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Development of a bridge circularity assessment framework to promote resource efficiency in infrastructure projects

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Abstract

Given the predominant use of virgin materials and the creation of vast amounts of waste in the construction sector, increasing its resource efficiency could result in a large improvement in overall use of resources. Bridges are a logical target for increasing resource efficiency, not only because of the large amount of materials involved but especially because a considerable number of bridges are demolished because of changing functional demands rather than technical failure. Furthermore, climate change increases future uncertainty and the likelihood of functionally motivated demolitions, which potentially exacerbates the creation of waste. Currently, it is not possible to measure and quantify the resource efficiency of bridge designs. In this study, a framework is presented that combines four indicators based on the principles of the Circular Economy. The four indicators are: (1) *Design Input*, (2) *Resource Availability*, (3) *Adaptability*, and (4) *Reusability*. Each indicator is further broken down into multiple sub-indicators. To test the usefulness of the proposed framework, it was applied to two real-world Dutch case studies. In addition, uncertainty and sensitivity analyses were conducted to determine the robustness of the indicator to changes in the design parameters and the weighting method used. Validation of the framework has shown that this bridge-specific circularity indicator is useful for determining the level of resource efficiency in terms of material use. This will allow clients to use resource efficiency, or circularity, as a selection criterion in the procurement process. This article met the requirements for a gold—gold JIE data openness badge described at http://jie.click/badges.

KEYWORDS
Circular Economy, circularity indicator, design strategies, industrial ecology, material efficiency, procurement

1 | INTRODUCTION

The construction sector is known as one of the main waste-creating sectors globally. It was responsible for 60% of the global consumption of mineral resources in 2015 and for about one third of the total solid waste produced in the European Union (Ecorys, 2016; Honic, Kovacic, & Rechberger,

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2019). Moreover, these levels of material consumption and waste generation show no signs of reduction. Simultaneously, material sourcing is getting increasingly difficult, requiring an increasing amount of ore to be mined per additional unit of resource extracted (Vieira, Ponsioen, Goedkoop, & Huijbregts, 2017). If the behavior of humankind does not change, the physical limits of the planet in terms of resource availability will soon be reached (Van Oers & Guinée, 2016).

The Circular Economy (CE) concept aims to maximize the functional value of resources by considering the entire life cycle of a product and closing resource loops. Rather than "temporarily" using virgin materials as part of an asset and then disposing of them afterward, the goal of the CE is to maximize the value over the entire life cycle of each particular resource used. By adopting these principles, resource efficiency can be drastically increased. In addition, there are major potential benefits regarding environmental impact and life cycle costs (Geissdoerfer, Savaget, Bocken, & Hultink, 2017).

Civil engineering works, and particularly those related to bridges, are ideal targets for resource-efficient design and construction. This is not only because they are numerous, and in many cases large, but also because of their lengthy life spans. Despite their significant use of materials and consequent waste, bridges are barely addressed in the literature on circularity and waste management (Anastasiades, Blom, Buyle, & Audenaert, 2020). In this paper, a framework to assess the circularity of bridges, including viaducts, is presented. Based on the premise that the CE concept cannot be fully captured in a simple indicator (Parchomenko, Nelen, Gillabel, & Rechberger, 2019; Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019; Anastasiades et al., 2020), the developed assessment framework consists of various indicators that are merged into a composite bridge circularity indicator. The proposed framework can be used by design companies in the procurement phase to facilitate the use of resource-oriented life cycle thinking principles in the design of bridges. This can ultimately contribute to reducing the construction and demolition waste (CDW) generated by bridges during their life cycle. As such, it aims to slow the depletion of abiotic resources.

2 | TOWARD CIRCULARITY MEASUREMENT IN BRIDGE DESIGN

A holistic approach toward waste prevention and resource efficiency can be seen in the Circular Economy (CE) concept. The CE promotes a system in which resource input, particularly of virgin resources, is minimized and waste eliminated. This is achieved by replacing the end-of-life (EoL) concept with one that strives for the reduction, reuse, recycling, and recovery of resources (Kirchherr, Reike, & Hekkert, 2017). For the sake of circularity, assets should be designed with as few virgin materials as possible, while ensuring that a useful EoL application is possible for released materials. Resources that become available when assets no longer meet the functional or technical requirements should be used in new applications—either with the same or with other functionalities. Despite the increasing recycling rates in the construction sector, to achieve the highest possible resource efficiency, it is often better to consider a wider range of strategies, such as life span extension and direct reuse in a situation that provides a similar functional value.

To enable bridge construction practices to incorporate life cycle considerations and to reward circular choices, clarity is needed as to what constitutes circular design choices. Given the requirement to observe procurement law, an objective way to measure and assess bridge circularity is crucial. Between 2015 and 2019, the literature on measuring resource efficiency and circularity saw significant growth. Several approaches for measuring circularity, either at the product or the asset level, were developed from 2015 onward (Elia, Gnoni, & Tornese, 2017; Iacovidou et al., 2017).

Parchomenko et al. (2019) performed an extensive analysis of existing indicators and concluded that there is a lack of methods that integrate product-centric and resource-efficiency aspects, and that this is required to assess the circularity of bridge designs. In a similar way, Saidani et al. (2019) concluded that specific design-oriented indicators are lacking. In addition, Kristensen and Mosgaard (2020) conducted an extensive literature review on micro-level circularity indicators and included, in contrast to the studies mentioned above, some design-oriented measures regarding disassembly, while acknowledging the lack of indicators related to life time extension and reuse.

Given the long life cycle of bridges and the unpredictability of the bridge management context, existing indicators are unsuitable as a means to promote circular design, construction, and management of bridges, given that one has to make assumptions regarding the later life cycle stages of the asset. Although all life cycle-oriented indicators involve some assumptions about the future, historical data show that the life cycle of a bridge is too unpredictable to use standardized life spans (Klatter, Roebers, Slager, & Hooimeijer, 2019). For example, unforeseen traffic developments or climate change can change the context such that an asset no longer meets the functional requirements and needs to be demolished before it reaches its potential EoL. Therefore, indicators that address lifetime extension through adaption and disassemblability need to be developed to assess the circularity of bridge designs.

To increase the circularity of the infrastructure sector, strategies that include life cycle thinking ought to be considered during the design phase. In this study, a circular design strategy is adopted in which the current inability to account for an uncertain future is overcome by introducing concepts that consider increasing the potential for responding to future changes and pre-EoL asset removal. In the past two decades, design-for-assembly, design-for-maintenance, design-for-disassembly, design-for-adaptability, and transformable design, amongst other approaches, have increasingly been acknowledged as ways to reduce waste in the construction industry (Addis & Schouten, 2004; Schmidt, 2014; Rios, Chong, & Grau, 2015; Geldermans, 2016). However, metrics and indicators that evaluate these design strategies are either barely addressed or disregarded by the

TABLE 1 Characteristics of the bridge circularity indicator (adopted from Saidani et al., 2019)

Type of characteristic	Application
Level of analysis	Meso-level, aimed at entire asset
Scope of circular economy	Full scope, aimed at material use
Circularity performance	Intrinsic, considering the bridge system
Temporal focus	*Ex ante*, aiming at potential circularity
Possible use	Action-oriented decision-making support
Transversality	Bridge specific
Dimensionality	Multi-metric, aggregated, and non-dimensional
Units of expression	Non-dimensional
Format	Microsoft Excel spreadsheet
Development background	Academic in collaboration with a governmental organization

existing circularity indicators, particularly when it comes to infrastructure. Given the many similarities in techniques, materials, and conditions, the CE principles already in use in the building construction sector will also apply to civil engineering structures (e.g., Brand, 1994; Addis & Schouten, 2004; Durmisevic, 2006; Schmidt, 2014; Crowther, 2015; Kibert, 2016). The key message in these studies is that enabling assets to structurally change increases their potential suitability for adaptation or reuse in the future, and hence contributes to waste reduction. Given the uncertainty linked to the impacts of climate change, adaptive assets are particularly relevant for preventing future waste.

3 | METHODOLOGY

The design science research (DSR) approach proposed by Van Aken, Chandrasekaran, and Halman (2016) was adopted as the basis for the methodology. The first step in the design process addresses the design problem and requires a clear understanding of the goals since, only if the desired requirements and characteristics are clear, can the design be developed and validated. Saidani et al. (2019) proposed a taxonomy for circularity indicators in which indicator characteristics are defined depending on the scope and the objectives of the study. These characteristics as applied in the bridge circularity assessment framework are listed in Table 1.

During the design process, professionals working for the Dutch infrastructure agency—further referred to as “experts”—were consulted on several occasions in the design and validation process during the development of the assessment framework. Two groups of experts were involved. First, four technical bridge experts from the Dutch infrastructure agency were consulted on issues regarding design options, structural safety, and bridge demolition. Second, five circularity and sustainability experts were involved in validating the circularity aspects of the assessment framework.

4 | THE BRIDGE CIRCULARITY ASSESSMENT FRAMEWORK

In this section, the design of the framework is presented.

4.1 | Unit of measurement

The framework primarily aims to quantify the long-term contribution of various bridge designs to material depletion. The indicators that relate to material depletion all refer to material mass, rather than volume, since the volume very much depends on the production technologies and the processing of materials used in the construction elements. That is, the central unit of measurement adopted in this study is “mass.” In addition, since some materials are more significant than others in terms of depletion, a material scarcity indicator is introduced that is coupled to the mass-related indicators.

4.2 | The assessment framework

The bridge circularity assessment framework is based on the four stages of the life cycle assessment (LCA) methodology defined in the ISO14044:2006 guidelines (ISO, 2016). In this study, the method is applied as follows: (1) definition of the goal and scope of the assessment; (2)

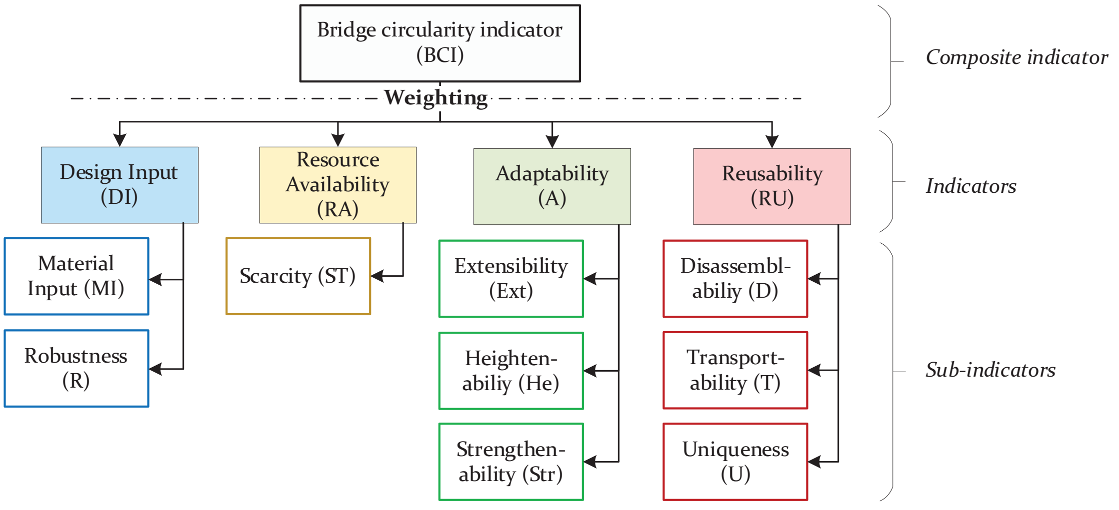

FIGURE 1 Outline of the composite bridge circularity indicator

inventory analysis, mainly involving the mapping of resource flows and bridge design data; (3) the actual assessment by means of the sub-indicators; and (4) the interpretation of the results. As such, the proposed framework follows the same steps as applied in the LCA methodology, although the actual calculation methods (the third step) are newly developed for analyzing the circularity of bridges.

4.3 | Composite bridge circularity indicator outline

Taking into account the goal of this study, as presented in Section 1, and the limitations of the existing circularity indicators discussed in Section 2, the outline of the composite bridge circularity indicator is shown in Figure 1.

The input of materials and their resource scarcity are both extensively covered in the literature, whereas indicators related to the adaptability and reusability aspects of bridges are still underdeveloped. Together, as shown in Figure 1, the four indicators and their underlying sub-indicators form the composite bridge circularity indicator. These indicators are discussed in greater depth in Section 4.4. The aggregation process, involving weighting and calculation procedures, is described in Section 4.5. The composite indicator is validated through its application in two case studies as described in Section 5, and an uncertainty analysis of the sensitivity of the results to changes in the weights, parameters, and main assumptions is discussed in Section 6.

4.4 | The indicators

Each indicator and its underlying sub-indicators are discussed in this section.

4.4.1 | Design Input

The *Design Input* indicator considers the origins of the materials used, whether or not the components are recyclable, and how robust the design is. The Material Circularity Indicator (MCI) forms the basis of this indicator (EMF and Granta, 2015). The existing MCI is adapted to reflect bridges and viaducts, resulting in the *Design Input* indicator. Two parts are distinguished: (1) the *Material Input*, which addresses both the material use and recyclability; and (2) the *Robustness*, which includes the potential for extended asset use and considers both life span extension and intensity of use. The element of the original MCI that focuses on material outflows is not considered in this study since determining the EoL use of bridge components and materials is too uncertain given that bridges can last more than a 100 years. Nevertheless, this indicator considers the recyclability of components. First, the flow of non-renewable virgin materials, referred to as the linear fraction (EMF and Granta, 2015), is calculated using Equation (1).

$$LF = 1 - (k \times FRec + FReu) - FRen, \quad (1)$$

where *LF* is the linear fraction, or the share of non-renewable virgin materials; *k* is the reducing factor for recycling (see below); *FReFRec* is the asset recyclability expressed as a fraction of recycled materials used, such as, for instance, crushed concrete (Equation 2); *FRe* is the fraction of materials from reused sources, such as, for instance, a reused beam; and *FRen* is the fraction of virgin renewable materials that are sustainably produced. This is, for instance, the case of an oak support beam. Unsustainably produced resources are always considered non-circular and are therefore part of *LF*.

The factor *k* in Equation (1) reflects the reality that the economic value of, for example, crushed concrete is many times less than that of concrete as part of a functioning component. Crushed concrete can be used in new concrete, but this requires reprocessing steps (recycling), which often require a significant use of energy. This differs from direct reuse where the value is retained without the need for further processing steps. The *k* value used in this study is 0.8, a value that favors reuse over recycling, while still valuing recycled materials significantly more highly than virgin materials.

Second, the asset *Recyclability* is calculated, which at this stage is merely a potential reflecting the possibility of using current recycling techniques. *Recyclability*, which ranges between 0 (non-recyclable) and 1 (fully recyclable), depends primarily on the composition of components and is calculated using Equation (2):

$$FRec = \frac{\sum_{j=1}^{J} Rc_j \times M_j}{\sum_{j=i}^{J} M_j}, \tag{2}$$

where *FRec* is the estimated asset recyclability; *J* is the total number of asset components; Rc_j is the recyclability of component *j*; and M_j is the mass of component *j*.

This, together with the *linear fraction*, forms the *Material Input*, which is calculated using Equation (3).

$$MI = \frac{LF + (1 - EFRec)}{2}, \tag{3}$$

where *MI* is *Material Input; LF* is the linear fraction, or the share of non-renewable virgin materials; and *EFRec* is the fraction of recyclable materials.

Finally, *Robustness* addresses the design strength of an asset to determine the actual lifetime value of a product or element. A more robust and thus stronger design has potentially a longer life span if there are no significant changes in functional requirements. In practice, there is usually a trade-off between *Robustness* and *Material Input*. In determining *Robustness*, the design is compared to the base line condition defined by the client regarding structural safety, using Equation (4).

$$R = \frac{RD}{RM}, \tag{4}$$

where *R* is the *Robustness*; *RD* is the relative overdesign of the structural safety of the asset, such as a bridge that is designed to meet the structural safety norms for 200 years rather than the minimum 100 years; and *RM* is the minimum level of structural safety, which is set by national and supranational bodies (e.g., in Eurocodes).

Designs can increase their circularity score both by using recycled, reused, and recyclable materials and by increasing their *Robustness*. However, even with a fully linear material flow, the *Design Input* should never be zero even if the *Robustness* is very high. Therefore, the *Robustness* is corrected by a constant which is expressed as a function of *Robustness* (Equation 5).

$$CR = \frac{a}{R}, \tag{5}$$

where *CR* is the *Corrected Robustness; R* is the *Robustness;* and *a* is a constant. In a report by EMF and Granta (2015), a value of *a* equal to 0.9 was suggested, since with a fully linear product with *Robustness* equal to 1, this sets the *Design Input* to 0.1. However, this is a somewhat arbitrary decision and could be updated if findings from practice provide cause for revision. The *Design Input*, which is the input-related part of the bridge circularity indicator, combines the *Robustness* and the *Material Input* functions according to Equation (6).

$$DI = 1 - MI \times CR, \tag{6}$$

where *DI* is the *Design Input*; *MI* is the *Material Input* determined from Equation (3); and *CR* is the *Corrected Robustness* score.

4.4.2 | Resource availability

Only considering materials in terms of their mass in the *Design Input* fails to capture their contribution to resource depletion. A metric ton of gold is considered far more valuable than a metric ton of gravel and the different values can largely be explained by the relationship between demand and supply, which largely depends on *scarcity*. Nevertheless, the market value does not fully reflect the actual reserves of a material (Henckens, 2016). As such, the classic price mechanisms fail to compensate for scarcity in the procurement process (Vogtländer, Peck, & Kurowicka, 2019). In our composite bridge circularity indicator, this is addressed by including a *Resource Availability* indicator. This indicator addresses the limited supply, relative to demand, of abiotic materials based on existing environmental databases. It is important to note that the *Scarcity* of a material is considered as independent of its source: reusing a scarce material is treated the same as using scarce virgin materials because both contribute equally to global resource depletion.

Many impact assessment methodologies consider resource depletion. The most frequently used methods, such as the *abiotic depletion potential* (ADP), rely on a distance-to-target approach (e.g., years of extraction left given the expected availability of a resource) (Van Oers & Guinée, 2016), but this does not take into account the extraction process and the inherent decrease in the grade of the ore (Vieira et al., 2017). The grade, which is the kilogram of the target material in each kilogram of mined ore, decreases as more ore is extracted. This aspect is addressed in the relatively new, but well-embedded, *surplus ore potential* (SOP) indicator (RIVM, 2017). This is adopted in this study as an indicator of the scarcity of abiotic resources. The *Resource Availability* is then calculated according to Equation (7).

$$RA = SF \times \frac{\sum_{i=1}^{N} SOP_i \times M_i}{\sum_{i=i}^{N} M_i}, \tag{7}$$

where *RA* is the *Resource Availability* of the asset; *N* is the number of materials used; SOP_i is the scarcity of material *i*; M_i is the mass of the material *i* in kilogram; and *SF* is a scaling factor adopted to ensure that the *Scarcity* of highly scarce and non-scarce assets are close to 1 and 0, respectively. The multiple case studies (Section 5) show that a *SF* of 70 is appropriate to place *Scarcity* between the other three indicators (see Figure 1), where 0 is very poor and 1 is very good.

4.4.3 | Adaptability

There are many interpretations and applications of the adaptability concept. Schmidt (2014) defined four characteristics that are generally linked to adaptability: (1) capacity for change; (2) sustaining fit-for-purpose; (3) value retention; and (4) through-life (and hence future) changes (Schmidt, 2014). This led Schmidt (2014) to offer the following definition: "*[adaptability is] the capacity of a building to accommodate effectively the evolving demands of its context, thus maximising its value through life.*"

In this study, *Adaptability* reflects the ability of a bridge to be adapted to changing intensities, dimensions, loads, and contextual circumstances. Four main adaptation possibilities can be distinguished for bridges: (1) broadening the crossing; (2) broadening the underpass; (3) strengthening the crossing; and (4) increasing the clearance of the underpass. These *design-for-adaptation* possibilities should be assessed because a combination of high *Adaptability* and high *Reusability* increases the opportunities for both widening and closing the loops.

To calculate *Adaptability*, the client or design assessor needs to determine whether and to what extent the four adaption possibilities are applicable. For example, it might not be necessary to consider widening the bridge deck because of limitations further along the road. It is then up to the designer to identify the components and elements that would need to be changed in order to facilitate this *Adaptability* option in the bridge design. The *Adaptability* of the asset is then calculated as shown in Equation (8).

$$A = W_{Ext} \times Ext + W_{Str} \times Str + W_{He} \times He, \tag{8}$$

where *A* is *Adaptability*; *Ext* is the *Extensibility* considering both the crossing and the underpass; W_{Ext} is the weight assigned to *Extensibility*; *Str* is the *Strengthenability*; W_{Str} is the weight assigned to *Strengthenability*; *He* is the *Heightenability;* and W_{He} is the weight assigned to *Heightenability*. Following an analysis of the reasons behind bridge demolitions in the Netherlands, the sub-indicators of *Extensibility* and *Strengthenability* were considered equally important. Thus, in the multiple case studies (Section 5) W_{Ext} and W_{Str} were both considered to be equal to 40%, whereas bridges are less likely to be demolished for insufficient clearance. As such, *Heightenability* was given half the weight (i.e., $W_{He} = 20\%$). All parameters are non-dimensional values between 0 and 1 and are determined on the basis of various technical statements related to design preconditions, such as, *"Can the bridge deck be raised without creating waste?"*.

4.4.4 | Reusability

Reusability is defined as the possibility for structural elements to be reused in another situation. *Reusability* considers both the asset and the component levels, depending on the aspect being measured. That is, the bridge can be considered as an object in itself, or as a combination of components. A component is considered to have a maximum reuse potential if it is easily disassembled and transportable over the available infrastructure and has a fairly standard design. Thus, *Reusability* needs to be determined for each component, and this involves its *Disassemblability*, *Transportability*, and *Uniqueness*. The former is determined on the asset level and the latter two on the component level. The *Reusability* of the entire asset is then calculated using Equation (9).

$$RU = q \times D \times T + (1-q) \times \frac{\sum_{j=1}^{J} (1-U_j) \times T_j \times M_j}{\sum_{j=1}^{J} M_j}, \tag{9}$$

where RU is the *Reusability* of the entire asset; q is a factor with a value comprised between 0 and 1 that accounts for the relationship between D and U; D is the *Disassemblability* of the asset; T is the asset *Transportability*, calculated according to Equation (10); J is the number of asset components, such as columns, abutments, railings, or pavements; U_j is the *Uniqueness* of component j; T_j is the *Transportability* of component j; and M_j is the mass of component j.

In calculating the *Reusability* of a component, *Disassemblability* and *Uniqueness* need to be given relative weights. A value of 0.7 is proposed for the parameter q, such that 70% of the emphasis is put on *Disassemblability* and 30% on *Uniqueness*. This value is based on the argument that the former has a larger effect on eventual reuse because an easily disassembled but very unique component is more likely to be reused than standard components that are difficult to extract. The *Reusability* sub-indicators are discussed in the following subsections.

Disassemblability sub-indicator

The disassemblability of a civil engineering structure largely depends on its internal component connections. Based on the theory proposed by Durmisevic (2006), several aspects are adopted to calculate the *Disassemblability* of a bridge. A calculation method based on the types and quantities of connections, as well as the positions of the components (Alba Concepts, 2019), results in the *Disassemblability* of the asset on several levels. This method has been adopted and tailored to bridges to provide insights into the mutual dependencies and relations of the components and the types of connections used, the possibilities, arrangements, and ease of disassembly within bridge designs. Briefly, first, all the interfaces between components need to be determined. Next, the connections used between the interfaces need to be clear. Each type of connection is given a value based on the ease of deconstruction. This *ease of disassembly* can be numerically converted to a single value between 0 and 1 to express the *Disassemblability* of a bridge design.

Transportability sub-indicator

If a component cannot be transported within applicable rules and legislation, it cannot be reused in another location. As such, *Transportability* is regarded as a precondition for reuse in the *Reusability* indicator. Whether a component, given the available infrastructure, is transportable after disassembly largely depends on two factors: (1) the dimensions of the component; and (2) the weight of the component. With bridge components, the weight determines the applicable laws regarding oversize loads. In practice, the dimensions of the component impose the main limitations regarding *Transportability*. To calculate *Transportability*, the available infrastructure in the vicinity of the bridge first needs to be determined (e.g., roads, rail, water), and each available type of infrastructure and their combinations given a score. For example, if a one-lane road and the railway are available, the combination of a one-lane road and railway is given a score of 1, whereas only a one-lane road or only a railway receive scores of 0.8 and 0.4, respectively, based on their usefulness in transporting components to another location. Next, for each component, the applicable combinations of transport infrastructure (e.g., water, rail, or road) must be determined based on the dimensions of the object. For example, a full in situ cast abutment with the dimensions $12 \times 5 \times 4$ m cannot be transported over a one-lane road, but could be transported on a barge along a river, which would qualify for a score of 0.4. Thus, the greater the extent to which the contextual infrastructure can be used to transport the specific component, the higher the *Transportability* score (between 0 and 1). The *Transportability* of a bridge is calculated using Equation (10).

$$T = \frac{\sum_{j=1}^{J} (M_j \times T_j)}{\sum_{j=1}^{J} M_j}, \tag{10}$$

where T is the asset transportability; M_j is the mass of component j; T_j is the transportability of component j; and J is the total number of asset components. *Transportability* is incorporated in the *Reusability* indicator as shown in Equation (9).

Uniqueness sub-indicator

A component will only be reused if there is a demand for it (Van den Berg, 2019). With public infrastructure authorities, this demand can often be linked either to internal projects or to other authorities. This tends to be for one-to-one direct replacement of components or assemblies, which is particularly common with short-span viaducts of which there are several thousand in the Netherlands (Rijkswaterstaat, 2016). However, if components have a unique design, they are less likely to fit in a new location. Therefore, the greater the *Uniqueness* of a component, the less it will meet the circularity principles.

Measuring *Uniqueness* is difficult given the lack of available references. Here, reference standards need to be developed that designed components can be compared with. The level of standardization of an asset is oppositely related to its *Uniqueness*. Standards only need to be developed for frequently used elements, such as precast concrete girders, piers, and connections. Moreover, standards should only consider the major geometric outlines. This is because architectural freedom will be called into question if standardization is implemented to an excessively detailed level. Thus, common components should only be standardized to the extent that they become exchangeable. Based on the explanations presented above, the *Uniqueness* of an asset is determined according to Equation (11).

$$U = 1 - \frac{\sum_{y=1}^{Y} M_y}{\sum_{z=1}^{Z} M_z}, \tag{11}$$

where U is the asset *Uniqueness*; M_y is the mass of the standardized component y, such as, for instance, a girder that is designed according to standardized design principles; Y is the total number of standardized components, M_z is the mass of a standardizable component z; and Z is the total number of standardizable components.

4.5 | Aggregation

Each of the four indicators presented in Section 4.3 addresses a specific component of circularity. Therefore, to represent the entire circularity of a bridge, they need to be aggregated into a composite bridge circularity indicator. The most common way to aggregate a multidimensional indicator consists of following the steps outlined by El Gibari, Gómez, and Ruiz (2018): (1) data enquiry, (2) data normalization, and (3) data aggregation. The OECD (2008) has published an extensive and instructive manual on how to structurally develop composite indicators. Their study formulated 10 steps to ensure a transparent, easy-to-interpret, reality-representing, and comprehensive composite circularity indicator that was appropriate for existing indicators (OECD, 2008). In this section, the four indicators developed above are normalized and weighted in order to provide a single composite indicator for an integrated bridge circularity assessment.

The development of indicators has resulted in a multidimensional set with varying scales and units of measurement. Normalization is thus essential before the aggregation of the indicators. There are several normalization methods to arrive at a coherent dataset. In this study, each indicator and sub-indicator is expressed as a number between 0 and 1, in which a value of 0 reflects either “lacking” or “very poor,” and a value of 1 “fully present” or “very good” in terms of bridge circularity. Non-extreme values are scaled accordingly on a continuous scale ranging from 0 to 1.

4.5.1 | Weights values

While some situations might call for a very adaptable bridge, others might want a bridge that is very robust to maximize long-term resource efficiency. Therefore, depending on the situation being analyzed, the importance of the individual indicators may vary and, therefore, fixed weights are inappropriate. Generally, priorities will be based on both the context of the asset and the objective of the analysis. Assigning weights to individual parts offers opportunities to stress particular aspects. It also enables one to provide a legitimate representation of reality. The diversity in bridge contexts and levels of uncertainty make a fixed set of weights undesirable. An expert session also emphasized that weights based on future scenarios would be difficult to determine because of the many different situations. Rather, basing weights on a specific bridge context allows context-specific weighting without losing objectivity and user independency. This avoids the need for a project team to manually determine the importance of each indicator for each particular bridge, which might introduce biases. In addition, it allows the use of a tailored set of weights that reflects the particular context of an asset.

To avoid inconsistency in the weights used and opportunistic behavior by the framework user, a predetermined weighting method has been developed. Three variables, that depend on the type of bridge and context, are defined to determine the set of weights that is used. They are as follows: (1) type of spanned area; (2) dynamicity of the area; and (3) expected lifetime of the asset. These three factors address the likelihood that a bridge will remain in place in an unchanged state for a certain period of time, and whether it will require either adaptation or removal at a certain moment in the future. The relationships between the indicators and the dependent variables were set using expert insights and are explained below (see also Section 3 on the use of experts). The relationships between these three variables and the four indicators are individually discussed below.

TABLE 2 Relation between the type of spanned area and dynamicity of an area with the circularity indicators based on expert judgement

Type of spanned area	Design input	Adaptability	Reusability
Roads	0.6	0.8	0.8
Railroad	0.8	0.4	0.6
Land	0.8	0.6	0.4
Water < 10 m	0.6	0.8	0.8
Water > 10 m, < 30 m	0.8	0.6	0.6
Water > 30 m	1.0	0.6	0.6
Dynamicity	**Design input**	**Adaptability**	**Reusability**
1	1.0	0.2	0.2
2	0.8	0.6	0.2
3	0.6	0.8	0.4
4	0.4	1.0	0.6
5	0.2	1.0	0.8

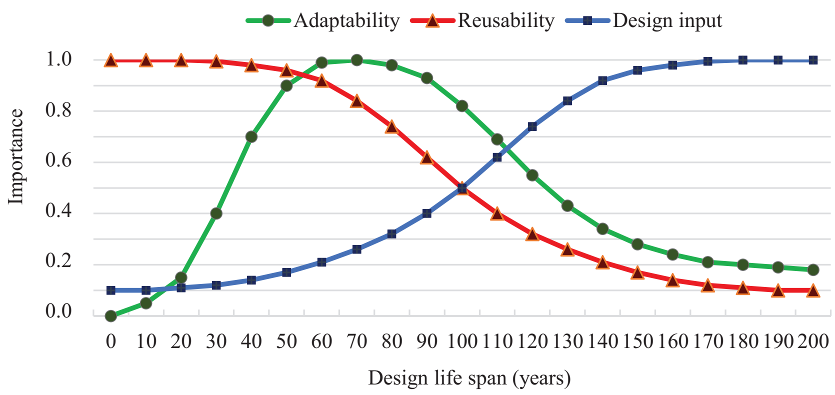

FIGURE 2 Relations between the expected design life span and the importance of the indicators

Depending on the area being spanned, certain characteristics will apply to the bridge context. These characteristics affect the expected unchanged life span and hence the *Design Input*, *Adaptability*, and *Reusability* indicators. Table 2 shows the corresponding values based on expert judgement and indicated on a Likert scale, from 0 (non-corresponding to parameter) to 1 (fully corresponding to parameter). Dynamicity is defined as the likelihood of functional changes based on the changing environment. This can be affected by factors that are natural (e.g., sea-level rise), traffic related (e.g., complex traffic intersections), or urbanization related (e.g., plans for city expansion). With a highly dynamic area, a strong emphasis is put on *Adaptability* and *Reusability*, while in a non-dynamic area, *Robustness* is more important (Table 2). The dynamicity is determined by examining the context rather than the design goals or the scope of the particular asset design. Dynamicity in Table 2 indicated on a five-point Likert scale, with the corresponding weight values for the three indicators ranging from 0 (static) to 1 (extremely dynamic) based on expert judgement.

The expected lifetime mainly reflects the design lifetime. That is, the intended time the designer foresees the asset remaining in a certain place in a certain condition. Figure 2 shows the importance of the various indicators for different expected life spans according to expert insights. The *y*-axis shows the importance of the various indicators for different life spans that ranges from 0 (non-applicable) to 1 (fully applicable). The skewed bell shape of the *Adaptability* curve derives from the fact that the longer the life, the more likely it is that the functional requirements will change. However, with a very long service life, *Adaptability* becomes less important given the decreasing structural safety of the asset.

4.5.2 | Weights elicitation

The three weighting variables explained in Section 4.5.1 can be combined into one aggregated set of weights. Each variable results in weights for the *Design Input*, *Adaptability*, and *Reusability* indicators. The fourth indicator, *Resource Availability*, can be related to *Design Input* since both indicators address the use of materials. A fixed relationship is proposed, in which the weight of *Resource Availability* is equal to 70% of that of *Design Input*. This relationship is based on expert discussions that suggested that *Design Input* and *Resource Availability* should together amount to approximately 50% of the weight in an average bridge context. The other three weights values are determined by calculating the average of the three variables for the

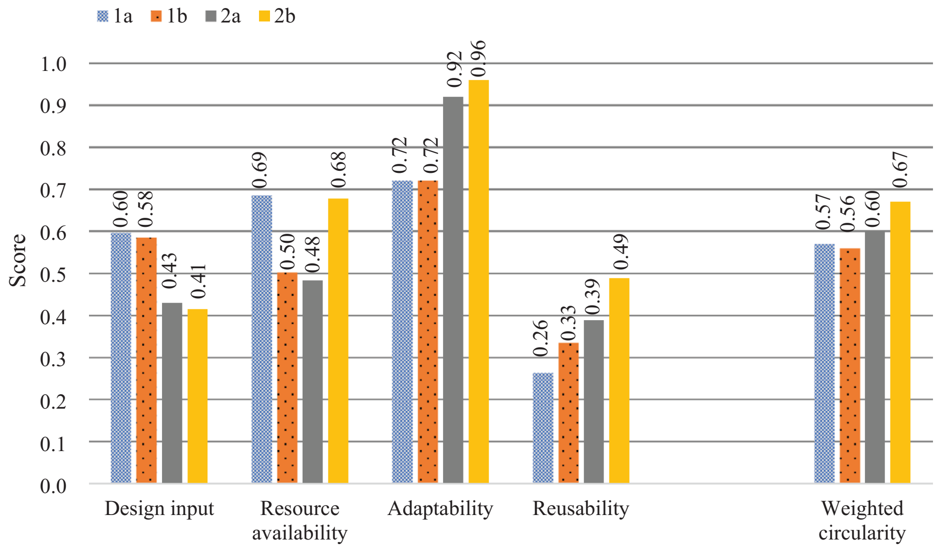

FIGURE 3 Indicator scores and final circularity scores for the four design alternatives in Case study 1

given context. First, the corresponding values (see Section 4.5.1) for the *Design Input*, *Adaptability*, and *Reusability* indicators are identified for the specific context. Next, the corresponding average of the values of the weighting variables is calculated for these three indicators (see Table 3 for two sample calculations), whereas the weight value for the fourth indicator (*Resource Availability*) is calculated based on that of the *Design Input* indicator. These four weight values are each divided by their sum to obtain the normalized weights. Two examples of this calculation procedure are shown in Table 3. The effects of the weights values on the final results are discussed in Section 7.2.

5 | CASE STUDIES

The applicability of the developed framework is now illustrated by means of two Dutch case studies. In Section 5.1, four design alternatives for a replacement viaduct are compared using the framework. In Section 5.2 a pre-labeled *circular* deck is compared with a conventional one. Background information on the analyses can be found in Section 1 of Supporting Information S1.

5.1 | Case study 1: Full or partial replacement?

The first case study considers a viaduct that is intended to be replaced because both the crossing and the roads that pass underneath can no longer handle the amount of traffic—thus for a functional reason. The current structure has two parts: (1) the southern part constructed in 1938 consisting of a cast-in-situ deck and (2) the northern part, built in 2005, which consists of a box-girder deck. Not only does the current structure not allow additional lanes to be added underneath, the structure that was built in 1938 also needs to be replaced for structural reasons. Several design ideas were developed, of which four were considered feasible. These were: (1a) replacement of the 1938 part with a new structure and retention of the 2005 part; (1b) replacement of the 1938 part by an extension of the 2005 part; (2a) full viaduct replacement with a central support; and (2b) full viaduct replacement without a central support. The main characteristics of the four design alternatives and the values of the parameters considered in the calculation of the four main circularity indicators are presented in Table 4. The spreadsheets with the calculations can be found in Supporting Information S2.1a, S2.1b, S2.2a, and S2.2b.

The overall circularity scores are calculated with the weighting variables applicable for a *100-year life span*, *dynamicity value* equal to 3, and function as a *road crossing*. This results in the following weights values: 24% *Design Input*, 17% *Resource Availability*, 35% *Adaptability*, and 24% *Reusability*. The results displayed in Figure 3 show that the overall circularity scores of the four alternatives are quite similar. Despite the similar overall scores, a comparison at the underlying sub-indicator level shows considerable differences. A notable outcome is that an increase in the *Design Input* score results in the decrease of the *Reusability* score. This is related to the old parts not being reusable, while using old parts would contribute strongly to the *Design Input* indicator. Another striking observation is that alternatives *1a* and *1b* score considerably lower on *Adaptability* than the other options. This is explained by the fact that these alternatives (that include part of the existing viaduct) will not allow further additional lanes to be

TABLE 3 Calculation of the weights values for two example situations using the corresponding values presented in Table 2 and Figure 2 in Section 4.5.1. Example 1 is a land crossing with dynamicity 4 and a life span of 150 years. Example 2 is a road crossing with a dynamicity of 3 and a life span of 50 years

		Bridge- and context-dependent weighting variables				
Indicator	**Example ID**	**Type of area**	**Dynamicity**	**Life span**	**Average of weighting variables**	**Normalized weight (%)**
Design Input (DI)	1	0.8	0.4	0.96	0.72	32
	2	0.6	0.6	0.17	0.46	20
Reusability (RU)	1	0.6	1.0	0.28	0.63	28
	2	0.8	0.8	0.90	0.83	36
Adaptability (A)	1	0.4	0.6	0.17	0.39	17
	2	0.8	0.4	0.96	0.72	31
Resource Availability (RA)	1	$W_{DI} \times 0.7$			0.50	22
	2	$W_{DI} \times 0.7$			0.32	14
					Sum example 1	100
					Sum example 2	100

TABLE 4 (a) Main characteristics of the four design alternatives in case study 1 used to calculate the Material Input, (b) values of the parameters used to calculate the indicators for the four design alternatives in case study 1, and (c) values of the weights, indicators and resulting aggregated bridge circularity scores for the four design alternatives in case study 1

(a)

Characteristics	Design alternative			
	1a	1b	2a	2b
	Replacement of old part by new separate part	Replacement of old part by extending the more recent part	Full replacement with central support	Full replacement without central support
Total materials used (metric tonnes)	1456	1772	1562	2404
Total virgin materials (metric tonnes)	694	889	1432	2256
Capacity for change	Low	Low	Moderate/high	High

(b)

		Design alternative			
Indicator	Parameter	1a	1b	2a	2b
Design Input (DI)	Recycled materials (%)	8	0	0	0
	Reused materials (%)	44	49	8	6
	Renewable materials (%)	0	0	0	0
	Recyclable materials (%)	59	58	65	64
	Added robustness (dimensionless)	0	0	0	0
Adaptability (A)	Extensibility (%)	30	30	80	90
	Strengthenability	Yes	Yes	Yes	Yes
	Heightenability	Yes	Yes	Yes	Yes
Reusability (RU)	Disassemblability (%)	30	40	40	50
	Transportability of disassembled parts (%)	88	83	97	98

(c)

		Design alternative scores			
Indicator	Calculated weights values	1a	1b	2a	2b
Design Input (DI)	24%	0.596	0.140	0.103	0.099
Resource Availability (RA)	17%	0.686	0.086	0.082	0.115
Adaptability (A)	35%	0.720	0.252	0.322	0.336
Reusability (RU)	24%	0.263	0.080	0.093	0.117
Bridge circularity (BCI)		**0.57**	**0.56**	**0.60**	**0.67**

added in the underpass. The use of similar materials, primarily concrete and steel, results in similar high scores for *Resource Availability*, although the use of relatively more steel compared to concrete in alternatives *1b* and *2a* results in slightly lower scores.

To conclude, the outcomes from applying the framework to this case study contradict some of the preconceived assumptions, such as that direct reuse is always better for circularity. However, in retrospect, these unexpected findings are perfectly understandable. This discrepancy between expectations and framework outcomes is a positive aspect resulting from the use of the framework and shows that this analysis can provide novel insights by considering circularity in a wider perspective, as opposed to that given by the exclusive consideration of the initial material use, which is often decisive in many circularity-related decisions. By considering resource efficiency in a broader perspective than existing indicators, this analysis shows that simply avoiding virgin materials does not necessarily lead to using less materials over their life cycle. However, the circularity of the "most circular" design (*2b*) could have been significantly increased by using higher percentages of recycled concrete. This would have increased the *Design Input* value and consequently the overall circularity score. The sensitivity of *Recyclability* and *Robustness* and their effect on the *Design Input* are discussed in Section 7. Also, designing the girder structure such that the girders could have been individually disassembled would have significantly boosted the *Reusability*, as demonstrated in the sensitivity analysis performed in Section 6 and discussed in Section 7.2.

TABLE 5 (a) Main characteristics of the two design alternatives in case study 2 used to calculate the Material Input, (b) values of the parameters used to calculate the indicators for the two design alternatives in case study 2, and (c) values of the weights, indicators and resulting aggregated bridge circularity scores for the two design alternatives in case study 2

(a)

	Design alternative	
Characteristic	**Circulaire Viaduct**	**Conventional box-girder viaduct**
Type of new bridge	Concrete segments that can be assembled in many configurations	Deck consisting of various girders placed next to each other
Total materials used (metric tonnes)	279	204
Total virgin materials (metric tonnes)	244	183
Capacity for change	Very high	Moderate

(b)

		Design alternative	
Indicator	**Parameter**	**Circulaire Viaduct**	**Box-girder deck**
Design Input (DI)	Recycled materials (%)	12	11
	Reused materials (%)	0	0
	Renewable materials (%)	0	0
	Recyclable materials (%)	59	59
	Additional robustness (dimensionless)	1.5	0.25
Adaptability (A)	Extensibility (%)	100	50
	Strengthenability	Yes	No
	Heightenability	Yes	Yes
Reusability (RU)	Disassemblability (%)	90	40
	Transportability of disassembled parts (%)	100	76

(c)

		Design alternative scores	
Indicator	**Calculated weights values**	**Circulaire Viaduct**	**Box-girder deck**
Design Input (DI)	16%	0.765	0.523
Resource Availability (RA)	11%	0.739	0.742
Adaptability (A)	33%	1.000	0.400
Reusability (RU)	40%	0.900	0.305
Bridge circularity (BCI)		**0.90**	**0.43**

5.2 | Case study 2: Circulaire Viaduct

The *Circulaire Viaduct* is a pilot project of a modular viaduct designed for flexibility and multi-life cycle use (Van Hattum en Blankevoort, 2018). The central idea is to design the viaduct out of small identical segments that are held together by reinforcement wires and bars such that they can be assembled as well as disassembled and reassembled, in any desired configuration. The main purpose of this case study is to determine whether this so-called *Circulaire Viaduct* is indeed more circular than a conventional box-girder design. The main characteristics of the two design alternatives and the values of the parameters used in the calculations of the four main indicators are presented in Table 5. The spreadsheets with the calculations can be found in Supporting Information S1a and S1b.

The scores for the individual and the aggregated circularity indicators are shown in Figure 4. Since the same types of materials are used, the *Resource Availability* is quite similar in both alternatives. The modular and deconstructable nature of the *Circulaire Viaduct* design, and the oversizing of the elements, result in considerably higher scores for the *Adaptability* and *Reusability* indicators. Given its ability to be extended, heightened, and

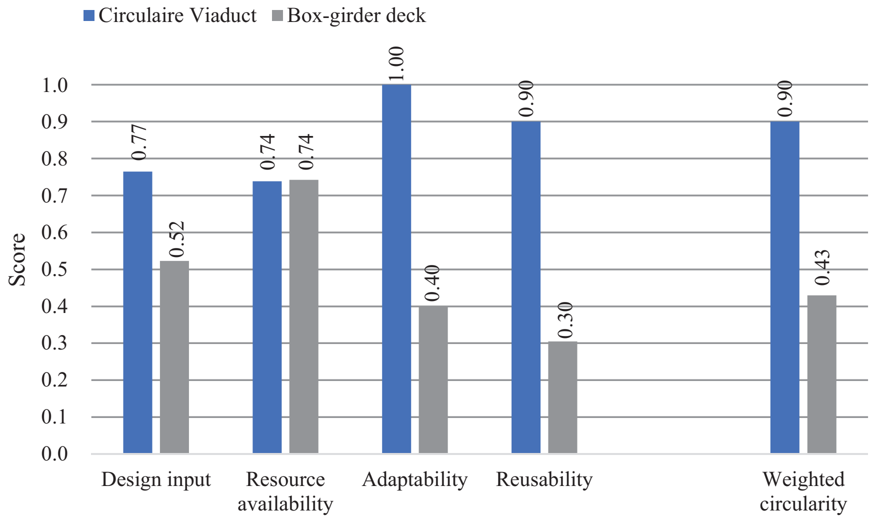

FIGURE 4 Indicator scores and final circularity scores for the two design alternatives in case study 2

strengthened by increasing the longitudinal reinforcement bars, the *Circulaire Viaduct* has an aggregated circularity score of 0.90, more than double of the score of the conventional alternative (0.43).

Overall, the claims of the designers regarding the circularity of the viaduct are justified by this analysis. Nevertheless, the underlying results show still considerable room for further improvement in the circularity in several design aspects of the *Circulaire Viaduct*. First, the *Design Input* could have been improved by replacing virgin materials with reused, recycled, or even renewable materials. This is discussed in section 7.2 by showing the impact on the circularity scores of increasing the share of renewable, recycled, or reused materials. Second, the girder segments contain various elements that are precast in the concrete and this may result in premature demolition. By functionally separating these parts, the *Disassemblability* could have been increased.

6 | UNCERTAINTY AND SENSITIVITY ANALYSIS

An important aspect to consider when building composite indicators is to what extent uncertainties and user freedom in the definition of the weights values affect the aggregated circularity score. Therefore, a stochastic exploration of the weights values has been performed to investigate this issue. This consists of stochastically determining samples of weights to reflect the hypothetical (or genuine) lack of knowledge about the characteristics of the bridge and context-dependent variables used to determine the weight values. Using these stochastically determined values, the user of the framework obtains an aggregated circularity score that takes into account all the possible weight combinations. The main findings from this analysis are discussed in Section 7.2. The methodology and the results obtained are explained in Section 2 in Supporting Information S1.

Furthermore, suggestions were made in Section 5 regarding potential design improvements to achieve higher circularity scores. However, it is still unclear to what extent the circularity score is impacted upon by variations in the values of the various parameters and the assumptions made. To determine how the results are affected by those aspects, a *one-factor-at-a-time* (OFAT) sensitivity analysis has been performed. First, the impact of the context-dependent weighting parameters on the final circularity score is determined. For each parameter (i.e., type of spanned area, dynamicity, and life span), low, average, and high values are considered. Design *2.2a* from case study 1 and the *Circulaire Viaduct* design from case study 2 are used as illustrative examples given the large difference in their indicator scores (i.e., 0.39 and 0.92). Second, the impacts on the *Design Input* indicator resulting from using more recycled and renewable materials, and making the design more robust, are determined. For this, the *Circulaire Viaduct* design is considered since this bridge design involves mainly virgin materials, which resulted in a relatively low score for the *Design Input* indicator. The most striking results are discussed below in Section 7.2, and the detailed results of this analysis can be found in Supporting Information S2.

7 | DISCUSSION

In this section, the main outcomes resulting from applying the framework to the multiple case studies are discussed (Section 7.1), followed by a discussion on the uncertainty and sensitivity analysis (Section 7.2) and the limitations of the framework (Section 7.3).

7.1 | Reflection on the results

As discussed in the introduction, the circularity of a bridge design cannot be fully grasped in a single indicator. Based on the literature review, an assessment framework was developed with 4 main indicators and 11 sub-indicators. Given that the existing indicators were not suited for a comprehensive assessment of the impact of material depletion from a multi-life cycle perspective (Section 2), the two case studies presented in Section 5 have revealed that the developed framework is useful in providing insights into various aspects that are included in the Circular Economy (CE) concept. In contrast to existing circularity indicators, this assessment framework has specifically been developed for one group of assets, namely bridges. The framework development process showed that the specific characteristics of bridges are crucial in assessing future potentials, such as *Adaptability* and *Reusability*. The typical life span and typical materials, along with the adaptability and reusability potentials, were found to be important characteristics in determining the circularity of an infrastructure asset. Further, the study revealed that the technical specificities on a sub-indicator level depend on the type of asset.

7.2 | Discussion of the uncertainty and sensitivity analysis

The results presented in Supporting Information S2 include all combinations of three extreme values for each of the three weighting parameters. The most unfavorable configurations for design *2.2a* in case study 1—short life span, low dynamicity, and crossing water more than 30 m wide—results in a circularity score of 0.51, while the most advantageous configuration—average life span, high dynamicity, and a road crossing—results in a circularity score of 0.61. For the conventional design in case study 2, the lowest score of 0.41 was obtained with a short life span, high dynamicity, and a road crossing, while the highest score of 0.59 was found with a long life span, low dynamicity, and a road crossing. Given these extremes and the fact that the standard deviation of the results for all 27 combinations is, respectively, 0.03 and 0.04 for the two case studies, the weighting parameters, and therefore the context, have a strong effect on the circularity scores. Moreover, the way a bridge should be designed to be considered circular depends on the contextual factors. That is, the type of design decisions that results in the largest increase in circularity score depends on the corresponding weights and hence the context of the bridge.

Case study 1 (Section 5.1) showed that, from a long-term perspective, the simple use of recycled materials or reused components is not necessarily the most circular option. For example, doubling the design life span, resulting in a *Robustness* of 2.0 instead of 1.0, would increase the circularity score of design *2.2b* by 0.07 points to 0.74. Furthermore, using only recycled materials would increase the circularity score by 0.08 points to 0.75, whereas both using only recycled materials and doubling the design life span would increase the circularity score by 0.11 points to 0.78 (Supporting Information S2). Also, case study 2 has shown that a circularity-oriented design (i.e., *Circulaire Viaduct*) had a circularity score which more than doubled that of a conventional bridge deck, largely a consequence of the considerably higher *Adaptability* and *Reusability* scores (Section 5.2). Further, in the *Circulaire Viaduct* case study, the sensitivity analysis shows that making the girders of renewable materials instead of virgin concrete would increase the overall score by 0.05 points to 0.95, while making it of fully reused elements only increases the score by 0.02 points (Supporting Information S2). This is because using renewable materials has a positive effect on the *Resource Availability* indicator. The impact of the *Disassemblability* score is also shown in the sensitivity analysis. If the *Circulaire Viaduct* had been designed to be non-disassemblable, the score would have been only 0.60, whereas full *Disassemblability* leads to a circularity score of 0.93. All other aspects remaining equal, a 1% increase in *Disassemblability* leads to a 0.26% increase in the circularity score for the conventional design, but to a 0.33% increase in the *Circulaire Viaduct* design. The smaller impact in the conventional design is explained by the*Transportability* sub-indicator in the *Reusability* score.

Finally, the relative difference is considered regarding the performance of two alternative designs given the uncertainties over the weights that should be used. Tables 2 and 3 in Section 2 of the Supporting Information S1 show that the relative difference in the CE scores of the alternative designs *2.1a* and *2.1b* is likely to be the most affected by changing the weights assigned to the indicators. Conversely, alternative designs *2.2a* and *2.2b* are likely to be the least affected. This difference can be explained by the differences in mutual deviation between the scores of the four indicators—the larger the deviation, the higher the effect of the weights. Overall, these results indicate that the CE scores are significantly sensitive to variations in the weights assigned to the four indicators.

7.3 | Limitations and future work

Despite the gaps addressed by the developed framework, it still has limitations.

First, although the bridge circularity indicator aims to include resource depletion over the full life span of bridges, this does not include energy use, greenhouse gas emissions, and other environmental impact categories. Therefore, it is strongly recommended that these aspects are incorporated as an additional indicator on top of the indicators that are commonly considered by sustainability rating systems such as LEED or BREEAM.

Second, even if a bridge were to be designed to be extensible or to be disassembled, it is hard to prove that this will be technically possible several decades into the future. Structural safety is crucial for reusing parts, and weathering, corrosion and structural degradation can lead to a reduction in properties that are crucial for adaptation or reuse. Consequently, additional research is required in the field of materials and the degradation of materials and components to address reuse and adaption possibilities.

Third, alongside drawing on scientific literature, decisions in the development process of this framework were based on expert insights from within the Dutch infrastructure agency. This approach is inevitably open to biases in the approach taken toward circularity. International validation is also necessary to align the framework with the overall conceptualization of the CE.

8 | CONCLUSIONS

Circularity has been proposed as a way to reduce the impact of bridges on resource depletion and to promote long-term resource efficiency. To this end, a framework has been developed to assess the circularity of bridge designs in terms of material use. Four indicators, each comprising various sub-indicators, lead to an aggregated circularity score. In contrast to existing circularity assessment methods, the framework not only considers material flows, but also the appropriateness of a design for possibly required adaptation and reuse in the future. This is particularly relevant given the possible consequences of climate change.

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CONFLICT OF INTEREST

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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