Development and Implementation of a Circularity Assessment Framework for the Historical Bridges of Amsterdam City

Master Thesis

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Summary

In the city of Amsterdam, where over 200 bridges have exceeded their lifespan and require intervention, the municipality is actively taking initiatives to implement circular design principles in asset management. However, assessing the circularity of historical bridges with the existing frameworks proves challenging. The existing framework requires an extensive amount of data for the assessment. In addition, historical bridges possess unique characteristics, such as their monumental status and uncertainties in components' condition, which require a more specialised approach. This research addresses the gap by developing the Historical Bridge Circularity Indicator (HBCI).

The research design for developing the HBCI framework involves multiple steps: literature review, framework development, and framework validation. The literature review encompasses exploring the existing definitions and principles of circularity, existing circularity indicators, bridge preservation strategies, and examples of existing historical bridges. The literature review includes a critical review of the existing circularity indicators, examining their strengths and weaknesses when applied to historical bridges. Then, the framework is developed by defining the charachteristics of the framework and turning circular concepts into sub-indicators. The next step is determining the framework indicators by analysing the variables and the type of data needed for the framework to ensure their relevance, analytical soundness, timeliness, accessibility, etc. The next step is data normalisation to ensure that all inputs have the same measurement unit and can be aggregated together. Then, sub-indicators are weighted based on their influence on the asset's circularity. Further, two case studies are applied to the framework, each serving a different purpose. Finally, a sensitivity analysis is conducted using the one-at-a-time approach to test the impact of changing the value of one parameter on the final score.

The framework features are determined using the taxonomy of circular economy indicators developed by Saidani et al. (2019). The framework assesses circularity on a micro level (organization, products, etc.), covering the full scope of the circularity feedback loops. The performance is captured on both intrinsic and consequential circularity. The framework is applicable to three different scenarios: general insight, strategic decision support, and deconstruction and demolition insight. The general assessment is a preliminary assessment of circularity potential for an existing situation. Strategic decision support is when the bridge requires interventions, and decisions need to be taken between different scenarios. Deconstruction and demolition is the end-of-life assessment to minimize waste generation and enhance resource efficiency.

The Historical Bridge Circularity Indicator (HBCI) assess the circularity level of historical bridges from 3 main perspectives: material, component, and bridge level. These main perspectives are assessed through the Modified Material Circularity Indicator (MMCI), Component Reusability Indicators (CRI), and Bridge Preservation Indicator (BPI). The MMCI captures the circularity performance on a material level by assessing the material flow, connection type, accessibility to material, and its availability. The CRI captures the circularity performance on a component level by assessing its dismantability, transportability, and health. Meanwhile, BPI captures the circularity performance on a system level by assessing how much is preserved from the original bridge and the ability of the bridge (potential preservation) to be widened and strengthened.

The framework has been used for two case studies. Case study A focused on the impact on circularity performance when an existing historical bridge is replaced but many of the original components are reused. The results showed an increase in the CRI and BPI scores due to better competent health and

preservation capabilities. The MMCI score has decreased in the new bridge due to the addition of new virgin material. However, the sensitivity analysis revealed that changes in the virgin material fraction have a slight impact on the final output. Case study B tested the robustness and consistency of the framework by applying it to two different bridges that share similar characteristics and intervention history. Despite the two bridges sharing the same overall HBCI scores, differences were observed on layer, component, and material levels, demonstrating the framework's ability to capture circularity performance differences even among bridges with similar characteristics and histories.

In conclusion, future research can further refine the framework by developing standardised data collection protocols, mitigating subjectivity in expert judgment through a comprehensive framework, enhancing the quantification process, standardising the HBCI framework to be applicable to all historical infrastructures, and exploring integration with Life Cycle Assessment (LCA) for a broader environmental impact assessment. Additionally, practitioners can benefit by utilizing multiple expert opinions for subjective areas, exploring economic value metrics for components alongside mass, and integrating the framework with cost analysis to validate the financial feasibility of circular interventions. By implementing these recommendations, the HBCI framework can reach its full potential, promoting circularity in historical bridge management and decision-making while safeguarding their cultural heritage.

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1. INTRODUCTION

The city of Amsterdam is well-known for its canals and bridges, boasting around 1600 bridges (Voortman, 2021). However, approximately 200 bridges have surpassed their estimated lifespan and require serious maintenance work, rehabilitation, or a complete renovation (Peduto, Elia, & Montuori, 2018). Historical bridges are recognised culturally significant structures that are eligible for preservation and protection, mainly based on their age of at least 50 years, architectural or historical significance, and contribution to national heritage (Ministerie van Onderwijs, 2023). Figure 1 showcases multiple types of historical bridges throughout the city of Amsterdam.

While many of these bridges are architectural landmarks and essential for transportation and connecting communities (Korrel, 2023), it's significant for the municipality to prioritise the maintenance work and determine future scenarios for these assets. Therefore, the city of Amsterdam is collaborating with diverse disciplines and researchers (NWO, 2021). Nebest, a consultancy commissioned by the municipality, is assessing the structural health of the bridges and exploring circular renovation scenarios to maximise the value of these assets, such as implementing life-extending measures or reusing parts of the asset (Nebest, 2022). These scenarios can be assessed by calculating the circularity score of all bridges for each scenario. Using the existing circularity indicators would not provide accurate estimates due to the challenges of having the needed data, data uncertainty, complexity of historical bridge structures, etc. Therefore, the development of a circularity assessment framework for historical bridges is necessary.

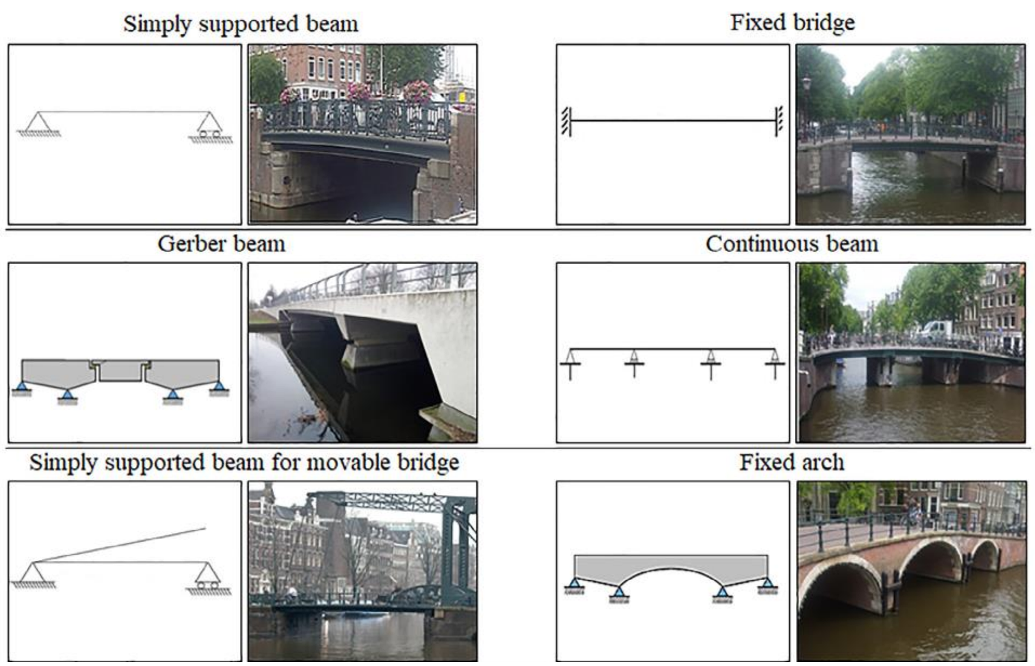


Figure 1: Bridges in Amsterdam city (Peduto, Elia, & Montuori, 2018)

1.1. From linear to circular economy

The construction industry has been continuously consuming more materials due to the increase in demand, which increases the cost of materials due to the scarcity of these materials (Adams, Osmani, Thorpe, & Thornback, 2017). In addition, many construction companies have been following a linear model of production, which can be seen as take, make, and then dispose (Benachio, Freitas, & Tavares, 2020). Consequently, these materials are more likely to become waste after the end of the infrastructure's lifespan, thus resulting in a negative influence on the environment (Dobbs, Oppenheim, Thompson, &

Brinkman, 2015). Circular economy systems help in determining ways to reduce the number of used materials, increase the efficiency of material use, produce less pollution, and bring up higher economic benefits in Construction projects (Adams, Osmani, Thorpe, & Thornback, 2017). In other words, the circular economy system represents a closed loop, which is a restorative or regenerative system. Therefore, many companies/institutions recently have been trying to switch towards a circular economy, where the production model doesn't result in waste disposal, biodiversity loss, air and water pollution, material depletion, etc. (Verberne J. , 2016). The research of Gravagnuolo et al. (2019) states that implementing circular economy principles to historical assets would lead to the prevention of using row material, reducing construction waste and landfill, promoting a second life, creating new products, and repurposing parts for new functions, and recycling when possible (Gravagnuolo, De Angelis, & Iodice, 2019).

1.2. Applying circular economy

Switching towards a circular economy can be done by following circularity principles and recommendations when making new designs or while developing existing infrastructure (Azar, El Asmar, & Antonio, 2022). Currently, the municipality of Amsterdam is trying to implement circular design principles by using the reclaimed wood from historical bridges in new bridges. As a result, this approach has reduced waste and preserved the historical character of bridges (Gemeente Amsterdam, Amsterdam Circular 2020-2025 Strategy, 2020).

Nebest has performed a reusability scan (HBS) for some of the historical bridges in Amsterdam city (Nebest, 2022). The reusability scan (HBS) is used to determine which parts/elements of the asset can be reused, and it includes activities such as archives data collection, visual inspection, residual life analysis, constructive assessment, verification, and monitoring. The HBS is very beneficial for collecting data about these assets in order to develop variant future scenarios for each asset (Maintain, demolish, reuse parts, etc.). Multiple criteria are taken into account to assess the functionality of these scenarios and decide the most fit scenario for each asset. Nebest currently uses a method called the 10R score, which is based on the scenario's level of circularity (Refuse, reduce, rethink, etc.) (see Table 2). The score varies from 1 to 10, where 10 is considered the most circular.

1.3. Measuring circularity

In the past 10 years, there has been a lot of research on developing Circularity Indicators for assessing infrastructure circularity levels. Several circularity indicators have been developed for bridges. Still, the existing indicators require an extensive amount of data about the structure of bridges and the material properties that are used to construct them (Jerome, Helander, Ljunggren, & Janssen, 2022). A couple of examples of frameworks that assess a bridge's circularity are the circularity assessment framework done by Coenen et al. (2021) and the circularity indicator that is implemented on a pedestrian bridge done by Vlasic et al. (2020). The developed indicators are highly dependent on data about infrastructure that is often unavailable for historical bridges (Gemeente Amsterdam, Amsterdam Circular 2020-2025 Strategy, 2020). Consequently, implementing the available indicators on historical bridges will require a large number of assumptions that will lead to uncertain results.

The current indicators require data about the material, such as mass and how much can be recycled, remanufactured, refurbished, etc. (Jerome, Helander, Ljunggren, & Janssen, 2022). In addition, more data is needed such as connectivity of components, functional dependence, technical lifecycle, etc. (Verberne J. , 2016). Consequently, the lack of data availability makes using the existing indicators or having an accurate circularity score challenging.

2. PROBLEM DEFINITION

Much research has been conducted on implementing circular principles and techniques and developing circularity indicators (Anastasiades, Blom, Buyle, & Audenaert, 2020). Arbolino et al. (2021) conducted a systematic review for measuring circular economy by analysing 61 existing indicators (De Pascale , Arbolino, Szopik-Depczyńska, Limosani, & Ioppolo, 2021). It was found that existing indicators vary in context, scope, and applicability potential for different types of infrastructures (Saidani, Yannou, Leroy, Cluzel , & Kendall, 2019).

When applied to historical bridges, existing indicators exhibit significant limitations and gaps. These indicators fail to capture or adequately assess the unique aspects of historical bridges, including their distinctive material properties, complex structural designs, and limited accessibility for inspection and maintenance (DAHP, 2011). In addition, the principles of dismantling and reuse of materials are very challenging due to the unique characteristics of these assets and the constraints of preserving cultural heritage.

The existing circularity indicators depend highly on detailed information about materials' properties such as mass, composition, recyclability, etc. (Jerome, Helander, Ljunggren, & Janssen, 2022). Unfortunately, many historical bridges were constructed at a time when documentation practices were less rigorous than they are nowadays. Moreover, many bridges contain traditional materials such as timber, stone, or earthen materials, which are not commonly used nowadays (Mort, 2008). Consequently, the properties of such material are not well documented or analysed regarding circularity. Limited access for inspection and maintenance occurs due to the structural complexity of the asset (elements' accessibility challenges), preservation concerns, and safety concerns. This results in difficulty in determining and quantifying all types of materials used in the asset (Mort, 2008).

The gaps in existing indicators regarding historical bridges are compounded by practical constraints, such as budget limitations, the need for skilled labor specialised in historical infrastructure, and technological availability limitations. These constraints pose additional challenges in collecting comprehensive data necessary for assessing circularity. Consequently, it is considered a struggle for disciplines to estimate the circularity scores with the existing indicators.

2.1. Fishbone diagram for measuring circularity of historical bridges

Figure 2 shows the fishbone cause and effect diagram for measuring the circularity of historical bridges. The fishbone diagram is a visual tool that is used to determine the potential causes of a specific problem and categorise them (Lewis, 2020). In the case of assessing the circularity of historical bridges, four main categories are found. The first category encompasses the limited applicability of the existing indicators due to the variance in the scope of each indicator, conflicts between circularity and preserving historical value, and the lack of the needed data (Gravagnuolo, De Angelis, & Iodice, 2019). The second category includes the difficulty in assessing the bridge's parts safety, which is crucial for circularity principles like reuse, repair, refurbish, and remanufacture (Sangiorgio, et al., 2022). For historical bridges, assessing safety is challenging due to the structural complexity, limited accessibility, ageing material and degradation, potential hidden defects, etc. This leads to the third category, data uncertainty, arising from the lack of documentation and the need for specialised methods, labor, and equipment to collect data (Conde, Ramos, Oliveira, Riveiro, & Solla, 2017). Lastly, significant monuments and heritage conservation regulations can influence repair and adjustment options, potentially conflicting with circular strategies

(Gravagnuolo, De Angelis, & Iodice, 2019). Overcoming these challenges is essential for developing a comprehensive circularity assessment framework for historical bridges.

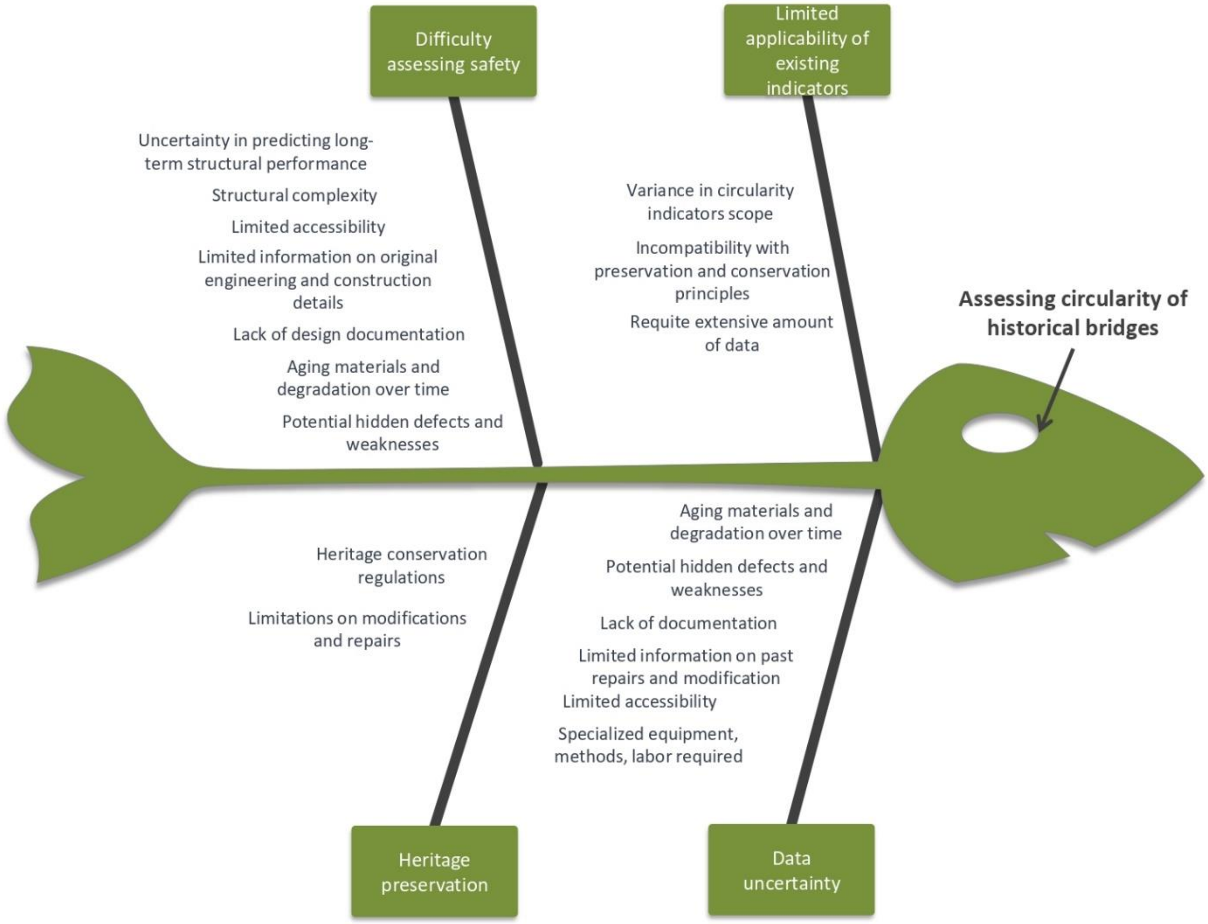


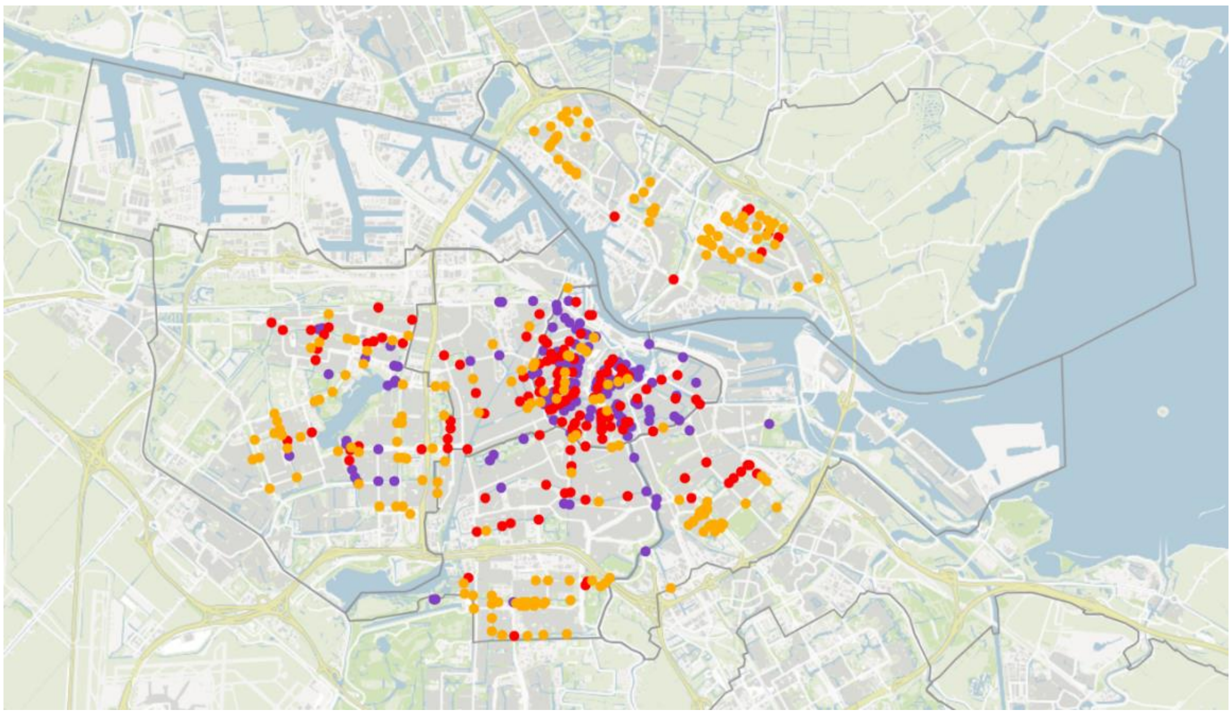
Figure 2: Fishbone diagram Assessing circularity of historical bridges

2.2. Research scope

This research aims to develop a circularity assessment framework specifically tailored for historical bridges. The focus is on deriving an accurate circularity assessment of these bridges while considering the existing challenges, such as the data availability and uncertainties, structural variance and complexity, and monumental preservation. These challenges will be further analysed, and the assessment framework will be developed to mitigate their influence. As a result, the framework can become feasible for historical bridges. The circularity assessment will cover the use phase and end-of-life phase of their lifecycle. Including more phases of the lifecycle of these assets is unfeasible due to the excessive lack of data for the earlier lifecycle phases. The cultural heritage values estimates are outside the scope of the assessment framework. Cultural heritage values are assessed mainly on-site and require specialised expertise, which should be done prior to the circularity assessment (Gravagnuolo, De Angelis, & Iodice, 2019).

2.2.1. Study area and bridges classifications

The study area will be confined to the historical bridges located within the boundaries of the city of Amsterdam, and the case study will be from the same study area. However, the framework should be feasible for assessing the historical bridges in other areas with similar characteristics. In the Netherlands, historical bridges are usually at least 50 years old, have historical or cultural significance, and aesthetic value, are associated with historical events, etc. (Ministerie van Onderwijs, 2023). The Valuation Map Protected City's View Center (De Waarderingskaart Beschermd Stadsgesicht Centrum) has made 3 main classifications for historical bridges, which are order 1, 2, and 3 (Commissie Ruimtelijke Kwaliteit, 2020). Order 3 includes the bridges built before 1940 with low architectural/cultural value and the bridges built between 1940 and 1970 with high architectural/cultural value. Order 2 includes the bridges built before 1940 and have high architectural/cultural value. Lastly, order 1 includes national monuments and is considered the most important order. The following figure shows the distribution of the three categories within the city of Amsterdam (see Figure 3).



Order 1 Order 2 Order 3

Figure 3: Historical bridges distribution in Amsterdam (Ordekaarten, 2020)

2.2.2. Data sources

Variant resources will be used to find data, such as conducting a literature review, Nebest database, Amsterdam Inspection Portal, and interviews with practitioners. The literature review explores the existing indicators, collects data on the types of bridges, determines the challenges for measuring the circularity of historical bridges, etc. Nebest has conducted several inspection works to assess the reusability of multiple historical bridges in the city of Amsterdam. Therefore, their database includes beneficial data about the structure of these bridges, safety assessment, and material properties and quantification. In addition, the Amsterdam Inspection portal has all the available documentation of drawings, renovations, and inspections of existing infrastructure in the city of Amsterdam.

2.2.3. Framework requirement & applications

The assessment framework must meet several critical requirements to effectively serve stakeholders and fulfil its objectives. Firstly, the framework should provide a comprehensive method for assessing the circularity of historical bridges. Secondly, the framework should incorporate strategies to mitigate data uncertainties concerning historical bridges. Thirdly, the framework must promote the preservation of historical bridges through a circular approach. Accordingly, 3 main uses are desired after the completion of the framework, which are:

- A tool for measuring the circularity level of historical bridges.
- Facilitating the identification of opportunities in resource optimization.
- An asset management instrument for decision-making and policy development.

Using the framework will allow users such as Nebest or the Municipality of Amsterdam to gain a better understanding of historical bridges' circularity performance. This understanding will facilitate resource optimisation and waste reduction by identifying opportunities for material reuse and recycling. Additionally, the framework contributes to infrastructure resilience by promoting practices that extend the bridge's lifespan, as circularity practices often involve maintaining and upgrading existing structures to withstand future challenges. Moreover, the framework should ease the process of planning interventions, prioritising investments, and policy development. Variants of renovation scenarios are proposed for maintaining historical bridges in the city of Amsterdam. The framework should ultimately be used before any intervention to determine which renovation scenario is more circular. However, it can still be used for renovated bridges by analysing the bridge's circularity and then identifying its potential for further renovation work.

2.3. Research objectives and questions

Based on the research scope, Figure 4 shows the research objectives. The primary research question driving this study is to develop a circular assessment framework tailored for historic bridges. Disciplines such as the municipality of Amsterdam or Nebest can benefit from deriving the circularity level, improved resource management, and more informed infrastructure planning. The indicator should facilitate identifying opportunities for resource optimisation and waste reduction, enhance infrastructure resilience, and improve the longevity of these assets. Users should be able to understand these infrastructure's status better and use the indicator as a decision-making tool for prioritising investments, planning interventions, and policy development. Accordingly, the primary research question is:

RQ1) How can the level of circularity of Historical bridges be measured?

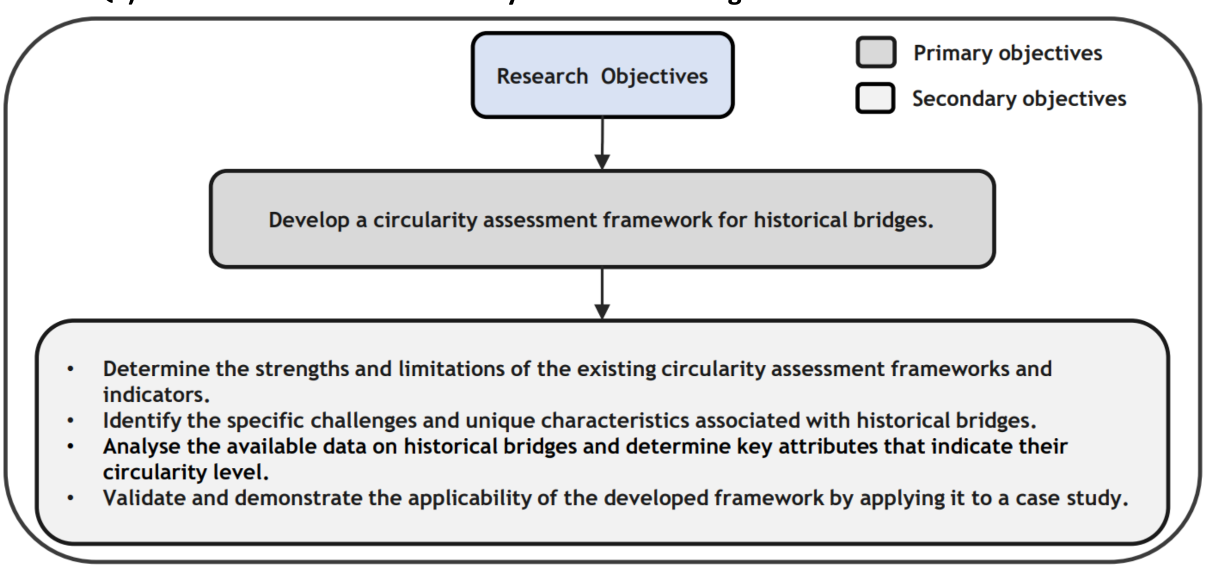


Figure 4: Research Objectives

Achieving the primary research objective involves analysing several key aspects. To accomplish this, secondary objectives have been established (see Figure 4). The first research objective will analyse the existing circularity assessment framework and indicators to identify their strengths and advantages. This will be done by conducting a literature review and exploring their key performance indicators. In addition, assumptions and trade-offs will be analysed to understand their influence on the final circularity score. Fortunately, there have been several studies done to assess the existing indicators and categorise them, which will help in picking the most fit approaches to develop the desired assessment framework. The research question that will guide this part is:

RQ2) What are the strengths and limitations of the existing circularity assessment frameworks and indicators?

Historical bridges possess distinct attributes such as unique material properties, complex structural designs, lack of data, limited accessibility for inspection, etc. These characteristics present challenges that require special considerations when assessing the circularity level of such assets. Therefore, the second objective of this research is to identify the specific challenges and unique characteristics of historical bridges that are not adequately addressed or accounted for in the existing assessment frameworks/indicators. By understanding the gaps in the current assessment tools and recognising the challenges in the mentioned unique characteristics, one can develop an understanding of how to tackle such challenges to develop an effective assessment framework. The research question that will guide this part is:

RQ3) What are the specific challenges and unique characteristics of historical bridges that stand as a barrier when assessing their circularity level?

Data availability plays a significant role in developing the assessment framework. The available data that indicate the circularity level of these assets will be further investigated. This data will be analysed by exploring the inspection work and identifying the attributes that are hard to estimate even with inspection experts. Accordingly, the available data is analysed to determine which attributes that can be used within the framework to measure circularity. In addition, the analysis involves considering the trade-offs that need to be made to compensate for any lack of data. This allows for determining which attributes are required and the indicators that can be used in the developed framework. The research question that will guide this part is:

RQ4) What attributes are best suited for measuring the circularity level of historical bridges?

The last objective is significant for validating the developed assessment framework. The developed framework will be tested on the historical bridges in the city of Amsterdam by comparing different scenarios such as intervention scenarios, temporal focus, etc. The case study for this research will be determined after the development of the framework. This will allow us to assess the practicality and effectiveness of the developed framework performance in a nonbiased real-world context. The research question for this part is:

RQ5) To what extent does the framework capture changes in the circularity performance of historical bridges across different temporal focuses and intervention scenarios?

2.4. Research structure

This research is distributed within 5 main phases (see Figure 5), and one can find at the bottom of each phase when research questions will be answered. The first phase was accomplished in the previous sections by defining the scope of the research, and research objectives and questions. The study's second phase is to do a comprehensive literature review to determine a specific circularity definition and identify the circularity principles that apply to historical bridges. The reason behind this step is due to variance in the definition and scope of circularity in different research (see section 4.). The different types of historical bridges that fall under the scope of this research will be determined in phase 2, and their unique characteristics will be explored. Moreover, the current circularity assessment framework/indicators will be investigated to get a better insight into the approach used to measure circularity and the challenges for their feasibility when applied to historical bridges. The third phase will include developing the framework. The fourth phase includes the implementation of the developed framework on a case within the study area and exploring areas of improvement. The Case study will be determined after the development of the framework to ensure a nonbiased real-world case. The last phase is dedicated to finalising the paper and preparing for the thesis defense.

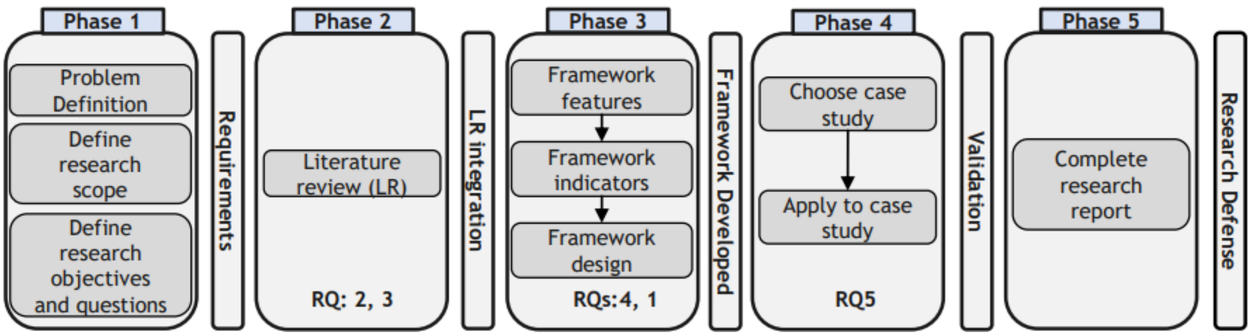


Figure 5: Thesis Phases

3. RESEARCH DESIGN

This study aims to develop a circularity assessment framework for historical bridges in the city of Amsterdam. A mixed-methods approach will be followed to achieve the objectives of this design research and derive answers to the research questions. The data collection process will include both qualitative and quantitative data, and it will be done at different times throughout the research. Moreover, the research will have a collaborative type of involvement, with active participants such as the interior and exterior supervisors and practitioners from different disciplines, such as Nebest and the municipality of Amsterdam.

3.1. Literature review

The first step in developing this framework will be a literature review, focusing on multiple dimensions of circularity. The literature review will encompass circularity definitions, explore the different levels of circularity, and analyse existing circularity indicators. The proposed framework will combine several approaches to suit the unique characteristics of historical bridges. Therefore, a critical review will be conducted on the existing indicators for measuring circularity. The critical review will look at their advantages and disadvantages and their suitability for applying to historical bridges.

3.2. Framework development

The second step is developing the framework to determine the framework characteristics, indicators, and design. The framework characteristics are identified by determining the framework features and providing more detailed and specific information on the scope. The framework's scope should include what exactly will be assessed and get a better understanding of the phenomenon that will be measured, which has been partially defined in section 2.2. Answering the first research question will provide more insight into the type of bridges that can be assessed by the framework. Based on the LR and the determined features, the circular concepts are translated into sub-indicator. These sub-indicators will be explored by looking at the required attributes and what output they provide.

The explored sub-indicators are highly dependent on data availability. Each indicator has unique factors to measure the circularity level of this infrastructure, and these unique factors require different types of data (Adams, Osmani, Thorpe, & Thornback, 2017). The circularity indicators mainly require data about the structural design of the assets, information on their construction materials (including material environmental impact and their sustainability characteristics), maintenance history, expected lifespan, end-of-life scenarios, data on historical and cultural significance, including any protections or designations that been put in place to preserve the heritage value, energy and resource consumption (such as energy usage, water usage, and waste generation), and parts connections. Therefore, the variables and the type of data needed for this framework are analysed. The analysis will include checking the relevance, analytical soundness, timeliness, accessibility, etc. The criteria used to assess the choice of these variables will be determined based on the explored circularity indicators and the unique characteristics of historical bridges.

The next step is the framework configuration, which includes data normlisation, weighting, aggregation, sensitivity analysis, and guidelines. Data normalisation, which is required due to the possibility of having different measurement units (Mir & Illahi, 2020). Normalisation could be done using several methods, such as ranking, standardisation, etc. The method used for this step will be determined later based on the nature of the collected data and the sub-indicators that will be used in the framework. Now that the sub-indicators are normalised, they need to be assigned different weights based on their influence on the asset's circularity. Weighting and aggregation are crucial to any assessment framework, decision-making, prioritisation, etc. Weighting includes assigning an importance value to certain dimensions and reflecting stakeholders' preferences, attributes, or objectives (Gan, et al., 2017). Aggregation is the process of combining the weighted inputs into overall scores or rankings (Gan, et al., 2017). Both of these processes are used to ensure that priorities are reflected and the credibility of the assessment. Several weighting and aggregation processes are implemented through the development of the framework. Therefore, these processes will be shown on different levels. Sensitivity analysis is a method used to determine how the different sources of uncertainty in the model influence the overall uncertainty and the output (Geffray, et al., 2010). The purpose of the sensitivity analysis is to increase the robustness of the developed framework and enhance transparency (Scholten, Schuwirth, Reichert, & Lienert, 2015). Varying the model's inputs and assumptions systematically allows one to observe the impact of these changes on the final results. This helps identify which parameters are most influential and which sources of uncertainty have the greatest impact on the outcome.

3.3. Framework validation

The practical application of the HBCI framework involves validating the tool through real-world scenarios. This begins with a selection process based on specific criteria that will be determined later. The chosen case study will be assessed using the developed framework. The results then will be visualised and a sensitivity analysis can be conducted by using the case study data. This approach would shed light on the applicability of the framework, understand how the framework would behave in a real-world scenario, and test its' robustness.

3.4. Addressing research questions

Table 1 shows an overview of when each research question has or will be answered during this study. The proposed approach from the Research design (Section 4) illustrates and answers how the primary research question for measuring the circularity of historical bridges will be answered. The second research question will determine the strengths and limitations of the existing circularity indicators. In the third research question, several challenges in assessing historical bridges' circularity have been identified in the problem definition section. Still, more research will be done to determine the challenges and unique characteristics of the chosen historical bridges. To get a better insight into these challenges, meetings with inspectors need to be conducted. Such interviews would provide detailed information on bridges' structure, inspection challenges, dealing with data uncertainty, safety assessment, etc. The fourth research question will be answered by turning circularity concepts into indicators. Finally, the last research question will be answered after the framework is developed, and the case study results will provide great insight into its effectiveness.

Table 1: Research questions status

Research Questions	Status
RQ1) Develop framework	Addressed in framework development (Section 5.)
RQ2) Explore indicators	Addressed in the Literature Review (section 4.)
RQ3) Identify challenges	Addressed in the Literature Review (Section 4.)
RQ4) Select attributes	Addressed in the framework development (Section 5.)
RQ5) Validate framework	Addressed in (Section 6.)

4. LITERATURE REVIEW

This chapter aims to address the second research question. The first step of the study is to conduct a comprehensive literature review to determine the best-fit circularity definition and identify circularity principles applicable to historical bridges. This step is necessary because different researchers have different definitions and scopes of circularity. Then, existing indicators and assessment frameworks will be investigated. Lastly, examples of historical bridges are explored.

4.1. Circularity definitions

Ellen MacArthur Foundation's definition of circularity has been used in much previous research (Kirchherr, 2017). Circularity was defined as making a restorative design to utilise products, components, and materials to the most possible and taking into consideration both the technical and biological cycles (Benachio G. L., 2020). Another definition was made by Lacy and Rutqvist (2015), which considers the circular economy as a circular approach that keeps resources used productively for the most possible (Lacy, 2015). Whereas the research of Pomponi and Moncaster (2016) defines the circular economy as designing, planning, building, operating, maintaining, and deconstructing a building in a way that corresponds to the circular economy principles (Pomponi, 2016). Furthermore, Kirchherr et al. (2017) have conducted a study to analyse 114 definitions of CE from different studies and concluded that a "Circular economy describes an economic system that is based on [technological advances and new] business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials [and energy] in production/distribution and consumption processes [in order to keep products at their highest possible value], thus operating at the micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, nation and beyond), to accomplish sustainable development, which implies creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations." (Kirchherr, 2017). These studies will be further investigated to use the most beneficial CE principles and get the most efficient approaches to implement circularity.

4.2. Circularity principles and concepts

Multiple circularity levels (principles) can be followed to reduce waste and reach a fully circular system (Verberne J. , 2016). Table 2 shows multiple references to different circularity levels that share similarities and a few changes. The first three levels of circularity are intended for the smarter use of products and manufacturing (Potting, Hekkert, Worrell, & Hanemaaijer, 2017). Refuse address preventing the use of raw material, rethink focus on using the product more intensively, and reduce address using less raw material (Potting, Hekkert, Worrell, & Hanemaaijer, 2017). The following 5 levels of circularity address extending the product's lifespan and its part. Reuse is using the product again in its original form, repair is when a product requires maintenance to be used again, refurbish is when the product needs to be returned to a sufficient condition (can be done by repairing major components or replacing some parts, or enhance the aesthetics), remanufacture is when the product is disassembled and recovered by using functioning parts and making a new product of these parts, repurpose is using the product again but for a different purpose, and recycle is recovering materials/converting materials into new lesser quality material/converting material into new higher quality material (Verberne J. , 2016). The final category consists of the useful application of materials and follows the last three levels of circularity. Energy recovery is converting non-recyclable materials into variable forms of energy. Incineration refers to the burning of waste according to legal guidelines, and landfill is for disposing of waste onto/into the land (Potting, Hekkert, Worrell, & Hanemaaijer, 2017).

Table 2: Level of Cricularity

Nine levels of Circularity (Cramer, 2014)	Butterfly model Ellen MacArthur (Ellen MacArthur Foundation, 2013a)	Ladder of Lansink (Millieu, stoffen, & Afvalstoffenbeleid, 2012)	Circular Economy (Potting , et al., 2018)
Refuse			Refuse
			Reduce
Reduce		Reduce	Rethink/Redesign
Reuse	Reuse	Reuse	Reuse
Repair	Repair		Repair
Refurbish	Refurbish		Refurbish
Remanufacture	Remanufacture		Remanufacture
Repurpose			Repurpose
Recycle	Recycle	Recycle	Recycle
Energy recovery	Energy recovery	Energy recovery	Recover
		Incineration	
	Landfill	Landfill	

The long lifespan of the historical infrastructure comes with challenges, such as changes in demand or the need to change functions. Consequently, the building adaptability concept has emerged to ensure the building's value is maintained and can cope with future changes. Variant definitions of adaptability have been developed with time. Heirdrich et al. (2017) define building adaptability as the ability of a building to absorb future demands to maximise the building's value and longevity (Heidrich, Kamara, Maltese, Re Cecconi, & Dejaco, 2017). Whereas, Geraedts et al. (2017) define the adaptive capacity of a building as the characteristics that enable the building to maintain its functionality in the most sustainable and economically profitable approach during its lifecycle (Geraedts, van der Voordt, & Remøy, 2017). The paper of Hamida et al. (2022) proposes a variant of variables that can determine the adaptive capacity of an asset (Hassanain & Hamida, 2023). These variables can be seen in Table 3.

Table 3: Adaptive Capacity/Adaptability/reuse adaptability

Adaptability determinants	Definition
Convertibility	Ability to give the asset a new function
Recyclability/reusability	Ability to facilitate material reuse/recycling
Transportability	Ability to move building components
Dismantlability	Ability to remove physical objects without causing any damage
Accessibility	Ability to access the asset's components without causing any damage
Refit-ability	Ability to enhance the performance of the asset's components
Flexibility/adjustability	Ability to enhance spatial configuration through minor interventions
Scalability	Ability to increase the volume of the asset
Generality	Ability to use spaces for different functions through no interventions

4.3. Taxonomy of circularity indicators

Saidani et al. (2019) propose an approach for the taxonomy of circular economy indicators (Saidani, Yannou, Leroy, Cluzel , & Kendall, 2019). This approach is significant due to the variance of the developed indicators' feasibility, objectives, etc. 10 categories are used to categorise the proposed framework (See Table 4). The first 4 categories are exclusive to the circular economy paradigm, while categories 5 and 6 relate to the indicator's usage and feasibility. Categories 7 and 8 describe the features of the indicator, while Category 9 specifies the assessment format tool. Finally, the last category specifies the actors' background in developing the indicator.

Table 4: Taxonomy of Circularity Indicators (Saidani, Yannou, Leroy, Cluzel , & Kendall, 2019)

Categories	Description
Level of analysis	• Micro-level (organisation, products, and consumers) • Meso-level (symbiosis association, industrial parks) • Macro-level (city, province, region or country)
Scope of circular economy	The feedback loops taken into consideration by these C-indicators, namely, maintain/prolong, reuse/remanufacturing and recycling, according to the techno-sphere part of the CE butterfly diagram proposed by the Ellen MacArthur Foundation (EMF, 2015)
Circular performance	1. Intrinsic Circularity: Definition: Intrinsic circularity refers to the inherent circular and sustainable characteristics of a product or system. 2. Consequential Circularity: Definition: It considers the broader effects and influences of circular practices.

Temporal focus	Retrospective or prospective - and makes a distinction between an actual and a potential circularity.it is useful to evaluate CE transitions by measuring progress before (ex ante), during (ex durante), and after (ex post) the transition process: 1. Ex ante evaluation is relevant to explore whether proposed CE transitions actually have the potential to bring about the intended CE effects. 2. Ex durante evaluation is important to monitor whether a CE transition process follows the planned route and leads to the desired effects. 3. Ex-post evaluations should determine whether the effects of the CE transition process are in accordanc 4. e with the set goals."
Possible use	(i) information purposes, helping to understand the situation (e.g. tracking progress, benchmarking, identifying areas of improvement); (ii) decision-making purposes, helping to take action (managerial activities, strategies formulation, policy choice); (iii) communication (internally on the achievements to the stakeholders, externally to the public); (iv) learning (education of workforce, awareness among consumers).
Transversality	the transversality of C-indicators among sectors, segments, or industries is indicated
Dimensionality	The seventh category aims to differentiate the dimensionality of C-indicators. C-indicators of low dimensionality -i.e., those that translate circularity into a single number- are helpful for managerial decision-making (Linder et al., 2017), whereas a high dimensionality can provide a higher degree of intelligibility more suitable for experts—e.g., designers or engineers—in the assessment of product circularity performance (Saidani et al., 2017a; b).
Units of expression	The eighth category gives information on the indicator units, allowing to distinguish the C-indicators in terms of their measurability, whether they use a quantitative or qualitative approach.
Format	Examines the format of the assessment framework associated with the C-indicators in order to ease their calculation.
Development background	C-indicators have been developed by multiple kinds of actors (i) Academia (ii) Industrial companies or consulting agencies (iii) Governmental or environmental organisations are not having the same requirements in terms of scientific validity

4.4. Existing circularity indicators

A diverse approach has been made to calculate the circularity score of assets (Khadim, Agliata, Marino, Thaheem, & Mollo, 2022). An example of this is the research of Verberne (2016), which proposes a building circularity indicator (BCI) that requires calculating the Material circularity indicator (MCI), Product circularity indicator (PCI), and system circularity indicator (SCI) (Verberne J. , 2016). The BCI approach assumes that a building is a combination of assembled materials that are connected to each other (Verberne J. , 2016). The MCI focuses on material input, output, and utilisation (EMF, 2019). Meanwhile, the PCI focuses on the design for disassembly and the functional separation of components (Verberne J. , 2016). The PCI is considered a practical circularity value since it contains adjustable factors based on the following Design for Disassembly principles. In contrast, the MCI score is considered a theoretical value (Cottafava & Ritzen, 2021). The SCI focuses on the system as a whole and analyses the building based on layers.

In this approach, the MCI is dependent on several characteristics to quantify the score, which is the virgin material mass used (V), unrecoverable waste after the end of its lifecycle (W), and utility factor (X) (Verberne J. , 2016). These attributes allow one to calculate the Linear Flow Index (LFI), and the Material Circularity Index products level (MCI_p). The MCI_p can be calculated by the assessment of parts material of a product. To provide accurate estimates, one must obtain detailed information on the product parts and material, which results in the necessity of making a material breakdown and Bill of Materials (BOM) (González & Adenso-Díaz , 2007). MCI_p require investigating the material input, material output, and the utility factor of the product (Braakman, Bhochhibhoya, & de Graaf, 2021). The first step of this approach is to determine the material input value using the equation (1).

$$V = \sum_x V_x \quad (1)$$

This is the summation of all types of materials that could be included in the system, such as the fraction of virgin materials (V), non-virgin materials (NV), recycled materials (F_{RC}), reused materials (F_{RU}), bio-based material (F_B), remanufactured material (F_{RM}), refurbished material (F_{RF}), etc (Verberne J. , 2016). The following equation shows how to calculate the fraction of virgin material for each subassembly (V_x) and here M_x is the total mass of this subassembly (see equation (2)). The fraction values can be provided in variants of units such as kg, m3, or a percentage of the total mass. In this case, the values vary from 0 to 1, where 0 is considered most linear, and 1 is fully circular (Verberne J. , 2016).

$$V_{(x)} = M_{(x)}\left(1 - NV_{RC(x)}\right) \quad (2)$$

The next step of this approach includes determining the material output. This step does not require distinguishment between materials that can be reused, recycled, refurbished, etc. (Verberne J. , 2016). As a result, all materials have the potential for a second lifespan. The materials that do not have a second lifetime, then can be used for generating energy or landfill and thus should be considered as waste (W) (Braakman, Bhochhibhoya, & de Graaf, 2021). Equation (3) can be used to calculate the amount of waste as an output of this product.

$$W = M(1 - F_{RU}) \quad (3)$$

The third step is to determine the utility factor that is dependent on two main factors, which are the lifespan (use phase) of a product (L_p) and the lifespan (use phase) of a system (L_{sys}) (Verberne J. , 2016). The L_{sys} is assessed for each layer that is given for the system. Thereafter, the utility factor (X) can be calculated using the equation (4).

$$X = \frac{L_p}{L_{sys}} \quad (4)$$

Now, it becomes possible to calculate the Linear Flow Index (LFI) using the equation (5) (Braakman, Bhochhibhoya, & de Graaf, 2021). The LFI indicates to the amount of material that has a linear flow, and its value varies from 0 to 1. 0 indicates to a restorative linear flow of material, and 1 is a fully linear flow (Verberne J. , 2016). To verify the scores derived from the previous steps are logical, two factors must be checked:

- $0 \leq V \leq M$ & $0 \leq W \leq M$

$$LFI = \frac{(V + W)}{2M} \quad (5)$$

By using equation (6), one can start determining the Material Circularity Indicator (MCI_P). In this equation, the function of the utility factor ($F(X_{p(a)})$) can be determined by the equation (7). Constant (a) is used to prevent having a negative value of the MCI score (Verberne J. , 2016).

$$MCI_{p(a)} = 1 - LFI_{p(a)}.F(X_{p(a)}) \tag{6}$$

$$F\left(X_{p(a)}\right) = \frac{a}{X\_p(\alpha)} \tag{7}$$

Furthermore, as aforementioned, the Product Circularity indicator (PCI) focuses on the connections and interfaces of the system, components, and materials by investigating the disassembly determining factors (DDF) (Durmisevic, Ciftcioglu, & Anumba, 2006). The study of E. Durmisevic et al., (2006) has identified the 7 main factors that reflect on the DDF and are divided into three categories, which are functional, technical, and physical decomposition (see Figure 6).

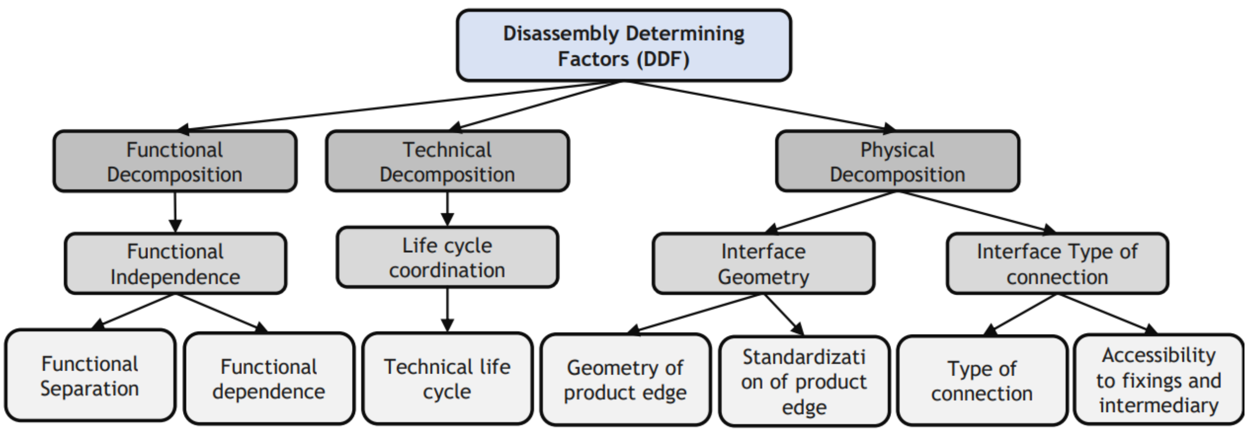


Figure 6: Disassembly Determining Factors (DDF) (Durmisevic, Ciftcioglu, & Anumba, 2006)

The first category is the functional decomposition, determined by the functional separation (for each composition) and functional dependence. The second category focuses on the technical life cycle of elements and its beneficial role in understanding the relationship between elements with different lifespans. The third category is physical decomposition, which investigates the accessibility to parts for maintenance, the geometry of products, and the type of connection. These factors are assessed by fuzzy variables, which can be seen in Appendix A. After the assessment, it becomes possible to calculate PCI based on each layer of the system (see equation (8)) (Verberne J. , 2016). F_d is the summation of all DDFs (see equation (9)).

$$PCI_p = \frac{1}{F_d}\sum_{i=1}^{n} MCI_p \, .F_i \tag{8}$$

$$F_D = \sum_{i=1}^{n} F_i \tag{9}$$

Before calculating the BCI scores, it is essential to realise the importance of each layer since products with shorter lifespans should get more attention compared to products with longer lifespans. Therefore, the layers of the building must be weighted based on the lifespan (Durmisevic, Ciftcioglu, & Anumba, 2006).

In this approach, each layer was provided an estimation of importance based on the lifespan of each layer by using fuzzy variables.

Thereafter, two values of the system circularity indicators can be determined which are The $SCI_{s(t)}$ represents the theoretical value system circularity indicator (see equation (10)), and $SCI_{s(p)}$ is the practical value of a system (see equation (11)). W_j is the is the mass of product j (see equation (12)).

$$SCI_{s(t)} = \frac{1}{W_s}\sum_{J=1}^{n} MCI_j \,.W_j \tag{10}$$

$$SCI_{s(p)} = \frac{1}{W_s}\sum_{J=1}^{n} PCI_j \,.W_j \tag{11}$$

$$W_s = \sum_{J=1}^{n} W_j \tag{12}$$

Finally, it becomes possible to calculate the theoretical and practical scores of the BCI (see equations (13) & (14)). Whereas LK_k represents the factor for system dependence and LK is the summation of all system dependencies (see equation (15)).

$$BCI_{(t)} = \frac{1}{LK}\sum_{K=1}^{n} SCI_{(t)k} \,.LK_k \tag{13}$$

$$BCI_{(p)} = \frac{1}{LK}\sum_{K=1}^{n} SCI_{(p)k} \,.LK_k \tag{14}$$

$$LK = \sum_{K=1}^{n} LK_k{}' \tag{15}$$

The paper of van Schaik (2019) proposes a different approach for measuring circularity. The framework measures circularity on three levels (Material, element, and system levels) and includes several preconditions prior to the usage of the framework and main drivers. Material circularity is captured by the material recyclability indicator (MRI), which focuses on the connection type and the accessibility of the material. The element level is captured by the element reusability indicator (ERI), which involves the quality, dimensions, and accessibility of the element. Lastly, the System reusability indicator (SRI) is used to capture the system level, and it involves looking at the diversity and the grid of the components (van Schaik, 2019). The main drivers of circularity are material scarcity, pollution, residual value, and reputation. Whereas, the preconditions are material toxicity, emissions of environmental pollutants, exhaustion of finite natural resources, and documentation.

Another approach that was implemented by Coenen et al (2021) to develop a circularity assessment framework for bridges ((Coenen, Santos, Fennis, & Halman, 2021)). The indicators used to develop the BCI assessment can be seen in Figure 7.

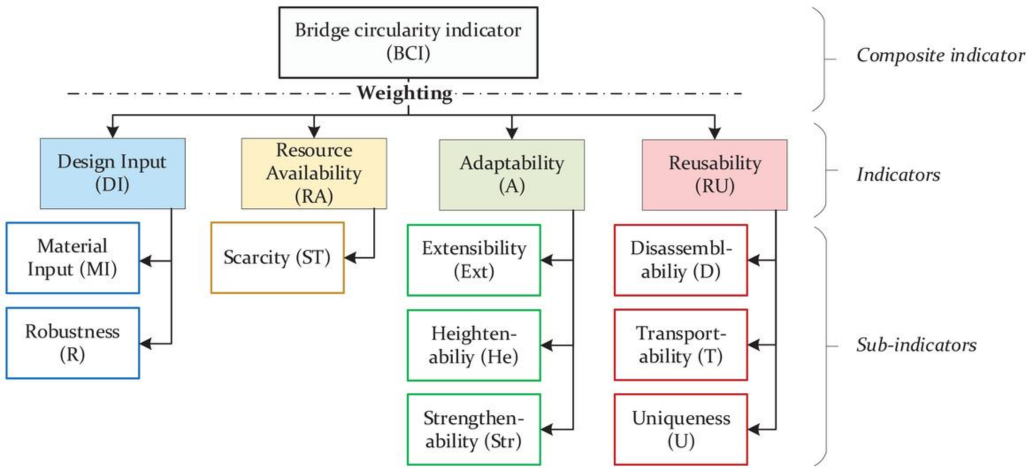


Figure 7: Composite bridge circularity indicator (Coenen, Santos, Fennis, & Halman, 2021)

The design input in this approach can be determined by calculating the Material input (MI) and Robustness (Coenen, Santos, Fennis, & Halman, 2021). In this case, the material output has been neglected due to the long lifespan of bridges which results in uncertainties at the end of asset's life. Robustness (R) is assessed to predict the actual lifetime of the asset. R can be determined by using the relative overdesign of structural safety (RD) and the minimum level of structural safety (RM') (see equation (16)).

$$R = \frac{RD}{RM'} \tag{16}$$

Then design input can be calculated by using equation (17). The CR is the corrected Robustness after dividing constant factor (0.9) by the derived robustness score (Coenen, Santos, Fennis, & Halman, 2021).

$$DI = 1 - MI.CR \tag{17}$$

The next indicator is the resource availability (RA), and this is determined based on the scarcity of material (see equation (18)). Here SF is a scaling factor for scarcity, and in this approach, it is assumed to be 0.70.

$$RA = SF \times \frac{\sum_i^N SOP_i \times M_i}{\sum_i^N M_i} \tag{18}$$

The next is to determine the adaptability of the components, which addresses the ability of bridges for changes in intensities, dimensions, loads, etc (Coenen, Santos, Fennis, & Halman, 2021). The adaptability (A) is assessed based on four main factors which are extensibility of crossing and underpass (E_{xt}), Strengthenability (S_{tr}), and heightenability (H_e) (see equation (19)). W_{xt}, W_{tr}, and W_e are the weights of each factor.

$$A = W_{xt} \times E_{xt} + W_{tr} \times S_{tr} + W_e \times H_e \tag{19}$$

Reusability (RU) is the ability to be reusing again the components of bridge based on the ability to disassembly of this component (D) and transport it (T), and uniqueness (U) (See equation (20)). J is the number of components, and M is the mass of components.

$$RU = q \times D \times T + (1 - q) \times \frac{\sum_{j=1}^J (1 - U_j) \times T_j \times M_j}{\sum_{j=1}^J M_j} \tag{20}$$

Furthermore, to implement the aforementioned approaches the structural design of the historical bridges will be investigated for the purpose of breaking them down into layers. Historical infrastructures are barely applicable to the DFD or material reuse principles due to the cultural value of monuments, and heritage preservation regulations (Gravagnuolo, De Angelis, & Iodice, 2019). The reason behind breaking it into layers is to ease the process of analysing each element of these assets, determining the material used in each component, analysing the manufacturer process of each component, and understanding the potential of each component to be disassembled, reused, recycled, etc. at the end of their lifecycle (Braakman, Bhochhibhoya, & de Graaf, 2021). Therefore, breaking down both assets will provide more accurate estimates for the circularity scores and give a clearer perspective on which layer, components, or elements require more adjustments to enhance the circularity level.

Brand (1994) proposes six layers subdividing buildings into site (location, skin (external surface), structure (foundations and load bearing elements), services (building systems), space plan (interior layout), and stuff (non-fixed furniture). In the research of Vlasic et al. (2020), a similar approach to Verberne (2016), has been implemented on a pedestrian bridge (Anastasiades, Van Hul, Audenaert, & Blom, 2020). This research will be beneficial for looking at the bridge breakdown of layers (see Figure 8).

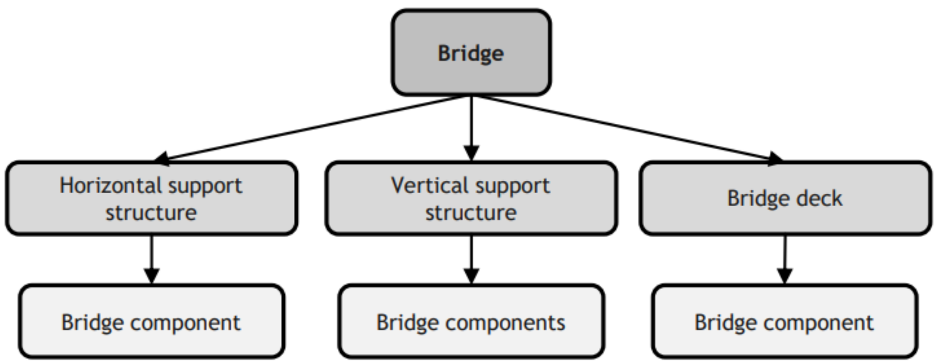


Figure 8: Bridge layer breakdown (Anastasiades, Van Hul, Audenaert, & Blom, 2020)

The bridge Engineering handbook of Wai-Fah Chen and Lian Duan (2014) provides detailed information on the layer breakdown for different bridges. Here, the bridge can be divided into four main layers: the foundation layer (includes abutments, foundation, bearing pads, etc.), substructure layer (includes columns, beams, bearings, etc.), structure layer (includes deck, parapets, drainage systems, etc.), and a protective layer (includes coating, waterproofing, anti-corrosion covering, etc.) (Chen & Duan, 2014). Meanwhile, the breakdown that is developed by Coenen et al. (2021) is more comprehensive (see Figure 9).

The paper of De Silva et al (2023) proposes an approach for using circularity principles to develop strategies and assess the circularity level when renovating old buildings (De Silva, Kumari, & Haq, 2023). To develop circular strategies, the approach used is similar to the 10R circularity ladder, but here, in this case, only rethink, reuse, repair, recycle, and recover are used. The OneClick LCA software is used to assess the circularity level of the buildings. The software is designated to be used on buildings and requires mainly adding the types of materials, factors weights, and lifespan details. In addition, the design for disassembly (DFD) and design for adaptability (DFA) can be integrated into the software and be included in the circularity score. Appendix B shows the developed framework for implementing circular economy principles for the renovation of buildings.

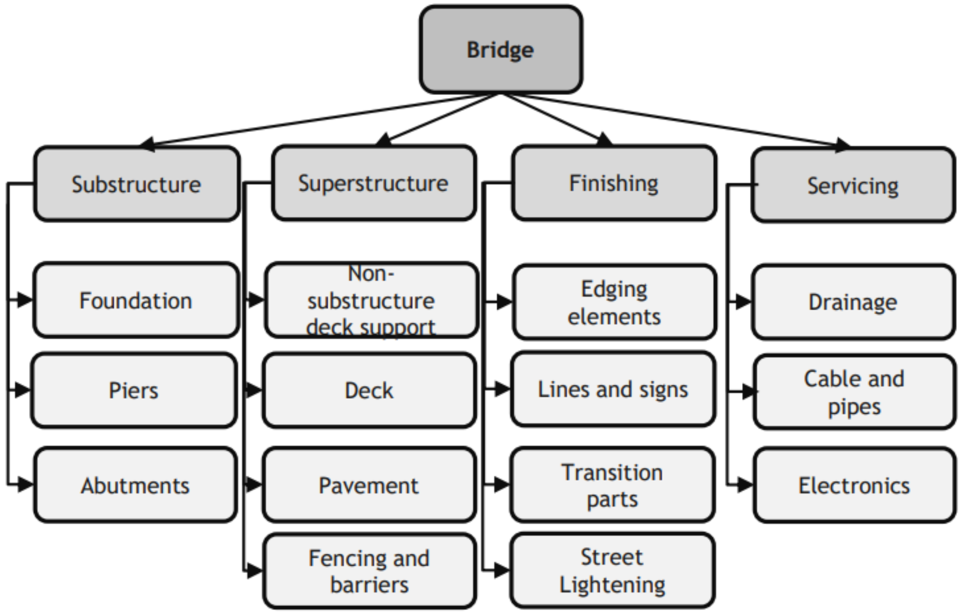


Figure 9: Bridge layer breakdown (Coenen, Santos, Fennis, & Halman, 2021)

Another approach to measure circularity was developed by the CB'23 (2022), which is a Dutch platform that assembled a variant of expertise (Market parties, scientists, and policymakers) from the country to ease the process of switching to a circular economy (CB'23, 2019). The circularity measuring method has three main goals and uses 6 indicators (see Figure 10). The objectives of the measuring method are preventing the exhaustion of material (Indicators 1-3), enhancing/maintaining the living environment quality (indicator 4), and maintaining quality and functionality (indicators 5-6) (CB'23, 2022). Appendix C shows the sub-indicators and the attributes needed to measure each indicator's value. Looking at the sub-indicators, one can notice that MFA partly corresponds to calculating the MCI. The MFA indicators and the environment preservation indicator take into account all life cycle phases. On the other hand, the two indicators of value preservation focus only on the end of the life cycle (demolition and processing phase and output flows). The final score is not aggregated in this approach as the aforementioned approaches.

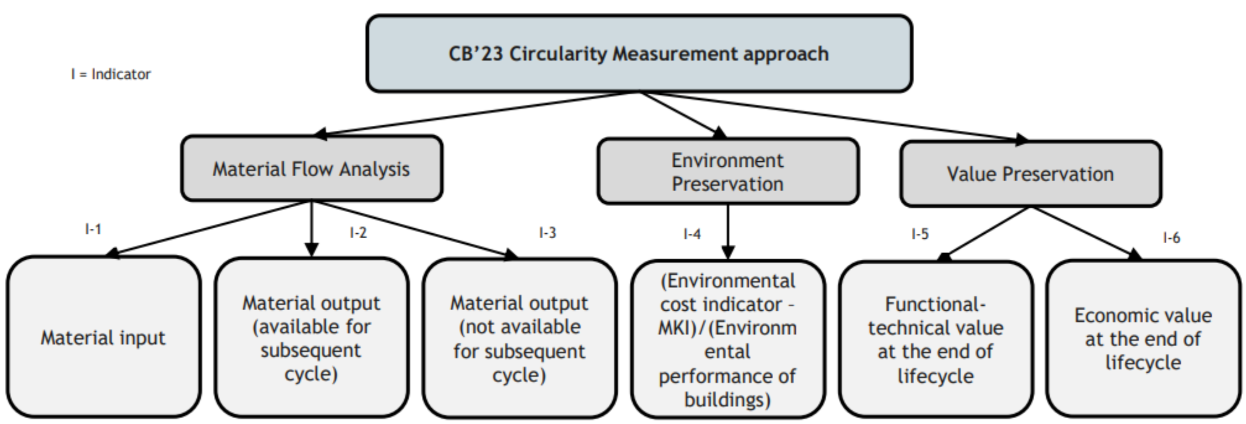


Figure 10: CB'23 Circularity Measurement approach (CB'23, 2022)

The MCI has been criticised for having over-optimistic assumptions in the paper of Jian et al. (2022). As a result, two new indicators are integrated into the MCI, which are the economic value (E) and residual value (R), aiming for a more accurate and realistic estimation (Jiang, Bhochhibhoya, Slot, & de Graaf, 2022). The main argument for using only the mass of materials is that it does not consider the scarcity of materials. Each material has a different economic value, whereas comparing different materials only based on mass would not provide an accurate estimation of the circularity score. Moreover, taking only the mass into consideration does not capture the value change of materials during their lifetime (Jiang, Bhochhibhoya, Slot, & de Graaf, 2022). In other words, the material has the same economic value at the start and the end of its lifespan. Appendix D compares how the MCI is calculated using mass and how it can be calculated using economic value and the residual value.

In conclusion, the review of the existing tools for measuring circularity highlights a range of methodologies to assess different asset types. Verberne'a (2016) BCI integrates material, product, and system circularity indicators, offering a comprehensive framework for evaluating circularity at different levels. Van Schaik (2019) proposes sub-indicators that measure circularity on different levels, covering Material Recyclability, Element Reusability, and System Reusability. His approach promotes material and component reusability within heritage preservation constraints. Coenen et al. (2021) extend these tools to bridge infrastructure, incorporating robustness and adaptability. Jiang et al. (2022) address the limitation of mass-based evaluations, promising a more accurate and realistic circularity assessment approach. Overall, all of the aforementioned approaches will be analysed in a critical review in (see section 4.5.). The analysis will include the strengths and weaknesses of each tool and its suitability for implementation on historic bridges.

4.5. Critical review of existing indicators and KPI's

Upon the literature review of the existing indicators, it becomes clear that they share a common objective, which is to assess circularity by focusing on material flow and the disassembly of components. However, the differences in the definition of circularity, scope, and trade-offs sets them apart.

Circularity has been interpreted in variant ways in these indicators. Each indicator defines circularity in its own way, which reflects the concept's adaptability to different contexts. These differences arise from the different aims of the circularity assessment tool uses, and why it is needed. This has led to differences in scopes, where some circularity indicators can be applied to a city level, system level, component level, and material level. Some indicators have prioritised focusing on material flow, the potential of reusing and recycling, extending the lifespan of assets, etc. Consequently, the different prioritisation have involved trade-offs that greatly influenced the final assessment. Therefore, in this section, a critical review is conducted to understand the strengths and limitations of each indicator (see Table 5).

The lifecycle assessment (LCA) The LCA assesses the environmental impact of components/systems for their whole lifespan, from raw material extraction to the end-of-life phase and what comes after (reuse, recycle, recover, etc.). This approach is valuable due to its ability to scientifically support its assessment of the environmental impact of a system. This approach does not take into account the unique characteristics of historical bridges in terms of specific materials and construction methods that may not accurately be comparable to modern counterparts used in the existing LCA databases, which limits its reliability in this case.

Material Flow Analysis (MFA) measures the material flow in a system, from raw material extraction to the end-of-life phase and what comes after (waste, emissions, etc.). One of the tradeoffs in the MFA approach is that all materials hold similar values and are dealt with in a similar approach in terms of material properties, condition, and historical significance. Such a tradeoff is not feasible in the case of historical bridges in the case of the existence of monuments, or the replacement of unique materials.

The Material Circularity Index (MCI) indicates the material's circularity level. The score varies from 0 (fully linear) to 1 (fully circular). The score is derived from computing the linear flow index (LFI and material Utility). The MCI has been criticised for its over-optimistic assumptions for assuming similar values for materials similar to the MFA. In addition, the MCI does not take material availability into consideration, wherein, in the longer term, the material might be available, which may influence the asset's life span or historical value. MCI' is quite similar to the MCI, but it employs the concept of economic value (E) instead of mass (kg). In addition, a residual value (R) is introduced, which estimates the decrease in value after every use cycle. Employing the economic value has tackled the issue of assuming similar values to material, but from another perspective, different issues have occurred, such as estimating the economic value of historical bridges. The Building Circularity Indicator (BCI) extends the MCI into four levels: material, product, system, and building, with the help of Brand's (1995) shear layer concept.

The Alba Concepts BCI is a circularity assessment tool for buildings developed by a Dutch company (Alba Concepts). This tool has brought new aspects of measuring circularity by dividing buildings into 3 shear layers: products, elements, and systems. In addition, the tool assesses the functional lifetime and Disassembly Index (DI). Unfortunately, Alba's concepts have not been widely publicised since the tool was created by a commercial company. A developed version was developed by Van Schaik (2019) called the Modified Alba Concepts (MAC), which is dedicated to foundations. Instead of disassembly, adaptability is used because it is considered a more promising form of flexibility in foundations. The MAC provides main drivers (Material scarcity, pollution, residual value, and reputation) and sets pre-conditions prior to the assessment (toxicity, pollutants emissions, natural resources exhaustion, and documentation).

Furthermore, historical assets pose further challenges due to the need for preservation. Such assets often include significant cultural and historical value, posing a dilemma between circularity and the preservation of their unique characteristics. The existing indicators focus primarily on material flow and disassembly, which may not fully capture the complexities of preserving historical structures and distinguishing between monumental components and components with non-historic significance. In addition, interventions that are aimed at enhancing the circularity performance must be carefully conducted to avoid compromising the historical authenticity of the bridge.

In summary, this critical review highlights two common challenges within the existing indicators. The first challenge is the data-intensive nature, which makes the existing indicators less applicable to historic bridges. The second challenge is the conflict between implementing circularity principles and preserving historical significance. Navigating these complexities is crucial for assessing circularity while preserving historical bridges.

Table 5: Circularity Indicators and KPI's Review

Method	Strengths	Limitations
Life cycle Assessment (LCA)	- Comprehensive and holistic approach to assessing environmental impacts of products and services. - Scientific support tool for proving the benefits of implementing circular	- Environmental impact on historical assets extends over centuries - Data-intensive and time-consuming

	economy principles (example: reuse over recycle)	
Material Flow Analysis (MFA)	- Quantifies material flows. - Can be used to identify opportunities for resource efficiency and waste reduction	- Does not consider the environmental impacts of material flows. - Does not account for the quality of materials. - All materials are of equal value and can be recycled or reused in the same way.
The Material Circularity Indicator (MCI) (Ellen MacArthur Foundation, 2021)	- MCI is relatively easy to understand, making it accessible to a wide range of stakeholders - Comprehensive assessment of the circularity of materials	- The loss of material during extraction, manufacturing, and transportation is not considered. - Over-optimistic assumptions about the quality of the salvaged products. - Does not consider the scarcity of materials.
MCI' (Jiang 2020)	- Considers Material scarcity - Tackle the over-optimistic assumptions in the original MCI - Creates a bias towards heavy materials. - Capture the value change of materials during their lifetime - Design for recovery and Design for disassembly strategies are taken into consideration	- Complexity of estimating economic value for historical assets. - MCI' works better for lightweight materials compared to the original version
Building Circularity Indicator (BCI) Verberne (2016)	- Uses DDF to incorporate disassembly to calculate Product Circularity Indicator (PCI) - Measures circularity on three different levels (Material, product, system)	- Mass-dependent. - Considers the materials required during the construction phase, neglecting the material requirements during the operation and maintenance phase - Reducing the mass (having good DDF and recyclability) of a product may decrease the circularity score
Alba Concepts BCI Alba 2018	- Take into consideration variant material scenarios and waste scenarios to segregate between different inputs and outputs - Disassembly is taken into consideration on two levels (product and element level)	- A commercial method with less publicly available information - Uses a semi-quantitative approach for normalisation
Modified Alba Concept (For Foundations) (MAC) Van Schaik (2019)	- Take into consideration variant material scenarios and waste scenarios to segregate between different inputs and outputs - Include main drivers and set preconditions before the usage of the index	- Several aspects of circularity are not included, such as energy, emissions, and economy. - Difficulty to balance between adaptation and preservation.

Circularity Indicator for Pedestrian Bridges (CIPB) Anastasiades et al (2020)	- Considers the DDF factors at the system and product levels.	- Only applicable for pedestrian bridges. - Does not incorporate the Recover from 10R approach
Bridge Circularity Assessment Framework (BCAF)	- Recycled material is given less value than reuse - The reusability indicator is more detailed	- Data-intensive and time-consuming - Induces subjectivity due to the inclusion of several sub-indicators
Platform CB '23	- Considers material scarcity - Comprehensive circularity assessment	- Several Indicators, such as the retained value of the product, functional and technical quality, degradation, and adaptive capacity, are still being developed. - The score of each indicator is not aggregated to a single overall score.

4.6. Bridge preservation strategies

The 10R framework and the Ellen McArthur Foundation's butterfly diagram are valuable approaches for circular solutions. However, both frameworks lack the segregation of the micro, meso, and macro levels, and none takes into consideration the historical value of the asset (Buring , 2022). Consequently, Huuhka et al. (2019) combined both frameworks and specified them for historical buildings; however, that can applied to bridges (Huuhka & Vestergaard, 2019). The strategies are divided into three different levels, which are the bridge level (micro level), component level (Micro level), and material level (Micro level). The primary focus of the proposed strategies is to prolong the lifespan of the current bridge components and preserve their historical value. In addition, there are national regulations for interventions for historical bridges and buildings in the Netherlands that must be followed to preserve them (see Table 6) (Commissie Ruimtelijke Kwaliteit, 2020).

Table 6: Historical bridges Intervention Limitations

Bridge order	Intervention Limitations
Order 1	1. The Starting point is preservation/restoration. 2. Changes (including adjustments, but also relocation and demolition) require a permit. The municipality is then the competent authority, but for important interventions, the municipality must request advice from the Cultural Heritage Agency (RCE). The municipality weighs all interests; the RCE absolutely takes this into account, but primarily views the interventions from a cultural-historical perspective.
Order 2	1. The Starting point is preservation/restoration 2. Original authentic elements must be maintained and repaired if necessary 3. The use of non-authentic materials is permitted, provided that they visually fully correspond to the original shape, colour and detailing 4. If the structural condition is too poor to maintain its original state, it is possible to rebuild under better conditions. - Shape must be symmetrical in case of a part replacement

	- Original authentic elements must be maintained and/or restored as much as possible
Order 3	1. The starting point is the preservation and restoration of the original authentic elements. 2. Changes in materials, dimensions and detailing are permitted, provided they do not disrupt the original characteristics of the building.

Based on the intervention limitations, one can see that the starting point for the different order of bridges is always the preservation of the original authentic elements of the asset, which indicates that regardless of the type of the bridge, the preservation of the original elements remains the highest priority when applying any intervention. Furthermore, more intervention scenarios have been investigated, such as the principle of minimum interventions that is used on architectural heritage structures. The approach has two core values: safety and that intended intervention must be decided based on the characteristics of the asset in terms of safety and durability with the least level of harm to the historical value (Borri & Corradi , 2019). Combining the core values of the minimum intervention with the approach of Huuhka and Vestergaard (2019) approach, the circular intervention strategies for historical bridges' preservation are developed (see Figure 11).

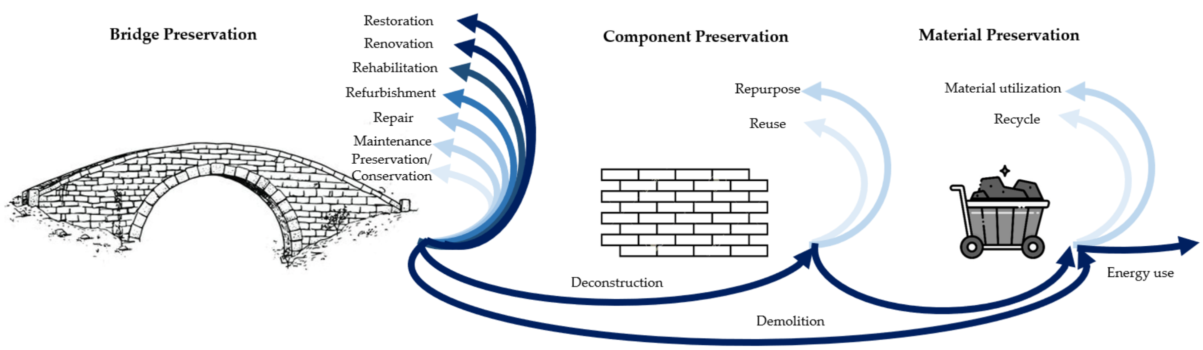


Figure 11: Circular economy strategies for historical bridges Preservation

Appendix E illustrates all intervention strategies and their feasibility on historical bridges. Determining the intervention strategies should be done on a bridge level, and if none of the 8 strategies can preserve the bridge, then there are two strategies left. The first strategy is to deconstruct the bridge and check from a component level whether each component can be reused or repurposed. If not, then the system can be repurposed as a reservoir of materials for future construction projects. Therefore, the demolition of the bridge to access raw materials should always be prevented and is considered a last resort. Circular strategies must be chosen from the highest priority levels, which are bridge preservation, then the component level, and lastly, the material level. For each level, the choice of circular strategies should be from the inner circles to the outer circles. Several strategies can be applied at the same time, but it should known that these strategies can interact with each other. These interactions may result in conflicts where prolonging the lifespan of a component might result in using more natural resources (Morseletto, 2020).

4.7. Examples of historical bridges in Amsterdam city

As part of understanding the practical applications of existing indicators to historical bridges, it is essential to explore variant types of existing historical bridges. This exploration will help in understanding the nature of these bridges and identifying challenges and opportunities. BRU0071 (De Duifbrug) is a reinforced concrete fixed bridge with a masonry arch that was built in 1871 (Figure 12 (a)). The old masonry wall below the waterline remains and is founded on wooden piles. Currently, the wooden foundation is in poor condition. Nebest has conducted the HBS and used the 10R approach in order to renovate the bridge in the most circular approach. Accordingly, it was decided to keep all bridge components in use. However, the wooden foundation and the masonry walls will remain, but they are no longer needed. Therefore, new foundation piles will be placed and connected to the existing bridge supports. Another bridge is the BRU0476, which is a fixed concrete bridge in situ that was built in 1957 (see Figure 12 (b)). In the year 2020, the municipality of Amsterdam decided to close the bridge since it was no longer safe to use due to damage in the concrete of the bridge deck and the presence of an alkali-silica reaction (Gemeente Amsterdam, 2020). Accordingly, several scenarios are proposed to prevent the passage of cars for this bridge and renovate it by using parts from two other bridges (BRU1919 and BRU1920) that are no longer safe to be used and need to be deteriorated. BRU0272 (Mariniersbrug) is a movable bridge that was built in 1935 (Rijks Monumenten, 2020) (see Figure 12 (c)). Movable bridges contain additional parts compared to other bridges, such as engines, counterweights, control rooms, etc. This type of bridge is significant for the framework's bridge breakdown development since many parts in movable bridges are not needed in fixed bridges. More bridges will be further investigated to ensure the feasibility of the developed framework for variant types of historical bridges.

(a) BRU0071 (Wikimapia, 2022)

(b) BRU0476 (Wikipedia, Brug 476, 2022)

(c) BRU0272 (Wikipedia, Mariniersbrug, 2023)

Figure 12: Historical Bridges (Amsterdam)

5. FRAMEWORK DEVELOPMENT

This chapter dives through the primary research question: how to measure the circularity level of historical bridges. In addition, RQ4 is addressed as part of the process of answering the primary research question. This is divided into three sub-sections: framework’s characteristics, indicators, and Design.

5.1. Framework characteristics

Developing a framework consists of determining its taxonomy. The framework's scope has already been identified (See section 2.2.). However, more details of the framework boundaries and preconditions will be provided. Then, sub-indicators are identified by analysing and dividing multidimensional circularity concepts.

5.1.1. Framework taxonomy

The framework taxonomy is specified based on the framework developed by Saidani et al (2019) (see Table 7). The first category determines the framework’s level of analysis; in this case, the analysis is designed to cover the entire bridge. The second category determines the circularity scope the framework captures. Some frameworks focus on specific circularity aspects such as material circularity, component reusability, etc. However, the developed framework should have a full scope on all circularity aspects from the techno-sphere part of the circularity economy butterfly diagram developed by the Ellen MacArthur Foundation.

Table 7: HBCI Framework taxonomy

Categories	Feasibility	Categories	
Level of analysis	Micro-level	**Transversality**	Historical bridge specific
Scope of circular economy	Full scope	**Dimensionality**	Non-dimensional
Circular performance	Intrinsic and consequential circularity	**Units of expression**	Multimetric and aggregated approach
Temporal focus	En ante, ex durante, and ex post evaluation	**Format**	Microsoft Excel sheet
Possible use	information purposes and decision-making purposes	**Development background**	Academic in Collaboration with consulting agency and governmental organisation

This framework offers a flexible approach for assessing the circularity of historical bridges by capturing different scenarios through the bridge's lifecycle stages. Accordingly, 3 scenarios are developed, each covering a different temporal focus (see Table 8). The first scenario provides a starting point for understanding a bridge's existing situation in terms of its circularity potential. The second scenario guides the decision-making process when multiple interventions are proposed to determine the most circular alternative. The third scenario addresses the end-of-life stage when the bridge needs to be demolished to gain insight into its potential in terms of components' reusability and materials' recyclability.

Table 8: HBCI assessment scenarios

Criteria/scenarios	General insight	Strategic decision support	Deconstruction and Demolition Insight
Objective	Achieve a foundation understanding of the bridge's circulatory status.	Comprehensive assessment of the circularity potential for different intervention scenarios (decision-making).	End-of-life assessment to minimise waste generation and enhance resource efficiency.
Circular performance	Information purposes	Consequential circularity	Information purposes
Temporal focus	Ex ante evaluation	Ex durante & ex post evaluation	Ex ante evaluation
Application	Preliminary assessment of circularity potential for an existing situation.	The bridge requires repairs, upgrades, or adaptation. Multiple intervention strategies are being considered.	The bridge has reached the end of its service life and is no longer structurally safe.

5.1.2. Bridges layers

Amsterdam city includes variant types of bridge structures that contribute to the city's unique charm. After investigating the historical bridges in the city of Amsterdam, three main types of structures are determined. Fixed beam bridges are simple bridges that include horizontal beams (girders), where each beam's end is supported. They can be constructed using wood, steel, or concrete (Xanthakos, 1994). Arch bridges are characterised by a curved shaped structure that provides great stability by the distribution of the load along the curve and can be constructed using stone or concrete (Xanthakos, 1994). Movable bridges are characterised by the ability to move/open to accommodate the passage of watercraft with different mechanisms (Opening Vertically or horizontally), and these bridges can be constructed from different types of materials (Wood, concrete, steel) (Xanthakos, 1994). Appendix F shows examples of multiple types of bridges in the city of Amsterdam. These examples are beneficial for the bridge breakdown into layers. Looking at different types of bridges will enable the categorisation of different components in the proper shear layers. Categorising components is essential to understanding their potential, such as accessibility, reusability, recyclability, etc.

The Brand's shear layers (1994) are the grouping of components into functional groups that share a comparable lifespan (Imam & Sinclair, 2022). Accordingly, the paper provides a lifespan range for each building shear layer. However, bridge structure complexity differs from buildings, which excludes some of the brand's shear layers, such as stuff (Imam & Sinclair, 2022). In addition, the variance of the components' lifespan in each layer for bridges is higher. The breakdown executed by Anastasiades (2020) cannot be used due to the differences in the complexity of the historical bridges in the city of Amsterdam in comparison to the pedestrian bridge that was analysed in this research (Anastasiades, Van Hul, Audenaert, & Blom, 2020). On the other hand, Coenen et al. (2019) have developed a functional decomposition for bridges, where components are grouped based on their mutual functions and lifespans (Coenen, Santos, Fennis, & Halman, 2021) (see Figure 13).

Nevertheless, the breakdown does not include the additional components of movable bridges. Therefore, a new layer called the mobility systems layer is added to the decomposition. The mobility systems layer includes the integrated network of mechanical, hydraulic, electrical, and control systems that facilitate the movement of the bridge components. Finally, the choice of the layer mainly depends on the component's functions, but the lifespan of these components is taken into consideration. This ensures that components with short lifespans are accessible without influencing components with longer lifespans.

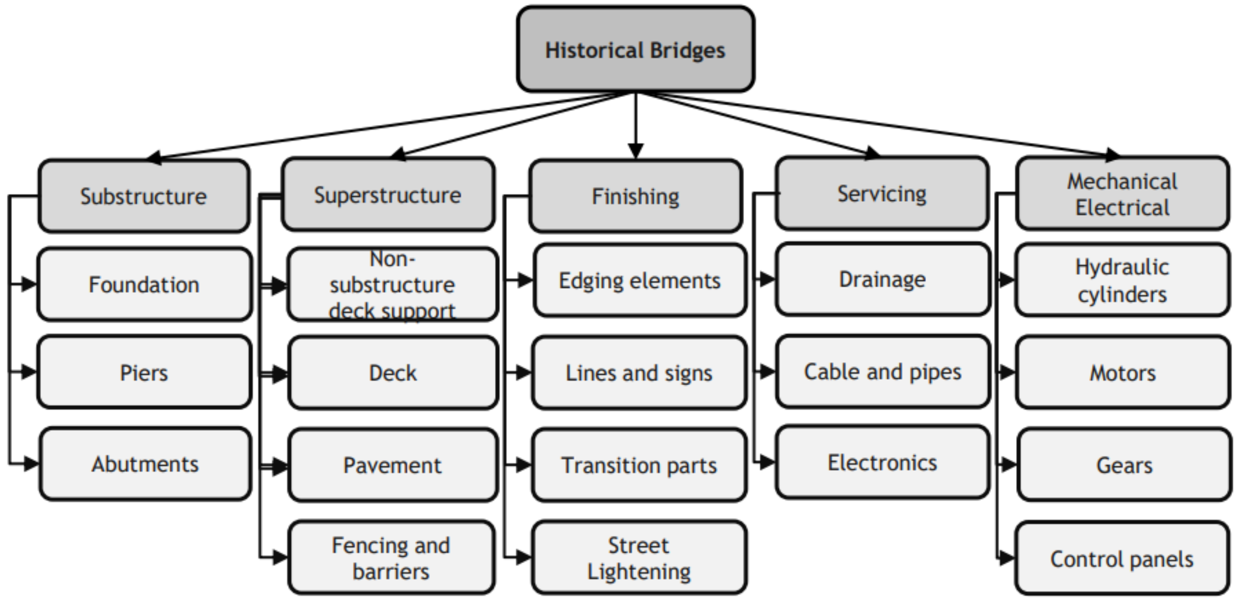


Figure 13: Bridge layer's breakdown

5.1.3. Circularity concepts transition into sub-indicators

Building upon the foundation established by the literature review and the framework taxonomy, the sub-indicators can now be developed. The framework indicators will be developed first in a flow chart form that shows the link of circular concepts to KPIs and, ultimately, to the sub-indicators that underpin the framework. The central circular economy concepts that best fit historical bridges are material flow, lifespan extension, and value retention. Further, the framework is divided into three main levels: system, component, and material levels (see Appendix G).

Material flow determines the efficiency of resources and materials management by tracking materials flows from extraction. In addition, tracking the material flow is vital for ensuring materials' circulation and minimising environmental impact, waste, and resource depletion. Material flow is determined by assessing the material input, material output, and resource efficiency. The material input consists of primary materials (Renewable and nonrenewable materials) and secondary materials (recycled, repurposed, etc.). Whereas material output includes recyclable material, reusable material, and waste.

Resource efficiency captures the usage of materials with high availability and preserves the existing bridge as much as possible. Material availability is based on assessing the material's scarcity and checking whether there is a risk in future supply. Material Retention is the ratio of the amount of material from the original bridge divided by the total mass of the Current bridge. This ratio provides insight into preserving architectural features, historical significance, and continuity in using the existing materials.

Lifespan extension is a fundamental component of circularity and the preservation of historical assets. Extending the lifespan of an asset has a significant impact on minimising waste and conserving resources. The Lifespan extension is measured by assessing the adaptability of the system and its health condition. Adaptability indicates the system's capacity to accommodate evolving needs, and it is assessed by transportability, dismantlability, accessibility, and flexibility (see Table 3). On the other hand, component health indicates to the component's overall condition and its structural integrity.

Value retention has been defined in the CB23 (2019) as the aim of keeping materials within the circular loop by upscaling the reusability and recyclability potential of the existing components (CB'23, 2019). Value retention is defined in another reference as retaining the functional and/or economic value by extending the lifespan/preserving components or materials as much as possible (Junior, 2021). Value retention indicates preserving and optimising the asset's value during its lifespan. Thus, it involved practices that maximise the asset's quality, functionality, and usefulness. Value retention is crucial for the preservation of historical bridges and for the conservation of their historical value. It is assessed by determining the material retention ratio and the scalability of the bridge. Material retention provides a ratio of how much is preserved from the original bridge, and scalability captures the system's adaptability for future uses.

The selection of the variables ensures that the framework covers the essential aspects of circularity. After the selection, each variable is analysed to determine whether it implicitly meets the SMART criteria. Data availability is taken into account in addition to the SMART criteria to ensure that the framework is practically implementable with accessible data sources. This approach provides a robust and actionable framework to assess the circularity of historical bridges.

5.2. Framework indicators

This research proposes the development of a holistic framework, the Historical Bridge Circularity Indicator (HBCI), for assessing the circularity level of historical bridges from 3 main perspectives: material, component, and bridge level (see Figure 14 & Equation 21). These main perspectives are assessed through the Modified Material Circularity Indicator (MMCI), Component Reusability Indicators (CRI), and Bridge Preservation Indicator (BPI). The MMCI captures the circularity performance on a material level by assessing the material flow, connection type, accessibility to material, and its availability. The CRI captures the circularity performance on a component level by assessing its dismantability, transportability, and health. Meanwhile, BPI captures the circularity performance on a system level by assessing how much is preserved from the original bridge and the ability of the bridge (potential preservation) to be widened and strengthened. The development of these indicators is based on the literature review and the analysis of the available data on historical bridges.

$$\mathrm{HBCI} = w_{MI}.MMCI + w_{M2}.\mathrm{CRI} + w_{M3}.\mathrm{BPI} \tag{21}$$

(w_{M1}), (w_{M2}), (w_{M3})are the weights for the KPIs

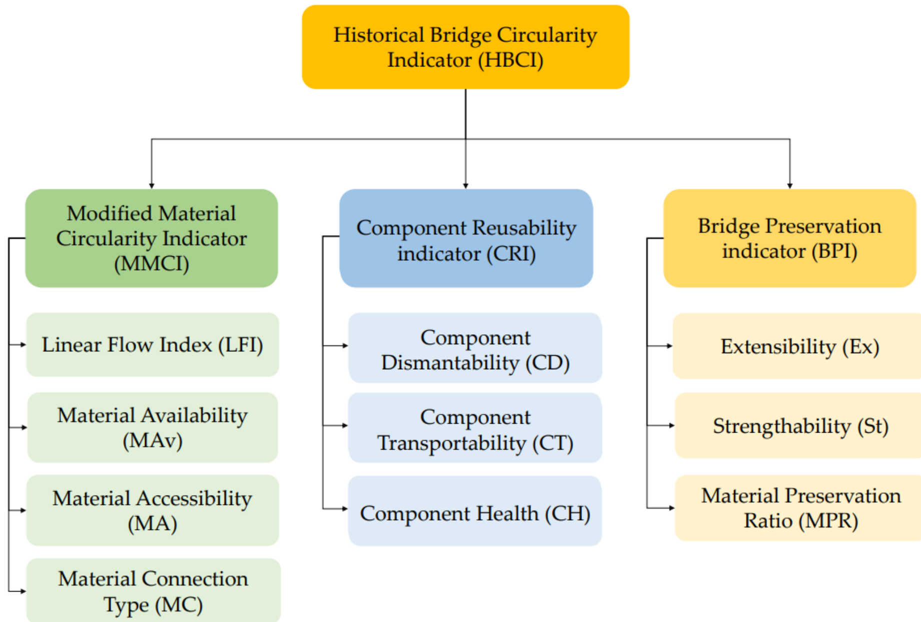


Figure 14: Historical Bridge Circularity Indicator (HBCI)

The sub-indicators combined will provide the HBCI scores for the whole bridge. The scores provide an assessment helping stakeholders understand the circularity performance of the asset and use it as a decision-making tool for variant scenarios, implementing circular and preservation measures (see Table 9).

Table 9: HBCI score's interpretation

Score	Interpretation
0.00 – 0.24	**Low circularity performance:** The bridge exhibits significant challenges in all circularity aspects, such as the linear flow of material, poor component reusability, and difficulties in preserving the bridge. Explore innovative approaches for enhancing component reusability. Assess the ability to implement innovative deconstruction techniques for higher material recovery and recyclability.
0.25 – 0.49	**Moderate circularity performance:** The bridge exhibits limitations in achieving circularity. The existing material, component design, and preservation potential hinder the circularity potential. Innovative techniques must be implemented to enhance the component design for reusability and the bridge's adaptability.
0.50 – 0.74	**Good circularity performance:** The bridge exhibits good potential for circularity by generating a low ratio of waste, good recovery and reusability of components, and a good preservation rate; however, there is room for improvement. Established operation plan prioritising longevity and potential future adaptability. Focus on maintaining and optimising existing circularity features.
0.75 – 1.00	**High circularity performance:** The bridge exhibits decent circularity characteristics (closed loop) through its lifecycle with a high level of material recyclability, high component reusability in terms of design and condition, and high preservation of the bridge.

	Established operation plan prioritising longevity and potential future adaptability. Focus on maintaining existing circularity features.

5.2.1. Modified Material Circularity Indicator (MMCI)

The modified material circularity indicator has been developed in this research to assess materials' impact on systems' circular performance by considering multiple factors (see equation 22). Combining concepts by including the linear flow index with the accessibility, connection type, and material availability can provide a comprehensive indication of material circularity. The indicator is beneficial for assessing the material flow and predicting the material behaviour for the whole life cycle of a system (see Figure 15). The LFI and material availability are quantitative measures, whereas connection type and disassembly are semi-quantitative measures.

$$MMCI_{mt} = w_{CI,mt}\left(1 - \frac{0.9}{X_j} LFI_{mt}\right) + w_C . M_{C,mt} + w_A . M_{A,mt} + w_{Ab} . M_{Av,mt} \quad (22)$$

(w_{CI}), (w_C), (w_A), (w_{Av}) are the weights for each parameter, (LFI) Linear flow index, (X_j) Product utility, ($M_{C,j}$) Connection type, (M_A) Material Accessibility, (M_{Av}) Material Availability.

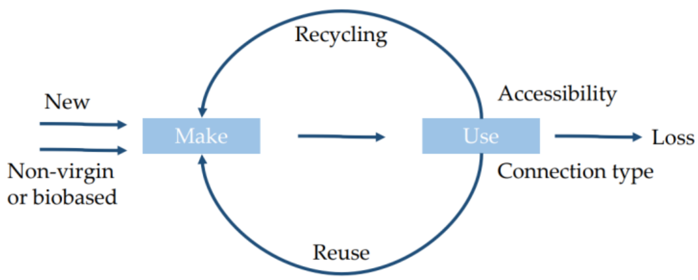


Figure 15: Material Flow

The LFI is dependent on several characteristics to quantify the score, which are the virgin material mass used (V), unrecoverable waste after the end of its lifecycle (W), and a fraction of recycled material (Verberne J. , 2016) (see equation 23). These attributes allow one to calculate the Linear Flow Index (LFI). A Constant (a) is used to prevent having a negative value of the MCI score (Verberne J. , 2016).

$$LFI_j = \frac{V_j}{2M_j} + \frac{(1 - F_{r,j})}{2}(V_j + W_j)/(2M_j) \quad (23)$$

(V_j) amount of virgin material for the component J, Fraction of recyclable material ($F_{r,j}$), (W_j) amount of waste, (M_j) mass.

The utility factor focuses on the longevity of the elements, and it's calculated by dividing the component lifespan by the market's average lifespan (see equation 24)

$$X_j = (L_j/L_{av,j}) \quad (24)$$

Component lifetime (L_j), the average lifetime of similar components on the market ($L_{av,j}$).

Material Availability (M_{Av}) indicates how much each material would be available in the future to ensure the maintainability of the asset. The assessment is derived from a life cycle impact (LCIA) model conducted by the RIVM (Rijksinstituut voor Volksgezondheid en Milieu). The report conducted a supply risk assessment for mineral resources on a National and European level (Deloitte, BGS, BRGM, & TNO, 2017). The supply risk assessment is conducted by analysing global and European supply data from different sources. In this situation, the material availability will be measured on a European level by using the Herfindahl Hirschman index (HHI) based on the World Governance Index (WGI). This parameter is based on the stability and level of concentration of producing countries. Appendix (H) shows the assessment results of the supply risk on a European level. The scores will be further normalised to aggregate them with other parameters. The materials provided in the list are all mineral sources. Consequently, mixtures need to be calculated manually by users based on the mineral material from which the mixture is made.

Accessibility to materials is significant for reaching them without damaging the surrounding parts of the asset and for easing the process of maintaining or recycling them. In addition, the type of connection is equally significant for dismantling the material for either reuse or recycling. The assessment is based on the diverse connections that impact on how easily the material can be dismantled. Both the accessibility and connection type are semi-quantified measures that are assessed based on the criteria found in Appendix A (see equation 22). This is derived from the fuzzy variables, but it is applied on a material level, not a component level. The fuzzy variables enable assessing multiple factors related to circularity and are used in multiple existing circularity assessment tools (Verberne J. , 2016).

Finally, the combined parameters will provide the MMCI scores for each material. The scores provide an assessment that helps stakeholders understand the suitability of the material for closing the loop and extending its' lifespan (see Table 10).

Table 10: Material scores interpretation

Score	Interpretation
0.00 – 0.24	**Limited material circularity:** Material generates high waste and is difficult to access and recover, which might require innovative techniques to reduce waste.
0.25 – 0.49	**Moderate material circularity:** Material generates waste and faces challenges in its recovery and reusability, which might require considering strategies that optimise material usage and reduce waste.
0.50 – 0.74	**Good material circularity:** The material exhibits good potential for circularity by generating a low ratio of waste and good recovery and reusability; however, there is room for improvement.
0.75 – 1.00	**High material circularity:** Material exhibits excellent potential for closing the loop and disassembly. Thus, it is recommended to maintain a high circularity score during its life cycle.

5.2.2. Component Reusability Indicator (CRI)

The Component Reusability Indicator (CRI) is a semi-quantitative measure developed in this research to assess bridge components' circularity and reusability potential (see Figure 16). The CRI combines 3 KPIs: Component Dismantlability (CD), Component Transportability (CT), and Component Health (CH) (see equation 25).

$$\mathrm{CRI} = w_{CD}.CD + +w_{CT}.C\mathrm{T} + w_{CH}.C\mathrm{H} \quad (25)$$

$(w_{CD}), (w_{CT}), (w_{CH})$ are the weights for each parameter.

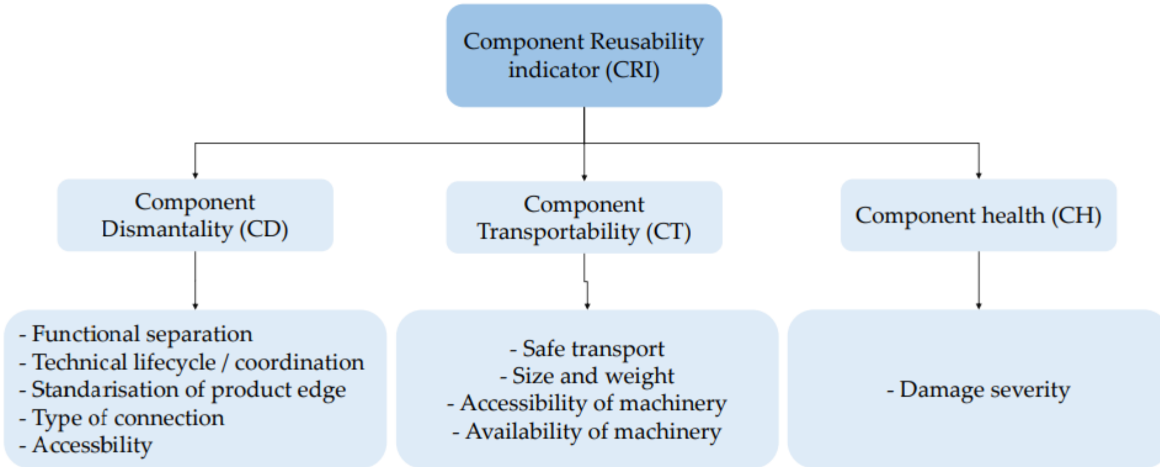


Figure 16: Component Reusability Indicator (CRI)

Component Dismantlability (CD) is based on the Fuzzy variables (see Appendix A) (see equation 26). Accessibility and connection are fuzzy variables and are assessed again on a component level (Durmisevic E. , 2006). Functional separation determines whether functions are integrated, incorporated, or separated. It's essential to ensure that a building component can be dismantled without affecting other components' functionality. In other words, by segregating functions, each component can be optimised for its specific purpose or dismantled without being constrained by other components' requirements. Technical life cycle/coordination is another parameter that compares the technical lifecycles of the component with the surrounding components. Components with shorter lifespans require interventions more than other components with longer lifespans. Consequently, these interventions might negatively influence the components with longer lifespans, leading to a lower circularity score (Bakx & Beurskens, 2015). The standardisation of product edge includes assessing whether the components' geometry is standardised. Standardised components result in more independent and exchangeable components, which positively impact circularity. Finally, the type of connection and accessibility of the components are already explained in the MMCI, but they are applied on different levels (Material Level – Component level).

$$\mathrm{CD} = w_{FS}.FS + w_{TLC}.TLC + w_{SPE}.SPE + w_{TC}.TC + w_{AP}.AP \qquad (26)$$

$(w_{FS}), (w_{TLC}), (w_{SPE}), (w_{TC}), (w_{AP})$ are the weights for each parameter.

Component Transportability (CT) is the ability to move components from an asset. It's rated based on four criteria (see equation 27). The criteria ensure that the component is well protected during transportation, its size and weight are transportable, the component is accessible by a transportation mode, and handling and lifting equipment is available.

$$\mathrm{CT} = w_{SF}.SF + w_{SW}.SW + w_{AM}.AM + w_{AVM}.\mathrm{AVM} \qquad (27)$$

$(w_{SF}), (w_{SW}), (w_{AM}), (w_{AVM})$ are the weights for each parameter.

Component Health (CH) assesses the component's overall condition and whether its condition requires any intervention. The CH is assessed by estimating the damage severity level of each component. This is derived from a heritage risk index developed by Ruiz-Jaramillo et al. (2020). The index prioritises interventions for deteriorated parts of the buildings (Ruiz-Jaramillo, et al., 2020). In addition, the CH is equivalent to the condition score that is used in inspections in the Netherlands based on NEN 2767-1

(NEN, 2021). The NEN 2767-1 proposes criteria for assessing the condition of the components that match the criteria used in the CH. Accordingly, the index contributes to knowing the potential for the reusability of the component. In other words, if a component has a high score, this indicates that the component is in a good condition and requires no interventions. Moreover, this can be used to assess the general health condition on a component, layer, and bridge level.

Finally, the combined parameters will provide CRI scores for each component. The scores provide an assessment that helps stakeholders understand the suitability of the components for reuse in diverse contexts (see Table 11).

Table 11: CRI scores interpretation

Score	Interpretation
0.00 – 0.24	**Limited reusability:** The component is not suitable for reuse due to the challenges in dismantling, transportability, and condition. However, some salvageable parts can be recovered with significant effort.
0.25 – 0.49	**Moderate reusability:** The component has some potential for reuse, but there are limitations in dismantling and transportation. Refurbishment or repairs are required prior to reuse.
0.50 – 0.74	**Good reusability:** The component has good potential for reuse with minimal modifications. Dismantling can be achieved using standard techniques, and transportation is manageable.
0.75 – 1.00	**High reusability:** The component is in excellent condition and can be reused without any significant modifications. Dismantling is straightforward, and transportation is feasible.

5.2.3. Bridge Preservation Indicator (BPI)

The integration of circular principles (resources reuse and recycling) poses a challenge to the traditional practices of preserving historical assets. Contradictions might occur when trying to preserve historical parts of the bridge by adding material to the asset and being circular at the same time. Therefore, the focus of this indicator is to ensure the preservation of the original bridge and the bridge's adaptation to future needs (preservation potential), such as widening or strengthening the bridge. Accordingly, the Bridge Preservation Indicator assesses circularity and preservation aspects on a system level by incorporating 3 parameters: Extensibility (Ex), Strengthenability (St), and Material Preservation Ratio (MPR) (See equation 28). These parameters aim to support the preservation of the original components of the bridge while enhancing its potential for future adaptation. This balance is necessary to ensure that the bridge's original components are preserved while the bridge still has the potential to be preserved (Being extended or strengthened).

$$\mathrm{BPI} = w_{Ex}.Ex + w_{St}.\mathrm{St} + w_{MPR}.\mathrm{MPR} \tag{28}$$

(w_{Ex}), (w_{St}), (w_{MPR}) are the weights for each parameter.

Extensibility (Ex) was developed by Coenen et al. (2019) for a bridge circularity assessment framework (BCAF) (Coenen, Santos, Fennis, & Halman, 2021). Extensibility focuses on adapting to potential future needs, such as widening the upper pass or the underpass with minimum negative impact (creating a significant amount of waste or significant adjustments to the original structure). This involves a change in the transportation mode or increased traffic, which requires adding new lanes to the upper pass or underpass of the bridge. The crossing of the bridge provides a pathway for different modes of transportation (pedestrians, vehicles, trains, etc. whereas the underpass is the pathway that underpasses the bridge, which provides a crossing for different modes of transportation (ships, pedestrians, trains, etc.). Extensibility aligns with the circularity principles of adaptability, longevity, and excluding the concept of complete replacement.

There is no direct or standard measurement for extensibility. However, it can be assessed from different circular perspectives (Coenen, Santos, Fennis, & Halman, 2021):

1. The connectivity and dismantlability of edging components.
2. The ability to add lanes with or without additional structural supports.
3. Space clearance for the traffic flow and additional supports for the future.
4. The amount of waste generated from the extensibility process is more/less than 5% of the bridge's mass.

The first perspective assesses the edging components' ability to connect with new components to extend the bridge. The second and fourth perspectives correlate by focusing on how much material is being added to the asset and the amount of generated waste. The third perspective ensures enough clearance for additional supports and traffic flow in the bridge's underpass. By combining the circular perspectives, the user can choose the criteria that match the bridge's characteristics (see Table 12) (see equation 29). For the criteria of the upper pass, it is possible to choose more than one criterion. Thus, the weights can be accumulated based on the criteria that are met. For example, if a bridge can be extended by adding one lane, it creates waste (<5%), and the other side requires additional support. Then, the extensibility of the bridge meets criteria 6 (0.4) and criteria 7 (0.3), which results in an extensibility score of 0.7.

$$Ex = \frac{Ex1 + Ex2}{2} \quad (29)$$

$Ex1$: Upperpass Extensibility, $Ex2$: Underpass Extensibility.

Table 12: Extensibility's criteria

Extensibility (Upper pass)	Extensibility (Underpass)
1) Adding lanes on both sides without generating any waste (1)	1) Adding lanes on both sides without generating any waste (1)
2) Adding lanes on both sides with minimal waste (less than 5%) and without additional support (0.8)	2) Adding a lane on one side (0.5)
3) Adding lanes on both sides with the need for support structures (0.6)	3) Both sides are non-extensible (0)
4) Adding bike lanes on both sides (0.4)	
5) Adding a lane on one side without generating any waste (0.5)	
6) Adding a lane on one side with minimal waste (less than 5%) and without additional support (0.4)	
7) Adding a lane on one side with the need for support structures (0.3)	
8) Adding a bike lane on one side (0.2)	
9) Both sides are non-extensible (0)	

Strengthenability (St) is developed by Coenen et al. (2019) for a bridge circularity assessment framework (BCAF). Strengthenability focuses on the adaptability of the bridge to future needs by enhancing the bridge's structural condition for an increase in traffic load or extending its lifespan (e.g. grouting, underpinning, additional supports, etc.). This often contradicts with circularity due to the need for additional material. Bridges' strengthenability techniques vary for each bridge condition. Consequently, there is no direct measurement of the bridge's strengthenability. However, Coenen et al. (2019) have identified binary criteria that determine the strengthenability of the bridge from a circular perspective:

1. Accessibility of workers to the components that require the strengthening measures (S1).
2. The geometry of the structure is compatible with the reinforcing measures (S2).
3. There is no decrease in other components' functionality as a result of the reinforcing measures (S3).

This approach only determines whether the bridge is strengthable from a circular perspective. Therefore, these conditions are turned into 3 main criteria that will be given ratings to assess how much the bridge is strengthable (see Equation 30). S1, the user has to determine the components that need to be accessed to implement the strengthening measures. These accessibility rates are then averaged to derive the value of the S1. S2 assesses whether the strengthening measures are compatible with structure geometry or not. S3 assesses the impact of the strengthening measures on other components. If any of the three criteria has a score of 0, then the strengthenability is immediately considered non-strengthable with a score of 0.

$$St = |x| = \begin{cases} S = \dfrac{S1 + S2 + S3}{3}, & if\ S1, S2, S3\ \neq\ 0 \\ S = 0, & if\ S1\ or\ S2\ or\ S3 =\ 0 \end{cases} \tag{30}$$

The Material Preservation Ratio (MPR), a key concept developed in this research, is an indicator for assessing the preservation of the bridge's original material in the case of the most recent intervention. The MPR is calculated by estimating the proportion of the preserved material mass to the original total mass of the bridge (see equation 31). The original bridge mass is defined as the total mass of the bridge prior to the last replacement applied to the bridge, including major modifications implemented on the bridge. To calculate the M_P, the user has to estimate the proportion value of the preserved material. Thus, the MPR value varies from 0 to 1, where the higher value indicates a more circular approach to preserving the existing material during its lifecycle. This ratio provides insights into the efficiency of material conservation or repurposing in a system.

$$\text{MPR} = \frac{M_P}{M_{Total}} x100\% \tag{31}$$

M_P : Mass of preserved material, M_{Total} : Total mass.

Finally, the combined parameters will provide the BPI score. The score provides an assessment that helps stakeholders understand the bridge's preservation potential and how much is preserved from the original bridge (see Table 13).

Table 13: BPI's scores interpretation

Score	Interpretation
0.00 – 0.24	**Low preservation and adaptability potential:** The bridge may require significant restoration/replacement in the near future (<30 years), especially in case of high material retention, which might limit potential preservation (adaptability).

0.25 – 0.49	**Moderate preservation and adaptability potential**: The bridge may require significant restoration/replacement in the future, especially in case of high material retention, which might limit its preservation potential (adaptability).
0.50 – 0.74	**Good preservation**: The bridge has a good preservation potential (adaptability) to survive for a long period and good preservation of its historical value due to the high-value retention.
0.75 – 1.00	**High preservation:** The bridge has excelland preservation potential (adaptability) to survive for a long period and good preservation of its historical value due to its high-value retention.

5.3. Framework configuration

Following the definition of the framework's characteristics and the development of its indicators, this section dives into the impact of the different temporal focus impact on the indicators, normalisation, assigning weights and aggregation, sensitivity analysis, and practical guideline for the transition from a framework to a tool.

5.3.1. HBCI scenarios' feasibility

The HBCI can be applied in variant scenarios that have been previously identified in section 5.1.1. (see Table 14). These scenarios are applied to understand the bridge's circularity potential or as a decision-making tool when an intervention is required for maintaining, upgrading, or adapting the bridge. The determined objectives of each scenario and data availability are the main factors that influence their feasibility for the assessment.

For the general insight scenario, the assessment's primary goal is to establish a foundation for understanding the bridge circularity potential. Thus, it has been developed to enable stakeholders to conduct an assessment with the minimum available data. Accordingly, having the asset's technical drawings and previous intervention reports are sufficient to perform the assessment. The assessment will cover the MMCI and CRI (without the component health) (See equation 32). The component health in this scenario is excluded due to the lack of data since extensive inspections are required to assess all the components' conditions. Most of the periodic inspections assess the condition of the components that are accessible to assess without dismantling/damaging the surrounding components. In other words, the most visible components are assessed more periodically compared to hidden components (e.g., foundation piles, etc.).

$$CRI_{Sc1} = w_{CD}.CD + +w_{CT}.C\mathrm{T} \tag{32}$$

$(w_{CD}), (w_{CT})$ are the weights for each parameter, Sc1 is scenario 1.

The strategies decision support scenario is applicable when a bridge requires intervention to conduct repairs or upgrade/adapt to future needs. This scenario should be assessed by using all the sub-indicators since the decision to implement any intervention requires conducting extensive inspection. In this case, the BPI provides valuable information for the impact of the intervention on the adaptability of the bridge by assessing its ability to be widened or strengthened. In addition, it captures the ratio of how much has been preserved of the bridge to ensure minimal modification of the bridge features.

Deconstruction and demolition are considered the last intervention strategies that can be implemented on historical bridges in terms of circular strategies (see Figure 11). For this decision, extensive inspection needs to be conducted. Therefore, a sufficient amount of information is available to conduct the assessment for all the indicators. However, the BPI assesses invaluable information in the context of

Deconstruction and demolition. The ability of the bridge to be widened or strengthened, or how much has been preserved from the bridge, becomes irrelevant. As seen in Figure 11, the focus switches from a bridge level to a component material level in this scenario.

Table 14: HBCI scenario's feasibility

Sub-indicators\ Scenarios	General insight	Strategic Decision Support	Deconstruction and Demolition Insight
MMCI	X	X	X
CRI	X (Without CH)	X	X
BPI		X	

5.3.2. Normalisation

During the development of the framework, normalisation was taken into consideration. Therefore, all the developed sub-indicators' scores range from 0 to 1. Developing the sub-indicators with similar score ranges eases the process of data interpretation, aggregation, and communication. The same was taken into consideration when choosing parameters. All parameters range from 0 to 1 except material availability and the criteria for weighting the layers (lifespan and historical significance estimates). In this section, these parameters will be normalised.

Two main types of normalisation can be distinguished by their reference system: internal (within study) and external (independent study) normalization (Norris, 2001). Internal normalisation transforms a dataset's values to the desired range (Laurent & Hauschild, 2015). External normalisation aims to transform the values of external information to the desired range (Laurent & Hauschild, 2015). Furthermore, the Jarque-Bera test is used to test the normal distribution of the data (Khadka, 2023). Having a normalised data is crucial for the validity and reliability of the model by ensuring consistency in scale, reducing bias, etc. The Jarque-Bera test includes calculating the p-value, and if its value is less than 0.05, then the data is not normally distributed (Khadka, 2023). This helps determine whether further adjustments to the data or the used approaches are needed. The Jarque-Bera test is conducted on the Material availability and layer weighting scores.

Material availability is derived from the European Supply risk, and the dataset values range from 0 to 5.7. This case requires an internal normalisation method such as the Min-max method. The normalisation method transfers the minimum value into 0, the maximum value into 1, and other values between 0 and 1 (Codecademy, 2024). However, this approach is sensitive to extreme values. When this approach is applied immediately, the p-value is less than 0.05. Therefore, the Cube Root Transformation makes the data more normally distributed by taking the cube root of each value (Zach, How to transform data in Excel (Log, Square Root, Cube Root), 2021). Taking the cube root reduces the impact of extreme value, which results in more normalised values. The data is then tested again by implementing the Jarque-Bera test to ensure that the cube root reduces the impact of extreme values, resulting in more normalised values.

On the other hand, the layer's lifespan and historical significance are estimated by the framework user to determine the weights of each layer (this is explained in the following section). Thus, this is considered an external normalisation method. The division by sum (DBS) method is used to normalise these two parameters. This method divides the score value by the sum of all the values (Laurent & Hauschild, 2015). Multiple inputs have been added to check whether data is normally distributed by conducting the Jarque-

Bera test. Therefore, square root transformation is applied to input both layers' lifespan and historical significance (Zach, How to transform data in Excel (Log, Square Root, Cube Root), 2021).

5.3.3. Weighting and aggregation

The sub-indicators are assigned weights using the Analytic Hierarchy Process (AHP). The AHP is a multi-attribute decision-making technique that decomposes problems into a hierarchical structure (OECD, 2008). This is done by comparing qualitative and quantitative data, which results in the weight of each sub-indicator. The AHP is chosen due to its ability to take different stakeholder assessments. Thus, the sub-indicators will be weighted based on the estimates of different experts related to circularity and historical assets. These estimates are averaged to derive the overall weightings of the sub-indicators, and then they can be accumulated by using additional aggregation. Section 5.2.4. shows the different scenarios for using the framework and how each scenario impacts the feasibility of the sub-indicators. Accordingly, Figure 17 shows the average weightings estimated by various stakeholders for the general insight and the decomposition and demolition insight scenarios (See Appendix I). Figure 18 shows the sub-indicators' weights when applying the framework for the strategic decision support scenario.

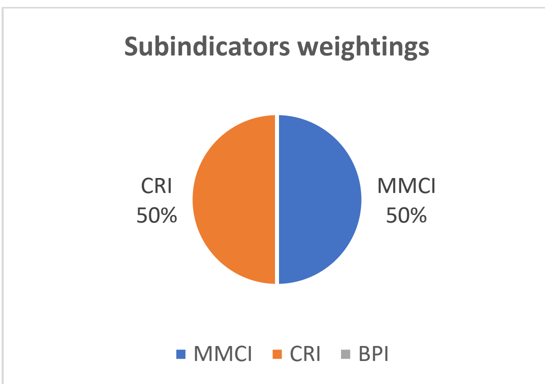


Figure 17: Scenarios 1 & 3

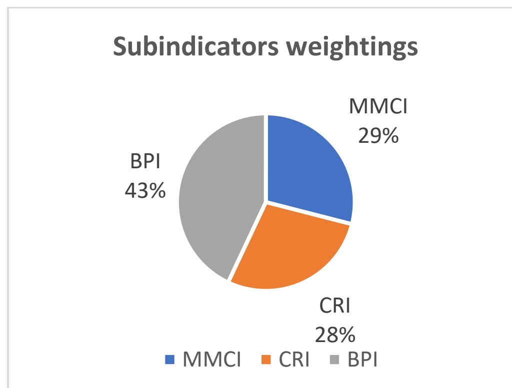


Figure 18: Scenario 2

Another level is the parameters within each sub-indicator (MMCI, CRI, BPI). The parameters of the sub-indicators (MMCI & CRI) are given equal weights. The MMCI parameter is quite similar to the Alba concept's material recyclability sub-indicator (van Schaik, 2019). There, the material's flow, recyclability, and the accessibility of the material are assessed. With these similarities, the parameters of the MMCI are assigned equal weights accordingly. In the CRI, all parameters are given equal weights. Even the CD and CT are assigned equal weights as well. The CD includes Fuzzy variables, which is quite similar to the PCI used in the BCI. Fuzzy variables are mainly given equal weights due to equal importance and lack of research in this scope.

The BPI consists of the bridge's strengthenability and extensibility, which indicates its preservation potential (adaptability), whereas material retention indicates how much has been preserved. When implementing this assessment in real cases, it is often observed that the score of material retention contradicts the scores of strengthenability and extensibility. This contradiction arises because high material retention typically means that a significant portion of the bridge's material is original and potentially quite old. Older materials may have deteriorated over time or may not meet modern standards, thus limiting the bridge's ability to be strengthened or widened. However, this is not always the case. For example, bridges built in the 1950s-60s may still have a high score for material retention while retaining the capacity to be strengthened or widened. This is due to the construction techniques used during that period and the components' condition, which are more likely to be compatible with strengthening or widening measures. The Ex, St, and MPR capture crucial aspects of the bridge's value and usability, ensuring that both historical components and functional adaptability are adequately considered. Thus, each is found equally important and is assigned equal weightings (see equation 33).

$$\mathrm{BPI} = \frac{Ex + \mathrm{St} + \mathrm{MPR}}{3} \tag{33}$$

Each sub-indicator's parameters are calculated using the additional aggregation. However, the MMCI and CRI are aggregated based on their mass by using the weighted sum method (WSM). The WSM is a quantitative technique that assigns weights to each factor, reflecting its relative importance (FasterCapital, 2024). Thus, the weights are assigned based on the contribution of each component/material on their mass contribution. The MMCI is calculated first on a material level (see equation 22), then it is aggregated to a component level using the WSM based on the mass contribution of each material in the component (see equation 34). Then, the scores are aggregated to a layer level using the WSM based on the mass contribution of each component to its layer (see equation 35).

$$MMCI_J = \sum_{n=1}^{N} \frac{M_{mt}}{.M_J} * (w_{CI,mt}\left(1 - \frac{0.9}{X_j} LFI_{mt}\right) + w_C . M_{C,mt} + w_A . M_{A,mt} + w_{Ab} . M_{Av,mt}) \tag{34}$$

N = Number of materials in the component, mt = material type, j = Component.

$$MMCI_L = \sum_{n=1}^{jn} \frac{M_j}{.M_L} * (MMCI_J) \tag{35}$$

$MMCI_L$ = MMCI score per layer, jn = component number.

The CRI is calculated first on a component level (see equation 25), then aggregated to a layer level using the same approach (see equation 36).

$$CRI_L = \sum_{n=1}^{jn} \frac{M_j}{.M_L} * (CRI_J) \tag{36}$$

With the scores aggregated on a layer level, several approaches have been used in the existing literature to assign weights to the layers. To make a good decision regarding the right approach, one must consider the appropriate criteria characteristics. SMART criteria are widely used in the literature, indicating that they must be specific, measurable, achievable, relevant, and time-bounded (Boogaard, 2024). Grafakos et al. (2017) advise that the criteria must be operational, value relevant, reliable, methodologically sound, measurable, non-redundant, and minimum in size (Grafakos, Enseñado, & Flamos, 2016).

The decomposition of layers is derived from the literature review. It is based on the function of the components and related lifespans. Layers with shorter lifespans have a negative impact on circularity as a result of the high amount of waste generated in a certain period (Rinke & Pacquee, 2022). These layers require more interventions in comparison to other layers, which may result in damaging the surrounding components. The user is provided a range of years to be selected in the model for each layer.

Layer dependency is another criterion that is derived from existing literature. It is estimated based on the dependency of each layer on other layers from a functional perspective. In other words, some functions are related to components from different layers. Thus, component replacement might have a negative influence on another layer's functionality (Wu, 2022). In terms of buildings, there are estimates for the brand's shear layers. However, there is not enough research on the bridge layer's dependencies, which does not match the desired criteria (being measurable and reliable).

On the other hand, introduced as a new criterion, historical significance assesses to what extent the layer has monumental components. The layer that includes historically significant components, such as monumental parts, is assigned higher weights. Thus, the layer's historical value has a positive correlation with its weight to ensure its preservation.

Accordingly, two main criteria are found best fit for the weighting of the layers: the layer's lifespan, and historical significance. Implementing these two criteria is crucial for achieving a balance between circularity and the preservation of historical assets (see Table 15). This composition allows the creation of a built environment that respects the past, adapts to the present, and thrives in the future.

Table 15: Layer's weighting Criteria

Layer's lifespan	Historical significance
Very Short Lifespan (0-10 years)	Unmatched historical impact (1)
Short Lifespan (10-30 years)	Exceptional historical significance (0.8)
Medium Lifespan (30-50 years)	Significant historical connections (0.6)
Long Lifespan (50-100 years)	Moderate historical importance (0.4)
Very Long Lifespan (100+ years)	Limited relevance to local history (0.2)
	None or minimal historical significance (0)

After determining the layers' weights, the MMCI and CRI scores on a layer level can be aggregated to a bridge level using equations 37 and 38.

$$\mathrm{MMCI} = MMCI_{L1}.w_{L1} + MMCI_{L2}.w_{L2} + MMCI_{L3}.w_{L3} + MMCI_{L4}.w_{L4} + MMCI_{L5}.w_{L5} \quad (37)$$

$$\mathrm{CRI} = \mathrm{CRI}_{L1}.w_{L1} + \mathrm{CRI}_{L2}.w_{L2} + \mathrm{CRI}_{L3}.w_{L3} + \mathrm{CRI}_{L4}.w_{L4} + \mathrm{CRI}_{L5}.w_{L5} \quad (38)$$

Now that criteria are prepared, a multi-criteria decision analysis (MCDA) is used as an additional aggregation method. The MCDA is a decision tool that is structured to assess complex situations with multiple conflicting criteria or objectives (Sharpe, Harwell, & Jackson, 2021). The MCDA can be helpful for prioritising, ranking, or weighting, which is used for the presentation of all alternatives (only when having multiple alternatives) at the end of the assessment (Dombi & Jónás, 2022). Thus, all the scores of the alternatives can be compared and ranked based on the most circular alternative.

5.3.4. Sensitivity analysis

Sensitivity analysis will be conducted on one of the case studies in the following section. This analysis utilises an understanding of the model's behavior and robustness. Sensitivity analysis explores changes in the parameters and their influence on the model's output (OECD, 2008).

The one-at-a-time (OAT) sensitivity analysis approach is used. The OAT consists of selecting a parameter and systematically varying it while keeping all other parameters fixed (ten Broeke, 2017). This step allows one to observe how changing one parameter would impact the scores in the mode. In other words, it captures the relationship between the varied parameters and the scores in the model while other parameters are kept fixed.

The model includes a high number of parameters, which makes it time-consuming to analyse all of them. Therefore, parameters have been chosen from each sub-indicator to ensure a representative analysis. The following parameters will be analysed: the fraction of virgin material, dismantlability, strengthenability, and Material preservation ratio.

5.3.5. Implementation of the HBCI framework in an Excel tool: brief guidelines

The HBCI framework has been developed into a tool to facilitate the circularity assessment of historical bridges through an Excel model. The tool enables stakeholders to measure, analyse, and enhance the circularity of bridges by inputting relevant data such as material quantification, design, condition, etc. The tool integrates the framework's indicators and methodologies, providing a comprehensive circularity assessment. Users receive detailed instructions and guidelines to ensure a user-friendly experience and high-quality input to gain an accurate analysis output.

The model consists of 13 Excel sheets divided into 3 categories. The first sheet includes the framework's guidelines, features, and scope. In this sheet, you can find instructions on what sheets need to be filled (yellow), ones that are used as a database (dark blue), and ones that are automatically filled (light blue). On the second sheet, one must add the project information, such as the bridge's name, owner, location, etc. The third sheet requires setting up the assessment by specifying the assessment scenario and the layer's lifespan and historical significance estimations. The following three sheets include the results of the framework on different levels. In those sheets, the results of the assessment are presented and visualised. Then, another 4 sheets are for the input, starting from general input to material level input to component level input, and lastly to a bridge level input. Then, there are 3 more sheets that are considered as pre-filled sheets. These include a database sheet that includes all reference data, such as criteria of the KPIs', and a data list of the required data to fill in the tool, and lastly material scarcity sheet that includes the EU support risk of mineral material. The material scarcity sheet is a pre-filled sheet. However, the user can add more materials in case of mixtures or if the material is not on the list.

6. VALIDATION PHASE

As the HBCI is developed, the practical application of this tool in real-world scenarios becomes possible. The objective of this phase is not only to validate the framework but also to illuminate the practical implications and outcomes of its implementation (answers RQ5). The first step in this phase is to investigate existing case studies and choose one based on the given criteria. Then, the framework will be applied to the case study, and the results will be visualised. The sensitivity analysis is conducted after the case study, then a demonstration of the framework's applicability and impact on different temporal scenarios. Finally, a conservation advisor at Nebest was interviewed to get feedback on the user interface.

6.1. Case study selection

The selection of a case study exemplifies the adaptability and effectiveness of the framework. Each case study provides a unique perspective, different challenges, and unique characteristics that allow one to explore the impact of scenarios on circularity performance. The case study selection process will be done by implementing multi-criteria analysis for different case studies. Table 16 shows the criteria for choosing a case study (Seawright & Gerring, 2008). These criteria ensure that the case study falls within the scope of this research.

Table 16: Case study selection criteria

Criteria	Description
Relevance to research	The case study should provide valuable insights into the research questions or objectives.

Representativeness	The case study should be representative of the phenomenon that is being investigated in this research.
Data availability	Ensure that data is accessible and adequate to implement the analysis.
Complexity and uniqueness	Case studies should involve some complexity or uniqueness to gain a deeper understanding of the topic.
Practicality	Ensure that there are sufficient resources, time, and budget to conduct the case study.
Temporal relevance	Take the case study timeframe into consideration and check whether it meets the research scope.
Geographic location	Take the case study's geographic location into consideration and check whether it meets the research scope.

7 case studies have been explored; each has unique characteristics. The Oranje Loper is a project for renovating 9 bridges in the West of Amsterdam (Mobilis, 2020). Some bridges are being completely replaced, whereas others will be renovated. The case studies that are chosen from this project are Niek Engelschmanbrug (Bridge 106), Huiszitbrug (Bridge 8), and Nieuwe-Wercksbrug (Bridge 63). These bridges have mainly had work on their foundations and the decks, and maintain their architectural features.

The Bullebak (Bridge 149) is a monumental bridge that was constructed in 1890. The bridge was renovated, which included replacing the old foundation piles, bridge cellars, mechanical parts, etc (BAM, 2023). Unfortunately, no data about the bridge was found in the Amsterdam Portal or Amsterdam Archive. Another bridge is the Hogesluisbrug (Bridge 246), which was replaced in 2011, but many old parts have been reused, so it maintains the original bridge's architectural features. This is an interesting case; however, the bridge has a complex structure, which may require more time than is possible for the case study. However, The Rode Loper is another project that included renovating/replacing several bridges in Amsterdam. Johanna Borskibrug (Bridge 41) was replaced by a new bridge, but many of the original components have been preserved and reused (Project_Rode_Loper, 2017). This case study is quite similar to Bridge 246, but the bridge structure is less complex and time-consuming.

When all bridges are assessed based on the criteria in Table 16, bridge 41 is best fit as a case study to apply the framework on. The new bridge will be compared with the original bridge, and both circularity performances will be assessed (Case Study A). Performing such analysis allows us to understand the intervention's impact on the circularity performance of the bridge. The case study assessment and more description are added to section 6.2. In addition, another case study is conducted on Bridges 106 and 136 from the Oranje Loper Project (Case Study B). This case study tests the framework's reliability and consistency when assessing two bridges with similar characteristics. Both bridges share similar histories, such as construction dates and previous interventions (see section 6.3.).

6.2. Case study A

Johanna Borskibrug (Bridge 41) is a national monumental (order 1) built over the Keizersgrcht in Vijzelstraat. There was a wooden bridge, but it was demolished in 1737. The bridge was replaced by a brick arch bridge with 3 spans. In 1881, the bridge was widened to accommodate the Trum traffic and lowered. Later, due to increased traffic flow, the bridge was widened again in 1923. In addition, the deck was entirly replaced in the year 2000. Lastly, during the Rode Loper project, the bridge was found not to be eligible to withstand traffic loads and meet safety standards (Project_Rode_Loper, 2017). Therefore, the bridge was replaced in 2020, but many existing components have been preserved (Sandra, 2022). The abutments, Trum track, fencing, bricks, and natural stone have been reused to maintain the bridge's characteristics (See Figure 19). This case study assesses two alternatives: the original bridge before the replacement and the new bridge by using the strategic decision support scenario in the HBCI.

The data for both bridges are mainly derived from the drawings available in the Amsterdam Portal. Amsterdam portal is an online database that the municipality uses to store all documents available on their assets, such as original drawings, inspection reports, etc. The drawings are significant for the bridge's decomposition, the components quantification, etc. However, inspection reports are necessary to assess the components' health and lifespan and the bridge's ability to be strengthened or widened. In addition, to calculate the utility factor, it's required to divide the component's lifespan by the average lifespan in the market. For the average lifespan, a reference from the municipality of Amsterdam is called Completion Instructions Amsterdam reference (Invulinstructie Amsterdam Reference). This reference includes when each component must be repaired/replaced. Thus, the estimated replacement date is used as the average lifespan for the components. If components are not found in the list, then looking for the average lifespan of the component among experts or online based on data availability is possible.

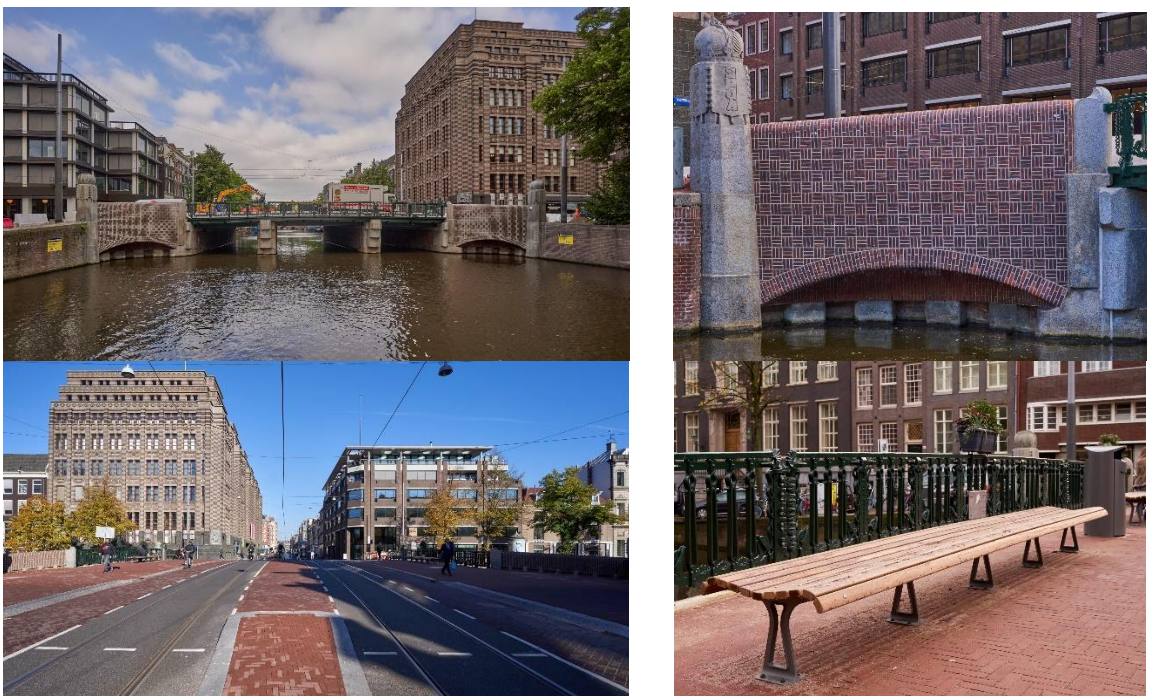


Figure 19: Johanna Borskibrug (Bridge 41) (Sandra, 2022)

The overall scores of the HBCI and sub-indicators for the two alternatives are presented in Figure 20. The newer bridge performed better, mainly on the component and bridge levels, which led to a big difference in the final HBCI scores.

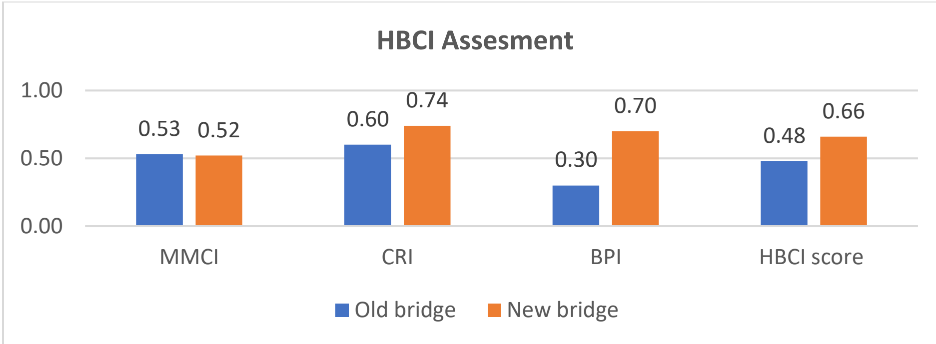


Figure 20: Brug 41 HBCI assessment

Starting from the BPI (See Figure 21), the new bridge is characterised by a good preservation performance. The high score comes from the bridge having moderate extensibility, high strengthenability, and a good material reservation ratio. When assessing the bridge, it is realised that the upper pass can be widened easily without resulting in much waste. In contrast, it scored 0.5 for the lower pass due to the geometry of the bridge's structure and the surrounding environment (not enough space for extensions). In terms of strengthenability, the bridge's geometry was found fit for strengthening the bridge, there is no negative impact on other functions, and the accessibility to parts that require strengthening is fair. Finally, the material preservation ratio has a score of 50% due to the preservation and reusing of many components from the original bridge. On the other hand, the older bridge scored almost half of the final HBCI score. This is mainly due to the much lower BPI score with a moderate preservation assessment. The moderate preservation comes from the bridge's limited extensibility and strengthenability, which both scored 0. Meanwhile, the material preservation ratio is relatively high, with a score of 0.9.

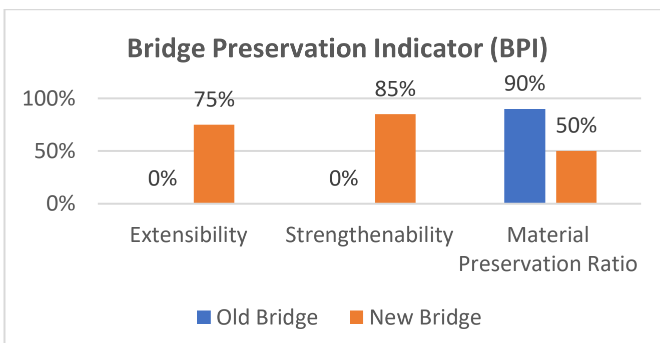


Figure 21: Bridge 41 BPI Assessment

Moving to the CRI and MMCI, the scores are presented on a layer level (See Figure 22). Thus, the performance of each layer for every alternative can be compared. The CRI scores higher for the new bridge than the older one mainly due to the component's health and the new components' better dismantablity (See Figure 23). Meanwhile, the MMCI has a close score mainly due to the fraction of virgin material and the utility factor. In the old bridge, it is assumed that all materials used are considered virgin materials due to the uncertainty of many of the material's history. On the other hand, 30% of the new bridge has reused material from the older bridge. The data utility in the older bridge is higher than the new one since many components have surpassed their average lifespan.

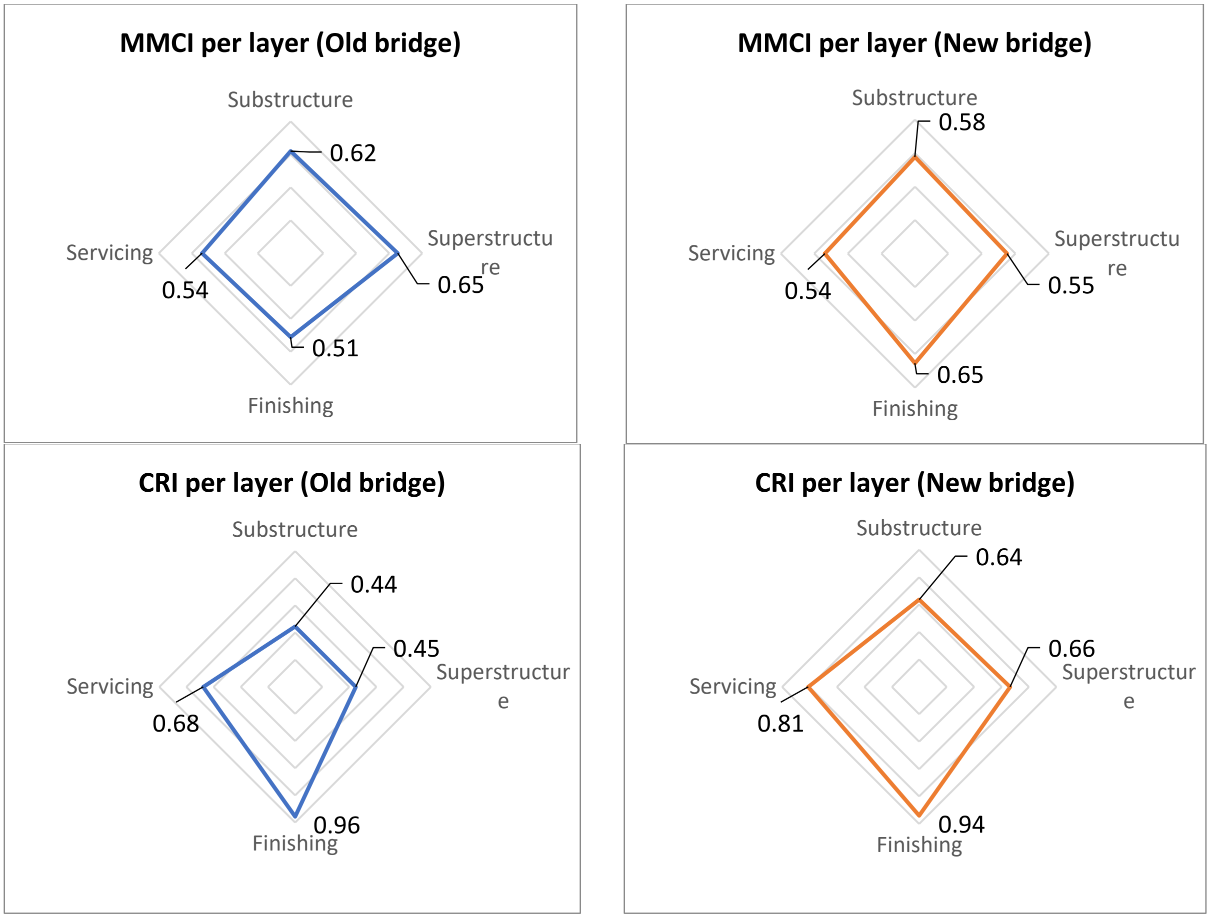


Figure 22: MMCI & CRI layers' performance (Bridge 41old and new)

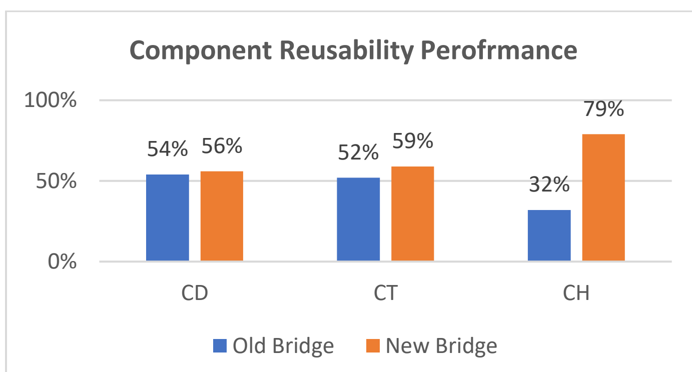
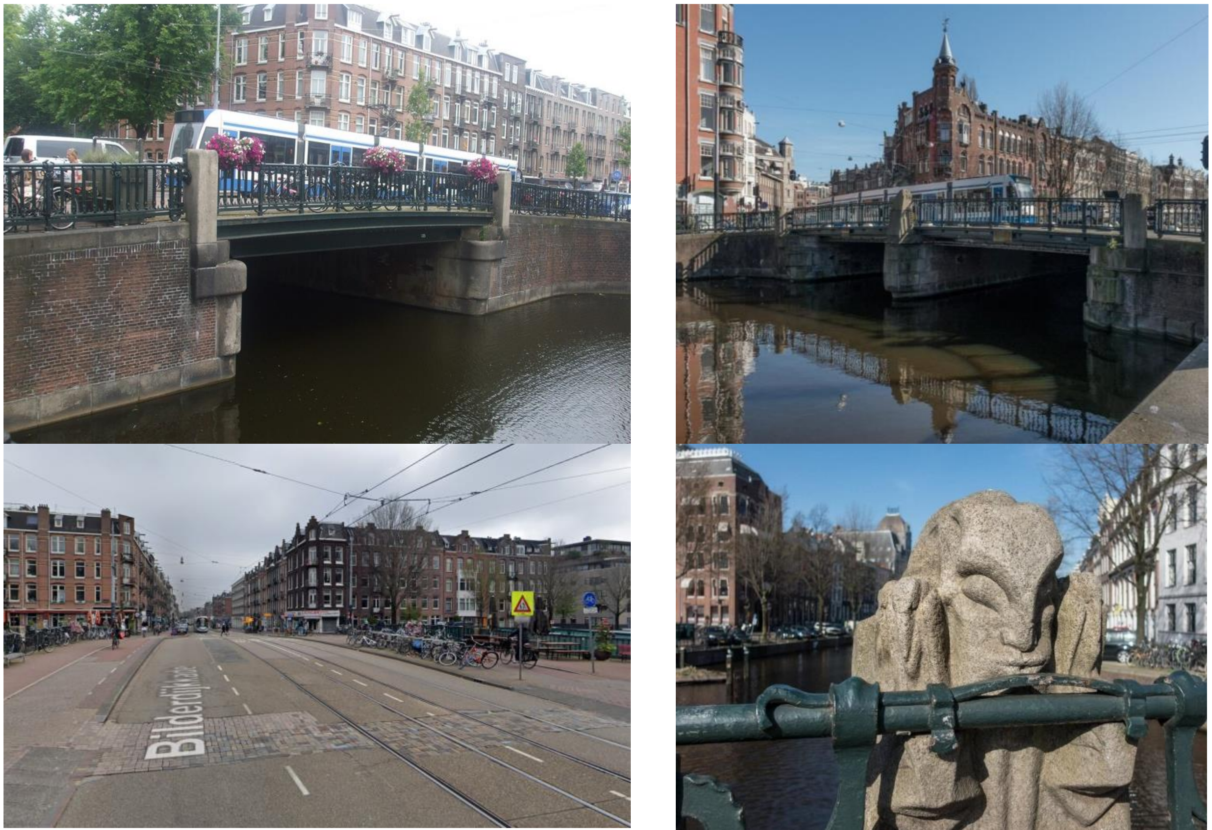


Figure 23: CRI Bridge 41 assessment

6.3. Case study B

De Ritsaert ten Catebrug (bridge 135) is a national monument (Order 1) built in 1902. It was widened in 1927, and the last major intervention was in 2008 (Amsterdam, 2021). The intervention of 2008 included renewing the bridge's deck by replacing multiple components in the superstructure layer (see Figure 24 (A)). Niek Engelschmanbrug (bridge 106) is a national monument (Order 1) that was constructed in the late 1890s and then extended in the year 1925 (see Figure 24 (B)) (Schip, 2021). The municipality is planning an intervention scenario for both bridges to preserve them as part of the Oranje Loper project. Both bridges require intervention in replacing components, mainly from the superstructure layer and restoring components such as natural stone. However, the two bridges' existing situation will be assessed and compared in the following section by using the strategic decision support scenario in the HBCI.



(A) Bridge 135 (B) Bridge 106

Figure 24: (a) bridge 135 (b) Bridge 106

The overall scores of the HBCI and sub-indicators for the two alternatives are presented in Figure 25. Both bridges are characterised by a fair circularity performance by getting the same score for both bridges (135 and 106). Thus, They generate a low ratio of waste, good recovery and reusability of components, and a good preservation rate.

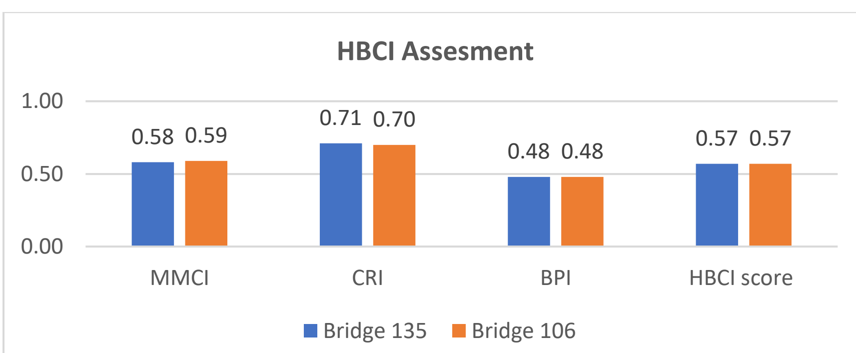


Figure 25: Bridge 135 and 106 HBCI Assessment

Starting from the BPI, both bridges have moderate preservation performance. However, they may require significant restoration/replacement in the future, especially in cases of high material retention, which might limit their preservation potential (Extensibility and Strengthenability). The two bridges have the original foundation and abutments, which limits their capability to be widened. Whereas, strengthening measures can be applied in the future without negatively impacting other functions. Both bridges have a 90% ratio for material preservation since most of the original components of the bridge are being preserved and still in use.

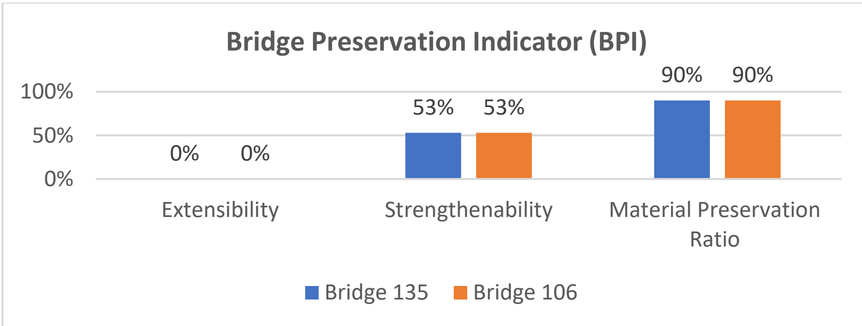


Figure 26: Bridge 135 and 106 BPI performance

Moving on to the CRI and MMCI, the two bridges have slight differences in their performance, which can be seen on a layer level. On the other hand, the overall scores of the MMCI and CRI are quite similar. Looking at the CRI in more depth, Bridge 135 components' health is in better condition than the components in Bridge 106.

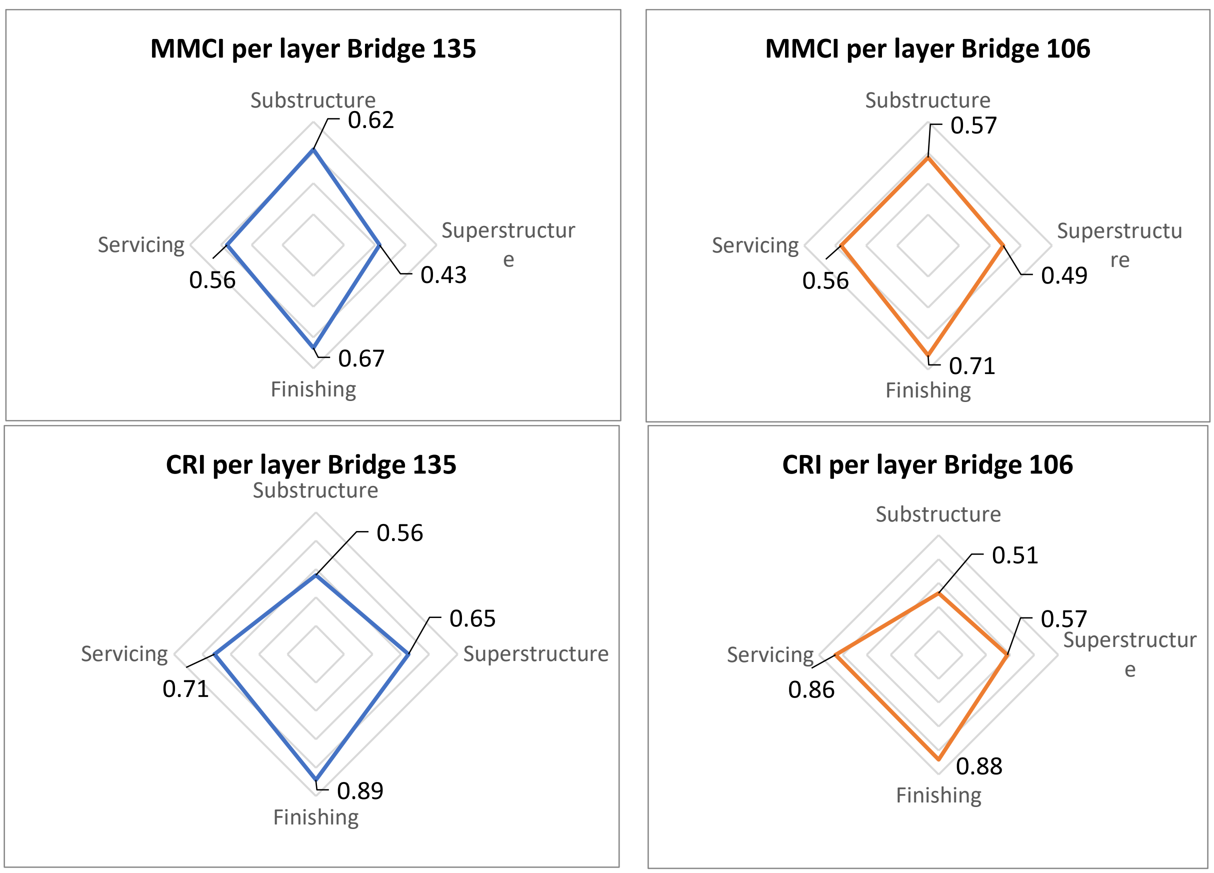


Figure 27: MMCI & CRI LAYERS' PERFORMANCE (BRIDGE 135 AND 106)

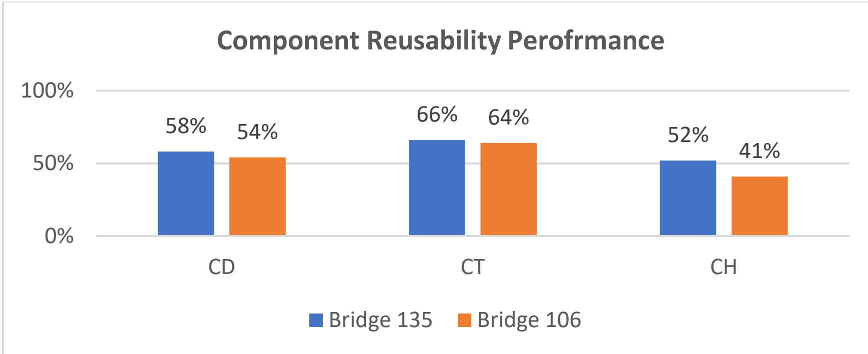


Figure 28: CRI BRIDGE 135 and 106 ASSESSMENT

6.4. Framework scenarios applicability

This sub-section demonstrates the frameworks' applicability to the different scenarios: General Insight, Strategic Decision Support, and Deconstruction and Demolition Insight. The choice of the scenario is dependent on the objective, temporal focus, and application of the study (see Table 8). The framework is used to assess bridge 41 in the three different scenarios to understand their impact on the final and sub-indicator scores (see Figure 29).

The MMCI remains constant in all scenarios, thus the scores are the same. The CRI score of the general insight scenario is different compared to the other two scenarios. This is due to the component health (CH) being excluded from the CRI calculations when applied to the general insight scenario. The BPI is only applied to strategic decision support scenario due to lack of data and irrelevance of data the sub-indicator provides in the other scenarios.

Finally, the HBCI scores of the different scenarios differ due to the changes that occur on the sub-indicators. This variation reflects the data availability levels and each scenario specific focus.

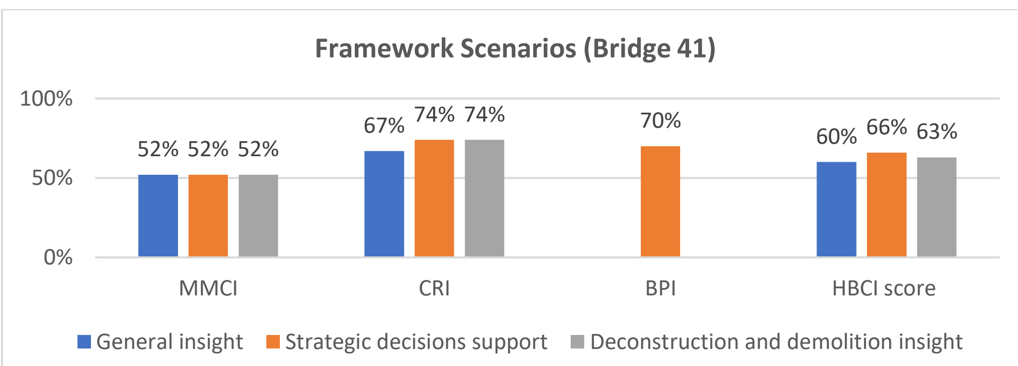


Figure 29: Framework Scenarios (Bridge 41)

6.5. Sensitivity analysis

Sensitivity analysis is a method used to determine how the different sources of uncertainty in the model influence the overall uncertainty and the output (Geffray, et al., 2010). The purpose of the sensitivity analysis is to increase the robustness of the developed framework and enhance transparency (Scholten, Schuwirth , Reichert, & Lienert, 2015). Varying the model's inputs and assumptions systematically allows one to observe the impact of these changes on the final results. This helps identify which parameters are most influential and which sources of uncertainty have the greatest impact on the outcome.

The one-at-a-time (OAT) sensitivity analysis is applied to the framework for the new bridge 41. Several parameters have been chosen from differrent sub-indicators, such as the fraction of virgin material, dismantability, strengthability, layers weighting, etc. The OAT is calculated by determining the influence of changing a parameter on the final output.

The fraction of virgin material has been chosen to detect the influence of using reused or recycled material instead of virgin material on the scores of the MMCI and HBCI (see Figure 30 (a)). The changes in the fraction of virgin material impact the MMCI with a sensitivity ratio of 12% and a standard deviation of 0.04. However, they have less impact on the HBCI score, with a sensitivity score of 3% and a standard deviation of 0.01.

The dismantabality of components has been tested to understand its impact on the CRI and HBCI (see Figure 30 (b)). The impact of dismantability is similar when changing the values of the component's transportability or health due to their equal weights when aggregated to the CRI score. The impact of changing their values has a sensitivity ratio of 33% and a standard deviation of 0.10 on the CRI score. It has a 16% sensitivity ratio and 0.05 standard deviation value for the HBCI score.

When aggregated to the BPI score (see Figure 30 (c) & (d)), the strengthenability, extensibility, and material preservation ratio have equal weights. As a result, their impact on the CRI and BPI is similar. The sensitivity ratio for the BPI value is 34%, indicating a moderate sensitivity, with a standard deviation of 0.095. In contrast, the sensitivity ratio for the HBCI score is 14%, with a standard deviation of 0.038, suggesting it is less influenced by the variations of the mentioned factors.

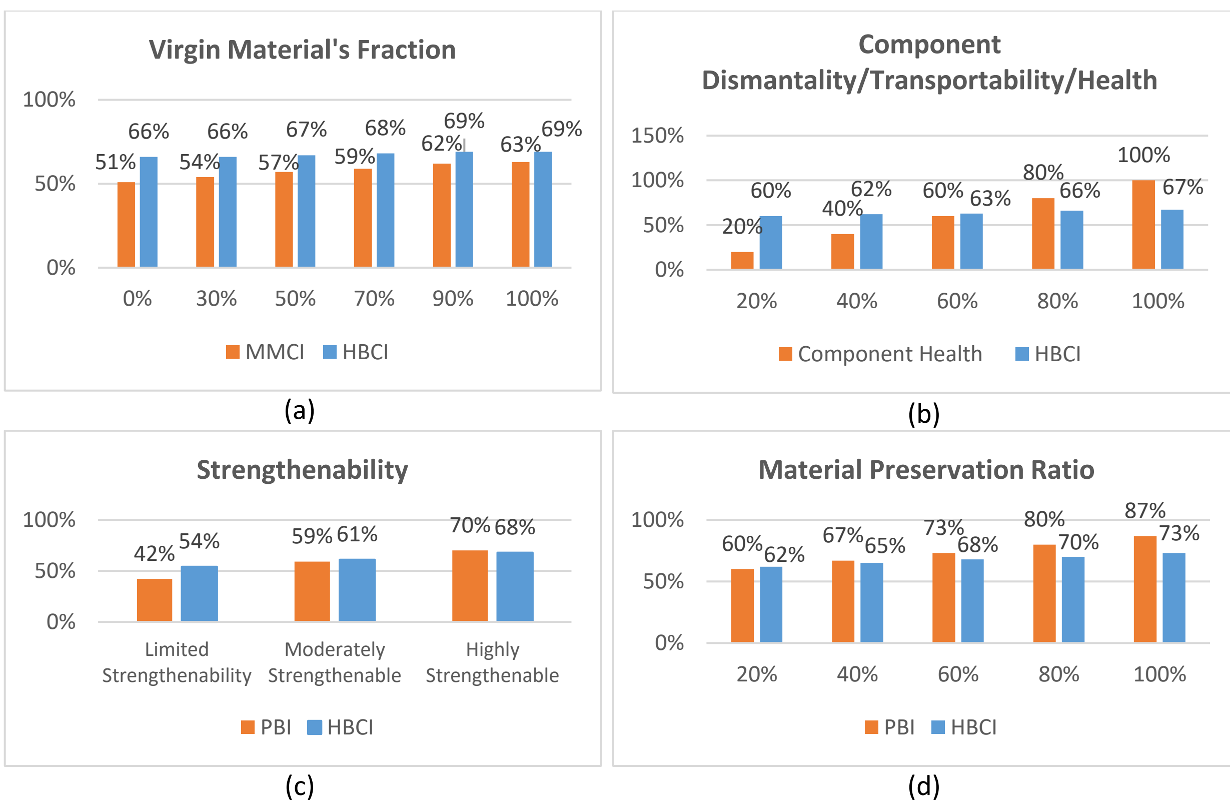


Figure 30: Sensitivity analysis

The weightings of the layers and sub-indicators are also analysed to understand their influence on the output. The weighting of the layers is determined by their estimated lifespan and historical significance. The estimated lifespan does not vary much; therefore, only the historical significance scenarios have been tested for each layer (see Appendix J).

In addition, historical significance is excluded from the model to test its' impact on the weighting of the layers and the final scores or the MMCI, CRI, and HBCI (The BPI remains constant since it's not related to the layers decomposition) (see Table 17). Another test is conducted on the model when the layers are assigned equal weights (see Table 17). This allows one to discern the relative importance of historical significance and assess whether certain layers are inherently more influential, ultimately refining the model's weighting scheme for an accurate assessment.

Table 17: Layers' weighting modification

	Without historical significance	Layers with equal weighting
Substructure	14%	25%
Superstructure	16%	25%
Finishing	35%	25%
Servicing	35%	25%
MMCI	51%	52%
CRI	81%	70%
HBCI	67%	66%

6.6. User feedback on framework usability and application

To assess the framework's usability and practical application, a Conservation Advisor at Nebest was interviewed. The Interview consisted of several questions aimed at understanding the user's experience, challenges, and overall satisfaction with the framework.

- Initial impressions and usability

The user's feedback noted that while the framework can Initially seem overwhelming for a first-time user, it becomes easier to familiarise with it. The objectives and guidelines are clearly stated, but it can be time-consuming to understand the content.

- Effectiveness and adaptability

The model effectively addresses circularity challenges and is adaptable to different contexts. Further, the model can integrate well with the existing processes at Nebest and can be potentially used as a circularity performance monitoring tool. Finally, the time invested in using the model is justified by the quality of the results.

- Limitations and Areas for improvement

While the framework is highly adaptable, the framework might be less effective for minor interventions. Thus, the advisor recommended incorporating more specific scenarios to improve its applicability. In addition, concerns over the effectiveness of the framework were expressed about the subjectivity of the Bridge Preservation Indicator (BPI) and data accessibility constraints.

7. DISCUSSION

The HBCI framework injects a new dimension into historical bridge management and decision-making. The framework provides guidance in investment and intervention strategies that promote both circularity and preservation of historical assets. This leads to fresh insight, such as identifying opportunities to reuse components, prolonging the bridge's lifespan, preserving historical components, etc.

- Data availability

When comparing to existing circularity indicators such as the Bridge Circularity Assessment Framework (BCAF) developed by Coenen et al (2021), it is realized the BCAF is data extensive and cannot be used with the available data for a general insight assessment scenario. In addition, the other indicators require an extensive amount of data, which might not be available for historical bridges. The framework solves this problem by having different temporal focuses, each requiring a different amount of data. The first scenario provides a starting point for understanding a bridge's existing situation, the second scenario guides the decision-making process when multiple interventions are proposed, and the third scenario addresses the end-of-life stage when the bridge needs to be demolished. This addition makes the framework more flexible, allowing it to be feasible to cover a wider range of historical bridges, even with limited data availability. Whereas most indicators do not offer the flexibility of having different scenarios of different requirements to use the tool.

- Frameworks scope

The Modified Alba Concept (MAC) developed by Van Schaik (2019) is applicable for foundations and the Circularity Indicator for pedestrian bridges (CIPB) developed by Anastasiades et al (2020) is applicable for pedestrian bridges. In addition, the layers decomposition proposed in the CIPB does not cover all bridge's components such as mechanical electrical components that exist in movable bridges. In contrast, the HBCI assesses circularity at a micro level, encompassing all bridge components. This approach provides several advantages such as conducting a comprehensive assessment of the whole bridge, avoiding overlooking any aspects, adjusting comparability between different structures and intervention scenarios, etc. Furthermore, the framework does not apply to different types of assets due to the BPI and layers decomposition that are tailored to historical bridges. However, the MMCI and the CRI are applied to other different assets. Thus, the HBCI has the potential to be standarised to all historical assets if the PBI is modified.

- Preserving national monuments and circularity

In some cases, there might be a conflict between being circular and preserving, such as having to use new materials in order to preserve national monuments. Most existing circularity indicators do not take into consideration the components that are considered as national monuments. This is taken into consideration in the MCI' developed by Jiang (2020) by using the economic value instead of the mass as a unit of measurement for the components with historical value. However, estimating the economic value of historical components is a complex process that requires extensive resources. Thus, this can stand as a barrier to using the MCI for historical bridges. The HBCI framework helps navigate this by assigning higher weights for the layers that consist of higher historical significance.

- Case studies

Applying the HBCI framework to the two case studies has provided valuable insights into the framework's capabilities and limitations when assessing circularity for historical bridges. In this the findings of the case studies are discussed, focusing on the results of the sensitivity analysis. Accordingly, the key performance indicators (KPIs) that are crucial for enhancing the circularity performance of historical bridges are determined. Finally, the limitations of the framework and recommendations are discussed.

The framework has been applied to different case studies, each serving a unique purpose. Case study A has been applied to HBCI to understand the impact on circularity performance when the bridge is replaced, but many of the original components are reused and preserved. The new bridge has performed better mainly on CRI and BPI, due to the better components' health and the bridge's capability to be preserved. On the other hand, the MMCI of the original bridge must be higher than the new bridge. Due to a lack of data, all material in the original bridge has been assumed to be virgin material. However, changing the value of the virgin material's fraction based on the sensitivity analysis, the final output would only change by 3%.

On the other hand, case study B is applied to test the robustness and consistency of the HBCI results. The two bridges share similarities such as construction complexity, intervention history, and historical significance. The two bridges shared the same HBCI scores, which provided valuable perspectives of the framework. The framework has proven to be consistent and reliable in its evaluation, enabling a comparative analysis of different bridges. Even though the final HBCI scores are similar, the scores differ when looking at layer, component, and material levels. This proves that the framework can capture the circularity performance differences even when bridges share similar characteristics and histories.

- Framework KPIS

Sensitivity analysis was conducted to find the tipping points where the output changes drastically due to a slight change in one of the parameters. By understanding these relationships, one can yield an understanding of the HBCI mechanisms and determine its' KPIs. The analysis findings match the proposed circular economy intervention strategies in Figure 11.

The bridge's material preservation ratio, extensibility, and stregthenability impact the HBCI the most. When applied to bridge 41, the HBCI sensitivity ratio is 14% and a standard deviation of 0.04. Meanwhile, when manipulating the parameters of the CRI (Component's Dismntality, Transportability, and Health), the sensitivity ratio goes down 9% with a standard deviation of 0.025. Accordingly, one should focus on enhancing higher-level parameters (from bridge level to component and then material level) for a greater impact on circularity performance. Furthermore, historical significance has a great impact on the layer weighting but a slight impact on the HBCI score. The slight impact on HBCI for this case study is explained by the close CRI and MMCI scores of components from different layers for this case study. Therefore, historical significance can have a greater impact on the final scores when applied to other bridges.

8. CONCLUSION & RECCOMENDATIONS

This chapter summarises the key findings of the research on assessing the circularity of historical bridges. It highlights the development and application of the Historical Bridge Circularity Indicator (HBCI). The first section provides a conclusion of the research, and the second section presents recommendations for future research and practitioners.

8.1. Conclusion

To conclude, this research has addressed the need for a structured approach to assessing the circularity of historical bridges while considering their unique characteristics and challenges. Thus, developing the circularity assessment framework for historical bridges (HBCI) represents further advancements in multiple fields, such as circularity, asset management, and historical asset preservation.

Following the research dsign, key criteria and indicators have been identified to assess circularity. These aspects encompass aspects such as material flow, component reusability, adaptability, and preservation of historical value. The approach included applying the framework to two case studies to ensure its reliability and robustness.

The framework offers a flexible approach to historical bridge circularity assessment by covering three scenarios that address different temporal focuses. These scenarios are applied to understand the bridge's circularity potential or as a decision-making tool for choosing an intervention strategy. Each scenario impacts the required data to conduct the assessment and the weightings of the sub-indicators. The different scenarios make the framework more flexible by ensuring the feasibility of the framework in different lifecycle stages and with different resources.

The HBCI provides a comprehensive assessment of circularity, yet it has certain limitations and potential for future improvements. Data quality impacts the final assessment, subjectivity due to semi-quantified measurements and dependence on expertise judgment, and quantification of components is time-consuming. On the other hand, future improvements can be applied to the framework for more comprehensive assessment. The lifecycle assessment (LCA) can be integrated into the framework, adding a broader value to the framework by including the environmental impact of resource use. While the framework uses mass as a unit for weighing components, economic value can be an alternative for a more nuanced understanding. However, this was found challenging due to the complexity of estimating the cultural value of monumental bridge components.

To conclude, while some limitations exist, the framework provides a valuable tool for stakeholders. It allows engineers to design more circular interventions and guides policymakers toward a more circular infrastructure management approach. In addition, it fulfills the main goal regarding historical bridges: to respect the past, adapt to the present, and thrive in the future.

8.2. Recommendations

This chapter provides insights for future research and practical application of the developed framework. The recommendations aim to address current challenges, highlight the potential of the framework for better usability the framework, and advice to users.

8.2.1. Recommendations for future research

Despite the framework's strengths, some challenges and recommendations must be addressed:

- **Develop a standarised data collection protocol**: data quality has a significant impact on the final score and the recommendation provided by the framework. In other words, the quality of the output is highly dependent on the quality of the input. Thus, developing a standarised data collection protocol would ensure consistent data gathering approaches across different bridge projects, minimizing inconsistencies and improving data reliability.
- **Develop a comprehensive expert judgment framework:** some evaluations require expert judgment, which introduces subjectivity and might lead to potential variation in results when

assessed by a different expert. The HBCI framework already provides guidelines and criteria for expert assessment. However, further improvements can be applied to mitigate any subjectivity in the assessment process.

- **Enhance quantification process:** the quantification process of the bridge's components can be time-consuming and thus can be enhanced in future research.
- **Adapt framework to additional tools:** explore the potential adaptation of the framework to different tools for covering more aspects of circularity or asset management, such as Life Cycle Assessment (LCA).
- **Standardizing the HBCI Framework for Historical Infrastructure:** The discussion highlights the HBCI framework's potential for standarised application across historical infrastructures. The Bridge Preservation Indicator (PBI) and bridge layer decomposition are currently tailored to historical bridges. Thus, developing a standardized infrastructure preservation indicator and layers breakdown for all types of historical infrastructure will facilitate consistent and reliable circularity assessment, enabling better decision-making for the preservation a renovation of these valuable assets.

8.2.2. Recommendations for practitioners

The framework can be used as a decision-making instrument by practitioners who are engaged in asset management. It eases the process of prioritising investments, planning interventions, and policy development in terms of circularity. The framework empowers practitioners with actionable insights and strategies to achieve enhanced circularity and resilience. Moreover, it eases the process of prolonging the lifespan of historical bridges and preserves their cultural value. To maximize the effectiveness of the framework, practitioners should consider the following recommendations:

- **Use Multiple expert opinions**: in areas where subjectivity may play a role (BPI), it is advisable to consider more than one expert opinion to ensure a well-rounded assessment.
- **Utilize economic value metrics**: the economic value of the components can be used as a metric instead of using the mass. Implementing this requires extensive work for estimating cultural value and coming up with an economic value. Accordingly, this is an area that can be enhanced by practitioners by finding a practical approach to facilitate the use of economic value.
- **Integrate the framework with cost analysis:** when comparing intervention alternatives, integrating cost analysis of the intervention scenarios would be beneficial to validate whether implementing the most circular interventions provides cost benefits in the long term. This addition to the framework would ensure that the recommendations of the tool are not only circularity but the potential economic benefits of implementing the most circular intervention scenario.

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10. CONFLICT OF INTERESTS

This work is funded by Nebest B.V.. However, there is no conflict of interest.

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APPENDICES

Appendix A

Table 18: Fuzzy variable for DDF (Verberne J. , 2016)

Functional separation	separation of functions	1.0
	integration of function with same lifecycle into one element	0.6
	integration of function with different lifecycle into one element	0.1
Functional dependence	modular zoning	1.0
	planed interpenetrating for different solutions (overcapacity)	0.8
	planed for one solution	0.4
	unplanned interpenetrating	0.2
	total dependence	0.1
Technical life cycle / coordination	long (1) / long (2) or short (1) / short (2) or long (1) / short (2)	1.0
	medium (1) / long (2)	0.5
	short (1) / medium (2)	0.3
	short (1) / long (2)	0.1
Geometry of product edge	open linear	1.0
	symmetrical overlapping	0.8
	overlapping on one side	0.7
	unsymmetrical overlapping	0.4
	insert on one side	0.2
	insert on two sides	0.1
Standardisation of product edge	pre-made geometry	1.0
	half standardised geometry	0.5
	geometry made on the construction site	0.1
Type of connections	accessory external connection or connection system	1.0
	direct connection with additional fixing devices	0.8
	direct integral connection with inserts (pin)	0.6
	direct integral connection	0.5
	accessory internal connection	0.4
	filled soft chemical connection	0.2
	filled hard chemical connection	0.1
	direct chemical connection	0.1
Accessibility to fixings and intermediary	accessible	1.0
	accessible with additional operation with causes no damage	0.8
	accessible with additional operation which is reparable damage	0.6
	accessible with additional operation which causes damage	0.4
	not accessible – total damage of bought elements	0.1

Appendix B

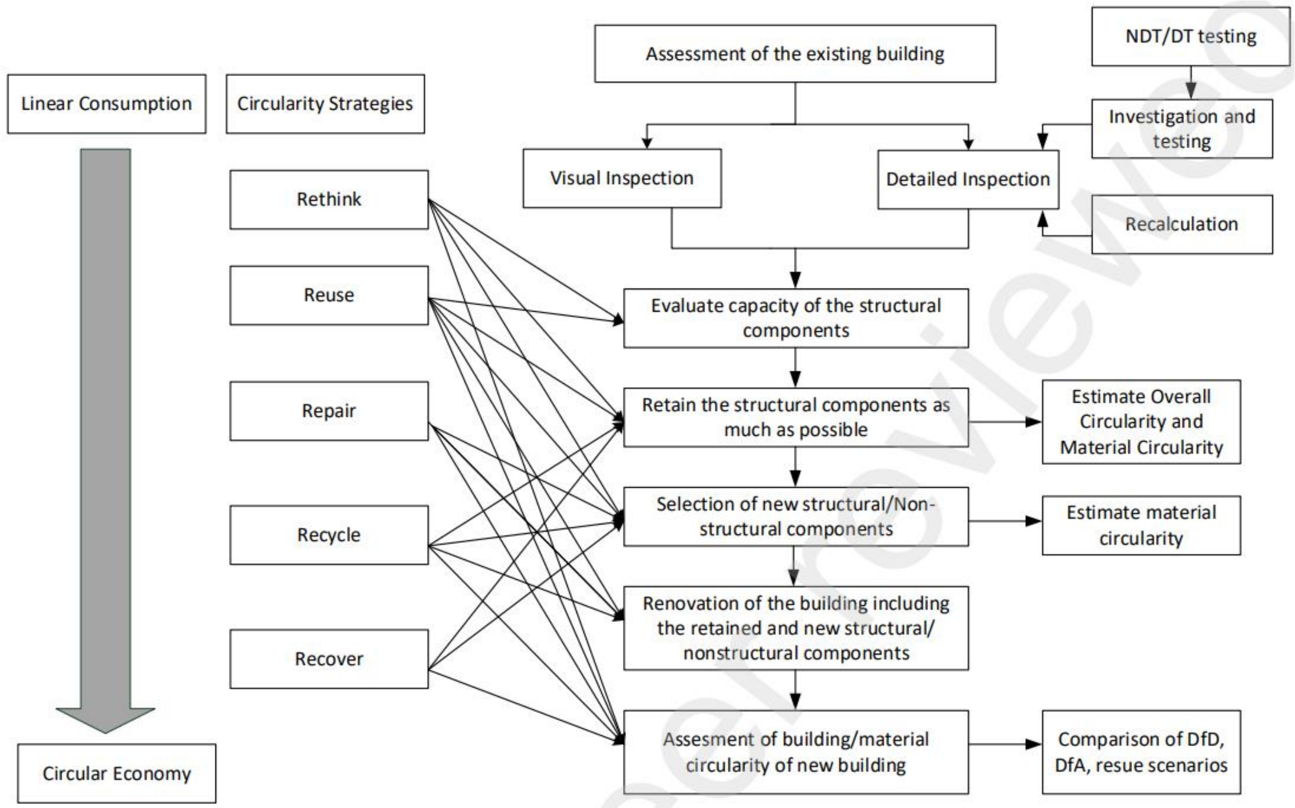


Figure 31: A framework to implement circular economy concepts during renovation of buildings (De Silva, Kumari, & Haq, 2023)

Appendix C

Table 19: CB'23 Measuring circularity sub-indicators and attributes (CB'23, 2022)

Indicators	Sub-indicators	Attributes
I – 1	Quantity of primary material	- Primary material - Sustainably produced renewable material - Unsustainably produced renewable primary material - Nonrenewable primary material
	Quantity of secondary material	- Secondary material from reuse - Secondary material from recycling
	Quantity of physically scare material	- Quantity of physical non-scarce material - Amount of physically scarce material
	Quantity of socio-economically scare material	- Socio-economically non-scarce raw material - Socio-economically scarce raw material
I – 2	Quantity of material for reuse	
	Quantity of material for recycling	
I – 3	Quantity of material to energy production	
	Quantity of material to landfill	
I – 4	Climate change (total, fossil, biogenic, and land use and land use change), Ozone layer degradation, Acidification, Fertilization of fresh water, Fertilization of sea water, Fertilization country, Smog formation, Depletion of abiotic resources (minerals and metals), Depletion of abiotic raw materials (fossil energy carriers), Water use, Fine dust emission, Ionising radiation, Ecotoxicity (freshwater), Human toxicity (carcinogen), Human toxicity (non-carcinogenic), Land use-related impact/soil quality	
I – 5	Functional quality at the end of the lifecycle	
	Technical quality at the end of the life cycle	
	Degradation at end-of-life cycle	
	Reuse potential at end-of-life cycle	
I – 6	Economic value at end of life	- Costs for disassembly, transport/storage, waste treatment and transformation - Scrap, raw material value or product - Residual value

Appendix D

Table 20: MCI Mass (M) and Economic Value (E) comparison (Jiang, Bhochhibhoya, Slot, & de Graaf, 2022)

Formulas MCI	Formulas MCI'
V = M * (1-Fu-Fr-Fb)	V' = E * (1-Fu'-Fr'-Fb')
Wo = M * (1-Cu-Cr)	Wo' = E * R * (1-Cu'-Cr')
W = Wo + Wc	W' = Wo' + Wc'
LFI = (*V* + *W*) / 2M	LFI' = (V'+W') / (*E* + *E**R)
MCI = max [0, 1-LFI * F(X)]	MCI' = max [0, 1-LFI' * F(X)]
Where:	
V/V'	Virgin feedstock expressed by mass or economic value
W/W'	Unrecoverable waste expressed by mass or economic value
Fu/Fu'	Fraction of reused sources based on material mass or economic value
Fr/Fr'	Fraction of recycled sources based on material mass or economic value
Fb/Fb'	Fraction of bio-based sources based on material mass or economic value
Cr/Cr'	Fraction of materials collected for recycling based on material mass or economic value
Cu/Cu'	Fraction of materials collected for reuse based on material mass or economic value
Wc/Wc'	Waste generated in the recycling process expressed by mass
Wo/Wo'	or economic value
LFI/LFI	Materials going to landfill/incineration expressed by mass or economic value
	Linear flow index based on mass or economic value
M	Material mass
E	Economic value
R	Residual value
F(X)	A function of the product utility

Appendix E

Table 21: Interventions feasibility to historical bridges

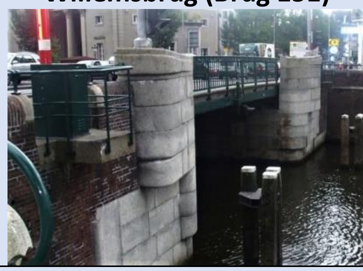
Intervention level	Type of Intervention	Intervention definition	Feasibility to historic bridges
Low	Preservation	Apply measures to maintain the existing materials, form, and integrity. This includes routine maintenance and preservation efforts that aim to sustain the structure's original characteristics, ensure its longevity, and reduce the impact of decay over time. It is part of the ordinary maintenance. It includes indirect measures e.g.	Takes into consideration protecting the historical value and maintaining it in a proper state on the component level.
	Conservation	Apply measures directly to asset's fabric aiming to prolong its' lifespan without the loss of authenticity and value. This includes remedial and preventive conservation encompassing actions for maintenance and stabilization measures.	This is directed at preserving elements to maintain historical significance and prolong the lifespan of the asset. Interventions that include using any chemical or physical treatment should be as gentle as possible.
	Maintenance	Apply route, cyclical, and nondestructive interventions throughout the asset's lifecycle to ensure its functionality. This includes preservation and conservation measures.	Interventions that aim to maintain the asset in a suitable state, slow down deterioration, and slight performance enhancement.
Medium	Repair	Apply measures to the whole asset or part of it aiming to recovering functionality and appearance. This might include minor repairs of the deteriorated materials.	For parts with historical value, repair is more favorable than replacement. In addition, new materials included should not affect the authenticity of the bridge.
	Refurbishment	Apply measures to modify the asset to enhance its performance to an acceptable condition. This includes extensive maintenance or repairs to achieve current standards.	Takes into consideration historical value by ensuring the compatibility of the added material and features.
	rehabilitation	Apply measures to make a historical asset functional again	Compatible modification of the historical asset to reach the

		and compatible with current standards. This might include modernisation, extensive work, and major structural alterations.	current standards with minimum change.
	Renovation	Apply measures to upgrade the asset on three assets level (material, component, and systems) to the current standards. This includes stabilisation and consolidation measures.	This is not considered as an conservative actions in regards to the historical value of an asset due to the difficulty in maintaining compatibility of the added material and the modern technical installations.
	Restoration	Apply measures to recover the asset to its original state. This includes reconstruction works for parts of the asset.	This is not considered as an conservative actions in regards to the historical value of an asset due to the difficulty in maintaining the historic and artistic value of deteriorated parts.
High	Deconstruction	Apply measures to disassembly/dismantle the asset with the goal of maintaining components and reusing them.	This intervention allow finding a new life in the adaptive reuse of the components. Thus, it aims at salvaging components that are still in good shape and detachable from the original asset unlike the tradition demolition that results in the loss of materials.
	Demolition	The process of removing the asset's materials and/or parts. Apply	This is not considered as an conservative action, as the main goal for the interventions are to preserve and maintain the asset.

Appendix F

Table 22: Examples of multiple types of bridges in the city of Amsterdam

Bridge type	Bridge name	Year	Order	Extra information
Fixed Beam bridges	**BRU0476** 	1957	Order 3	Concrete bridge, Concrete in situ 3
	Krijtbergbrug (Bru 3) 	1883	Order 2	Land bridge span , stone bridge 2
	The Vondelbrug (bridge 200) 	1892	Order 2	The form of a viaduct , Concrete bridge 2
Movable bridge	**The Mariniersbrug (BRU272)** 	1935	Order 1	bascule bridge, Steel Bridge1
	Blauwbrug (BRU236) 	1884	Order 1	Stone Bridge1

	Magere Brug (brug nr. 242) 	1691	Order 1	National Monument, Wood and steel
	Willemsbrug (Brug 151) 	1928	Order 1	Concrete bascule.
	Berlagebrug (bru423) 	1931	Order 1	Concrete bascule
Arch bridges	**BRU71+ BRU0072, BRU0073** 	1871	Order 1	Concrete supporting structure, masonry arch
	Reguliersgracht Bridge (Brug 39) 	1902	Order 1	Stone and Brick

	Torensluis nr. 9 		Order 1	Stone and Brick
	Keizersgracht Bridge (Brug 46) 	1928	Order 1	Stone and Brick

Appendix G

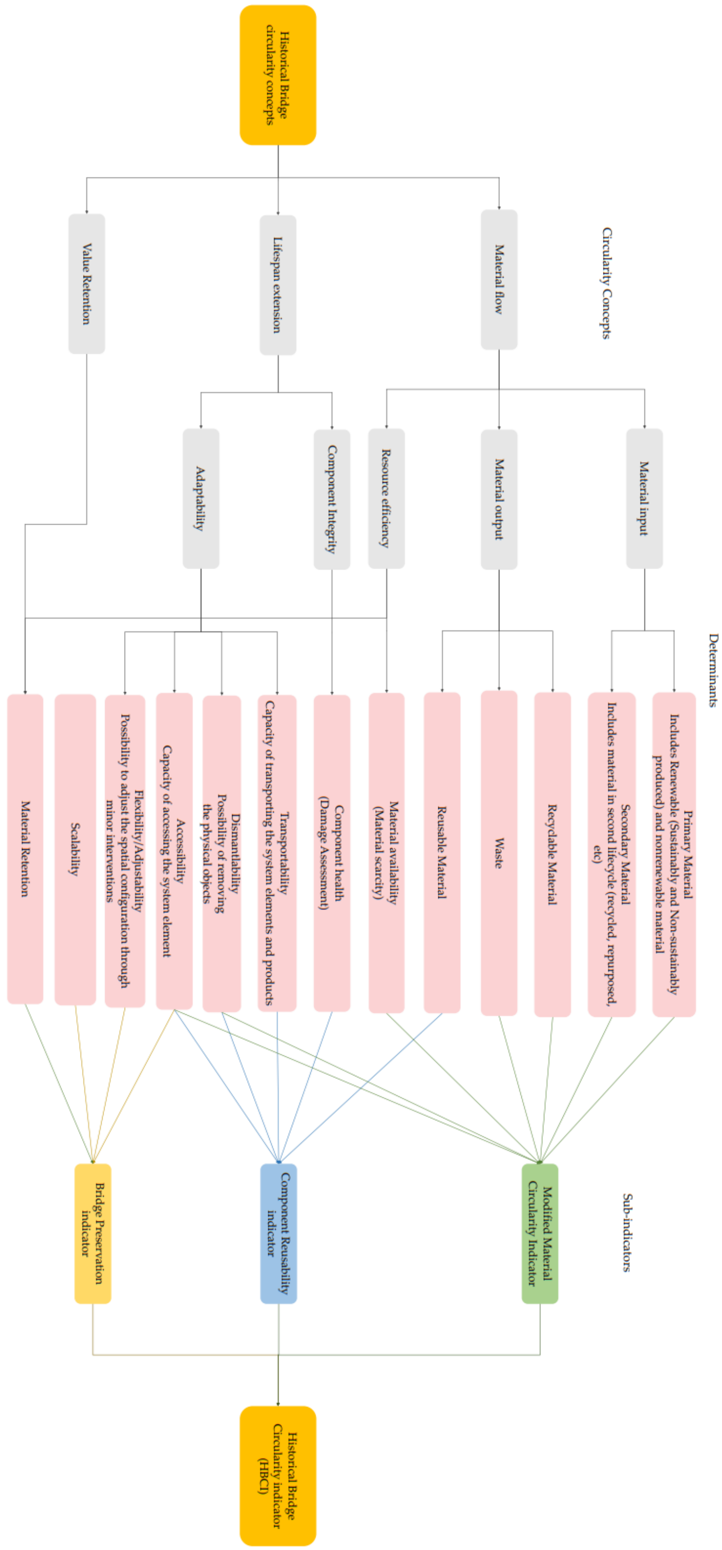


Figure 32: Circularity concepts transition into sub-indicators

Appendix H

Table 23: EU Supply Risk (HHIWGI-t) (Deloitte, BGS, BRGM, & TNO, 2017)

Mineral Resource	EU supply risk	Mineral Resource	EU supply risk
Aggregates	0,20	Manganese	1,20
Aluminium	0,30	Molybdenum	1,10
Antimony	5,70	Natural cork	1,30
Baryte	1,80	Natural graphite	2,90
Bauxite	3,10	Natural Rubber	1,00
Bentonite	0,50	Natural Teak wood	1,80
Beryllium	0,00	Neodymium	1,80
Bismuth	4,20	Nickel	0,40
Borate	5,00	Niobium	2,50
Cerium	2,60	Palladium	0,00
Chromium	1,10	Perlite	1,70
Cobalt	1,30	Phosphate rock	0,80
Coking coal	0,30	Phosphorus	4,50
Copper	0,50	Platinum	0,00
Diatomite	0,30	Potash	0,80
Dysprosium	1,80	Praseodymium	1,80
Erbium	1,60	Rhenium	2,00
Europium	1,80	Rhodium	0,00
Feldspar	0,70	Ruthenium	0,00
Fluorspar	0,70	Samarium	1,60
Gadolinium	1,80	Sapele wood	1,80
Gallium	1,10	Scandium	3,40
Germanium	1,50	Selenium	0,40
Gold	1,00	Silica sand	0,30
Gypsum	0,50	Silicon metal	0,40
Hafnium	1,40	Silver	1,60
Helium	1,30	Sulphur	0,70
Holmium	1,80	Talc	0,40
Indium	0,80	Tantalum	4,60
Iridium	0,00	Tellurium	0,70
Iron ore	0,80	Terbium	1,80
Kaolin clay	0,50	Thulium	1,80
Lanthanum	1,80	Tin	0,80
Lead	0,30	Titanium	0,50
Limestone	0,30	Tungsten	1,90
Lithium	1,40	Vanadium	3,30
Lutetium	1,80	Ytterbium	1,80
Magnesite	0,70	Yttrium	1,80
Magnesium	5,20	Zinc	0,40

Appendix I

Table 24: AHP Involved Stakeholders

Position	MMCI/CRI	Score	MMCI/BPI	Score	CRI/BPI	Score
Technical manager (Municipality of Amsterdam)	CRI	5	BPI	9	BPI	5
Conservation Advisor (Nebest)	CRI	5	BPI	7	BPI	3
PhD student	CRI	1	BPI	3	BPI	3
Assistant professor	MMCI	3	BPI	3	BPI	3
Post Doc Researcher	CRI	3	BPI	5	BPI	3
Student	MMCI	3	MMCI	3	BPI	3
Researcher	MMCI	3	MMCI	3	BPI	3
Researcher	MMCI	5	MMCI	3	BPI	3
PhD student	CRI	3	MMCI	3	CRI	3
PhD student	MMCI	1	BPI	1	CRI	3
Scientist Integrator (TNO)	CRI	3	BPI	3	CRI	1

Appendix J

Table 25: Substructure historical significance score modification

Historical significance score	Substructure	Superstructure	Finishing	Servicing	MMCI	CRI	HBCI
0%	7%	48%	28%	18%	52%	76%	67%
20%	15%	41%	26%	18%	52%	76%	66%
40%	21%	36%	25%	18%	52%	75%	66%
60%	26%	33%	24%	18%	52%	75%	66%
80%	29%	30%	23%	18%	52%	75%	66%
100%	32%	28%	23%	18%	52%	74%	66%

Table 26: superstructure historical significance score modification

Historical significance score	Substructure	Superstructure	Finishing	Servicing	MMCI	CRI	HBCI
0%	48%	8%	26%	18%	53%	75%	66%
20%	43%	15%	25%	18%	53%	75%	66%
40%	38%	20%	24%	18%	53%	74%	66%
60%	35%	25%	23%	18%	52%	74%	66%
80%	32%	28%	23%	18%	52%	74%	66%
100%	30%	31%	22%	18%	52%	74%	66%

Table 27: Finishing historical significance score modification

Historical significance score	Substructure	Superstructure	Finishing	Servicing	MMCI	CRI	HBCI
0%	35%	30%	18%	18%	52%	73%	66%
20%	32%	28%	23%	18%	52%	74%	66%
40%	30%	26%	27%	18%	53%	75%	67%
60%	28%	25%	30%	18%	53%	76%	67%
80%	26%	23%	33%	18%	53%	77%	67%
100%	25%	22%	35%	18%	53%	78%	67%

Table 28: Servicing historical significance score modification

Historical significance score	Substructure	Superstructure	Finishing	Servicing	MMCI	CRI	HBCI
0%	32%	28%	23%	18%	52%	74%	66%
20%	30%	26%	22%	22%	52%	75%	66%
40%	28%	25%	22%	26%	51%	75%	66%
60%	26%	23%	21%	29%	51%	76%	66%
80%	25%	22%	21%	32%	51%	76%	66%
100%	23%	21%	21%	34%	50%	76%	66%