concrete girders, a stock-constrained structural optimization is performed, in which the available concrete girders are incorporated in the design with minimal cut-off waste. The optimal configuration of the available concrete girders then follows from the multi-objective design optimization.

### *2.1.3 Design variables and constraints*

A set of parametric models of the bridge was created with a number of design variables to be optimized. The range of possible values of these design variables can be constrained to obtain realistic or feasible values. Parameters have a fixed value that cannot be varied during optimization. The design of the bridge is considered in (1) the longitudinal direction and (2) the transverse direction. Both directions are illustrated in Figure 2. The list of all design variables and corresponding constraints is given in Table 1.

Table 1. Design variables

Design parameter	Symbol	Unit	Constraint
Number of spans	$n_{\text{spans}}$	-	$3 \leq n_{\text{spans}} \leq 8$
The number of piers (supports) and associated foundation piles are related and equal $n_{\text{spans}} + 1$ .			
Type of existing girder per span	-	-	Is chosen from list of available girders G1 to G9; see Table 2.
Reinforcement in bridge deck (longitudinal) <sup>1</sup>	$A_{s,\text{long}}$	m <sup>2</sup>	
Number of girders in transverse direction	$n_{\text{girder}}$	-	$2 \leq n_{\text{girder}} \leq 5$
Thickness of new concrete bridge deck	$h_{\text{deck}}$	m	$0.1 \leq h_{\text{deck}} \leq 0.3$
RCA replacement percentage of gravel (mass-%) (concrete deck)	$r$	-	$0.001 < r < 1$
Water-to-cement ratio (concrete deck)	$wcr$	-	$0.45 < w/c < 0.65$

<sup>1</sup> This concerns the longitudinal reinforcement at the supports and the dowel connections between the girders and the deck, which are both determined based on the % of the total bending moment in the span for which the connection at the support is designed. Additional reinforcement for shrinkage/creep is also included.

### Longitudinal direction

In longitudinal direction, the total length of the bridge is predetermined and equal to 100 m. The design variables are the number of spans and corresponding number of piers (supports), type of existing girder per span and reinforcement area in the bridge deck in longitudinal direction. Table 1 lists all the design variables in longitudinal direction including constraints. The available girders and their properties are listed in Table 2.

The aim is to utilize the girders in their original state in the design, with a minimal number of cuts and thereby a minimal amount of cut-off waste. An example of possible variations in the bridge design is illustrated in Figure 3. The bridge design may be either symmetrical or asymmetrical in longitudinal direction, i.e. an even or an uneven number of spans. This can be chosen upfront by the designer if required in the design. The length of each span is equal to the length of the reclaimed girders used. In the case of an uneven number of spans, only for one span it is allowed to shorten reclaimed girders to obtain the desired total length of the structure. In the case of an even number of spans, it is allowed to shorten

Table 2. List of available girders and their properties

Girder type	Length [m]	Width [m]	Height [m]	Bending moment capacity $M_{Rd}$ [kNm]	Number of available girders											
G1	17.50	0.60	1.30	4985	40											
G2	20.00	0.60	1.30	4760	30											
G3	25.00	0.60	1.75	8120	45											
G4	28.50	0.60	2.00	11045	30											
G5	32.50	0.60	1.50	15650	25											
G6	35.00	0.60	1.50	15470	40											
G7	42.00	0.60 <td 2.00	24420	45	G8	12.50	0.60	1.00	2428	45	G9	15.00	0.60	1.00	2392	45
G8	12.50	0.60	1.00	2428	45											
G9	15.00	0.60	1.00	2392	45											

the length of two spans by cutting off part of the reclaimed girders. The length of the cut-off part is limited to 25% of the total original length of the girder. All other spans have a length that is equal to the length of the uncut reclaimed girders chosen. Figure 4 shows examples of possible bridge girder configurations.

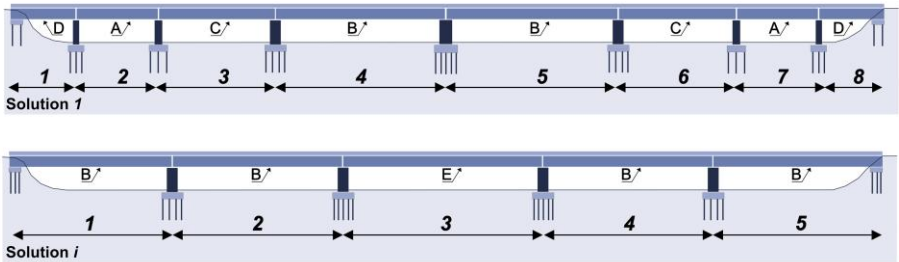


Figure 3. Example of a possible variation in bridge design in longitudinal direction

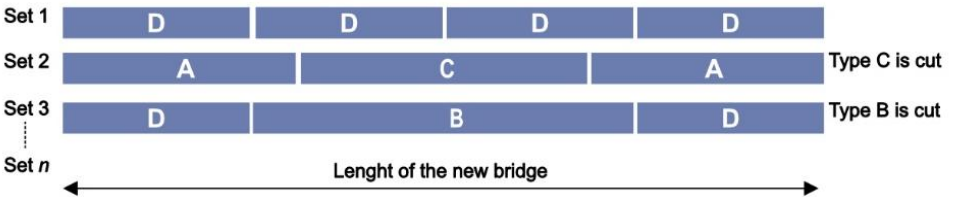


Figure 4. Example of possible bridge girder configurations in longitudinal direction

The bending moment resistance of each reclaimed girder is predetermined by its physical dimensions and reinforcement; however, by applying longitudinal reinforcement in the concrete deck and dowel connections between the girders and the deck, the girders can act as continuous instead of simply supported beams, increasing their load-bearing capacity.

The piers are constructed with walls on a foundation strip with prefabricated piles. The design of the bridge piers and foundation is included in the use case in a simplified way. The piers have a fixed height and width in the transverse direction, which is equal to the bridge width; the thickness of the piers is determined based on the reaction force from the girders. The number of piers is related to the number of spans in the design. The foundation piles have a fixed dimension and capacity. The number of piles per pier is determined based on the load on the pier. Furthermore, it is assumed that the same concrete mix as in the concrete deck is used for the piers and the foundation piles.

### Transverse direction

The design of the bridge in transverse direction is schematically shown in Figure 5. In transverse direction, the total width of the bridge is predetermined and equal to 8.0 m. The in-situ cast concrete deck is supported by a variable number of reclaimed girders. The design variables are the number of girders in transverse direction  $n_{girder}$  and the thickness of the new concrete bridge deck  $h_{deck}$ , with minimum and maximum values as listed in Table 1. The reinforcement area of the transverse reinforcement is calculated as a function of the number of girders in transverse direction, the deck thickness and the concrete compressive strength, which on its turn is a function of the concrete composition (see Section 2.1.6).

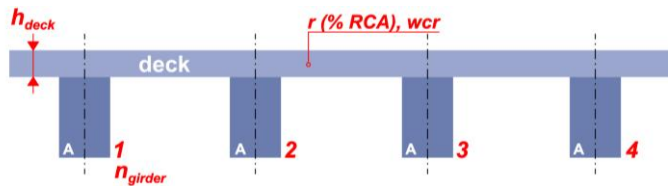


Figure 5. Design of bridge in transverse direction (cross-section) and design variables

Because the design is not only optimized on element level, but also on material level, the RCA replacement percentage of coarse aggregate  $r$  and the water-to-cement (w/c) ratio  $wcr$  of the new concrete in the deck are also introduced as design variables. This is further described in Section 2.1.6.

#### 2.1.4 Loads

The self-weight of the structure is computed based on the design; a concrete self-weight of  $25 \text{ kN/m}^3$  is assumed. In addition to the self-weight of the bridge structure, a fixed traffic load on the bridge deck is included in the structural considerations. This traffic load is simplified to a distributed load which is equal to  $10 \text{ kN/m}^2$ . The loading on the bridge structure is further specified in Annex B.

#### 2.1.5 Structural calculation models

The structural analysis and design of the concrete structures was performed according to NEN-EN 1991-1-1, NEN-EN 1992-1-1 and NEN-EN 1992-2. Calculations have been performed using in-house developed spreadsheets and Python scripts. The design and calculation of the reinforcement is based on NEN-EN 1992-1-1. All design checks must result in a unity check (UC) below 1.0, to ensure structural safety.

A limited number of structural aspects is considered, such as bending, crack width, maximum and minimum amounts of reinforcement, detailing requirements, creep and shrinkage of the deck and the interaction between the two cross-sections of the bridge deck and the reused bridge girders. Other aspects, such as shear, deformations and fatigue have not been considered in this case study: the aim of this study is to demonstrate the application of multi-objective optimization to structural design, and not to provide a complete design calculation.

#### 2.1.6 Material models for material-specific input in structural calculations

In this case study, the relevant material properties of the concrete, being concrete compressive strength and creep and shrinkage properties, are explicitly modelled as a function of the material-related design variables, namely the w/c ratio and RCA replacement percentage of coarse aggregate. The RCA replacement percentage is not limited to a certain maximum value as is the case in Eurocode 2, but can vary between 0 and 100%. Modelling material properties based on concrete composition contrasts with the current practice of selecting a concrete class in the design and relating all other properties to the strength regardless of compositional effects on properties. The state-of-the-art models used here are not yet part of building codes and regulations and can therefore not be used to validate the performance of a structure within the current framework of codes and regulations. However, the models are used here to illustrate the potential of using

material parameters in design optimization and gain insight into trade-offs between material quality and overall performance indicators of the entire structure.

Two simple models are used to calculate the concrete compressive strength  $f_c$  as function of the w/c ratio  $wcr$  and RCA replacement ratio  $r$ . First, the concrete compressive strength  $f_c$  is calculated as a function of the w/c ratio  $wcr$ , assuming natural aggregate (NA), with Equation 1 (Betonhuis, 2021):

$$f_c = a \cdot Nn + \frac{b}{wcr} - c \quad (1)$$

The values of  $a$ ,  $b$ ,  $c$  and  $Nn$  are given in Table 3.

Table 3. Values of  $a$ ,  $b$ ,  $c$  and  $Nn$  per cement type

cement type	$a$	$b$	$c$	$Nn$	density cement
CEM I 42.5N	0.85	33	62	42.5	3150 kg/m <sup>3</sup>

Next, the concrete compressive strength of concrete with RCA  $f_{c,RCA}$  is calculated as function of the RCA replacement ratio  $r$  according to Equation 2, using a strength reduction factor based on the density of the RCA.

$$f_{c,RCA} = (1-r) \cdot f_{c,NA} + r \cdot a \cdot f_{c,NA} \quad (2)$$

in which

$r$  is the ratio between the mass of the RCA and the total coarse aggregate mass;

$$r = \frac{\text{mass RCA}}{\text{total coarse aggregate mass}}$$

$f_{c,NA}$  is the concrete compressive strength of concrete with natural aggregate NA, (given in Eq. 1),  $f_{c,NA}$  is taken equal to  $f_c$ , given in Eq. 1;

$a$  is the ratio between the density of the RCA and the NA;  $a = \frac{\rho_{RCA}}{\rho_{NA}}$

It is noted that these models are a simplified way of taking the effect of RCA into account. New models to take this effect more adequately into account are currently being developed.

The effect of RCA on creep and shrinkage is included by using the models in the new *fib* Model Code 2020 (International Federation for Structural Concrete (*fib*), 2022), as proposed by Tošić and Torrenti (2021). Together with the concrete compressive strength of concrete with RCA, this is used as input for the structural calculation models.

In this case study, the amounts of primary materials in the concrete (water, cement, sand, gravel) are calculated using a standard mix of 1 part cement, 2 parts sand (fine aggregate) and 3 parts gravel (coarse aggregate). The amount of water is determined based on the w/c ratio. The following densities are assumed for the RCA and NA:  $\rho_{\text{RCA}} = 2100 \text{ kg/m}^3$ ;  $\rho_{\text{NA}} = 2650 \text{ kg/m}^3$ .

## 2.2 Design objectives

Corresponding to the sustainability framework in the *fib* Model Code for Concrete Structures 2020 (International Federation for Structural Concrete (*fib*), 2022), all three pillars of sustainability, i.e. social, economic and environmental performance, should be considered to obtain a structural design that is sustainable. Circularity is another important aspect of sustainability that is often considered by clients and stakeholders, especially given the ambitious goal of the Dutch government to have a fully circular economy in The Netherlands by 2050 (Ministry of Infrastructure and Water Management, 2023). Mostly, the aim for introducing circularity, is to avoid depletion of Earth's materials. A number of approaches for the assessment of circularity can be found in literature, including the framework as proposed by Coenen (Coenen, 2019), the guideline for measuring circularity as developed by Platform CB'23 (Platform CB'23, 2022) and the Material Circularity Indicator (MCI) (Ellen MacArthur Foundation and ANSYS Granta, 2015). These approaches each include a number of indicators for circularity, such as resource use and resource availability, adaptability and reusability.

The selection of relevant performance indicators to optimize for in the design is project-specific and should be defined based on client and stakeholder requirements and needs. In this use case, five design objectives and corresponding indicators have been selected as an example. These objectives reflect the three pillars of sustainability and include circularity aspects. It is noted that the structural safety of the design is adopted as constraint, by ensuring that all unity checks are below 1.0.

The following two optimization objectives are considered in the use case to take into account the environmental impact and costs of the design:

- Environmental impact objective: to minimize the environmental impact, which is expressed as MKI shadow costs of the design.
- Cost objective: to minimize the costs of the design, expressed as direct costs of the structure in euros (€).

In addition to these two objectives, three circularity objectives are considered:

- Adaptability objective (or societal performance objective to enhance adaptability to future heavier traffic loads and to reduce vulnerability to future hazards): to maximize the design resistance compared to the design load effect, which is modelled by minimizing the unity check (UC) values, and by minimizing the differences between UC values of structural elements of the same type.
- Secondary material objective: to maximize the share of secondary (recycled and reused) materials in the total material use, which is expressed as the fraction of secondary materials in the design.
- Total material use objective: to minimize the total mass of used materials.

Each objective is described in detail in the sections below.

### 2.2.1 Environmental impact objective

The environmental objective considered in the use case is to minimize environmental impact. The Dutch environmental cost indicator, MKI [*MilieuKosten Indicator*], is used to express this impact. The shadow pricing approach to determine the MKI applies a weighting factor to each of the eleven considered environmental impact categories to come to a single score. The characterized impact scores per environmental impact category are determined using the characterization factors prescribed by the *Nationale Milieu Database* (NMD, 2020).

The environmental impact assessment model includes demolition and treatment processes (C1-C4) of reapplied recycled materials and reclaimed elements as harvested from the donor structure and the production and construction (A1-A5) LCA stages of the bridge under consideration in this case study. This is an unconventional scope, as conventional

environmental life cycle assessments (LCA) studies rather focus on the environmental impact over the complete life cycle of a single element or construction, from cradle-to-grave which implies that harvesting of the secondary materials is not being considered as it takes place before the 'cradle'. Hence, the environmental impact related to demolition and end-of-life processing of reused recycled materials and reclaimed elements before the end-of-waste point would be attributed to the life cycle of the donor construction and not to the production and construction stages of the new structure as is done in this study. The alternative scope allows for the optimization of reuse processes occurring at this moment in time, which can still be influenced by the project now. The main limitation is that future implications of decisions made during the optimization of this project are not (yet) considered. This approach is particularly chosen since these implications occur in a distant future for the objects assessed, which is subject to considerable uncertainty (Bizarro & Lennartz, 2022).

The function to determine the environmental impact is formulated as:

$$f_{\text{env}}(\mathbf{x}) = \sum_i A_i(\mathbf{x}) \cdot I_{\text{env,MKI},i} \quad (3)$$

where:

- $f_{\text{env}}(\mathbf{x})$  is the total environmental impact of the design [s€ (MKI shadow cost)].
- $\mathbf{x}$  is the vector of design variables.
- $A_i$  is the activity data of each process ( $i$ ) [process dependent].
- $I_{\text{env,MKI},i}$  is the environmental impact factor (MKI) of each process ( $i$ ) [s€/(unit of  $i$ )].

The environmental impact objective is to minimize the function  $f_{\text{env}}(\mathbf{x})$ .

Activity data describe the extent to which a process is carried out. The data is retrieved from design variables, often in combination with supplementary information. The applied function to determine the activity data differs amongst the processes. Examples of activity data functions are presented below for the following processes: crane use during disassembly to reclaim girder (Eq. 4), transport of gravel to the production facility (Eq. 5) and material extraction of sand (Eq. 6).

$$K_{\text{Lifting}}(\mathbf{x}) = K_{\text{Lifthing}} \cdot n_{\text{girder}}(\mathbf{x}) \quad (4)$$

where  $K_{\text{Lifting}}$  represents the crane operation time per reclaimed girder to lift it onto a truck expressed in [h/girder] and  $n_{\text{girder}}$  represents the number of girders.

$$A_{\text{Transport}}(x) = d_{\text{Transport}} \cdot m_{\text{Gravel}}(x) \quad (5)$$

where  $d_{\text{Transport}}$  represents the distance a truck needs to travel to transport the gravel from the source to the construction site expressed in [km] and  $m_{\text{Gravel}}$  represents the mass of gravel in [t].

$$A_{\text{Mining sand}}(x) = m_{\text{Sand}}(x) \quad (6)$$

where  $m_{\text{Sand}}$  represents the mass of sand in [t].

The activity data functions and the corresponding environmental impact factor datasets have not been included in this paper due to their size. Information is available from the authors upon reasonable request.

### 2.2.2 Cost objective

The cost objective considered in the use case is to minimize direct costs of the structure, expressed in euros (€). In this study, the costs are determined using a simplified model that includes the production costs (stage A1-A3) for which the purchase price of the different materials is used, the costs of transport to the construction site (stage A4) and the construction costs (stage A5). The costs of demolition and processing (stage C1-C4) of the recycled materials (RCA, steel reinforcement) from the donor structure are included in the purchase price of the materials.

Only the costs of processes that are expected to vary significantly between different potential design solutions are included in the cost calculation, since these differences will influence the results of the design optimization. Costs that do not vary much between different potential design solutions are left out of the scope of the cost calculation, since these costs will be similar for all design solutions and will therefore not have any significant influence on the results of the design optimization. For this same reason, the costs of the use stage (B1-B7) are left out of the scope, since these costs are assumed to be comparable for all design solutions. It is important to note that the cost calculation used for

the cost objective therefore does not reflect the total cost of the structure, but only the costs as described in this section.

The function to determine the total direct costs of the structure is formulated as:

$$f_{\text{cost}}(x) = \sum_j A_j(x) \cdot C_j \quad (7)$$

where:

$f_{\text{cost}}(x)$  are the total direct costs of the structure [€].

$x$  is the vector of design variables.

$A_j$  is the activity data of each process ( $j$ ) [process dependent], similar to  $A_i$  to assess the environmental impact.

$C_j$  is the cost factor for the included processes ( $j$ ), per process unit [€/ (unit of  $j$ )].

The cost objective is to minimize  $f_{\text{cost}}(x)$ .

The production costs of the different materials (purchase price), the transport costs and the construction costs of the relevant processes are project-specific. These costs must be determined for each project separately and can be varied per project in the multi-objective design optimization. Annex A lists the production costs (purchase price), transport costs and construction costs that have been used as input in this use case.

### 2.2.3 *Adaptability objective*

The adaptability objective reflects the circularity of the structure in terms of potential for life span extension and adaption for future (increasing) loads, but it can also be considered as a societal objective to reduce vulnerability to future hazards (resilience). The objective steers towards a structural design with a higher design resistance than required given the current design loads, i.e. higher structural safety. With a higher design resistance, the structure can more easily be adapted to future heavier traffic loads for which a higher load bearing capacity is required.

In this case study, the adaptability of the structure is related to the level of structural safety of the structure expressed by unity check (UC) values: a higher structural safety (lower UC) implies that the structure can more easily be adapted to future heavier traffic loads, as

previously described. Next to this, the adaptability objective also steers towards a minimum scatter between the different UC values of elements of the same type, to avoid high differences in dimensioning of single elements in the structure.

The adaptability objective is therefore formulated using two ‘sub-objectives’:

- 1) To maximize the structural safety of each structural element (or critical section).
- 2). To minimize the difference between the safety level of different structural elements (or critical sections) of the same type, to ensure that the safety level is as homogeneous as possible.

By using the UC values, i.e. the ratio between the design load effect and the design resistance, as indicators of structural safety, the two aforementioned objectives can be rewritten in formulas as follows (the constraints are not listed here):

- 1) minimize the UC values for each structural element:

$$\min \max(UC_{j,1}, UC_{j,2}, \dots, UC_{k,n_j}) \quad (8)$$

- 2) minimize the differences between the UC values of structural elements of the same type:

$$\min \sum_{i=1}^{n_j} (UC_{j,i} - \text{avg}(UC_j))^2 \quad (9)$$

in which:

$j \in \{1, 2, 3, 4\}$  representing the group of structural elements: spans, girders, piers and piles.

$UC_1$  is the UC of the bending moment in the transverse direction of the bridge deck:

$$UC_1(x) = \frac{M_{Ed,deck}}{M_{Rd,deck}}$$

$UC_2$  is the UC of the bending moment in the reused girders:  $UC_2(x) = \frac{M_{Ed,beams}}{M_{Rd,beams}}$

$UC_3$  is the UC of the axial force in the piers:  $UC_3(x) = \frac{N_{Ed,piers}}{N_{Rd,piers}}$

$UC_4$  is the UC of the axial force in the piles:  $UC_4(x) = \frac{N_{Ed,piles}}{N_{Rd,piles}}$

$n_j$ , represents the number of the structural components to be designed for group  $j$ . For instance,  $n_1$  is the number of spans,  $n_2$  is the number of girders,  $n_3$  is the number of piers and  $n_4$  is the number of piles of the bridge.

The rationale behind the two-stage optimization proposed in this paper is as follows. By minimizing the maximum UC value for each limit state condition, the level of structural safety of the structure is maximized according to the partial factor method. To ensure adequate structural safety for all solutions, the condition  $UC \leq 1,0$  is adopted as constraint to the design optimization. Among all design solutions found, those characterised by the minimum scatter of the UC values for each limit state condition are preferred to avoid unnecessary over-dimensioning. Changing the order of this two-stage optimisation is tested and did not significantly influence the final outcome.

It should be noted that the current practice of structural design usually aims to design solutions characterised by UC values that are as close as possible to one. This solution is optimal in terms of minimum smaterial use for reaching adequate structural safety. In the multi-objective design approach proposed in this paper, however, material usage is considered individually in a separate objective.

#### *2.2.4 Secondary material objective*

The secondary material objective considered in the case study reflects the circularity of the structure in terms of secondary material use: the secondary material objective is to maximize the (mass-based) share of secondary (recycled and reused) materials in the total amount of materials. Together with the total material use objective (see next section), this allows to steer the design towards a minimal use of primary materials and efficient and high-quality utilization of construction demolition waste. This aspect of circularity can also be found in literature, and is for instance reported in (Coenen, 2019), in the guideline for measuring circularity by Platform CB'23 (Platform CB'23, 2022) and in the Material Circularity Indicator (MCI) (Ellen MacArthur Foundation and ANSYS Granta, 2015).

The function  $f_{sec}$  that is used for the secondary material objective is expressed as the fraction of secondary materials in the design, consistent with the Material input indicator as proposed by Coenen (Coenen, 2019).

$$f_{\text{sec}} = \frac{m_{\text{recycled}}}{m_{\text{total}}} + \frac{m_{\text{reused}}}{m_{\text{total}}} \quad (10)$$

where:

$m_{\text{recycled}}$  is the total mass of the used recycled materials in the design in [kg];

$m_{\text{reused}}$  is the total mass of the used reused elements in the design in [kg];

$m_{\text{total}}$  is the total mass of the structure.

The secondary material objective is to maximize  $f_{\text{sec}}$ . In calculating the values of  $f_{\text{sec}}$  in the optimization process, the following assumptions are made:

- $m_{\text{reused}}$  consists of 100% of the mass of the reclaimed concrete girders, after cutting: only the mass of the girders that are used in the new design are considered, since this concerns the circularity of the design;
- $m_{\text{recycled}}$  consists of 100% of the mass of the RCA in the design and 82.2% of the mass of the steel reinforcement (Stichting Nationale Milieudatabase, 2023).

### 2.2.5 Total material use objective

The total material use objective is to minimize the total mass of used materials in the design. When only the fraction of recycled and reused materials is maximized by the secondary material objective, the use of more reused (or recycled) material in the design is rewarded, even if this leads to higher overall material usage in general. This is not desirable in view of sustainability. To counter this effect, minimization of the total mass of materials is introduced by the additional function  $f_{\text{mat}}$ :

$$f_{\text{mat}} = m_{\text{total}} \quad (11)$$

The total material use objective is to minimize  $f_{\text{mat}}$ . Together with maximization of  $f_{\text{sec}}$ , the use of materials is minimized while still maximizing the use of secondary materials in the design, promoting a high-quality utilization of construction demolition waste.

## 2.3 Multi-objective design optimization

Multiple methods exist which can solve multi-objective optimization problems and generate a multitude of design solutions which are all Pareto optimal (Pareto fronts). In the considered use case, the jMetalPy framework (Benítez-Hidalgo et al., 2019) is used for the multi-objective design optimization. In this framework, the evolutionary optimization

algorithm GDE3 (Generalized Differential Evolution (Kukkonen & Lampinen, 2005)) is used.

An evolutionary algorithm was selected for this research because of beneficial properties such as, but not limited to: wider solution space, less likely to end up in local optima, gradient-less and suitable for multi-model problems (Sangwan, 2018). Evolutionary algorithms are mainly successful for continuous multi-objective optimization problems. Specifically for mixed-integer problems, such as in this case study, the literature shows mostly positive results using evolutionary algorithms in mixed-integer problems such as (Wu & Chow, 1994), (Ndiritu & Daniell, 1999), (Tong, Chowdhury, & Messac, 2014), (Jankauskas, Papageorgiou, & Farid, 2019) and (Sadowski, Thierens, & Bosman, 2021). In this research the evolutionary algorithm was used without modifying components of the algorithm, which is still supported by the papers as a valid option, but not always the most efficient. The previously discussed advantages of evolutionary algorithms combined with their potential effectiveness for mixed-integer problems provide a solid basis in using such an approach.

The multi-objective design optimization algorithm generates Pareto optimal design solutions in a solution-space spanned by the objectives. A solution is Pareto optimal if that solution can only be further improved with respect to one objective by sacrificing its performance in other objective(s), also known as trade-offs. The benefit of using the Pareto optimal definition is that all solutions that are Pareto optimal will lie on the border between objectives where trade-offs occur. The trade-off border between objectives is what is known as the Pareto front, on which all Pareto optimal solutions lie. For example, in the case of an optimization on four objectives, the following holds for any chosen design solution on the Pareto front: If you consider one of the optimized design solutions with a set of specific outcomes on three of the four objectives, then the outcome on the fourth objective cannot be better than the one corresponding to the Pareto front. All other solutions for this considered set of outcomes on three objectives that gave a worse outcome on the fourth objective, are not lying on the Pareto front and have been left out. The advantage of visualizing and generating the Pareto front is that trade-offs are made transparent and not hidden in the multitude of underlying models. Based on the preferences and requirements of the decision maker and the dependencies between the different objectives, a decision can be made on the preferred design solution.

Following the convention of the standard form, all objectives have been reformulated in the optimization algorithm as minimization functions, even the ones that in fact concern maximization. For the latter, a minus sign is added to the function before minimization (so it is in fact a maximization). An advantage is that it eliminates the need to remember for each objective which end of the spectrum is “better”. Especially, when comparing results graphically, it is easier to remember that for all objectives the results are presented such that ‘the lower is the better’.

#### *2.4 Multi-objective decision making aided by multi-objective design optimization*

Multi-objective optimization can be used to aid decision-makers to find their preferred optimal solution (Purshouse et al., 2014). To do so, the study of Groenia et al. (2024) proposes an interactive decision-making method. This method is illustrated in Figure 6. In the first step of this method, the decision-makers are introduced to multi-objective design optimization and their design problem. In the second step, the decision-makers examine the multi-objective design optimization outcomes, and gain insights into the trade-offs between the multiple objectives. In the third step, the stakeholders provide their initial preferences on each of the objectives. These initial preferences are implemented in the optimization model, which results in regions of interest (ROIs). These ROIs contain a set of solutions which reflect the implications of the initial preferences (Xin et al., 2018). In the fourth step, the decision-makers examine their ROIs. To summarize, in step 1 until 4 of the interactive process, the decision-makers learn about their multi-objective problem by investigating the optimization results with respect to their initial preferences (Hakanen et al., 2022). From step 4, the decision-makers switch from learning to decision-making. After a review of the individual ROIs, the decision-makers can search together for feasible overlap between their preferences, or even slightly change those, using the insight of optimization results in order to find a joint ROI. At the end, they (preferably) select a balanced solution for all.

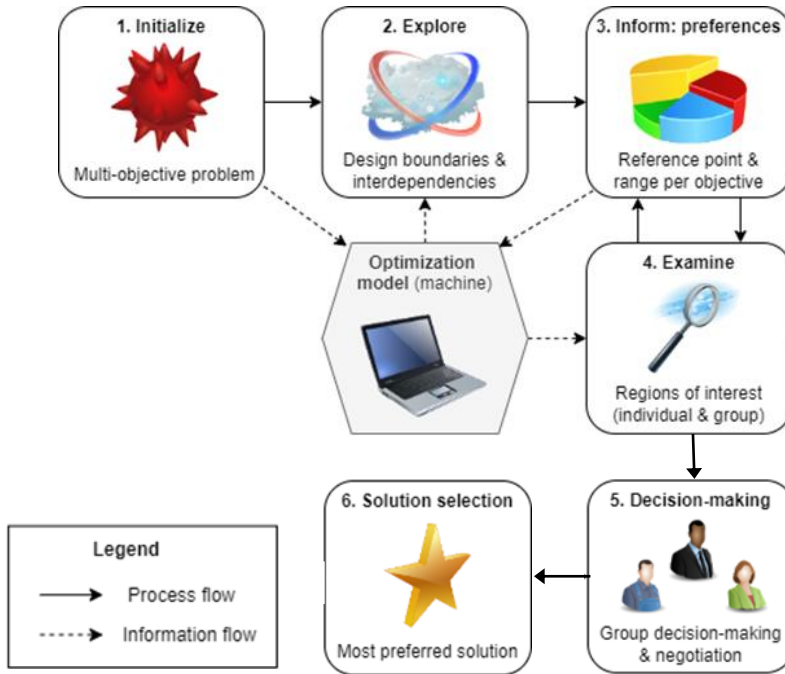


Figure 6. Interactive decision-making process (Groenia et al., 2024)

To summarize, the interactive decision-making process enables stakeholders to learn about the trade-offs of their optimization problem, adjust their preferences, and select their preferred optimal solution, through a transparent decision-making process (Groenia et al., 2024). The structured support for all decision-makers is critical for a balanced and feasible design outcome: it improves overall satisfaction and when performed in phases starting from the earliest decisions in a design process, it may prevent disappointment due to not reaching unrealistic ambitions that were formulated without support of insight in feasible designs. Ultimately, an interactive process results in the selection of a balanced and justified design solution.

### 3 Results and discussion

For visualization of the Pareto optimal solutions, parallel coordinate plots are made using Plotly (Plotly Technologies Inc., 2015). A parallel coordinate plot provides an overview of all Pareto optimal design solutions within the solution space: each line represents one optimal design solution. For each solution, the corresponding values of the design

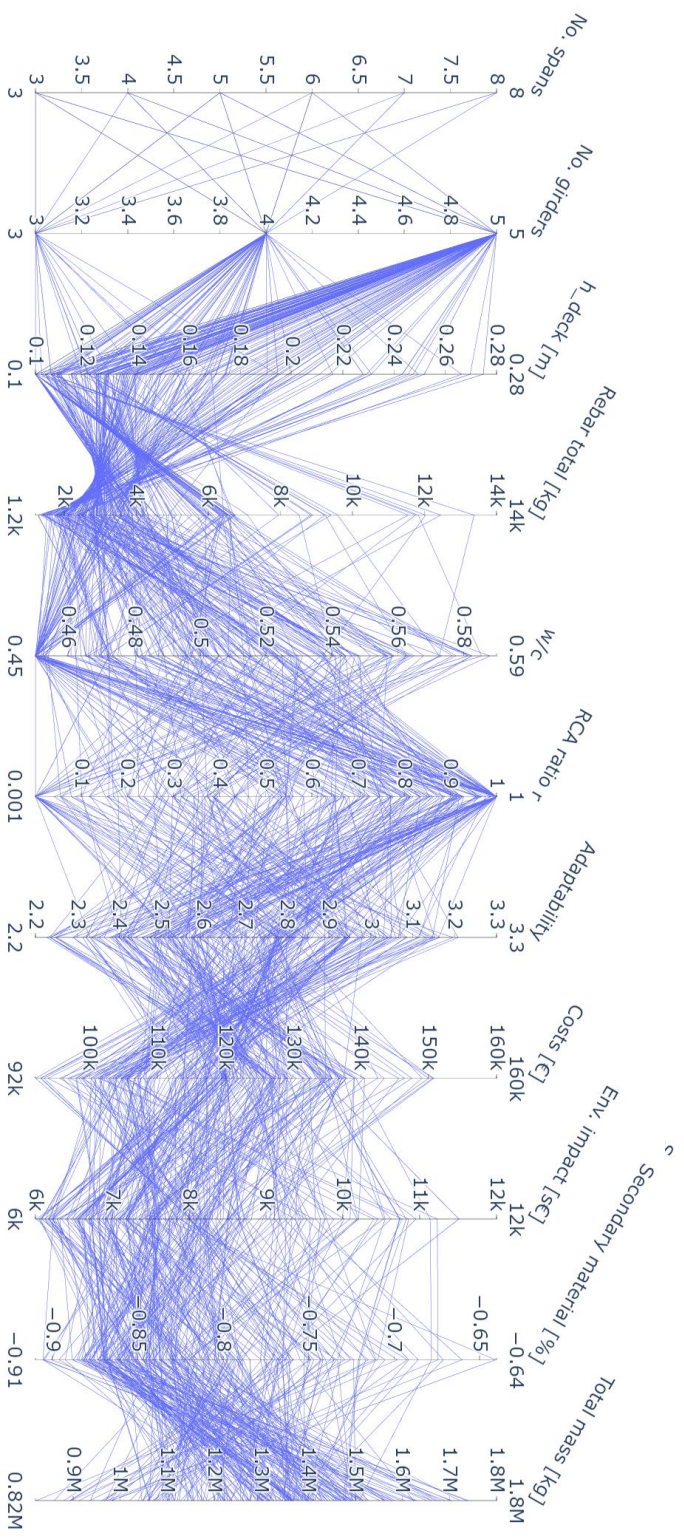


Figure 7. Parallel coordinate plot with all Pareto optimal solutions from the design optimization

variables are shown on the parameter axes. The corresponding value of each optimization objective is shown on the objective axes. Figure 7 shows the results of the design optimization: the full set of the 300 Pareto optimal solutions are plotted in a parallel coordinate plot with a selection of design variables and objectives on the axes. For readability reasons, the names of the axes are simplified. Table 4 gives a detailed description of each axis. All objectives have been formulated as minimization functions, so that for each objective axis, ‘the lower the better’, see also Section 2.3.

Table 4. Description of axes in parallel coordinate plots

	Name of axis	Description
Design parameters	No. spans	Number of spans of the bridge
	No. girders	Number of girders per span, in transverse direction
	$h_{deck}$ [m]	Deck thickness, in m
	Rebar total [kg]	Total reinforcement in bridge deck (transverse and longitudinal direction). Total amount in kg
	RCA ratio $r$	RCA replacement percentage of coarse aggregate (ratio based on mass)
	w/c	Water/cement ratio of the concrete
Objectives	Adaptability	Sum of maximum UC of each structural element type (bridge deck, reused girders, piers and foundation piles; see Section 2.2.3)
	Costs [€]	Costs of the structure expressed in euros (€), according to cost function (Eq. (2.7))
	Env. impact [s€]	Environmental impact of the structure expressed in terms of MKI shadow costs (s€), according to environmental impact function (Eq. (2.3))
	Secondary material [%]	Share of secondary (reused and recycled) materials in the design, according to Eq. 10
	Total mass [kg]	Total mass of structure, including the deck, girders, piers and foundation piles

The solutions in Figure 7 show discrete values for the number of spans (no. spans) and number of girders per span (no. girders), since only discrete values are possible for these parameters. For the design variables no. girders,  $h_{deck}$  and w/c ratio, solutions are found

over only a part of the constraint range. Furthermore, the parallel coordinate plot shows clear interdependencies between some design variables and objectives: for example, the deck thickness ( $h_{deck}$ ) and total reinforcement (rebar total) are conflicting, as well as the adaptability and costs objective.

### 3.1 Interdependencies between design variables and objectives

The parallel coordinate plot in Figure 7 provides the structural engineer and other stakeholders insight into the full range of optimal design solutions. In current design practice, the number of structural design alternatives considered is limited: a selection is often already made upfront by making use of best practices or rules of thumb (e.g. regarding deck thickness, fixed choice for concrete strength or minimizing reinforcement). Moreover, the design solutions considered may be optimized on only two objectives at once, while other objectives (such as environmental impact) are only evaluated afterwards. This may result in overlooking more optimal design alternatives. In contrast, the multi-objective design optimization approach used in this study provides the structural engineer with a comprehensive range of optimal design solutions. These solutions are automatically generated by taking into account all relevant objectives and boundary conditions (such as requirements following from codes and guidelines) simultaneously, without assigning any weights to the objectives beforehand. The objectives are all maximized or minimized and treated equally. Only afterwards, during the decision-making process as described in Section 2.4, preferences are brought in and adjusted following the insight into feasibility of the designs (see next Section 3.2).

The multitude of solutions in the parallel coordinate plot provides insight into the interdependencies between design variables and objectives. As an example, to illustrate this, Figures 8, 9 and 10 show the solutions corresponding to different numbers of girders (3, 4 or 5) per span. The solutions with 5 girders per span (Figure 10) all have relatively low amounts of total reinforcement in the deck, which can be explained based on the limited distance between the girders in transverse direction, and thus limited span length of the deck. When the number of girders per span in transverse direction decreases to 4 or 3, the total amount of reinforcement in the deck increases, as expected.

When the interdependency between the number of girders and the deck thickness ( $h_{deck}$ ) is considered, Figure 10 shows that among the design solutions with 5 girders, the deck

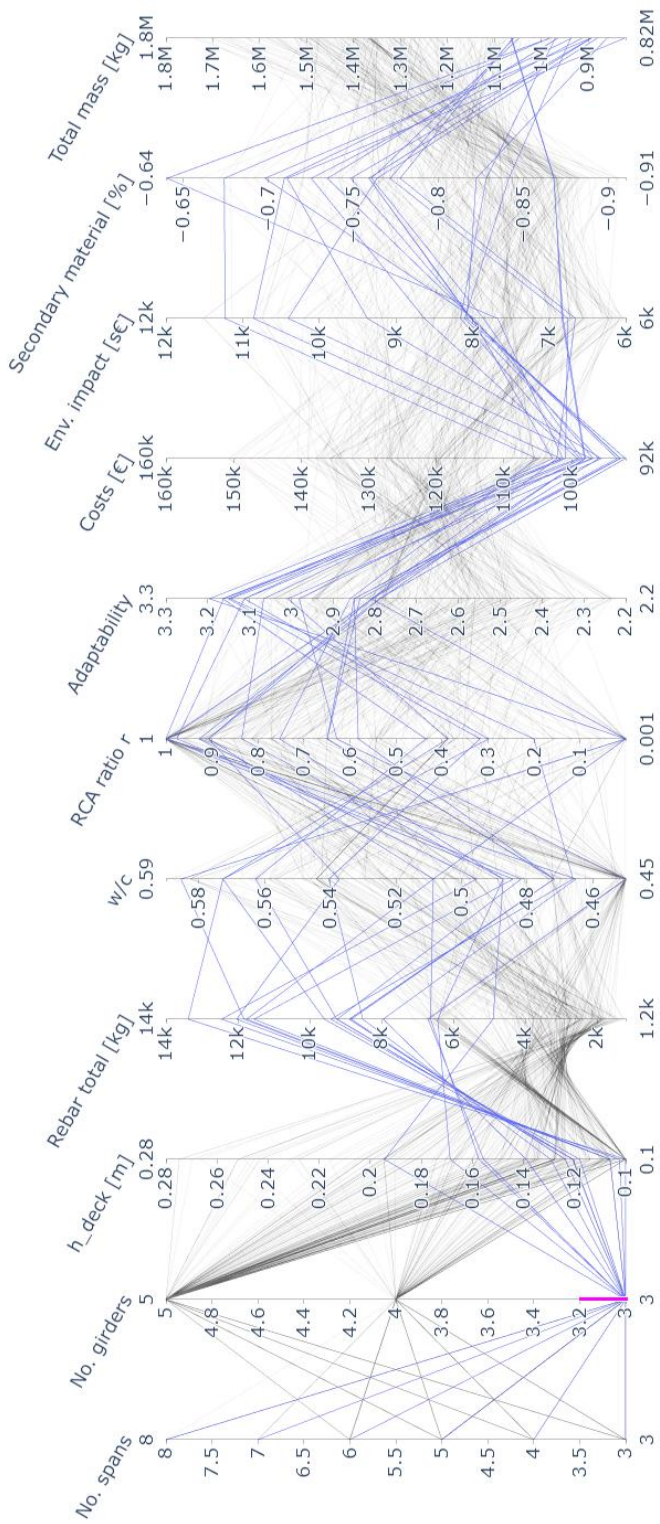


Figure 8. Parallel coordinate plots with same solutions as Figure 7  
 Solutions in blue correspond to all solutions. Selection of solutions with 3 girders per span.

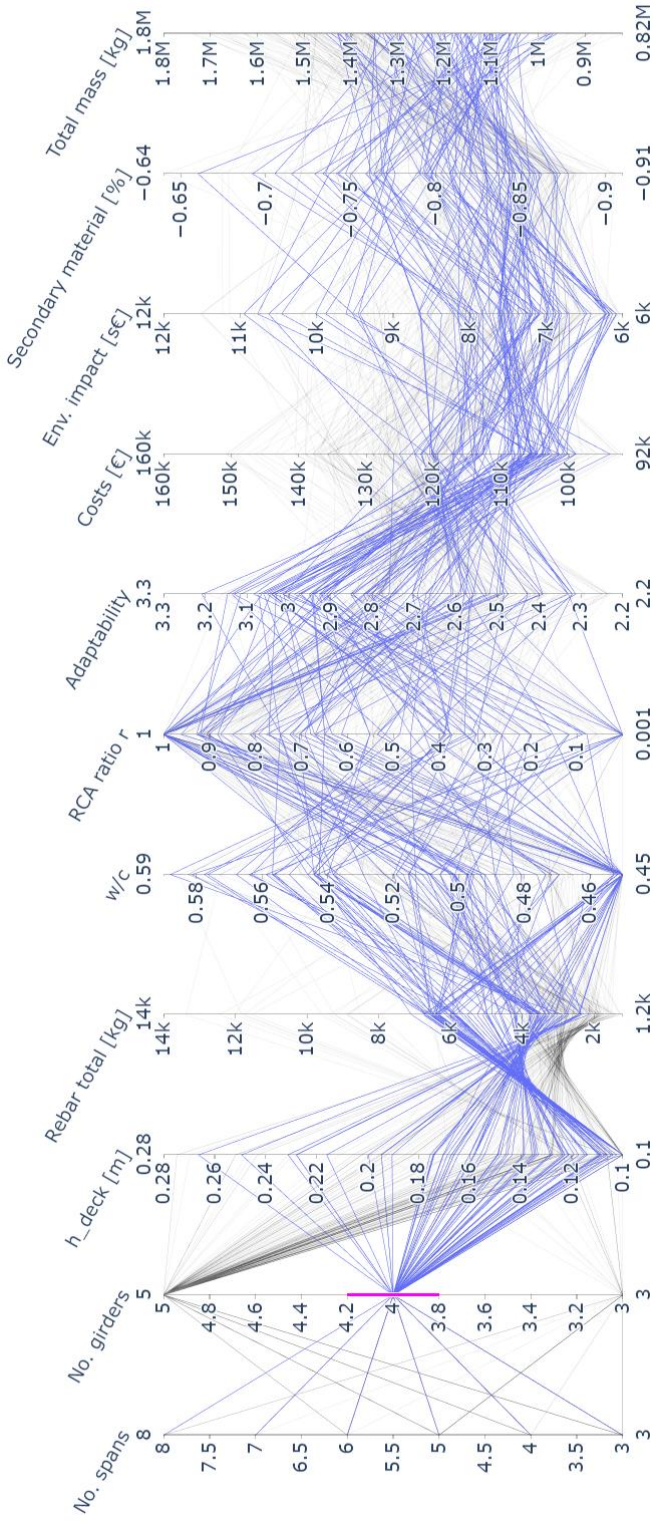


Figure 9. Parallel coordinate plots with same solutions as Figure 7  
 Solutions in blue correspond to all solutions. Selection of solutions with 4 girders per span.

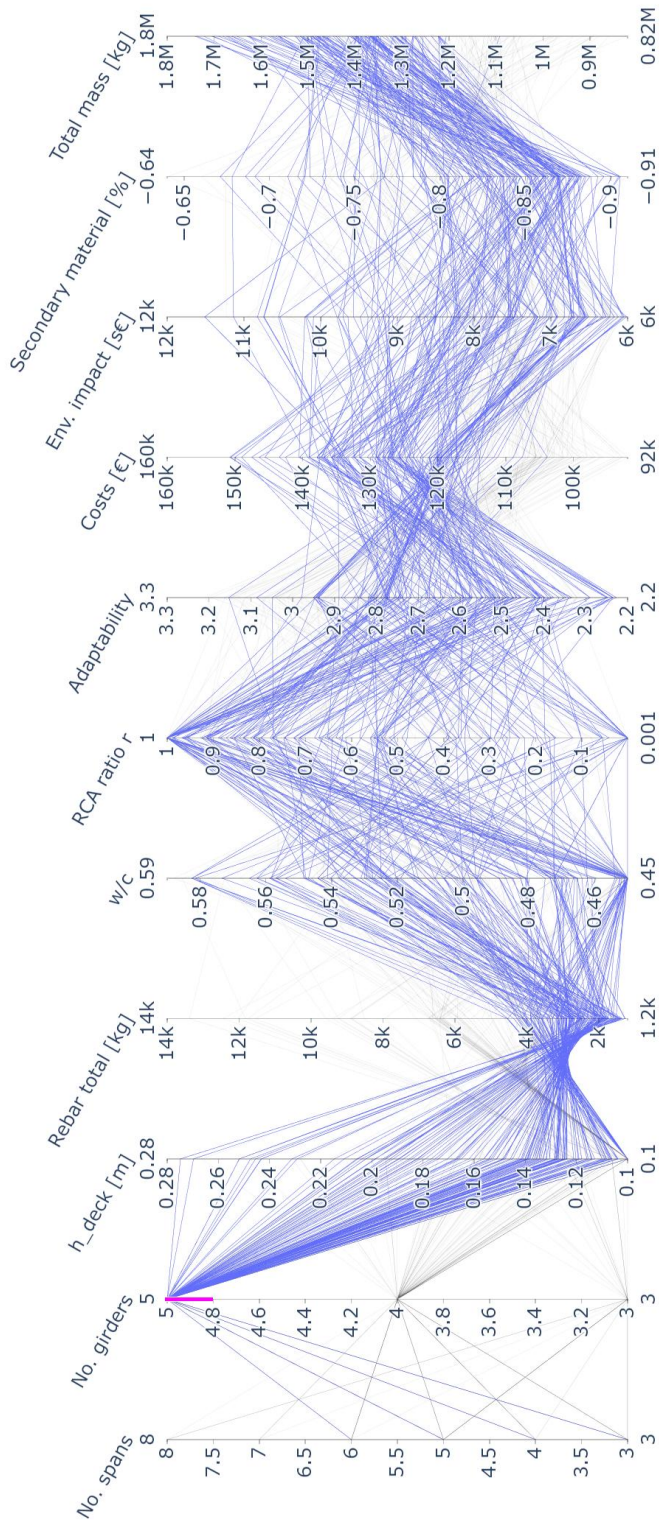


Figure 10. Parallel coordinate plots with same solutions as Figure 7  
 Solutions in blue correspond to all solutions. Selection of solutions with 5 girders per span.

thickness varies over the full range of possible values; i.e., for each thickness value, a Pareto optimal solution can be found with 5 girders. However, for the solutions with 3 girders (Figure 8), only solutions with a deck thickness  $< 0.2$  m are found. From a structural point of view, one would expect to find solutions with higher deck thicknesses as well, since the span length of the deck in transverse direction becomes larger when only 3 girders are used per span. In a design with a limited number of girders, the load on each girder is relatively high and increases when the deck thickness increases. For deck thicknesses higher than 0.2 m, the load bearing capacity of the reclaimed girders might be exceeded, leading to unity checks higher than 1.0 and therefore non-feasible solutions. Due to the given load bearing capacity of the girders and maximum unity check as a boundary condition, the adaptability of the design cannot be further increased by increasing deck thickness.

The interdependency between the number of girders per span and the different objectives can also be considered. Solutions with an increased number of girders per span (4 or 5 girders) include solutions with better adaptability values. Furthermore, it appears that a higher number of girders per span generally leads to higher cost values. Finally, the number of girders does not appear to limit the possible environmental impact and secondary material values.

As another example of interdependencies, Figure 11 considers the cost objective in relation to the different design variables. This figure shows that design solutions with low cost values ( $< 105$  k€) only include solutions with a low deck thickness ( $h_{deck}$ ). This is to be expected, since the costs of the design are partly governed by the amount of concrete in the design. However, the costs do not appear to be governed by the total amount of deck reinforcement: the lowest costs values in Figure 11 still include design solutions with a high amount of deck reinforcement. This contrasts with current structural engineering practice, in which the focus lies primarily on limiting the amount of reinforcement as much as possible to reduce costs. By showing that low costs can be achieved by a structure with a limited amount of concrete and a relatively large amount of reinforcement, the results of the design optimization provide additional insights compared to current design practice.

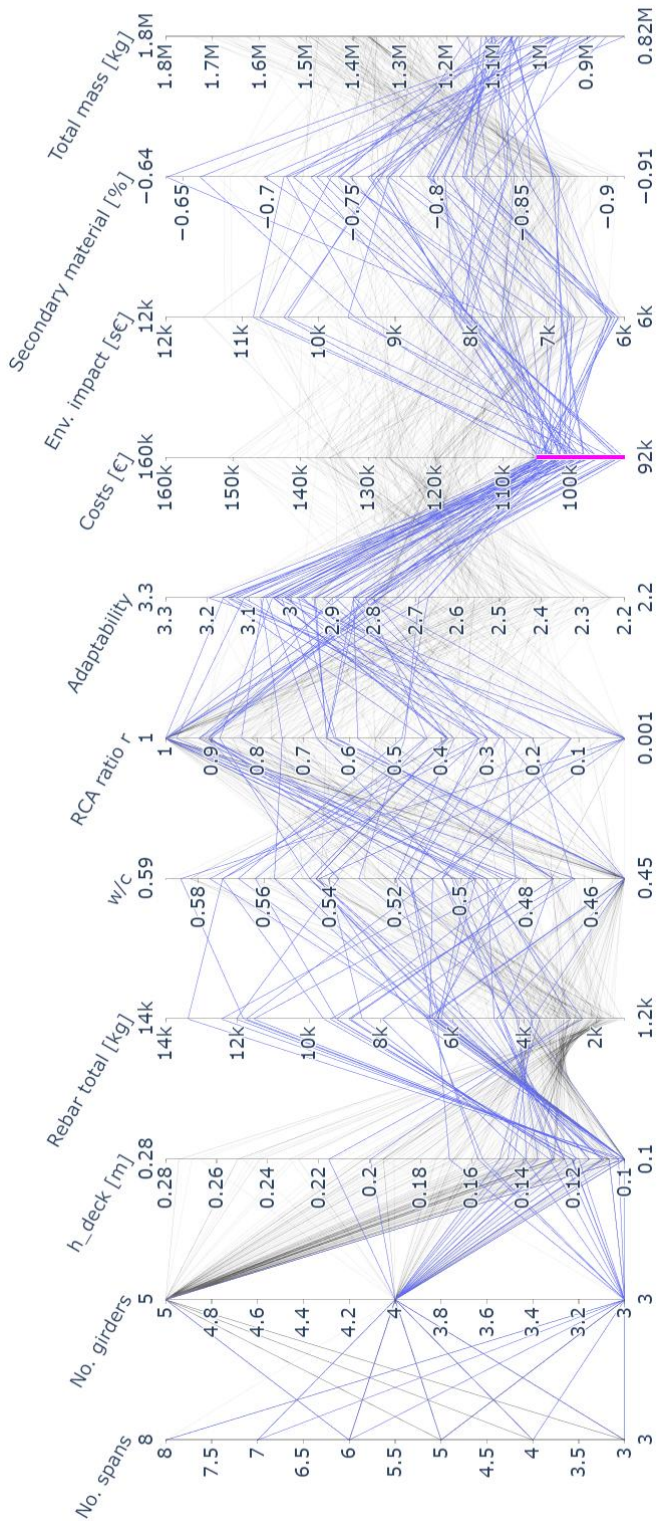


Figure 11. Parallel coordinate plot with same solutions as Figure 7  
 Only solutions are shown within a selected cost range (92k – 105k)

### 3.2 *Interdependency amongst objectives*

The visualization of optimal design solutions allows all stakeholders involved to gain insight into the interdependencies between objectives and make realistic, well-balanced trade-offs, as previous research by Groenia et al. (2024) has shown. For instance, a client can see directly the effect of a cost reduction (or increase) on circularity objectives such as structural adaptability and amount of secondary material. Also, an environmental impact expert and a circularity expert (e.g. MKI calculator, LCA analyst, circularity consultant) can assess the effect of a reduction in environmental impact on the adaptability and secondary material and vice versa.

When considering the cost and adaptability objectives in the case study, for example, one can see in Figure 7 that for the majority of the solutions, lower costs (desirable) lead to lower adaptability (undesirable). The conflict between these objectives is expected, since the cost objective in this case study is dominated by material use, and more material (higher cost) is needed to obtain a higher structural capacity for greater adaptability. Trade-offs such as these are made visible in the parallel coordinate plot. As an example, Figure 12 shows the same results as Figure 7, after applying a filter on the adaptability objective: only solutions with an adaptability score  $< 2.4$  are shown. With this filter, no solutions with low costs ( $< 110k$ ) and low environmental impact ( $< 7k$ ) are left. However, adjusting the criterium for adaptability to values between 2.6 and 2.8 (see Figure 13) leads to a lot more solutions with low costs and low environmental impact. In this way, trade-offs can be quantified and made visible to all stakeholders.

Furthermore, an architect or an engineer can see how certain design choices (e.g. the number of girders used per span) affect the interdependency between different objectives, which is not the same for every solution. Insight in these 'variable' interdependencies allows actors to choose the most satisfying outcome on objectives simultaneously and justify why they make certain design decisions and trade-offs. This is a clear improvement compared to many existing multi-criteria assessment tools, which do not provide in-depth insights into the full range of possible interdependencies, but merely provide a preferred solution from a set of alternative solutions based on qualitative ratings (Zhu et al., 2021).

It should be noted that these interdependencies between objectives, are an inherent consequence of how each objective is modeled as a function of (combinations of) design variables and intermediate outcomes thereof (for example, total mass of a structure).

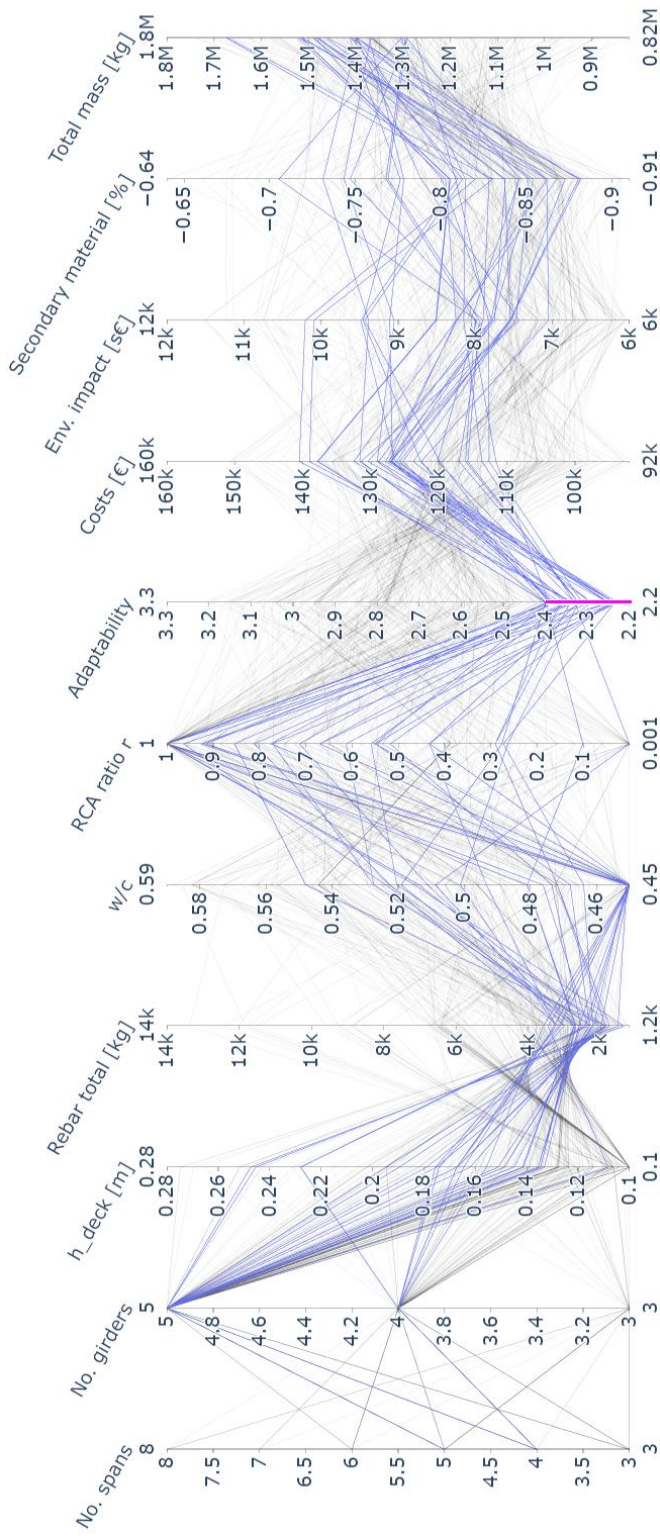


Figure 12. Parallel coordinate plot from Figure 7  
 Only solutions are shown within a selected adaptability range ( $< 2.4$ )

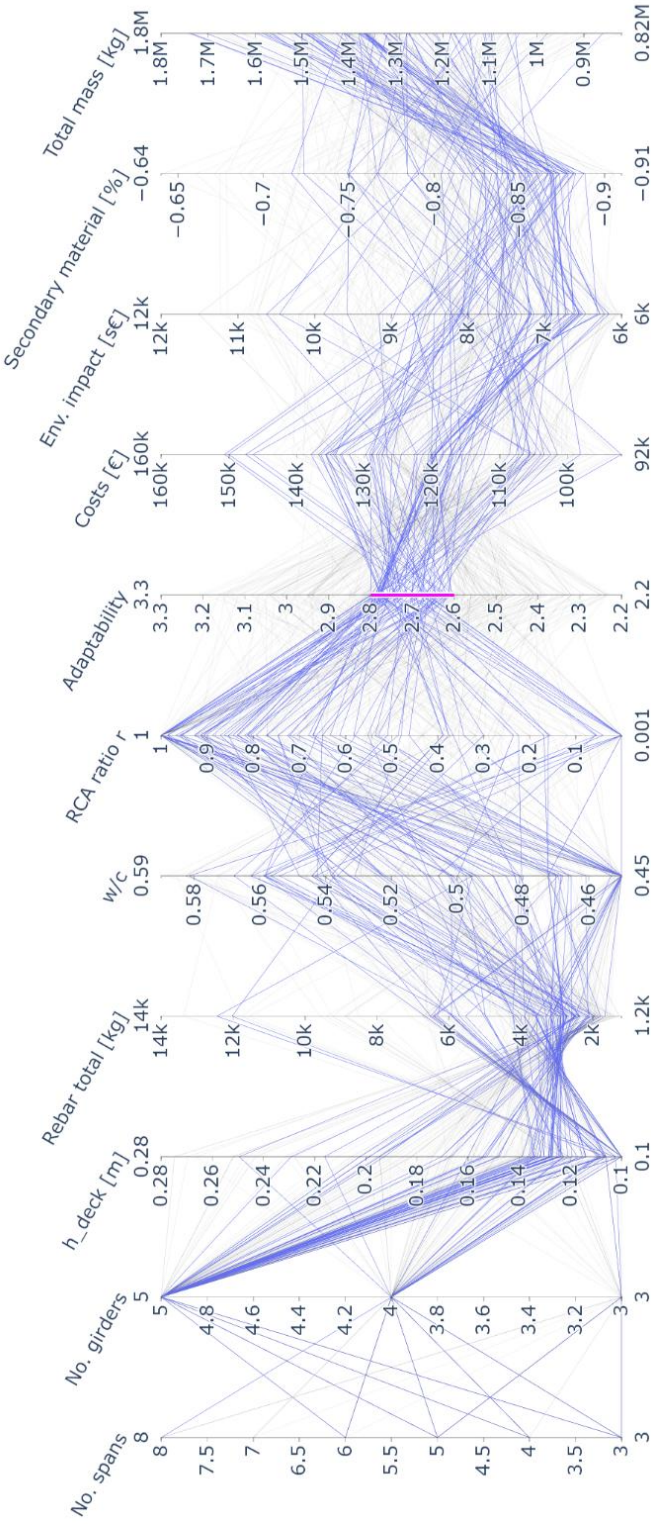


Figure 13. Parallel coordinate plot from Figure 7  
 Only solutions are shown within a selected adaptability range (between 2.6 and 2.8)

Adaptability is formulated as a function of unity checks (see Chapter 2), which are related to structural reliability and amount of material (mass) used. This means that this adaptability objective is inherently related to other objectives which are a function of material mass, such as the circularity objective minimizing total material used, or to the environmental impact objective, which is largely dominated by amount (mass) of material produced causing CO<sub>2</sub> emissions, and to transport and handling of materials. Because of a high number of design variables (in this case over 50) and models relating these variables to (intermediate) outcomes such as total mass, and further to objectives, variation arises in the interdependencies between objectives per solution. A decision process can be used to find solutions with minimal trade-offs according to stakeholder preferences, but it is impossible to generalize how the interdependencies between objectives will always be. The extent to which objectives are dependent on the same variables and therefore on each other does have an influence on how dominant these variables and objectives may be in decision making. This can be investigated using sensitivity analyses (see Chapter 3.3).

### 3.3 *Future research and outlook*

#### 3.3.1 *Model assumptions*

Critical for the automated generation of optimal design solutions is the introduction of proper models in the design optimization that on the one hand, give more insight in interdependencies of design and objectives than best practices and assumptions, but on the other hand, are not too complex to slow down calculation times. Although the algorithmic approach is designed to handle a high number of analytical models, making connection to computationally time-consuming numerical programs, for example for structural analysis, may generate larger calculation times but not necessarily lead to different design choices in the end. The limitations of a model should always be properly documented upfront, as well as the assumed values for parameters. So, even though the models used in the optimization method are deduced from state-of-the-art and regulations (such as the Eurocode), once a design solution has been selected based on a trade-off decision process, it is necessary to conduct final (detailed) regulatory validations for that particular solution, such as a complete structural analysis.

The extent to which certain assumptions in models and parameters affect results on the objectives (e.g. costs of reclaimed girder) may be assessed by sensitivity studies. This type of sensitivity analysis can systematically provide additional information to the pareto

analysis by isolating the interdependency of individual design variables with objectives. This is complementary to the pareto analysis, because in the pareto analysis the interdependencies are always multiple variables to a single objective (many-to-one). In this case specifically, there is an interest in the individual (one-to-one) interdependencies. Using sensitivity analyses such as (Sobol', 2001), (Borgonovo, 2007) and (Li, et al., 2010) provide magnitudes for the various individual interdependencies for a specific objective and comparing these magnitudes gives insight into which variable plays a dominant role. Such approaches for sensitivity analyses might also be used to assess which aspects of the design need further detailed modelling, and which aspects are having less influence on the overall design outcomes and can be covered by simple assumptions.

### 3.3.2 *Decision making processes*

Interactive parallel coordinate plots work very well for interactive group decision-making, by facilitating in-depth discussions and informed decision-making (Groenia et al., 2024). Design teams with multiple experts from different fields (e.g. architect, engineer, circularity expert) can discuss design objectives, trade-offs and alternative design solutions together based on their preferences and value. However, previous research has shown that actors can struggle with assessing and valuing the different indicators of objectives (Groenia et al., 2024). For example: *"What is the value of gaining 1k s€ of environmental impact in return for 0.5 less 'adaptability'?"* Further development is needed of the interface for visualisation and translation of objective outcomes into value (using preference or value functions), in order to improve the understanding of different objectives by all actors involved. In the future, multi-objective design optimization and decision-making could also be integrated into existing design processes on digital design platforms, for example, BIM and CAD (Ng et al., 2021).

### 3.3.3 *Multi-phase design processes*

Next to the usage of multi-objective optimization for (detailed) structural design, it may also be used for other (combinations of) phases of the design process, even in tenders. When setting requirements in tenders, clients may use multi-objective optimization for generating conceptual design possibilities, on the basis of which feasible bandwidths can be deduced for objectives and realistic requirements. Such tenders asking for performance in realistic bandwidths rather than aiming for specific solutions, are more attractive for innovative contractors as these provide opportunities to explore novel design solutions. In

addition, project actors can reduce (or prevent) re-work due to unforeseen conflicting requirements and/or frequently changing requirements.

In order to broaden the application of multi-objective design optimization in structural design, future research is needed to test the usage of multi-objective design optimization in various construction projects, with a specific focus on the concerns and experiences of practitioners. Design cases with other materials than concrete could also be explored, for example hybrid structures consisting of wood and concrete.

## 4 Conclusions

This paper has illustrated the potential benefits of multi-objective design optimization by applying this approach to the structural design of a bridge with reclaimed concrete elements and a bridge deck with concrete containing recycled concrete aggregate (RCA). The following advantages of this multi-objective design optimization approach have been shown by the case study:

- In contrast to optimizing for a limited number of objectives and considering a selected set of solutions, multi-objective design optimization allows to automatically generate the full range of optimal design solutions, taking into account all relevant objectives and boundary conditions for the design. No weights are assigned to the objectives upfront. Based on the multitude of generated optimal design solutions, designers and other stakeholders can obtain insight into the interdependencies between design variables and objectives.
- The multi-objective design optimization approach enables transparent decision-making, by visualizing all possible interdependencies between the objectives. Based on this visualization, realistic and well-balanced trade-offs can be made by all stakeholders involved during an interactive process of gradually filtering and selecting solutions. This is an improvement compared to existing multi-criteria assessment tools, which often use qualitative ratings with less complete insight in possible interdependencies between objectives.
- The results of the case study show how trade-offs are not the same for every solution and can be minimized during decision making processes, which would not always

become clear when considering only a few solutions. Also, it shows that generalizations about overall sustainability based on one design exercise cannot be made easily. How much environmental impact or costs can be reduced, is dependent on how trade-offs are being made by stakeholders with all other criteria involved.

Further research is suggested into methods to study the sensitivity of the optimization results to variations in (non-)design (fixed) parameters and models. Furthermore, the interface for visualization of the optimization results could be further improved and value or preferences included, for better understanding of the solutions and trade-offs by all stakeholders. The application of multi-objective design optimization could also be broadened to other phases of the design process, and could even be used in tenders to determine realistic requirements. Finally, to facilitate broader use of multi-objective design optimization in the construction practice, it is suggested to further test the usage of multi-objective design optimization in other construction projects, for which the case study in this paper can set an example.

### *Acknowledgements*

The authors acknowledge that this contribution is developed as part of the TNO Early Research Program Circular Structures (ERP CS) 2021-2024.

## References

- Archidat bouwkosten. (n.d.-a). Archidat bouwkosten. Retrieved May 6, 2024, from <https://bouwkosten.archidat.nl/>
- Archidat bouwkosten. (n.d.-b). Archidat bouwkosten.
- Arnoldussen, J., Essink, J., Meuwese, B., & Saitua, R. (2017). De effecten van een prijsopslag op beton. [https://www.eib.nl/pdf/De effecten van een prijsopslag op beton.pdf](https://www.eib.nl/pdf/De%20effecten%20van%20een%20prijsopslag%20op%20beton.pdf)
- Benítez-Hidalgo, A., Nebro, A. J., García-Nieto, J., Oregi, I., & Del Ser, J. (2019). jMetalPy: A Python framework for multi-objective optimization with metaheuristics. *Swarm and Evolutionary Computation*, 51, 100598. <https://doi.org/10.1016/J.SWEVO.2019.100598>
- Betonhuis. (2021). Betonpocket 2020. Betonhuis, Woerden.
- Betonstaal. (n.d.). STA 754 staafnet Ø12mm | 6000 x 1100mm | 150 x 150. Retrieved May 6, 2024, from <https://www.betonstaal.nl/bouwstaalmatten/staafnetten/sta-754/>
- Bizarro, D. E. G., & Lennartz, J. (2022). Environmental life cycle and circularity assessment in structural design; an alternative approach. In S. Stokkeland & H. C. Braarud (Eds.), *Concrete innovation for sustainability* (pp. 88-97). International Federation for Structural Concrete.
- Borgonovo, E. (2007). A new uncertainty importance measure. *Reliability Engineering & System Safety*, 771-784.
- Bouwmaat. (n.d.). Enci Portlandcement A CEM I 42,5 N 25 kg. Retrieved June 3, 2024, from <https://www.bouwmaat.nl/enci-portlandcement-a-cem-i-425-n-25-kg/product/0000209103>
- Brütting, J., Senatore, G., Schevenels, M., & Fivet, C. (2020). Optimum Design of Frame Structures From a Stock of Reclaimed Elements. *Frontiers in Built Environment*, 6. <https://doi.org/10.3389/fbuil.2020.00057>
- CBS. (2024a). Marktprijzen Energie, 2000-2023. <https://www.cbs.nl/nl-nl/maatwerk/2024/15/marktprijzen-energie-2000-2023>
- CBS. (2024b). Pompprijzen motorbrandstoffen; brandstofsoort, per kwartaal. <https://www.cbs.nl/nl-nl/cijfers/detail/84991NED>
- Chen, Y., Ren, Z., Hu, B., & Zheng, H. (2023). Investigation of the Critical Factors Influencing Multi-Stakeholders' Participation in Design Optimization of EPC Projects. *Buildings*, 13(7). <https://doi.org/10.3390/buildings13071654>
- Coenen, T. B. J. (2019). Circular bridges and viaducts: development of a circularity assessment framework. University of Twente.

- Dede, T., Kripka, M., Togan, V., Yepes, V., & Rato, R. V. (2019). Usage of Optimization Techniques in Civil Engineering During the Last Two Decades. *Current Trends in Civil & Structural Engineering*, 2(1), 1–17. <https://doi.org/10.33552/CTCSE.2019.02.000529>
- Ellen MacArthur Foundation and ANSYS Granta. (2015). *Circularity Indicators: An Approach to Measuring Circularity*. Ellen MacArthur Foundation, December 2019, 12. <https://doi.org/10.13140/RG.2.2.29213.84962>
- European Commission. (2019). *The European Green Deal*. European Commission.
- European Commission. (2020a). *A new Circular Economy Action Plan For a cleaner and more competitive Europe*.
- European Commission. (2020b). *Stepping up Europe’s 2030 climate ambition: Investing in a climate-neutral future for the benefit of our people*.
- European Commission. (2020c). *Waste statistics - Construction and Demolition Waste*. Eurostat.
- Evides. (n.d.). *Tarieven Groot zakelijk*. Retrieved May 6, 2024, from <https://www.evides.nl/zakelijk/groot-zakelijk/tarieven>
- Fivet, C., & Brütting, J. (2020). Nothing is lost, nothing is created, everything is reused: structural design for a circular economy. *The Structural Engineer*, 98(1), 74–81.
- Groenia, S., van den Berg, M., Volker, L., Valcke, S., & Barros, E. (2024). *Multi-objective decision-making for sustainable construction: Designing an interactive method for multi-actor project settings*. Paper Presented at 40th Annual *ARCOM Conference 2024: Looking Back to Move Forward*, London, United Kingdom, 417–426.
- Grondverzet. (n.d.). *Menggranulaat prijs per m3*. Retrieved May 6, 2024, from <https://grondverzet.nu/menggranulaat-prijs-per-m3>
- Hajek, P. (2023). Sustainability perspective in fib MC2020: Contribution of concrete structures to sustainability. *Structural Concrete*, 24(4), 4352–4361. <https://doi.org/10.1002/suco.202300022>
- Hakanen, J., Rados, S., Misitano, G., Saini, B. S., Miettinen, K., & Matkovic, K. (2022). Interactivized: Visual Interaction for Better Decisions With Interactive Multiobjective Optimization. *IEEE Access*, 10, 33661–33678. <https://doi.org/10.1109/ACCESS.2022.3161465>
- International Energy Agency. (2018). *Technology Roadmap: Low-Carbon Transition in the Cement Industry*.
- International Federation for Structural Concrete (fib). (2022). *1st complete draft of the fib Model Code for Concrete Structures 2020*. fib.

- Jankauskas, K., Papageorgiou, L. G., & Farid, S. S. (2019). Fast genetic algorithm approaches to solving discrete-time mixed integer linear programming problems of capacity planning and scheduling of biopharmaceutical manufacture. *Computers & Chemical Engineering*, 212-223.
- Kukkonen, S., & Lampinen, J. (2005). GDE3: The third evolution step of generalized differential evolution. In 2005 IEEE Congress on Evolutionary Computation, *IEEE CEC 2005. Proceedings (Vol. 1)*. <https://doi.org/10.1109/CEC.2005.1554717>
- Küpfer, C., Bastien-Masse, M., & Fivet, C. (2023). Reuse of concrete components in new construction projects: Critical review of 77 circular precedents. *Journal of Cleaner Production*, 383, 135235. <https://doi.org/10.1016/j.jclepro.2022.135235>
- Li, G., Rabitz, H., Yelvington, P. E., Oluwole, O. O., Bacon, F., Kolb, C. E., & Schoendorf, J. (2010). Global Sensitivity Analysis for Systems with Independent and/or Correlated Inputs. *The Journal of Physical Chemistry A*, 6022-6032.
- Ministry of Infrastructure and Water Management. (2023). Circular Economy Programme 2023–2030. In The Hague: Ministry of Infrastructure and Water Management. <https://www.government.nl/documents/reports/2023/09/27/national-circular-economy-programme-2023-2030>
- Ndiritu, J., & Daniell, T. (1999). AN IMPROVED GENETIC ALGORITHM FOR CONTINUOUS AND MIXED DISCRETE-CONTINUOUS OPTIMIZATION. *Engineering Optimization - ENG OPTIMIZ*, 589-614.
- Ng, M. S., Graser, K., & Hall, D. M. (2021). Digital fabrication, BIM and early contractor involvement in design in construction projects: a comparative case study. *Architectural Engineering and Design Management*, 19, 39–55. <https://doi.org/10.1080/17452007.2021.1956417>
- NMD. (2020). Bepalingsmethode Milieuprestatie Bouwwerken. [https://milieudatabase.nl/media/filer\\_public/08/97/08978af7-15a0-4412-a782-28aee7a91b83/bepalingsmethode-milieuprestatie-bouwwerken-juli-2020.pdf](https://milieudatabase.nl/media/filer_public/08/97/08978af7-15a0-4412-a782-28aee7a91b83/bepalingsmethode-milieuprestatie-bouwwerken-juli-2020.pdf)
- Platform CB'23. (2022). Leidraad - Meten van circulariteit - Meetmethode voor een circulaire bouw. <https://platformcb23.nl/aan-de-slag/2020>
- Plotly Technologies Inc. (2015). Parallel Coordinates Plot in Python. Plotly Technologies Inc. <https://plotly.com/python/parallel-coordinates-plot/>
- Purshouse, R. C., Deb, K., Mansor, M. M., Mostaghim, S., & Wang, R. (2014). A review of hybrid evolutionary multiple criteria decision making methods. 2014 IEEE Congress on Evolutionary Computation (CEC), 1147–1154. <https://doi.org/10.1109/CEC.2014.6900368>

- Riuttala, M., Harala, L., Aarikka-Stenroos, L., & Huuhka, S. (2024). How building component reuse creates economic value – Identifying value capture determinants from a case study. *Journal of Cleaner Production*, 443, 141112. <https://doi.org/10.1016/j.jclepro.2024.141112>
- Sadowski, K. L., Thierens, D., & Bosman, P. A. (2021). Optimization of multi-objective mixed-integer problems with a model-based evolutionary algorithm in a black-box setting. In Proceedings of the *Genetic and Evolutionary Computation Conference Companion* (pp. 227–228). New York, NY, USA: Association for Computing Machinery.
- Samenwerkingsverklaring: Om in gezamenlijkheid toe te werken naar een bouwmaterialenakkoord. (2024).
- Sangwan, S. (2018). Literature Review on Genetic Algorithm. *International Journal of Research*. 5., 1142-1146.
- Sobol', I. (2001). Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. *Mathematics and Computers in Simulation*, 271-280.
- Stenberg, E., Hernández Vargas, J., & Huuhka, S. (2022). Recreate: Deconstruction and reuse instead of demolition and waste. *ARQ (Santiago)*, 112, 84–95. <https://doi.org/10.4067/S0717-69962022000300084>
- Stichting Nationale Milieudatabase. (2023). NMD-processendatabase (v3.6).
- Tong, W., Chowdhury, S., & Messac, A. (2014). A New Multi-Objective Mixed-Discrete Particle Swarm Optimization Algorithm. *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, V02AT03A017.
- Tošić, N., & Torrenti, J. (2021). New Eurocode 2 provisions for recycled aggregate concrete and their implications for the design of one-way slabs. *Gradjevinski Materijali i Konstrukcije*, 64(2), 119–125. <https://doi.org/10.5937/GRMK2102119T>
- Valcke, S., Braendstrup, C., Allaix, D. L., Bigaj-van Vliet, A. J., Barros, E., & Godoi Bizarro, D. (2022). Multi-criteria optimisation for sustainable concrete structures. Proceedings of the *Fib Congress Oslo 2022*, 861–870.
- van Lookeren Campagne, F., Sonneveld, M., van der Meer, F., Noteboom, C., & Kavoura, F. (2023). Truss bridge design with reclaimed steel elements by performing a stock-constrained shape and topology optimisation. *Ce/Papers*, 6(3–4), 401–406. <https://doi.org/10.1002/cepa.2468>
- Vergoossen, R., van Eck, G. J., & Bakker, R. (2021). Re-using existing prefabricated prestressed concrete girders. In *IABSE Congress, Ghent 2021: Structural Engineering for Future Societal Needs*. <https://doi.org/10.2749/ghent.2021.0215>

- Vergoossen, R., van Eck, G. J., & Jilissen, D. (2022a). Hergebruik prefab T-liggers (2): Demonteren en aanpassing liggers voor toepassing in nieuw viaduct. *Cement*, 8, 40–49.
- Vergoossen, R., van Eck, G. J., & Jilissen, D. (2022b). Re-using existing prefabricated prestressed concrete girders in new bridges. In *IABSE Symposium Prague, 2022: Challenges for Existing and Oncoming Structures - Report*.  
<https://doi.org/10.2749/prague.2022.0554>
- Vergoossen, R., van Eck, G. J., & Jilissen, D. (2023). Re-use of existing load-bearing structural components in new design. In *Life-Cycle of Structures and Infrastructure Systems - Proceedings of the 8th International Symposium on Life-Cycle Civil Engineering, IALCCE 2023*. <https://doi.org/10.1201/9781003323020-13>
- Vullings, M. W. F., Wijte, S. N. M., & Huuhka, S. (2022). Guidelines for a BIM-aided pre-deconstruction audit.
- Wu, S.-J., & Chow, P.-T. (1994). Genetic algorithms for solving mixed-discrete optimization problems. *Journal of the Franklin Institute*, 381-401.
- Xin, B., Chen, L., Chen, J., Ishibuchi, H., Hirota, K., & Liu, B. (2018). Interactive Multiobjective Optimization: A Review of the State-of-the-Art. *IEEE Access*, 6, 41256–41279. <https://doi.org/10.1109/ACCESS.2018.2856832>
- Zhu, X., Meng, X., & Zhang, M. (2021). Application of multiple criteria decision making methods in construction: a systematic literature review. *Journal of Civil Engineering and Management*, 27(6), 372–403. <https://doi.org/10.3846/jcem.2021.15260>

## Annex A. Data for cost objective

### *Production and construction costs*

The production costs and construction costs of the relevant processes as used in the use case are listed in Table A.1 and Table A.2, respectively.

*Table A.1 Production costs of raw materials used (purchase price)*

Material	Costs	Unit	Source
Cement (CEM I)	0.245	€ per kg	According to (Bouwmaat, n.d.).
Gravel	0.068	€ per kg	According to (Archidat bouwkosten, n.d.-a).
Sand	0.043	€ per kg	According to (Archidat bouwkosten, n.d.-b).
Water	0.001	€ per kg	According to (Evides, n.d.).
RCA – conventional <sup>1</sup>	0.021	€ per kg	Based on mixed granulate according to (Grondverzet, n.d.).
RCA – innovative <sup>1</sup>	0.031	€ per kg	No information available, assumed to be 50% more expensive than RCA-conventional.
Steel reinforcement <sup>1</sup>	0.996	€ per kg	According to (Betonstaal, n.d.).
Reclaimed girders <sup>2</sup>	365.00	€ per m <sup>3</sup>	According to (Arnoldussen et al., 2017).

<sup>1</sup> The costs of demolition and processing of the recycled materials (RCA, steel reinforcement) are included in the purchase price of the materials.

<sup>2</sup> The uncut length of the girders is used to determine the costs of the girders. The parts of the beam that are cut off do not have any residual value in the optimization. The mass of the parts that are cut off can however be quantified as output, so that its value can be quantified by stakeholders after optimization.

*Table A.2 Construction costs of relevant processes*

Process	Cost	Unit	Justification
Cutting of reclaimed girders	18,03	€ per m <sup>2</sup>	Process inputs in line with impact assessment process for 'cutting of reclaimed girders'. Assumed labour price of € 45/hour. Diesel price (1,811/l) according to (CBS, 2024b). Equipment cost unknown.

Production of foundation piles	0,03	€ per kg	Process inputs in line with impact assessment process for 'production of foundation piles'. Diesel price (€1,811/l) according to (CBS, 2024b) and natural gas (€0,52 / M3) and electricity price (€ 0,09615 / kWh) according to (CBS, 2024a). Labour and equipment cost unknown.
Drilling of reused girders	1,81	€ per l	According to (CBS, 2024b). Equipment and labour cost unknown.
Pouring concrete (in-situ)	39,33	€ per m <sup>3</sup>	Process cost, including equipment and labor cost, according to (Archidat bouwkosten, n.d.-b).
Crane use for reused girders	322,62	€ per hour	Equipment cost according to (Archidat bouwkosten, n.d.-b), with 50% mark-up factor as a larger crane is used. Assumed labour price of € 150/hour.

#### ***Transport costs to construction site***

The costs of transport to the construction site are estimated based on a simplified model and a number of assumptions. The different materials are assumed to be transported by truck with a given capacity and an hourly wage. The transport cost per unit mass [kg] for each material as function of the transport distance  $d$  is determined according to Equation (A.1), in which the loading and unloading of the materials can be seen as a constant transport cost and the slope is determined by the desired distance relative to the reference transport distance of 20 km.

$$t_{eco}(d) = \frac{\frac{a}{d_0} d + b}{m_0} \quad (\text{A.1})$$

with

$$a = \frac{2t_0}{60} r_{wage}$$

$$b = \frac{t_{load} + t_{unload}}{60} r_{wage}$$

in which

- $t_{\text{eco}}(d)$  is the transport cost per kg for a given distance  $d$  [€/kg];
- $d$  is the transport distance to the construction site in km; assumed distances per material can be found in Table A.3;
- $d_0$  is the reference travel distance in km, equal to 20 km (one way trip);
- $r_{\text{wage}}$  is the hourly wage in €/hour; assumed to be 80 €/hour per truck;
- $m_0$  is the load carrying capacity of the truck in kg, assumed to be equal to 30 tonnes (30.000 kg);
- $t_{\text{load}}$  is the time needed to load the contents of the truck in minutes; assumed to be 10 minutes;
- $t_{\text{unload}}$  is the time needed to unload the contents of the truck in minutes; assumed to be 10 minutes;
- $t_0$  : time needed for transport distance  $d_0$  in minutes, assumed time is 20 minutes (one way trip).

The resulting transport cost per kg for a given transport distance  $d$ ,  $t_{\text{eco}}(d)$ , can then be used in the cost function:  $t_{\text{eco}}(d)$  represents the cost factor  $C_i$ , determined as function of the transport distance  $d$ . The corresponding activity data  $A_i$  is the mass of each material in kg.

The transport cost of reclaimed girders is estimated by a different model, since these costs are not only governed by mass but also by the dimensions of the reclaimed girders. The transport costs are assumed to be 6.30 €/km for a 60-tonnes-truck. The number of girders per truck is dependent on the width of the girders and the weight of the girders:

No. of girders per truck	Maximum width girder ( <i>max. width of freight = 3.0 m</i> )	Maximum weight per girder ( <i>max. weight of freight = 45 tonnes</i> )
3	≤ 1.0 m	≤ 15 tonnes
2	≤ 1.25 m	≤ 22.5 tonnes
1	> 1.25 m	≤ 45 tonnes

If the weight of the girder exceeds 45 tonnes, special transport is needed (1 girder per truck). In that case, transport costs are doubled.

Based on the above information, the cost of transport can be estimated for the different types of reclaimed girders that are used in this case study. These transport costs per km can then be used in the cost function as cost factor  $C_i$ . The corresponding activity data  $A_i$  is the transport distance of the girders and the type of girders in the design.

The assumed transport distances from the production or storage site to the construction site for each material are listed in Table A.3.

*Table A.3 Transport distance to construction site (stage A4) for each material*

Material	Sub-material	Transport distance from production/storage site to construction site [km]
Concrete prefab products		75
Concrete in-situ	Cement	35
	Gravel	35
	Sand	35
	Water	35
	RCA	35
Steel reinforcement		150
Reclaimed girders		50

## Annex B. Structural analyses of the concrete bridge structure

The structural analyses used in the optimisation is explained in this Annex. The different steps used in the structural analyses are also explained.

### Loading

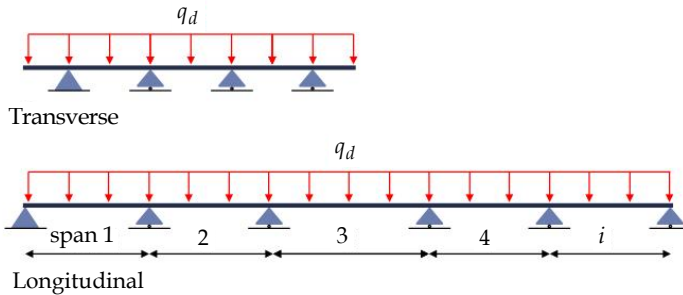
Dead load ..... The volume of the bridge deck, girders, piers and foundation is multiplied by the mass of concrete ( $25,0 \text{ kN/m}^3$ ). Dead load =  $q_G$

Live load ..... A uniformed applied traffic load of  $10,0 \text{ kN/m}^2$ . Live load =  $q_Q$

Partial factors .....  $\gamma_G = 1,20$  and  $\gamma_Q = 1,35$  (design traffic load, consequence class 2)

Design load SLS ..  $q_G + q_Q = q_{rep}$

Design load ULS .  $q_G \times \gamma_G + q_Q \times \gamma_Q = q_d$

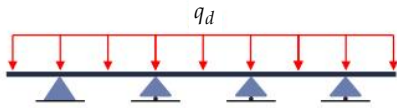


### Internal forces

$M_{Ed}$  ..... The design value of the bending moments in the girders, based on previous diagrams, is calculated with a FEM analysis.

$R_{Ed}$  ..... The design value of the reaction force in the supports is calculated with the same FEM analysis. The reaction forces are used in the design of the piers and foundation piles.

A similar FEM analysis is used to determine the internal forces in transverse direction of the bridge deck. The calculation in transverse direction is made first and the results are used (reaction forces) to compute the acting loads on the girders in longitudinal direction.



Transverse



Moment diagram

### Material properties

Concrete class .... can vary between C25/30 and C50/60.

C35/45 is used in this Annex, as example

$f_{ck}$  ..... 35 MPa (for concrete class C35/45, as example)

$f_{cd}$  .....  $\alpha_c f_{ck} / \gamma_m$  (MPa)  $\alpha_c = 1,0$  and  $\gamma_m = 1,50$

Concrete steel ..... Default class is B500

$f_{yk}$  ..... 500 MPa

$f_{yd}$  .....  $f_{yk} / \gamma_s$  with  $\gamma_s = 1,15$

### Calculation in transverse direction

$A_{s,transverse}$  ..... The reinforcement in transverse direction is calculated in accordance with Eurocode 2. For this the next procedure is used to design the reinforcement and perform the necessary checks. The reinforcement is calculated for the maximum design value of the bending moment and applied at the top of the deck and the bottom of the deck.

Calculation of bending reinforcement:

$A_s$  .....  $\frac{M_{Ed}}{z f_{yd}}$  (mm<sup>2</sup>)

$z$  .....  $d - \beta x_u$  (mm)  $\beta = 0,39$  and  $d = h - c + \frac{1}{2} \varnothing$

$f_{ud}$  ..... Design yield strength of reinforcement, default value used is 435 MPa

$$x_u \dots\dots\dots \frac{d - \sqrt{d^2 - \frac{4\beta M_{Ed}}{\alpha b f_{cd}}}}{2\beta} \text{ (mm)}$$

$\alpha$  ..... 0,75

$b$  c..... Width of the concrete section; default 1,0 m for the deck.

Checks:

$$A_s \geq A_{s,\min} \dots\dots A_{s,\min} = \min(1,25 A_s ; 0,16\% \text{ of } A_c)$$

$$A_s \leq A_{s,\max} \dots\dots A_{s,\max} = 2,25\% \text{ of } A_c$$

Cracking:

$s_{\max}$  ..... maximum spacing between rebar, environmental condition default XC1

$\varnothing_{\max}$  ..... maximum diameter of the rebar, maximum crack width is default 0,30 mm. The maximum values is based on the steel stress in SLS.

$$f_s \dots\dots\dots f_{yd} \cdot \frac{A_s}{A_{\text{applied}}} \cdot \frac{M_{SLS}}{M_{ULS}} \quad \text{default } \frac{M_{SLS}}{M_{ULS}} = 0,85$$

$$f_s = 160 \text{ MPa} \dots\dots s_{\max} = 300 \text{ mm} \text{ and } \varnothing_{\max} = 32 \text{ mm}$$

$$f_s = 200 \text{ MPa} \dots\dots s_{\max} = 250 \text{ mm} \text{ and } \varnothing_{\max} = 25 \text{ mm}$$

$$f_s = 280 \text{ MPa} \dots\dots s_{\max} = 150 \text{ mm} \text{ and } \varnothing_{\max} = 12 \text{ mm}$$

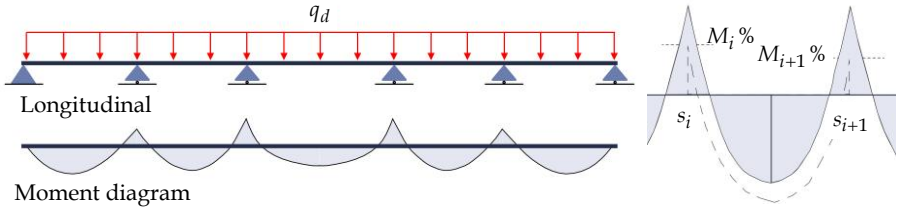
$$f_s = 360 \text{ MPa} \dots\dots s_{\max} = 50 \text{ mm} \text{ and } \varnothing_{\max} = 8 \text{ mm}$$

The designed reinforcement is applied in the total deck in transverse direction. 20% of the transverse reinforcement is applied in longitudinal direction over the total length of the bridge deck.

### **Calculation in longitudinal direction**

In the longitudinal direction the bending moment is calculated (moment diagram) and in the optimization process a percentage of the moment at the support is chosen. Each support can have a different percentage of the calculated bending moment. The percentages reduce the bending moment at the supports and increase the bending moment in the middle of the spans.

By increasing the support bending moment the required bending moment capacity of the reused girders (in the middle of the span) is changed. To make this possible the reused girders must be connected to the new bridge deck. This is done by drilling open stirrups in the top of the girders. The number of stirrups is calculated based on the shear forces in the girders.



$$M_{Rd,max,girder} \dots \geq M_{Ed,span,middle}$$

The bending moment is determined with a FEM calculation.

$A_{s,longitudinal,support} \dots$  The reinforcement at the supports is located at the top of the deck. The bending moment  $M_i$  is used to calculate the reinforcement (see previous procedure). The next parameters are used in the calculations.

$h \dots \dots \dots h_{girder} + h_{deck}$  (mm)

$w \dots \dots \dots$  Width of the deck measured from the middle of the span on the left side to the middle of the span on the right side of the girder. The properties of the concrete of the girder are used for the design of the support reinforcement in the deck.

$A_{s,stirrups} \dots \dots \dots$  These are the connections between the reused girder and the new deck. The design of the open stirrups is based on the shear force in the girders. The changes in the bending moments in the girder are accounted for.

$\tau_{Ed,max,support} \dots \dots \dots$  This is the horizontal shear force at the interface between the girder and the deck. The design reinforcement is based on article 6.2.5 of the NEN-EN 1992-1:

$$V_{Rdi} = c f_{ctd} + \mu \sigma_n + \rho f_{yd} (\mu \sin \alpha + \cos \alpha) \leq 0,5 v f_{cd}$$

Only the dowel function is used in the stirrup design.

$V_{Rdi} \dots \dots \dots \rho f_{yd} (u \sin \alpha + \cos \alpha)$  default  $\alpha = 90^\circ$ ,  $c = 0,45$  and  $u = 0,70$

$\rho = A_s / A_i$ , with  $A_s$  is the area of the stirrups and  $A_i$  is the area of the contact surface.

The reinforcement in the longitudinal direction is added to the total reinforcement in the bridge deck. The weight of the longitudinal reinforcement and stirrups is calculated for all supports and added to the total values.

**Supports (piers and foundation piles)**

Piers ..... The reaction forces  $R_{Ed}$  (kN) are used to calculate the required thickness of the piers. The piers have a default length equal to the width of the bridge and a height of 2,60 m.

$R_{Rd}$  .....  $\geq R_{Ed}$   
 $(w \times l)_{\text{contact area}} \times 0,6 \times f_{ck}$ ), the factor 0,6 is used to prevent splitting of the concrete.  
 $w$  is the thickness of the pier and  $l$  is a default value 1,0 m.

Piles ..... The reaction forces  $R_{Ed}$  (kN) are also used to calculate the number of piles needed for the supports.

Number of piles ..  $R_{Ed}/R_{Rd,\text{pile}}$ , the capacity of a pile  $R_{Rd}$  is fixed as a default value of 500 kN.