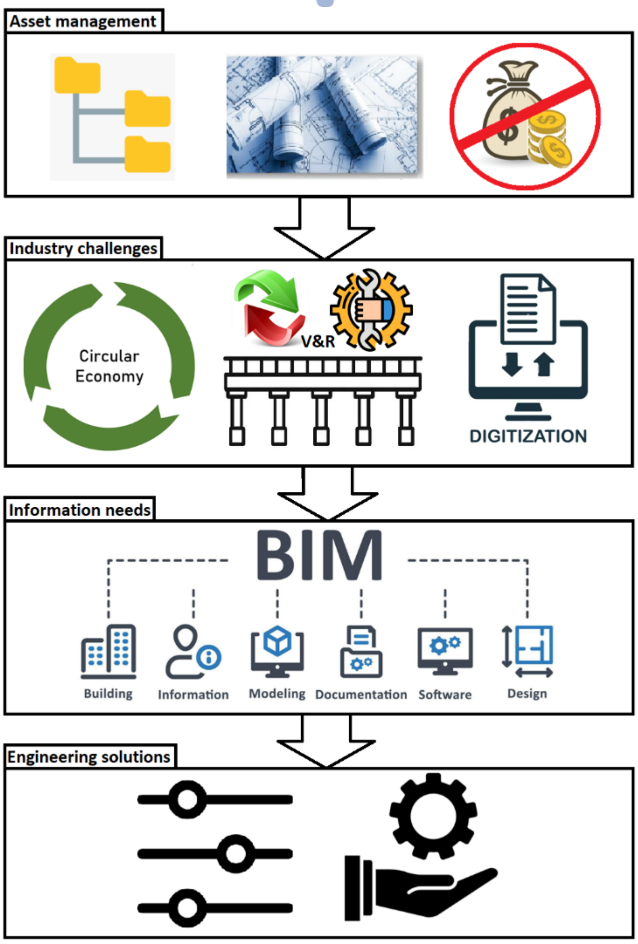
REVERSE ENGINEERING 3D-BIM OF EXISTING BRIDGE INFRASTRUCTURE USING PARAMETRIC TOOLING TO ACCELERATE DIGITIZATION IN ASSET MANAGEMENT

A Research & Development study by Colin Reit



MAY 14, 2023

WITTEVEEN+BOS & TU DELFT

Witteveen+Bos

TU Delft

Contact information

Graduating student:

Name:	C.A.J. (Colin) Reit
University	Delft University of Technology
Faculty	Civil Engineering and Geosciences
Master track	Construction Management & Engineering
Specialization	Engineering & Systems

Graduation Committee:

Name (chair)	Dr.ir D.F.J. (Daan) Schraven
University	Delft University of Technology
Department	Materials, Mechanics, Management & Design (3Md)
Section	Integral Design & Management
Name	Dr. Ir. Yuguang Yang
University	Delft University of Technology
Department	Engineering structures
Section	Concrete structures
Name	Dr.ir. M. (Maria) Nogal Macho
University	Delft University of Technology
Department	Materials, Mechanics, Management & Design (3Md)
Section	Integral Design & Management
Name	ing. M.R. (Maarten) Visser MSEng
Company	Witteveen+Bos
Profession	BIM & Asset information management

Preface

This report represents my master thesis called: *Reverse engineering 3D-BIM of existing bridge infrastructure using parametric tooling to accelerate digitization in asset management.* This thesis has been written as part of the Master of Science Construction Management & Engineering with a specialisation in Engineering & Systems. In the past 7-8 months I have dedicated my time to both research a common problem in three large challenges in the construction industry and developing a potential solution to part of this problem. Throughout this time, close collaboration with Witteveen+Bos and TU Delft had taken place to guide me.

When I started this journey, I had three concepts in mind that I wanted to integrate in my research: Circular Economy (CE), Building Information Modelling (BIM), and Parametric Engineering & Modelling (PEM). The CE has increasingly caught my attention throughout my academic career as it is a large and complex puzzle that has a significant impact on the industry. Secondly, BIM has been my interest since my Bachelor as it embodies new potential for the industry, and I have always been passionate about innovation. Lastly, PEM was something that I explored in my free elective space, where I learned of its potential in the future. In each of these subjects I have learned an incredible amount. While I hope the output of this research is a contribution in itself to both the academic and business worlds, it is merely a step in the right direction which requires increasingly more effort in the coming years and decades. It was my desire to not 'just' research but also develop something (potentially) valuable for the industry, in which I hope succeeded as Witteveen+Bos has already signalled they want to proceed with the development of the RE-design tool.

One of the key challenges I faced during this thesis was the containment of scope given the complexity and size of the included themes: Circular Economy transition, Bridge Replacement & Renovation task, and the digitization transition in asset management. I want to give special thanks to Maarten Visser, who guided me on a weekly basis throughout this research and helped me get in contact with the right people. Secondly, I want to thank my Witteveen+Bos colleagues for being available to share knowledge, feedback, and documents with me to improve the quality of my research. Lastly, I want to thank my TU Delft committee members Daan Schraven, Maria Nogal, and Yuguang Yang for their specialised knowledge and providing me with valuable and constructive feedback, especially on the report structure. I hope you enjoy reading this report!

Colin Reit
Delft, April 2023

Abstract

Amid global climate change challenges, the construction industry faces an urgent transition from a linear production model towards a Circular Economy (CE) model. Current initiatives in Dutch transition roadmaps and recommendations in literature predominantly focus on ensuring a future circular built environment, while lacking concrete actions addressing one of the primary barriers to short-term reuse: high-quality centralized data of existing assets. Dutch CE roadmap timelines and interventions are developed based on Material Flow Analysis (MFA) studies with highly uncertain data input for infrastructure objects, calling for more accurate bottom-up material quantification methods. This uncertainty causes either over- or underestimation of future material stock flows (secondary material potential), consequently negatively impacting the environment or economy due to inaccurate implementation of policies to achieve the set CE-goals.

The Replacement & Renovation (R&R) task of civil structures poses a threat for Asset Management (AM) due to the limitations in capital, contractor capacity, and material resources required to facilitate this peak. Currently available data quality at public organisations is generally insufficient for conducting structural assessments required for effectively managing this expected decommissioning peak using the maintain/extend/renovate/ replace strategies and reusability scans for reuse realisation. This disincentivizes reuse realisation in practice as there is too much risk involved for demand parties.

AM is transitioning towards a 3D-centralised strategy in line with Building Information Modelling (BIM) and digital twins, while existing assets are still in 2D with often incomplete and fragmented data documentation. This lack of data is caused by the absence of technology & client demand at time of construction, and loss of (tacit) knowledge resulting from staff replacements over time. Consequently, a large data quality gap is forming between newly constructed and existing assets. This led to the following research question: ***How can centrally stored, quantified, and visualised asset data of existing infrastructure impact the CE-transition, bridge R&R-task efficiency, and AM practices?***

Through interviews, the above findings were validated, the current information standards at various industry stakeholders were gauged, alongside their ambitions and barriers for upgrading towards 3D centralised AM. It was concluded that an upgrade towards 3D-BIM is necessary to bridge this data gap for the industry's long-term needs, though the costs are currently too large to justify this. Upgrading to 3D-BIM facilitates higher quality- and more accessible asset specific information that can be used in reusability scanning and structural assessments, material quantification for increased MFA input accuracy, and numerous AM benefits (e.g., improved condition monitoring, maintenance & decommissioning preparation, and data traceability). An opportunity was identified for modelling 3D-BIM of existing bridge infrastructures from 2D drawings and project specifications using a modular approach to Parametric Engineering & Modelling (PEM), aiming to reduce modelling efforts and the investment threshold for accelerating the digitization transition at public organisations.

Using Information Systems (IS) theory, this opportunity was further explored. Fixed beam and plate bridges were selected for the development of a prototype tool due to their standardized nature originating from strict design standards, its functional purpose, minimal architectural influence, and reusability potential. A Cost-Benefit-Analysis (CBA) showed potential long-term profits for making the upgrade using conventional modelling practices, though it involved large uncertainties. From the analysis of the tool's output end-use, a Level-of-Detail (LOD) of 500 was set for geometry, and 700 for the information registration potential (customizable for user's needs). The largest risk for of the tool's effectiveness concerns the short-term availability and quality of data due to recovery costs/capacity.

The developed tool (RE-design) was tested with 4 beam bridge projects (20-30m spans) using 2D drawings from Witteveen+Bos to develop the model and an existing 3D model of the project for validation, with a limited design variant database. To limit the scope of the prototype, retaining/sheet pile walls, expansion joints and edge elements were excluded. The results were measured using two quantitative metrics (volume accuracy & required modelling time) and three qualitative metrics (robustness, adoptability & adaptability). The volume accuracy represents the resemblance in material volume of the generated model compared to the actual 3D model, measured per element. The required modelling time concerns the time to study the drawings, extracting parameter values and running the model to obtain the 3D model (excluding assigning attribute data).

Across the 4 projects, an average of 97.41% on volume accuracy was obtained which required 1.75-2.5h per project. These results were obtained by the author and need more validation and user-testing by designers to increase reliability, as the modelling time and accuracy are highly dependent on the user's ability to extract information from drawings efficiently and the element database depth. However, it indicates significant time reductions compared to manual modelling practices from 2D drawings (12-20h) and calls for further development, also for other types of infrastructure. The robustness of the prototype is defined by the element database but has the potential to model most beam/plate bridge once saturated. To accompany the tool, a user's guide was developed to increase user adoptability alongside a whitepaper for policymakers to accelerate the upgrade to 3D centralised AM at public organisations. It was concluded that with this user's guide the tool has a relatively low entry barrier, but it requires more skill to add new variants to the database or alter the model's functionalities. Lastly, the tool showed potential for other applications such as parametric 3D structural & reusability assessments, reinforcement approximation, and optioneering & circularity scoring for the design phase. To put the tool's use in perspective, a roadmap towards 3D centralized AM and a reuse economy was developed for asset managers to navigate the CE-, R&R-, and digitization transitions more efficiently, see Figure 1. The sooner the transition towards 3D centralised AM is initiated with data gathering on existing assets, the longer the benefits can work to recoup the initial investment.

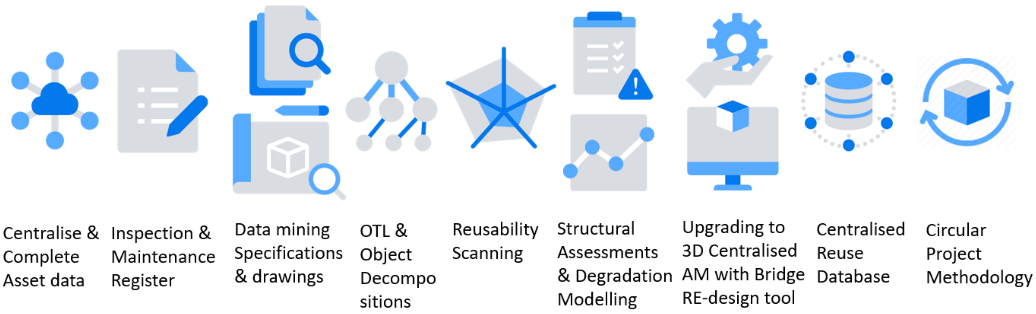


Figure 1: AM roadmap overview

Table of Contents

Table of Figures

Table of Tables

List of abbreviations

Term	Meaning
AM	Asset Management
BAU	Building/Business As Usual
BIM	Building information modelling
CE	Circular Economy
CDW	Construction Demolition Waste
ECI	Environmental Costs Indicator
LCA	Life Cycle Analysis
LCCA	Life Cycle Costing Analysis
MCDA	Multi Criteria Decision Analysis
MFA	Material Flow Analysis
MP	Material Passport
R&R	Replacement & Renovation – In Dutch: Vervanging & Renovatie (V&R)
T3D	Totaal 3 Dimensionaal; effort by Amsterdam, Rotterdam & the Hague to digitize cities
W+B	Witteveen+Bos

Chapter 1: Research setup

1.1. Introduction

This report comprises the research and development of a tool that aims to help the construction industry move towards a more Circular Economy (CE). The study was conducted in cooperation with TU Delft and Witteveen + Bos, a leading engineering consultancy headquartered in the Netherlands but active all around the world. The topics that will be addressed in this research include the data quality issues of infrastructure assets and the impact this has on the industry in relation to the CE, digitization transition, and bridge Replacement & Renovation (R&R) task. This study will provide an analysis of all the previously mentioned challenges and a roadmap to tackle them more effectively and efficiently. Moreover, a tool will be introduced that aims to significantly reduce design efforts for upgrading existing bridge infrastructure asset data to 3D BIM.

1.2. Research context

1.2.1. The CE transition in the construction industry

The construction industry has long been deemed as one of the major contributors of environmental emissions. The involved processes (resource mining, transportation, manufacturing, construction & operation) and final disposal cause serious environmental harm, specifically air, soil, and water pollution (Shen, Lu, Yao, & Wu, 2005). When also taking into account the predicted population growth from 8 to 9.7 billion people by 2050 (UN, 2022), a middle class population increase from 2 billion to over 4 billion people by 2030 (Kharas, 2017), and the global urbanisation trend, the need for construction will only increase. Furthermore, the materials become more scarce with time due to the limited stock of natural resources (Hossain, Ng, Antwi-Afari, & Amor, 2020). On top of that, geopolitical developments such as the war in Ukraine and worldwide health issues like COVID-19 have displayed our vulnerability and dependence on resources from all over the globe. Already, the European construction industry emits approximately 40% of total emissions in Europe, consumes 50% of raw materials and is responsible for 23-30% of the total solid waste (Sauter, Lemmens, & Pauwels, 2020) (DesignBuildings, 2022). This reality forces the Netherlands to become proactive in transitioning from a linear economy towards a Circular Economy (CE), which implies investing in pioneering solutions and embodying the frontrunner role for adopting new technologies, business models, and construction methods in order to meet the international agreements (50% circular by 2030 and 100% circular by 2050 (Rijksoverheid, 2016)) and limit climate change implications. The linear and circular economy models are simplified in Figure 2.

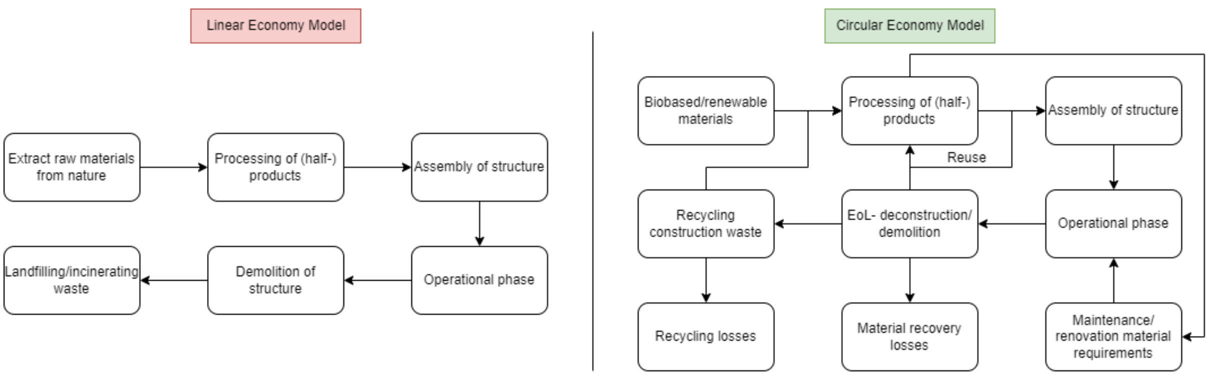


Figure 2: Linear & Circular economy models

The construction industry is very much known for its conservativeness towards innovations, small profit margins, tight standards, strict regulations, a complex supply chain, and product development for high lifetimes, each contributing to a more difficult CE-transition process (Akadari & Fadiya, 2013) (Hwang, Ngo, & Teo, 2022) (Papadopoulos, Gayialis, & Zamer, 2016) (BSI, 2021). Roadmaps are being developed and updated continuously to navigate the industry towards implementing realistic initiatives and achieving milestones in line with the climate agreements (Circulaire Bouweconomie, 2018). These initiatives are either focussed on laying the foundation that allows for a circular construction industry in the future or aim to leverage the existing built environment for short-term circularity. Current projections show a 13% theoretical material deficit by 2050 to accommodate a fully circular economy (EIB & Metabolic, 2022). This highlights the problems in the construction industry and calls for urgent action to reduce construction activities, improve recycling technologies and increase reused materials in projects. Only in doing so, can the primary material extraction be reduced, and a circular economy be achieved.

1.2.2. The bridge R&R-task

Besides the CE-transition, another challenge arises for asset managers: the Replacement & Renovation (R&R) task for bridge infrastructure. After the second World War, a large construction exercise was set in motion, a large part of this concerned (re-)building the infrastructure network. In the Netherlands, there are many bridges and viaducts that were constructed in the period of 1960-1980. Considering the 80-year design lifetime for bridges in that time and the higher-than-anticipated degradation due to increase in traffic intensity and loading, a peak in decommissionings can be expected between 2030 and 2060, as displayed in Figure 3. This peak will cause shortages in funds and capacity when this is not managed properly and timely by spreading out the peak (green line). Bridges represent a significant part of the material mass in the civil sector and therefore have a large impact on Asset Management (AM) and the CE-transition, as it will require vast amounts of (primary) resources and investments (>41 billion Euros for fixed bridges alone, see Figure 4).

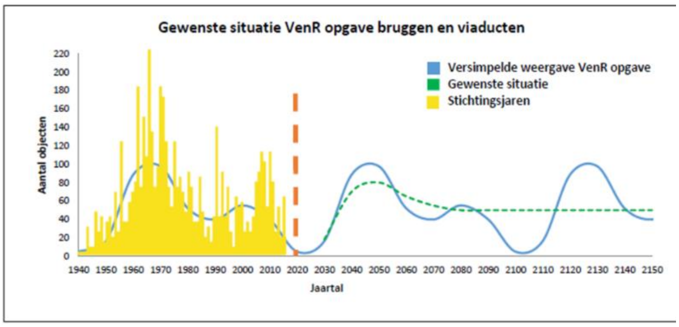


Figure 3: R&R-task decommissioning projection (Schaafsma, 2022)

Infrastructuur	Areaal	Vervangingswaarde miljoen euro
Beweegbare brug	8.457	14.226
Vaste Brug Beton	34.389	19.283
Vaste Brug Staal	10.034	13.538
Vaste Brug Hout	31.693	8.885
Tunnels en onderdoorgangen	3.042	9.119
Duikers	82.642	2.108
Damwanden	779 km	2.961
Sluizen	2.011	239
Gemalen	7.792	448
Kades en steigers	2.423 km	1.939
Stuwen	33.154	249
Overkluizing	182	55
Totaal		**73.049**

Figure 4: Overview R&R-task (Bleijenberg, 2021)

While this challenge poses a threat to AM and the CE-transition, there is also a large opportunity to be captured: reuse of construction elements. Reuse is preferred over recycling due to the ‘downcycling’ of concrete into road foundation, which is not a sustainable process for the CE. However, the foundation of reuse realisation concerns quality asset data that can be used for communicating the available elements to other parties via intermediary reuse databases such as DUSPOT (Duspot, 2023) or Bruggenbank (Bruggen bank, 2023). This data availability is currently very limited, and reuse is only sporadically achieved through intra-organisational systems or one-off innovation projects.

1.2.3. Digitization transition for AM & CE

One of the key drivers for improving the recycling and reuse rates concerns the data documentation of existing structures. More accurate, and high-quality data allows for better opportunities at the end of life of structures. Due to the lack of information registration at time of construction and negligence throughout the asset lifetime, existing assets lack high quality asset data. New infrastructure projects increasingly adopt Building Information Modelling (BIM) and other digital technologies to increase the information quality at handover for better opportunities during the operational phase of the asset and its End of Life (EoL) (Ullah, Lill, & Witt, 2019). This creates a disparity between data documentation of old and new infrastructure, as they require different AM strategies. The transformation of asset data documentation over time is represented (simplified) in Figure 5, clearly showing the differences over time. It can be concluded that a lot of the challenges in the industry (CE, R&R, and digitization) lead back to AM. A large task awaits the asset managers to efficiently navigate through these challenges.

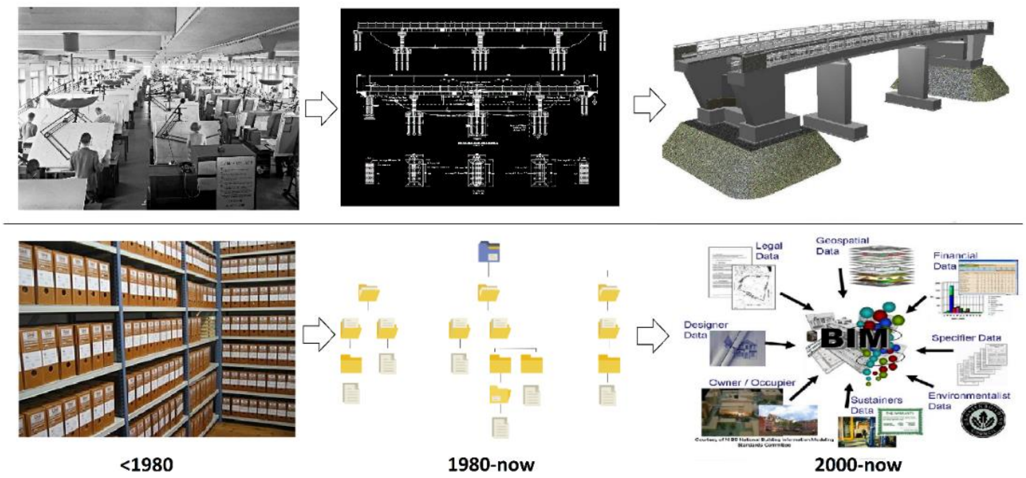


Figure 5: Overview of construction asset documentation over time

1.3. Problem description

CE-transition roadmaps tend to focus its initiatives on laying the foundation to realize a circular construction economy in the future. In doing so, the largest short-term circularity potential is partially overlooked: the existing built environment. Below, three problems surrounding this issue are introduced. Collectively, they comprise the overarching problem statement of this research.

1. Due to changing asset documentation standards over time a large data quality gap is forming between existing and newly constructed assets, upgrading this data quality for improved and centralised AM can currently not be justified because of the large upfront costs and limited budget.

Over the years, construction technologies have advanced significantly by transitioning from 2D hand drawings to Computer Aided Design (CAD) to 3D BIM. During the construction 'boom' in 1960-1980, the asset data documentation standards (design specifications and drawings by hand) were different to that which is currently required for newly constructed assets (3D-BIM). Moreover, AM demands were limited as infrastructure assets were perceived as low maintenance and would be disposed of when deemed unsafe (Lunenborg, 2022). Current asset data storage standards at public organisations are generally incomplete, fragmented across platforms, and very diverse between organisations, with drawings and specifications often (temporarily) lost (Halfawy, 2008) (Janssen, 2022). Consequently, an increasing gap between asset data quality standards between existing and newly constructed assets is forming, requiring different management strategies.

This leaves asset managers with three options: integrating new 3D-BIM assets in the current 2D AM-systems, adopting separate strategies for new and existing assets, or upgrading the existing assets' data quality to semi-accurate 3D-BIM. The first option risks losing valuable information and AM-potential of the BIM-models (current approach), while both the first and second options leave the existing acreage to be managed with the incomplete asset data until they are replaced, which could take at least another 40-50 years. Considering the importance of higher quality asset data on existing structures for the CE-transition and R&R-task (see following sub-statements), the last option is the most logical. However, this requires large upfront investments for data gathering and modelling practices and/or 3D scanning technologies to centralise and upgrade the asset data (Wolbrink, 2023). Practice shows that asset managers prioritize short-term needs (maintenance, renovation & replacements) with the already tight budgets (Halfawy, 2008), and are less inclined to adopt innovation yielding long-term benefits as the required change (new skills & training) hinders the implementation (Attencia & Aperacida de Mattos, 2022) (Lunenborg, 2022). Additionally, the decisionmakers responsible for budget distribution tend to be reluctant towards innovation and digitization for long-term benefits (Mathijssen, Pedersen, Besseling, Rahman, & Don, 2008). Despite the bottom-up awareness on needing to upgrade asset data quality & documentation standards, the traditionally conservative nature of public organisations and limited funding possibilities outside of 'innovation funds' stagnate the digitization transition.

2. Infrastructure asset data input uncertainty for material flow models negatively impacts the reliability and effectiveness of CE-transition roadmap timelines and interventions/initiatives.

The absence of accurate material specifications, remaining lifetime, and material quantities of most existing structures have accumulating consequences on the reliability of material flow models on both local and global scales (EIB & Metabolic, 2022). Especially for infrastructure, the input data is highly uncertain due to poorly maintained centralised data storage caused by the diverging AM-strategies adopted by the individual public organisations and oversimplification and extrapolation of model input (EIB & Metabolic, 2022). The model output is used for developing CE-transition roadmaps, based on which transition timelines are developed, regulations implemented, and investments allocated with respect to the CE-transition (Transitieteam Circulaire Bouweconomie, 2022). Conservative goalsetting (overestimating material stocks) leads to environmental repercussions as it will require less radical changes for the industry and missing the CE-goals as a consequence. While overly ambitious goalsetting (underestimating material stocks) leads to an ineffectively operating construction industry due to the consequent strict goals for reuse/recycling and limitation in material usage which impacts the industry, thereby creating undesired negative economical, safety, and accessibility consequences. Obtaining more accurate bottom-up material quantities and EoL estimates is invaluable for the CE-transition as top-down regulations and investments are generally implemented more promptly with lower uncertainties (Mathijssen, Pedersen, Besseling, Rahman, & Don, 2008) (Rijksoverheid, 2023) (Bleijenberg, 2021).

3. Current asset documentation standards do not allow for efficient (high-quality) information storage on the element level, which is the foundation for conducting and documenting structural & reuse assessments, improving reuse realisation (CE), and managing the R&R-task timeline.

Asset data is the foundation of realising circularity in projects (Drager, Letmathe, Reinhart, & Robineck, 2022). In addition to the absence of material specifications and quantities of existing infrastructure, there is generally also no 3D model with attribute data linked to the individual elements (e.g., geometry, material, reinforcement, condition, etc.) (Janssen, 2022). Firstly, this information serves as the starting point for (re-)approximating the remaining lifetime of structures and its individual elements through structural/reuse assessments. This data then influences the EoL decision-making (replace, renovate, or maintain) for managing the expected decommissioning peak by aligning with (local) contractor availability (both demolition and construction) while aiming to optimize the remaining value of the asset through realising reuse (Bleijenberg, 2021) (De bouwcampus, 2022) (Klatter, 2022). Secondly, without such information and physical representation readily available, linking supply and demand for reuse of (bridge) elements becomes significantly more difficult and the uncertainty profile for the demand side remains high (Copper8, 2022) (Delgado & Oyedele, 2020). Consequently, there is little incentive for exploring reuse in new projects due to the low supply of quality elements in reuse databases, causing large upfront investments for extensive studies on the elements without guaranteed benefits (Kanters, 2022). In doing so, a large circularity potential is wasted, and asset value lost. Lastly, because little is known about the physical structure of the asset, maintenance and demolition/deconstruction activities could require additional site visits for preparation, this could partly be avoided and optimized with 3D BIM data (Van den Berg, 2019) (Delgado & Oyedele, 2020).

Due to the incomplete, fragmented, and diverging data quality and documentation standards on existing infrastructure and limited funding availability at public organisations, AM-practices, the R&R-task and short-term circularity realisation are extremely complicated, there is not yet a cost-efficient method available to upgrade this data quality and accelerate the digitization transition.

1.4. Research questions

Main research question:

How can centrally stored, quantified, and visualised asset data of existing infrastructure impact the CE-transition, bridge R&R-task efficiency, and AM practices?

*Quantified by means of registered asset data as well as physical material quantification.

Sub research questions:

1. What is the impact of the lack of available high-quality asset data on existing infrastructure on the CE-transition and the R&R-task?
2. What are the current standards for data availability and documentation, what led to this present lack of asset data, and what future developments can be expected in AM?
3. What is the potential performance and impact of a modular parametric design tool for fixed bridge infrastructure on the digitization transition at public organisations?
4. What are the practical implications of the research findings on the construction industry and asset management in the context of the digitization-, CE-, and R&R-challenges?

1.5. Research & development objectives

The aim of this research & development project can be divided into the following objectives:

1. Obtain industry perspective on asset data availability & documentation practices at Dutch public organisations, the barriers they face and ambitions they have for the CE-transition, R&R-task, and digitization challenges.
2. Describe the urgent need and potential of upgrading the existing assets' data quality and developing a roadmap for asset managers on transitioning to 3D centralised AM and better manage the R&R-challenge and CE-transition goals ahead.

3. Develop cost-efficient design tooling for obtaining semi-accurate 3D-BIM of fixed bridge infrastructure to decrease the investment threshold for public organisations and accelerate the transition to 3D centralised AM.

In doing so, the following indirect objectives are targeted:
1. Enhance MFA data input certainty for bridge infrastructure to increase output reliability and improve CE-transition roadmap goalsetting and policymaking (guidelines, regulations, & investments).
2. Provide a better data foundation and storage potential for conducting reusability- and structural assessments in the context of the CE-transition and R&R-task management.
3. Increase reuse realisation of bridge infrastructure objects in practice by enabling low-effort saturation of reuse databases with 3D-BIM elements to decrease risk and incentivizing more research into the applicability of reused bridge elements.

1.6. Scope
To limit the scope of this research and development study, the scope was confined by the limitations stated below, a distinction is made between the research aspect (literature study & interviews) and the development aspect (design tool and roadmap for AM).

1.6.1. Research scope
The qualitative literature study was first and foremost confined to the CE-transition within the context of the Dutch construction industry. Considering the scope of this topic on its own, this part was constrained to providing an overview of some of the most important aspects to set the stage for the rest of the research. As the study progresses, the scope was further limited to the role of existing infrastructure assets in the CE-transition. Consequently, fixed bridges (predominantly built between 1960-1980) were singled out for their role in the R&R-task and potential for reuse realisation. Then, the study was limited to AM-digitization transition in the construction industry with the focus on asset data documentation from 1950-2040. Lastly, a look into the state of the art was presented to reflect on the findings and provide perspective. In conducting this research, the main target group concerns public organisations that own and manage infrastructural objects and designers at engineering firms. Through semi-structured interviews, the perspectives of a variety of asset managers from public organisations and experts from an engineering firm (W+B) were included in the research to validate the literature findings and provide boundary conditions for the tool development. The public organisations included two municipalities and a province.

1.6.2. Development scope
The design tool was developed for public organisations, used by designers, and utilises Revit, Dynamo and Excel software. This software was selected for adoptability and comprehensibility reasons. The development time was restricted to 1.5 month. The tool is limited to concrete beam- and plate bridge structures as these have the largest reusability potential (derived from literature study) and are most common in practice. It is furthermore limited to the most essential structural elements and elements with reuse potential. The level of detail of the tool-output geometry was set to LOD400 as a baseline and LOD500 for elements with higher reuse potential as gathered from the literature study, reinforcement approximation is therefore excluded. Moreover, the output is limited to providing the possibility to store higher quality asset data (LOD700) of what can be gathered from the project drawings and specifications, this data extraction potential is not further researched. Considering the limited time allocated to the development, the final script was a proof-of-concept (prototype) with

limited design variants. To validate the tool output, 4 'new' projects were tested against their 3D model developed by W+B using only the 2D drawings as input. The tool aims to solve a part of the larger goal for all infrastructure assets at public organisations. To accompany the tool, a roadmap was developed for asset managers to guide the transition towards 3D centralised AM and a reuse economy. While this roadmap was developed with bridges in mind, it applies to all infrastructure types. To limit the scope, it was constrained to 9 steps including description, information requirements, examples, and advice for execution. As each step does not have one objectively correct approach, the details remained open considering the differences between organisations.

1.7. Research relevance

The research relevance is divided in three points linked to the problem statements, described below.

1. Exposing the urgency of improving asset data quality & documentation of existing infrastructure for the digitization transition at public organisations and providing tooling to accelerate this process.
From a scientific point of view, this research contributes to the general understanding of some of the major challenges in the construction industry for the coming decades. One of these challenges concerns the fragmentation and lack of detailed asset information on existing assets to effectively manage the R&R-task and CE-transition demand for reuse. To address this issue, digitization of AM is essential as it provides asset managers with numerous opportunities including improved decision-making quality for AM, facilitating centralised storage for better information communication and traceability (saving time and omitting the need for constant site visits), optimization potential for the supply chain and maintenance activities, among many other benefits (Attencia & Aperacida de Mattos, 2022). Besides these benefits, digitization is perceived as an enabler for CE initiatives (Elghaish, et al., 2022). Knowing the importance of digitization in this context, this research contributes by analysing the barriers that currently stagnate this transition in practice and aims to discretize the problems that result from this such that it urges the industry to put effort into finding solutions.

From a practical perspective, this research contributes to providing a novel (partial) solution to one of the key barriers for digitization at public organisations: the high upfront costs required for upgrading the asset data to 3D-BIM. In doing so, allowing public organisations to accelerate their digitization transition and facilitate other challenges in the industry.

2. Addresses the gap of tooling for quantifying infrastructure assets to improve global & local MFA.
This study adds to the current literature field of MFA of the anthropogenic material stock as it addresses the gap of tools and methods that aim to address the input uncertainty. MFA is an important tool for the CE-roadmap development as it governs the timeline of milestones, the implementation of regulations, and allocation of budget. Considering the urgency and impact of the construction industry on the CE-transition, the consequences for inaccurate decision-making and goal setting can be detrimental to either the environment (overly conservative goals) or economy (overly ambitious goals). Current studies that aim to reduce this input uncertainty predominantly focus on the building sector and employ top-down methods due to the lack of individual asset data. While obtaining bottom-up material quantity data currently yields little benefits for AM.

This study contributes to solving part of a larger problem by providing tooling to approximate material quantities of existing fixed bridge infrastructure more accurately to reduce data uncertainty for MFA. When adopted on a large scale, MFA reliability on both local and global scales can be improved through more accurate data input, thereby also impacting CE-transition roadmap effectiveness.

3. Addressing the CE-transition and R&R-task challenges by developing tooling to obtain better data foundations for conducting and documenting reusability and structural assessments as well as a roadmap for transitioning to 3D centralised AM and a reuse ecosystem.
The CE-transition is widely regarded as the most impactful change to the construction industry in recent decades and requires significant changes in the deeply rooted methods that shape the current practices. Whereas most current efforts and initiatives from CE-transition roadmaps and literature recommendations focus on laying the foundation for a future CE, this study aims to lay the foundation for leveraging the enormous reuse potential of existing infrastructure and the bridge R&R-task. Short-term reuse realisation is essential for meeting the CE-transition goals set by the Dutch government. The bridge R&R-task provides a great opportunity to leverage these ageing assets for reuse but is currently scarcely explored due to the lack of asset information. Consequently, many resource are going to waste as recycling of the most important construction material: concrete, is far from being a sustainable process for a CE due to downcycling. This research focuses on the role of this lack of asset information of existing infrastructure on short term circularity realisation and efficient management of the bridge R&R-task. Moreover, the interdependencies between the digitization transition, CE-transition, and R&R-task are analysed to assess the changes required in the industry.

While the tooling developed in this research does not directly solve the information need to the degree required for conducting the assessments, it does provide a data foundation where the currently available data is centrally stored to streamline these processes through the design tool development for semi-accurate 3D-BIM. The prototype that is developed in this study could also be further developed for more automated (preliminary) structural/reusability assessments once the level of information detail is upgraded. On the short-term, the output model elements can be communicated in reuse databases to improve the currently poor supply quality and increase reuse exploration activity. Moreover, this study adds to the overarching challenge for asset managers to transition to 3D centralised AM and standardizing reuse practices in projects by providing a roadmap that provides an overview of what is required, supported by examples and advice on how to execute.

1.8. Methodology

In this research and development project, two frameworks have been adopted to structure the methodology, these are the double diamond model and Information Systems (IS) theory for design. The former primarily being focussed on process, while the latter also adds structure on the products. Additionally, a development method was adopted to ensure an efficient development process. First these frameworks will be explained, followed by an overview the research steps.

1.8.1. Double diamond model

The double diamond model, presented in Figure 6, is a simple model used in design processes that distinguishes four phases in the design process. The first two phases make up the first diamond, that goes from a broadly defined problem (diverge or discover) to something concrete through research (converge or define). The method is explained using the definitions from the Design Council (DesignCouncil, 2019). The discover phase asks the designer to dig into the true origin of the problem to understand rather than assume everything related to it. Once this knowledge base is developed, the designer is required to discretize this broad problem into a concrete problem definition that can be solved. The second diamond concerns the development of a solution for the problem defined at the end of the first diamond. Again, this starts by diverging (the now concrete) problem into potential solutions and gathering information, data, and knowledge required to make a substantiated decision on the design approach. This solution is then further preprared and executed until a final product is delivered. In this research, the final delivery will be a prototye of a parametric design tool for bridges. How this model is integrated in the research is explained in section 2.7.2.

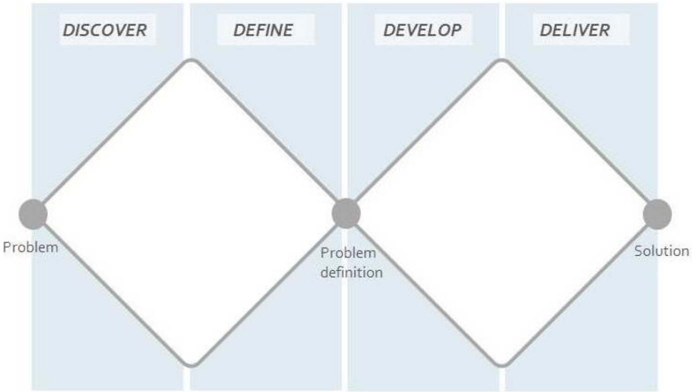


Figure 6: Double diamond model (University of Copenhagen, n.d.)

1.8.2. Information systems theory

For this research and development study, the IS theory is adopted to provide further structure to the research setup. The IS concept is closely linked to this research first by the interrelatedness to AM and BIM and secondly by the design of a new system for generating information as an objective of this research. The focus of design in information systems is on design of IT artifacts. Markus et al. (2002) adopt a more practical view of design theories by using these theories to explain the means– ends relationship as a practical, prescriptively causal mechanism to justify design components. This definition of IS theory was also embodied in this research through the development of a design tool. Figure 7 displays the model that is used as a frame of reference throughout this research.

In this framework, the environment defines the problem space in which reside the phenomena of interest (Simon, 1996). Within this environment, the business needs are assessed and evaluated in the context of organizational strategies, structure, culture, and existing business processes. They are positioned relative to existing technology infrastructure, applications, communication architectures, and development capabilities. Together these define the business need or 'problem' as perceived by the researcher. Given such an articulated business need, IS research is conducted in two complementary phases. Design science addresses research through the building and evaluation of artifacts designed to meet the identified business need. Purposeful artifacts are built to address heretofore unsolved problems. They are evaluated with respect to the utility provided in solving those problems. In this research, a model artifact is constructed (guideline 1, Figure 8). Models use constructs to represent a real-world situation – the design problem and its solution space (Simon, 1996). A differentiation is made between routine design and design research, where routine design refers to applying existing knowledge to organisational problems using best-practices and design research addresses important unsolved problems in unique or innovative ways.

In this research, the environment would be described as asset managers of public organisations in the construction industry that are faced with the digitization transition, CE-transition, and R&R-task. These challenges form the context for creating the relevance, or business need to improve their asset data quality and documentation strategy. The knowledge base concerns parametric design & engineering theory, bridge design and practice, AM practices, and BIM theory. Rigor is achieved by appropriately applying existing foundations and methodologies on the 'business needs' to create the IS. The development concerns a parametric model for bridge design that is continuously evaluated and refined using real-world data. Although PEM is not a new method in bridge design, the application that is being used in this research has not been done in this scale to the best knowledge of the author. The research is therefore justified as 'design research'. Within this framework, the guidelines presented in Figure 8 were continuously kept in mind throughout the research and will be referred to in section 1.8.2.

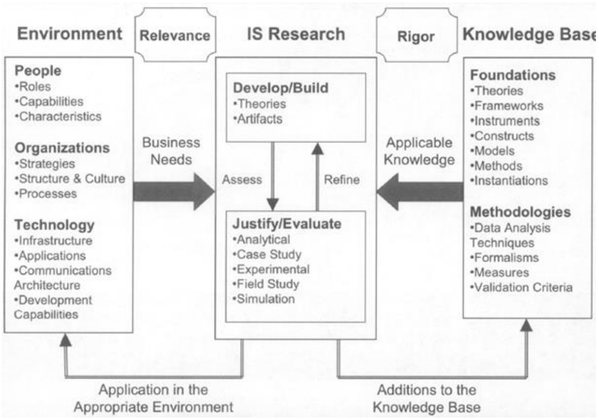


Figure 7: IS research framework (Hevner & March, 2004)

Guideline	Description
Guideline 1: Design as an Artifact	Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
Guideline 6: Design as a Search Process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

Figure 8: Guidelines IS framework (Hevner & March, 2004)

1.8.1. Build-measure-learn loop

To build upon the build-and-evaluate loop introduced in the previous section, a framework developed by Eric Riess (2011) was used: the build-measure-learn loop. This method was used purely for the development phase of the tool and adopts a perspective of a start-up. The concept is simple, once an industry problem and a potential solution are identified, the designer forms a set of 'leap-of-faith-assumptions' about the solution space that are required to be true were the innovation to succeed. After eliminating the 'low-hanging-fruit' assumptions through interviews, the designer builds a Minimum Viable Product (MVP) to start testing the remaining assumptions. This MVP is to be as basic as possible to validate the assumptions it sets out to test. From this testing/measuring (technical or commercial), the feedback is used to develop a follow-up MVP to test more assumptions. By implementing short feedback loops, ineffective design efforts can be avoided. See Figure 9 for a visualisation of the method.

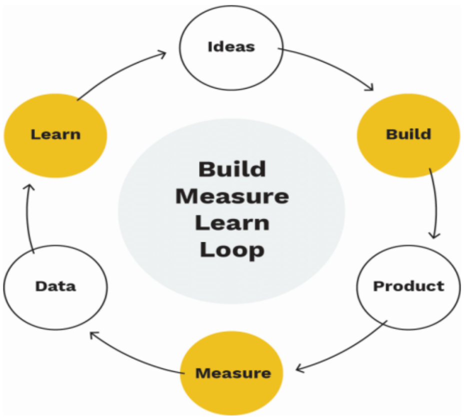


Figure 9: Build measure learn loop (Stankevičius, 2018)

1.8.2. Research setup

The research methodology overview is presented in Figure 10. In this graph, the research steps are indicated in groups (coloured boxes). Additionally, the research sub questions (RSQ) from section 2.3 are linked to the respective sections in which they are (predominantly) addressed, though they will be answered in the conclusion. In the background, the double diamond model indicates what phase each research process is located in. Below, each step is discussed individually in more detail.

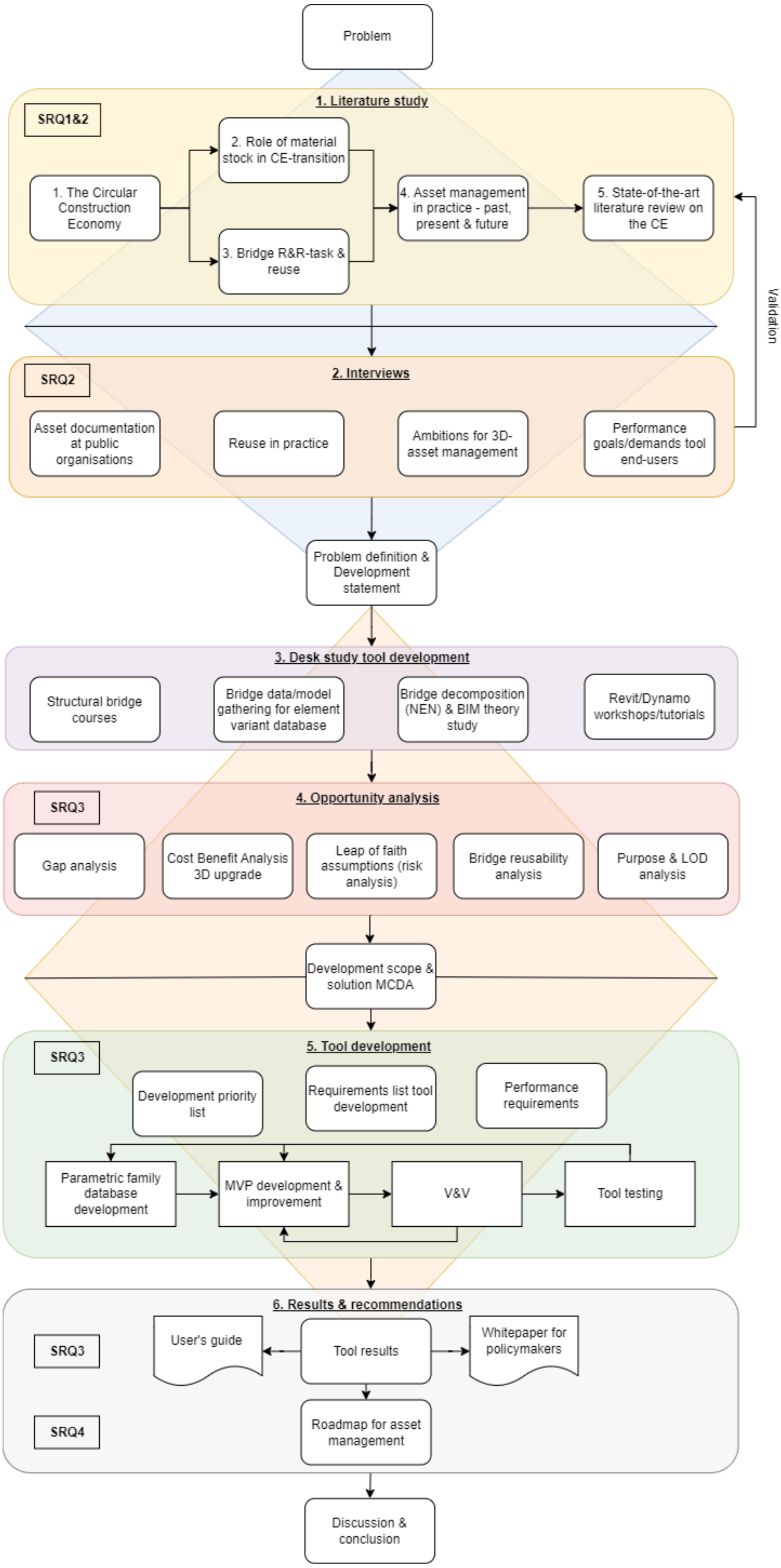


Figure 10: Research overview

1.8.2.1. Literature study (diverge)

The literature study comprises of four sections: 'The circular construction economy', 'The role of material stock in the CE-transition', 'Bridge R&R-task & reuse' and 'Asset management in practice – past, present & future'. Last three mentioned relate to RSQ1 &2. To enforce the findings in this study, a review of the state-of-the-art on the CE transition was conducted. This study represents the 'discover' stage in the double diamond model to obtain more knowledge about the overall problem described in 2.1 and aims to validate its assumptions. A qualitative approach was adopted to obtain the information for this study, mainly through consultation of literature on the key-concepts and deriving relevant studies from there, supplemented by (Dutch) national transition pathway documents. The first section introduces the CE, the recurring theme throughout this research. Then, the research questions are investigated separately, and related to a second recurring theme: asset management. Finally, the conclusions were bundled in the summary to present the problem at hand.

1.8.2.2. Interviews (converge)

The next step in this study concerned interviews with asset managers from various public organisations to validate the literature study findings, assess the data quality and documentation standards, gauge the ambitions/plans for digitization, reuse realisation, and managing the R&R-task, and performance demands for a potential artifact. Additionally, W+B experts were interviewed informally regarding design standards, practices, and industry insights. The interviews were semi-structured to allow for improvised follow-up questions based on the interviewee's responses. With permission, the interviews were recorded for documentation purposes only and have been deleted afterwards. This section marks the start of the conversion process of 'defining' in the double diamond model. Collectively, the literature study and interviews describe guideline 2 and RSQ2.

1.8.2.3. Desk study tool development (diverge)

Once the problem was defined, a new diverging phase commenced: 'develop'. Here, a knowledge platform was constructed within the domain of the development statement by means of a desk study. This desk study included four sections: structural bridge design courses, bridge data gathering, bridge decomposition (NEN-2767) standard and BIM theory, and Revit & Dynamo tutorials/workshops. Courses that were followed included Concrete bridges and Steel Bridges at the TU Delft. This knowledge platform allowed the author to develop and assess potential solutions on feasibility, robustness, and impact in the following stages. The intermediate findings of this section are not directly documented in the report. This research step ensured guideline 5.

1.8.2.4. Opportunity analysis

Next, the opportunity emerging from the problem definition was explored and documented in the development statement. Then, the 'market gap' was analysed by addressing the functionality of PEM in the context of bridge modelling and a market analysis was performed on existing tools within this domain to ensure the contribution to the to-be-developed artefact's domain (guideline 4). Secondly, a Cost Benefit Analysis (CBA) was conducted using traditional modelling practices for upgrading an example municipality's acreage from 2D to 3D and the benefits of 3D centralised AM from the literature review. These results were later be used as benchmark to quantify the potential artifact's performance. Then, 'leap-of-faith-assumptions' were drawn up to analyse the business case dependencies. Consequently, a reusability analysis was conducted on fixed bridge infrastructure and the elements of the most promising category. Finally, the Level-of-Detail (LOD) requirements for the tool output (3D BIM models) were drafted by analysing its purpose in practice, that being asset management, realising circularity and material quantification. In doing these analyses, the artifact's utility, quality, and efficacy would be demonstrated (guideline 3), and the solution space was set.

1.8.2.5. Tool development (converge)

Using the previous steps, the development scope was drafted. This provided the framework for developing potential solutions and selecting the final design using MCDA. With the selected concept, multiple development loops were executed as presented in Figure 9, using Revit 2023, Dynamo visual programming (integrated in Revit), BIM theory and Excel. This software was selected as they are considered standard practice in the industry. Due to the time constraint for this research, four development loops were realised as described below. Each development round was concluded with a customized Verification & Validation (V&V) process based on its respective development goal set. The end-product of the development process concerns a prototype of the desired tool to demonstrate its potential in practice before expanding the scope (guideline 6).

1. Basic functionality of a bridge model using (1) pre-modelled family per element, restricted to the fundamental bridge elements. Technical validation of the concept within modelling environment and end-goal perspective.
2. Expanding design elements and optioneering possibilities within the tool. Tested against bridge databases for model robustness.
3. Integrating automated material passports. Tested with BIM-theory and expert knowledge.
4. Increase number of design variants per element to 2 or 3 and optimize runtime efficiency and usability. Validation on performance metrics with real projects with feedback to users (designers) and end-user (municipality).

1.8.2.6. Results & recommendations

To conclude, the tool performance was tested against real project data (2D drawings & 3D model) obtained from design projects at W+B. The quantitative performance metrics included required modelling time and model accuracy. Moreover, three qualitative metrics were included that assess the adoptability and adaptability of the tool for additional purposes, and the theoretical robustness of the design tool using a bridge dataset. Next to testing, a user's guide was developed to facilitate future users (designers) to yield consistent results and provide the opportunity to expand the robustness of the tool by contributing to the family database and script. The user's guide was developed with the desired outcome of the tool in mind: large scale adoption in the industry and improving AM and circularity realisation. In addition to the user's guide, a white-paper was developed to introduce the tool to policymakers to push for the use of this tool within organisations to incentivize top-down implementation. In doing so, adhering to guideline 7. Consequently, the tool's potential value was placed in perspective by analysing the future positioning in the market using an implementation timeline, data availability scenarios, and expert insights from public organisations and W+B. To conclude this research, a roadmap for asset managers was constructed based on the literature study, interview findings, and expert knowledge to provide the asset managers in the industry with tangible steps to execute for efficiently managing the digitization transition, CE-transition, and R&R-task.

Chapter 2: Literature study

This literature study comprises of five sections. The first section entails a general overview of the Circular Economy transition within the construction industry, providing context for the industry's most radical transition in recent time and lays a foundation for the following chapters. The second section dives deeper into the role of existing infrastructure in the CE-transition and the impact of material flow modelling. Next, the bridge Replacement and Renovation (R&R) task is introduced in section three, which will play a large role in the asset management discipline the upcoming decades. Tied into this section is the function of reuse in relation to the R&R-task and CE. The fourth section addresses a recurring theme in the previous sections: the lack of high-quality asset information on existing (bridge) infrastructure and how this can be explained from a literary perspective. This section also includes an overview of the ongoing digitization transition and how this affects current- and future asset management practices. Section five represents a literature review of the state-of-the-art on the CE-transition to put the findings of sections 1-4 in perspective. A summary of the key findings of the study is presented in Appendix: A.

2.1. The Circular Economy transition in the construction industry

The construction industry is one of the major contributors of environmental emissions. The involved processes (resource mining, transportation, manufacturing, construction & operation) and final disposal cause serious environmental harm, specifically air, soil, and water pollution (Shen, Lu, Yao, & Wu, 2005). When also taking into account the predicted population growth from 8 to 9.7 billion people by 2050 (UN, 2022), a middle class population increase from 2 billion to over 4 billion people by 2030 (Kharas, 2017), and the global urbanisation trend, the need for construction will only increase. Furthermore, the materials become more scarce with time due to the limitation of natural resources (Hossain, Ng, Antwi-Afari, & Amor, 2020). These findings are counteractive, and a solution needs to be found as the business-as-usual approach will only enlarge the climate change problems. In the table below, a variety of sources indicate the magnitude of impact the construction sector has on the environment and resources. The variation in values can be attributed to the boundary systems adopted by the researchers. For example, the inclusion of operational phase can increase the emission profile of buildings significantly, while including developing countries can impact the solid waste output due to less strict regulations (Probert, Miller, Ip, Beckett, & Schofield, 2010).

Table 1: Construction industry scale impacts on climate

Scale	Carbon emissions	Resource consumption	Solid waste
Global (Khasreen, Banfill, & Menzies , 2009)	50%	20-50%	50%
Europe (Carvalho, Braganca, & Mateus, 2019)	32-40%	40-50%	25-30%

The table indicates the urgency to mitigate such impacts is urgent and highlights the responsibility the construction industry carries with respect to the climate change transition. Traditionally, the construction industry has worked with a linear economy model of the material flows where materials are 'taken' from nature and disposing them after End-of-Life (EoL), as presented in Figure 11. Over the last decades, a paradigm shift has slowly been taking place in the industry at large, with the adoption of a CE-model (Benachio & Freitas, 2020). This model aims to keep the materials in a closed loop to retain their maximum value, therefore with a greater potential of reducing the waste production and resources extraction for the construction industry (Platform CB'23, 2020). A CE thus contributes to the comprehensive sustainability task we are facing: combating climate change, loss of biodiversity, and the overburdening of our planet. Knowing this, the trigger needs to be pulled to fully adopt the CE-model as soon as possible (Platform CB'23, 2020).

The new circular construction model is displayed in the right section of Figure 11. The CE-model is based on 4 principles: reducing raw material usage through rethinking, sharing, or increasing efficiency, extending lifetimes through reuse and maintenance, increasing recycling technology efficiency to keep materials in the chain and introducing renewable biobased materials to replace non-renewable and harmful materials (Transitieteam Circulaire Bouweconomie, 2022). In this model, the taking and disposing of materials as represented in the linear model are omitted and replaced by biobased renewable materials, recycling, and reusing materials from the structure at EoL. It is thereby a closed loop system as materials stay in circulation for the long durations. It is the ambition of the Dutch national government that the economy should be entirely circular by 2050 and the use of primary raw materials should be halved by 2030 (Rijksoverheid, 2016).

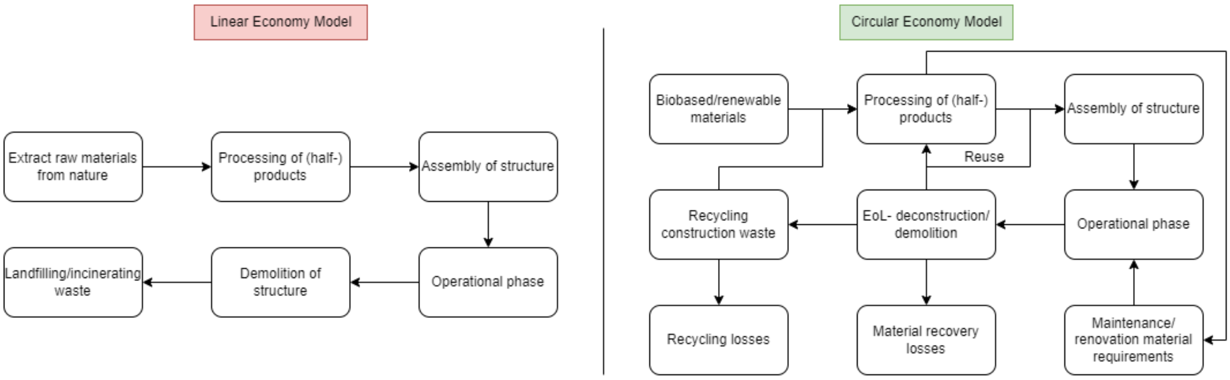


Figure 11: Linear & circular economy models

In literature, many definitions have been attributed to the term 'circular economy'. In this research, the following integrated definition has been adopted for the circular construction economy: "The use of practices, in all stages of the life cycle of a building or infrastructure, to keep the materials in a closed loop as long as possible through repair, reuse, and recycling methods Thereby reducing the use of natural resources in a construction project, all while considering the restorative, regenerative, and physical limitations of resources within our planets boundaries." (Abrelpe, 2018) (EMF, 2015). Considering the deep-rooted methods and the sheer size of the construction industry, as indicated by the figures in Table 1, this transition is not an easy process by any metric. However, there is increasing awareness on the value of resources and the importance of using them sensibly, which brings the CE concept to the frontline for conserving the value of resources and promoting their efficient usage (Sfakianaki, 2015). This awareness is reflected in the market by a developing movement to reduce material and energy consumption during the design, construction, operation, and decommissioning phases, as well as in the academic world by the increased attention in research in recent years (Hossain, Ng, Antwi-Afari, & Amor, 2020). Despite the increasing awareness, the CE-transition is still in its early years in the construction industry. Below, first the barriers for adoption are briefly discussed, followed by the trends, tools, and techniques (or: initiatives).

2.1.1. Barriers for adoption of the circular economy model

For the analysis of the adoption barriers of the CE-model, the PESTEL model was used: or Political, Economic, Sociological, Technological, Environmental & Legal. Charef et al. (2021) and Wuni (2022) have conducted a critical reviews of journal papers where barriers for the circular construction economy were analysed. The key findings of these papers are synthesized in the PESTEL-format with additions from other studies referred to separately. The full analysis can be found in Appendix: A, with a summary of each analysis point provided below.

Political

The major political obstacles are the lagging regulations for enforcing circularity in projects and standardization of practices. Without regulations, circularity efforts are often the first that fall in projects. Without standardized practices, project teams are unsure on how to execute circular concepts in projects as it involves larger risks and uncertainties compared to traditional methods. Governmental bodies tend to be risk averse as they represent the taxpayer's money, also leading to dropping circularity efforts first in projects. Moreover, policymakers generally tend to allocate funds to projects with short-term benefits for their personal gain, delaying projects with long-term benefits that are highly necessary for the CE-transition. Due to the decentralized management system in the Netherlands, a unified approach is lacking, as organisations tend to develop their own agenda's.

Economic

There is a general lack of budget at governmental bodies to push for circular concepts to be integrated in 'all' projects. Circular projects demand higher upfront costs (for research and measurements) with benefits that often materialise far in the future, making them uncertain and difficult to quantify. Consequently, this requires innovation funds to pay for innovative pilots, while these funds are limited. Moreover, using raw materials is (still) financially more attractive than integrating circularity. As the construction industry is known for its tight margins, unnecessary risks caused by circular concepts are generally not welcomed, especially with the global economic trends.

Sociological

The construction industry is traditionally a highly conservative industry, transitioning away from the deeply rooted methods and practices will take time. Global trends like population growth and urbanization calls for higher productivity while resource consumption is to be reduced, these trends are counteractive. Moreover, the perception of reused elements is generally 'low-quality', thereby disincentivizing reuse as safety is the top priority. Decision-makers are often seniors who have worked their career one way and tend to be slower in adopting the new methods unless it is forced. Similarly, companies wait until methods and technologies have diffused before making the transition.

Technological

There is a lack of asset data on existing infrastructure that complicates circularity assessments and projections of the waste streams and secondary material availability. Without this data, it is almost impossible to realise reuse of elements due to the large uncertainties regarding strength and dimensions. Recycling companies are currently unable to upcycle concrete, therefore requiring large amounts of raw materials for civil structures and buildings in the foreseeable future. Moreover, biobased material research is still too immature to replace raw materials and is physically limited.

Environmental

Reusing materials is mainly constrained to local scales due to the logistic and environmental impact constraints of transportation, limiting supply and demand. Deconstruction and material separation is also limited by site constraints and time-sensitiveness. More importantly, there is a projected imbalance in construction waste output and material demand in the next decades, even when 100% of materials are upcycled or reused, requiring more raw materials to meet this demand/productivity.

Legal

Integrating reused elements into new designs increases project risk, the traditional liability schemes can therefore not be used as it exposes the contractor to (too) much risk. Additionally, safety and functionality standards need to be revised to allow more reused elements in projects. Tender specifications and awarding criteria are not always aligned with respect to the ambition for circularity integration in the project, making it difficult for circular bids to win. When parties do win, they often refuse to share their data to keep a competitive edge for following projects, thereby slowing down the transition. Current standard contracts are generally not the most suitable for enabling circularity.

2.1.2. CE-initiatives

With the previously discussed barriers towards the CE, significant initiatives are required to overcome these barriers. This goal of this section is to provide an overview of some of the main developments and trends (concepts/technologies/processes) that are being-, or need to be, realised to achieve a circular economy. It is by no means a complete list of every initiative and should not be construed as such. With this overview, the reader is informed on the ongoing changes in the context of the construction industry and the CE-transition, this should provide a knowledge base to have a better understanding of the concepts discussed in the following sections. It is not the purpose to provide an in-depth analysis of how these mechanisms work or should be deployed in practice, as this is beyond the scope of this research.

The CE-transition is driven by client demand, industry action, increasingly strict regulations, and technological developments (Abrelpe, 2018). The client demand is a market pull mechanism, where clients (generally public organisations) demand for more circularity integration within their project specifications and awarding criteria in tenders. Industry action on the other hand is a market push mechanism, as companies integrate circularity concepts in designs, develop new methods and tools to push for circularity without it being specifically demanded by clients. Increasingly strict regulations ensure that the bar for circularity integration is gradually improved, which pushes the industry to find new solutions to adhere to these regulations. Central in the CE-transition is the development of technologies that enable the realisation of these new regulations.

Below, the main initiatives are summarized, for more extensive discussion, see Appendix: A. In this analysis, the main sources were the (Circulaire Bouweconomie, 2018) & (Platform CB'23, 2020), complemented with literature where indicated. It is recommended to the reader to familiarise with these concepts in the Appendix before continuing reading, however this is not mandatory.

1. Development of standards and information exchange platforms to increase awareness and realising a unified approach and knowledge platform within the industry.
2. Rules & regulations for enforcing circularity measurements and integration in projects.
3. Education & training to prepare the current- and future workforce optimally to realise a CE.
4. BIM-based projects for more accurate asset data during operation and EoL, automized material passport generation & improved reuse communication.
5. Material passports for improved traceability of asset information, circularity performance and EoL-value.
6. Material databases to centrally store all asset data for improved transition management and creating a material market for (reused) construction materials.
7. 10-R’s framework to guide both asset managers and project teams in selecting the most circular pathway.
8. ‘Design for’ – strategies and prefabrication to ensure that structures can be deconstructed, adapted, and (partly) replaced more efficiently in the future.
9. New contract types & business models that incentivize circular efforts and better fit the new environment.
10. Research & Development into upscaling and upgrading recycling technologies and biobased material construction to phase out raw materials faster.

Considering the variety of initiatives, coherent strategies are required to put this into practice in a structured manner. There are diverging strategies and agreements written out by organizations on different scales (UN, EU, national, regional), the objectives for the Dutch construction sector are set out in the Transitieagenda Circulaire Bouweconomie (2018) and the associated implementation programme (De Bouwagenda, 2018). Other notable platforms are the Buildings as Material Banks pathway for a circular future setup by 7 European countries (BAMB, 2020), and Platform Circulair Bouwen ’23 (Platform CB’23, 2020). Despite the differences in target groups, scale, and time-horizon, they have the same overarching goal and are all necessary to realise a CE in 2050. However, after analysing their contents, it was concluded that the initiatives predominantly focus on developing a built environment where circularity is more accessible in the future, while there are remarkably little concrete efforts in overcoming the lack of data on existing assets that enables short term circularity.

2.2. Material stock & existing infrastructure

This chapter discusses the role of this existing built environment in the CE-transition and the importance of material flow modelling in relation to transition roadmaps. Then, a deeper dive into existing material data acquisition methods is conducted to uncover what is missing in practice.

2.2.1. Material stock interaction

Material stock can be divided in two sections: natural material stock and anthropogenic material stock. The former being materials that are nested in the earth and yet to be extracted (primary materials) while the latter concerns extracted materials currently stored in infrastructure and other products developed by humankind. The balance between natural and anthropogenic stock is key in phasing out raw materials, as together they make up the material availability for construction activities (among other industries) (Winterstetter, et al., 2021). This relationship is represented in eq. 1. A final distinction is made between renewable and non-renewable resources, where metals and aggregates are considered non-renewable while wood and hemp are renewable, or ‘biobased’. Currently, biobased materials have a share of ~2.1% in the material input in construction (NIBE, 2019).

$$\textit{Material demand} = \textit{primary materials (NR*)} + \textit{secondary materials} + \textit{biobased materials} \qquad (1)$$

*NR = Non-Renewable

The larger the anthropogenic stock becomes; the more materials will become available for reuse and recycling from the built environment in the future (secondary materials). When the secondary material potential increases, less raw materials are required to meet a certain material demand for construction. Extracting raw materials is becoming increasingly more difficult due to the implementation of EU and national regulations, the environmental impacts involved, and resource depletion; more ores are required to be mined per additional unit of resource (Vieiera, Pensioen, Goedkoop, & Huijbrechts, 2017). As biobased materials are constrained to planetary limitations and secondary materials input dependent on the output of the built environment and recycling & reuse technologies, the only remaining variable to account material demand fluctuations raw material extraction. Both secondary and renewable resource stocks need to be enlarged to drive down the dependency and share of non-renewable primary materials in construction. Another solution is to drive down future material demand, however this is more complicated as it directly impacts quality of living (Zou & Ergan, 2019). The paradigm needs to shift from extracting resources from mines towards viewing the existing built environment as a material bank (Capelle, 2019). To do so, structures need to be deconstructed, elements reused, and the remaining waste materials recovered and recycled (with high value).

2.2.1. Material flow modelling

Now that the impact of the existing built environment has been construed, Material Flow Analysis (MFA) practices are introduced. First the two applications are introduced in the context of the construction industry, after which two major issues with the current state of material flow modelling practices are discussed.

2.2.1.1. Global scale

Material flow modelling on a global scale models a region's (country, EU, world, etc.) balance of material consumption and production over time, to develop suitable guidelines and regulations. In such studies, the local aspect of materials is disregarded for simplicity. Global scale models generally take a smaller representative sample size of a certain dataset (e.g., satellite data area, asset type, etc.) that is then extrapolated to the entire boundary system using statistical data on the sample data. In doing so, making assumptions and simplifications of the real world to limit complexity. With this data, the total anthropogenic material stock can be approximated, and secondary material flows can be predicted. Combining this with statistical projections on reuse- and recycling rates over time and material demand predictions based on market trends and data (e.g., housing need, expected renovations & replacements, etc.), the raw material requirements can be mapped out over time. This process is schematized on the left side of Figure 12.

The main variables in a global material flow model that can be influenced by policy interventions concern the recycling and reuse rates and the material demand for construction. With this model, scenarios can be generated where these variables are simulated over time to obtain a transition pathway. Based on this information, more realistic roadmaps can be developed, and regulatory and financial instruments can be implemented in line with the model output to help ensure that the CE-goals will be met. Moreover, due to the constant changes of development plans, regulations, and innovations in the industry, this model needs to be updated continuously such that the output represents reality as accurate as possible, and strategies can be adjusted accordingly. The downside of this modelling approach is the uncertainty that is involved with extrapolation of data and simplification of the real world, as shown by the EIB & Metabolic study (2022). To minimize the uncertainty of these models, more accurate material quantity data of assets is required from bottom-up to increase the robustness of the dataset.

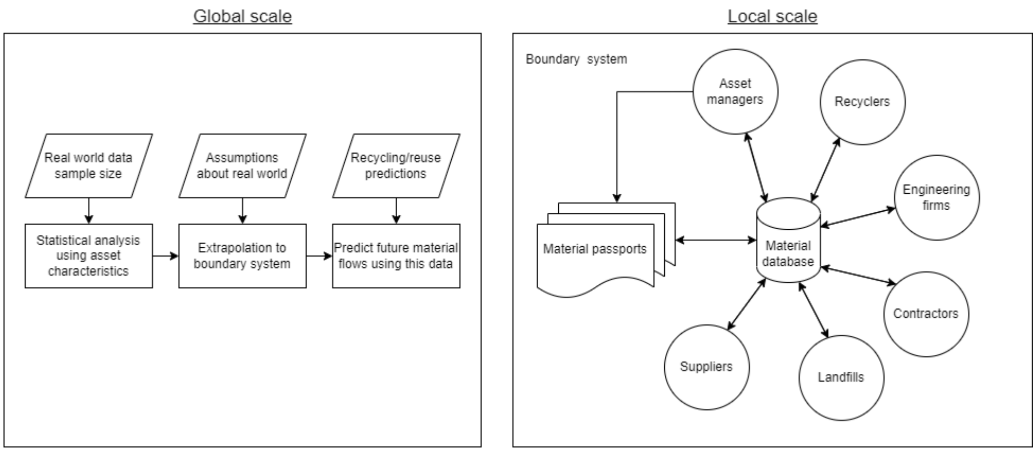


Figure 12: Global and local material flow modelling approaches

2.2.1.2. Local scale

In addition to the MFA on a global scale, it can also be highly valuable on a local scale, for example in a city. The concept for the local scale is similar to that of a global scale: predict material over time using real-world input. The difference is that at a local scale, no assumptions/simplifications are made, and all the data input must coincide with the real world within the model's boundary system. Moreover, the local aspect of the actual materials or assets are documented and physically tracked/predicted over time. For example, when it is known that a certain share is to be reused at another location, recycled at a certain plan, or landfilled. This provides the opportunity to set up local circular economies where material flows are modelled, and supply chains can be tracked and optimized. In the context of the construction industry, material passports of assets can be used as foundation of the model input. The local material flow is schematised on the right side of Figure 12.

Both local and global scale material flow models will play a key role in the CE-transition. However, considering the data input required for local scale models, they are still far from being used in practice. Looking at global scale models, their role is already set in current CE-transition practices, as material stock approximation and future material flow predictions are the foundation for developing transition roadmaps (Transitieteam Circulaire Bouweconomie, 2022). However, there are two issues arising from using these models that complicate this transition. These are discussed below.

1. **Insufficient outgoing materials to meet demand.**

Just like any other industry, the construction industry has periods of low and high productivity, often correlated to the economy. With MFA studies, the historical fluctuation of construction activity and productivity can be retraced using the construction years and design lifetimes of existing assets and future material availability predicted. Material demand on the other hand, is more difficult to predict. Future market conditions, such as material prices or the economy, and the demand for housing and infrastructure are highly uncertain. However, the replacement and renovation activities of existing structures can be predicted to a certain degree using asset data. To achieve a fully functional and self-sustaining CE, the secondary material + biobased material input should always be equal to- or higher than the material demand, as per eq. 1. Due to the fluctuation in construction activities over time and relatively unchanged design lifetimes of infrastructure (80-100y), there will also be a fluctuating supply of outgoing materials that limit the construction activities of the future. For now, raw materials can be extracted to account for this imbalance, but this will not be allowed anymore in the future due to restrictions in line with the CE-transition.

Based on a national material flow study that is used in transition roadmaps, theoretical material deficiencies of 35%, 27% and 13%, in 2019, 2030 and 2050 respectively are predicted for the Dutch civil sector; assuming business as usual construction activities and a utopian 100% high value recycling/reuse rate of construction materials (EIB & Metabolic, 2022). Therefore, the raw material extraction that is required to compensate for this will generate serious emissions, already potentially harming the environment to an extent that might not be reversible (Gassnes, Lederer, & Fellner, 2020). Figure 13 displays a Sankey diagram of the material input (left) and output (right) of the Dutch civil sector in 2019, clearly showing the imbalance. It must be noted that the primary to secondary material input ratio paints a misleading picture, as the majority of the secondary share is actually 'downcycled' material which is not a sustainable practice in a CE. Similarly, the recycling output share is 97% downcycling of aggregates used in road foundations (Zuidema, Saitua, & Smit, 2016). For an enlarged graph and more relevant data on the construction industry's current material flows, see the synopsis of the Metabolic & EIB study in Appendix: B. To make this issue worse, CBS (2012) reported that approximately 68% of the raw material usage in the Netherlands is important from abroad, while even more concerning: the EU as a whole depends for 90% of its critical material usage on imports from outside of Europe (European Comission, 2014). This dependency requires the Netherlands (and EU) to be on the forefront of the CE-transition to limit future impacts on the industries and economy.

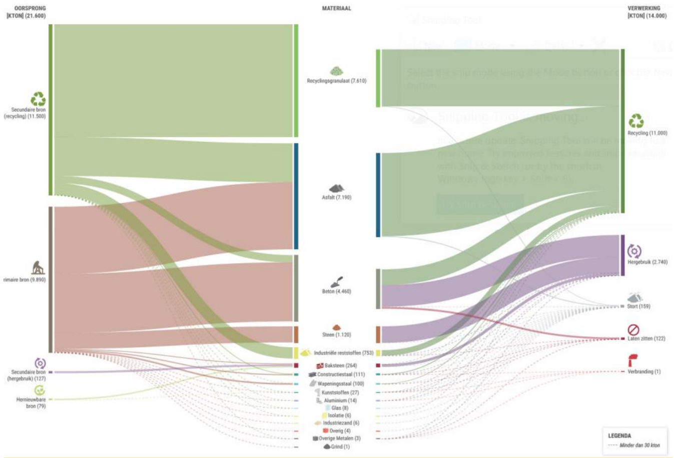


Figure 13: Material input and output flows of the Dutch construction sector in 2019 (EIB & Metabolic, 2022)

2. **Lack of material local quantity data**

A second issue arises from the lack of material quantity data on existing infrastructure and buildings (Platform CB'23, 2020). This lack of data makes it difficult to accurately estimate how large the anthropogenic stock in the built environment is, where these materials exactly are, and when they become available. In case of the Dutch civil sector, there were specifically large uncertainties involved due to this lack of data (EIB & Metabolic, 2022), as will be further discussed in section 2.2.2.2. CE-transition roadmaps use these studies as a guideline for setting circularity goals for phasing out raw materials, meaning that these roadmaps are based on highly uncertain data which could have implications on their reliability (Transitieteam Circulaire Bouweconomie, 2022). It is therefore likely that the goals set in these roadmaps are either overly conservative or ambitious. By using overestimated data of the existing material stock and future availability resulting from this, it is implied that there will be a larger secondary material potential through reuse and recycling to meet the future material demand. Thereby requiring less severe interventions and regulations than what is actually necessary, causing negative impacts on the environment and CE-transition. The opposite happens when the material stock is underestimated; the interventions will be too extreme, which could hurt the industry and economy, considering that the construction sector is responsible for 10% of the GDP in the Netherlands (Bouwend Nederland, 2022). Moreover, it impacts the recycling industry as there are large uncertainties on the projected local supply of materials.

To solve these problems, a large database of material passports is required that includes material quantity & specification, expected EoL-date, EoL-destination (e.g., recycling plant, landfill, or second-life location), and location (Brunner, 2011). The material passports must be continuously updated to optimize the exchange of information between the different actors along the value chain and to coordinate the supply and demand for materials (Heinrich & Lang, 2019). By developing such a database, the material flow studies can be improved in accuracy and level of detail, which can have countless of benefits for the CE-transition as well as AM. Additionally, four measures can be considered to tackle the material shortages:

1. Applying the Refuse, Reduce & Rethink methods more frequently from the 10-R framework.
2. Prioritize reuse to extend the element’s lifetime while recycling technologies are innovated to upcycle construction materials, so once EoL is reached; materials can be kept in the cycle.
3. Manipulating decommissioning dates of structures through renovations or premature decommissioning to balance supply.
4. Setting up partnership models with neighbouring countries for material exchange to help balance the fluctuating supply cycles.

2.2.2. Data gathering methods for material quantities

There are two potential routes one can take to obtain material quantity data to fill the knowledge gap on assets, the so-called bottom-up and top-down approaches in material stock estimations. Yang (2015) defined these approaches as follows: "The bottom-up approach combines inventories of materials including all service units that contain the certain substance with the material use intensity in each service unit to quantify the overall material usage. On the other hand, the top-down approach determines regional material use by multiplying per capita material use and regional population using national or worldwide data.". In other words, bottom-up methods look at individual material quantities of assets and sums them up, while top-down combines statistical information on the built environment, GIS data and algorithms to obtain estimates. Bottom-up is considered more accurate but also more time consuming and dependent on information availability from field inspection and/or construction plans, while top-down methods are prone to oversimplifying the complex built environment (Oezdemir, Krause, & Hafner, 2017). Which method should be adopted depends on the need for information and the availability of information on the structure. Below the two are assessed on their applicability, limitations, and presence in literature in relation to Material Flow Analysis (MFA) and the CE-transition. Figure 14 contains a general introduction to the methods.

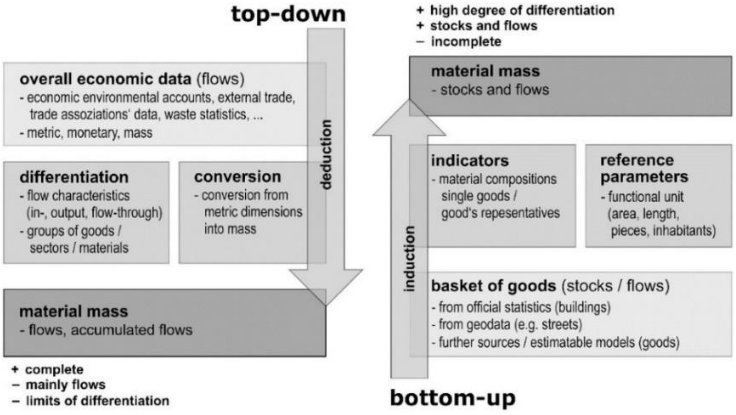


Figure 14: Top-down vs Bottom-up MFA (Schiller, Muller, & Ortlepp, 2017)

2.2.2.1. Top-down approach

Briefly analysing the top-down method first. Top-down MFA methods generally focus on larger scope and scales. The top-down approach is often consulted when characterizing the material stock for larger regions or a country, represented in Sankey diagrams like figures. Top-down MFA studies tend to be limited by the lack of regional data statistics on material quantities, low data quality (e.g., of satellite imagery) and overall data uncertainty that could result in very large inaccuracies on a large scale (Imran, 2020). In addition to the lack of data, there is also a limitation in applicability of data on other locations due to the variation in cities, regions, and countries with respect to characteristics of the built environment, causing studies to yield very different results (Heinrich & Lang, 2019). Moreover, due to the statistical nature of the method, it is often a black box model, limiting its validity (Oezdemir, Krause, & Hafner, 2017) (Ajayabi, et al., 2019). Benacchio & Freitas (2020) have analysed multiple top-down MFA-studies and conclude that the usage of top-down MFA methods can be highly valuable for the CE-transition for estimating material quantities in large regions but require more accurate bottom-up asset- and material property data to improve the statistical datasets and better estimate the secondary material potential of the built environment. similar conclusions were obtained by a study by (Haas, Krausmann, M. Weidenhoger, & Heinz, 2015) (Krausmann, Lauk, Haas, & Weidenhofer, 2018) (Stephan & Athanassiadis, 2018). This type of information is valuable for developing high-level transition roadmaps. However, these models cannot predict the time-of-availability of the specific materials in structures, which is an essential piece of information in realising circular efforts, therefore limiting its use. Moreover, it was observed that most of the top-down studies are focussed on buildings.

2.2.2.2. Bottom-up approach

As for bottom-up methods, not many studies have been conducted yet that can be applied on a larger scale due to the size and complexity of the built environment. The main reason for this being the lack of data availability on individual assets at public organisations, making the effort an impossible task without using oversimplifications or assumptions. An example of such a method is the study conducted by Metabolic & EIB, mentioned in the previous section. The data gathering process can be described by the following steps:

1. Obtaining production numbers (counts) and construction years of assets from the centralised platform called the Basisregistratie Grootschalige Topografie (BGT), where all buildings and assets can be documented with some basic information. This platform is generally incomplete and not actively maintained by asset managers making the data very unreliable.
2. Using a sample set of assets with high-quality data to characterise the asset type on material quantities and average lifetime. Extrapolating this data using the data from step 1.

The fallacy with this method is that when the sample set is misrepresentative for the average of that asset type within the boundary system, the model output is immediately inaccurate due to the extrapolation. Considering that infrastructure assets are relatively standard in design elements, there is an opportunity there for AM to improve this method by obtaining more detailed asset data and feed this into a statistical model that approximates material quantities and average lifetimes. However, this will require significant efforts from which they do not directly benefit.

In recent times, the digitization transition has blown new life into realizing large scale bottom-up studies with higher accuracies for obtaining material quantities directly from 3D models. Where traditionally buildings and had to be modelled manually from 2D drawings, now Artificial Intelligence (AI) technologies such as image recognition, reality capture cameras, 2D CAD to 3D model generators, terrestrial laser scanning (Figure 15), digital photogrammetry, and ground penetration radars, often in harmony with BIM software (Edirisinghe, London, Kalutara, & Aranda-mena, 2017) (Gu, Ergan, & Akinci, 2014) (Cetin, Gruis, & Straub, 2022) (Hossain & Yeoh, 2018). Figure 16 shows some pros and cons of these technologies. An issue with most of these methods remains the costs and data-heaviness of the output. With the large-scale requirements, these methods would require huge investments and require serious time and computing power to be completed. This is unrealistic for asset owners to spend their money on currently. For very large, complex/architectural/historic, and one-off structures, this method might prove to be a more viable option.

Figure 15: Terrestrial 3D scanning (Jickling, 2020)

	Digital Photogrammetry	Terrestrial Laser Scanning	Ground Penetration Radar
Relative Accuracy	Low (1cm to 1m)	High (1cm to 1mm)	NA
Use in Low-light conditions	No	Yes	Yes
Relative Weight	Low	High	Medium
Relative Cost	Low	High	High
Relative Degree of Expertise	Low	Medium	High

Figure 16: Pros & cons 3D scanning (Hossain & Yeoh, 2018)

Evidently, the bottom-up method will require new innovations or cost reductions before it will be superior in terms of efficiency to top-down methods. However, literature shows that while the top-down method allows macro-scale projections with regard to highlighting the scale of secondary material potential, it lacks in providing a sound basis for practitioners and policymakers which may require detailed information for sector specific applications of secondary resources (Arora, Raspall, Cheah, & Silva, 2020). This last point highlights the need for bottom-up methods.

2.3. Replacement, Renovation & Reuse of bridge infrastructure

This part of the literature study concerns a deeper dive in the bridge R&R-task and how reuse is entangled in this enormous challenge the upcoming decades. The R&R-task comes as both a threat and an opportunity for the CE-transition, which of the two will be dominant relies on how this transition is managed. First, the background and core characteristics of the task are introduced, followed by a high-level discussion on the practices and strategies involved to manage the R&R-task. Next, the obstacles for achieving reuse in practice are discussed. Finally, literature is consulted on the implementation of reuse in practice and what changes are required compared to current practices.

2.3.1. Introduction to the R&R-task

The civil sector is composed of many asset-types such as locks, bridges, viaducts, tunnels etc., see Figure 17 (excluding roads). To avoid confusion, it is here emphasized that the term 'bridge infrastructure' will be used as term for both fixed bridges and viaducts alike, moveable bridges will not be part of this study. The same study also shows the ownership distribution among the public entities in the Netherlands, with municipalities owning the majority share of (73%), followed by water boards (17%), Rijkswaterstaat (5.3%, and provinces (3.4%) (Bleijenberg, 2021). The exact number of bridges in the Netherlands is relatively uncertain as centralised data platforms Basisregistratie Grootschalige Topografie (BGT) are not actively maintained by all organisations (Bleijenberg, 2021) (EIB & Metabolic, 2022). This problem is mainly caused by the distributed management strategy that is adopted in the Netherlands, where Rijkswaterstaat, provinces, water authorities, and municipalities all have their own acreages, assets, and AM strategies. Moreover, it is not uncommon that there is confusion about ownership of certain assets (Boer, 2022).

Infrastructuur	Areaal	Vervangingswaarde miljoen euro
Beweegbare brug	8.457	14.226
Vaste Brug Beton	34.389	19.283
Vaste Brug Staal	10.034	13.538
Vaste Brug Hout	31.693	8.885
Tunnels en onderdoorgangen	3.042	9.119
Duikers	82.642	2.108
Damwanden	779 km	2.961
Sluizen	2.011	239
Gemalen	7.792	448
Kades en steigers	2.423 km	1.939
Stuwen	33.154	249
Overkluizing	182	55
Totaal		**73.049**

Figure 17: R&R civil structures overview (Bleijenberg, 2021)

Figure 18: Bridge constructions over time (Bleijenberg, 2021)

Out of all the civil structures, bridge infrastructure is specifically interesting due to their large count, value, average weight, and the fact that many of them will be at their EoL in the near future (2040-2060) (Schaafsma, 2022). This task requires large renovation or replacement investments, displayed in the right column of figure, showing that fixed bridges make up over 57% of the 73 billion Euro renovation costs of civil works (Klatter, 2022). To compare, the Bruggencampus (2022) estimates a total of 80 billion Euros (excl. 16 billion Euros of failure costs). From the 75.300 fixed bridges included in the material flow study by EIB & Metabolic (2022), a total weight of over 125.000 ktonnes was estimated, or 62% of all the civil artworks, while Bruggencampus (2022) estimates 200.000 ktonnes of materials will be required as well as produced in waste materials. Lastly, the material flow study by EIB & Metabolic (2022) presented a distribution of materials for fixed bridges (excl. viaducts) of 83.3%, 9.3%, and 7.4% for concrete, steel, and timber bridges respectively, compared to 45.2%, 41.6%, and 13.2% as reported by (Bleijenberg, 2021). Despite the uncertainty involved in these estimates, these figures still indicate the relatively large economic and environmental impact that bridges have within the infrastructure sector. Especially considering that surrounding countries face similar issues, for example Germany (Bridgeweb, 2021).

After World War II there was a surge in construction activities, much infrastructure (including bridges) had to be (re-)built in a short period of time. This surge continued due to the growth of automobile adoption and demand for accessibility (Klatter, 2022), as can be discerned from Figure 18. With the average design lifetime of approximately 80-100 years (Offenbeek, 2022) (Nicolai, 2019), it is expected that many bridges need to be decommissioned due to technical safety concerns between 2035 and 2060. That is, when the bridges are constructed- and maintained properly with load cases true to what was predicted in the design. In practice, traffic bridges often do not fulfil their design lifetime for functional reasons. Functional changes include an increase in traffic intensity, maximum truck loading, and changes in axles compared to what it was designed for (Florida department of transportation, 2000), thereby causing accelerated deterioration of the bridge and uncertainty on the structural integrity, which is dangerous. Functional changes could also mean expansion plans for the bridge or spatial design changes of the surrounding area. Conversely, practice has shown that as concrete hardens with time, the recalculations often show that this hardening extends the lifetime of the bridge (Janssen, 2022). This gives asset managers two choices, either invest in structural recalculations (expensive), or take the conservative route and decommission the bridge prematurely (lost value). Either way, a decommissioning peak can be expected in the upcoming decades (Figure 19, blue line).

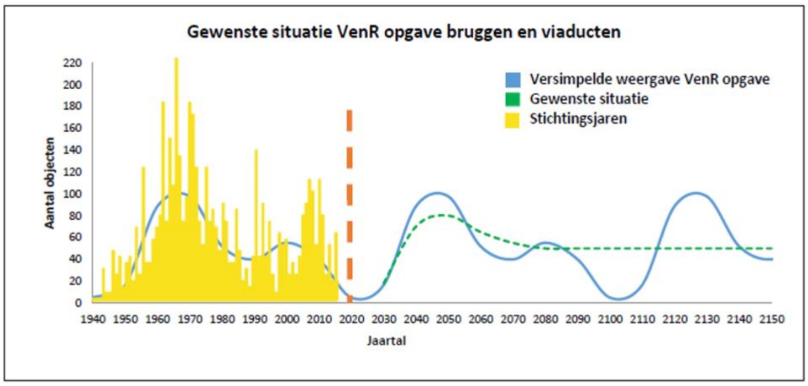


Figure 19: Decommissioning projections bridges (Schaafsma, 2022)

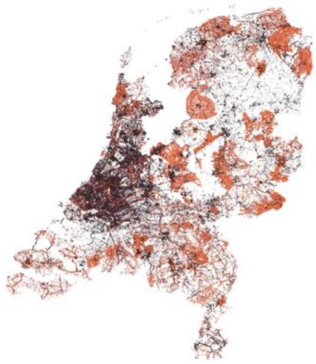


Figure 20: Distribution in civil works (Bleijenberg, 2021)

It is expected that the required contractors capacity to execute so many construction, demolition/deconstruction, and renovation jobs in such a short time window, is simply not there (De bouwcampus, 2022) (Klatter, 2022). Therefore, action is required now to spread out this peak by delaying or retracting decommissioning dates through interventions such as renovating, maintenance, enhancements, or premature decommissioning to ensure that accessibility and safety are impacted minimally (green line, Figure 19) (Schaafsma, 2022). In addition to the physical and economic challenges, construction projects must adhere to increasingly strict sustainability & circularity criteria as discussed in Chapter 2.1, complicating the execution even more. Looking at the plot in Figure 20, the distribution of civil artworks in the Netherlands is displayed. This shows the correlation between population density & surface water exposure with the need for civil artworks (Bleijenberg, 2021). This is highly problematic as considering that the construction exemption for temporarily exceeding nitrogen emissions is retracted by the Council of State (BouwTotaal, 2022). Finally, there is the ambition within the EU to become less dependent on importing resources, making reuse an increasingly urgent topic in this task (Rijksoverheid, 2022). To manage all these challenges in the upcoming decades will require innovative solutions, new AM strategies, and collaboration to solve this problem.

2.3.2. Asset End-of-Life practices

For asset managers, this challenge will be the most impactful, considering the little effort these civil infrastructures required over their lifetime, as maintenance increases with asset life (Frangopol & Liu, 2007). As concluded by (Klatter, 2022), AM strategies need to shift from reactive to proactive. Asset managers should always use the 10R-ladder (see Figure 21) when assessing what to do with an asset, as discussed Chapter 2.1. However, this is not yet standardized practice across the industry (Kishna, Rood, & Prins, 2019). One of the major issues with putting this framework into practice is that the actual condition of the asset is relatively uncertain due to lack of asset data quality and monitoring (Bleijenberg, 2021). Without such information the remaining lifetime of the asset, or its individual components, is difficult to assess, which in turn complicates the application of high 'R-strategies'.

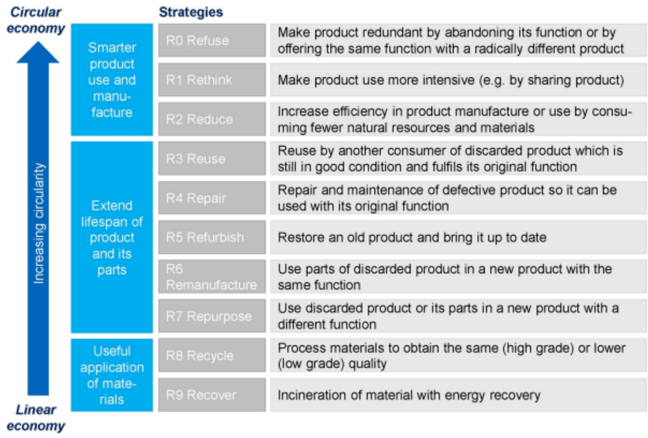


Figure 21: 10-R strategies

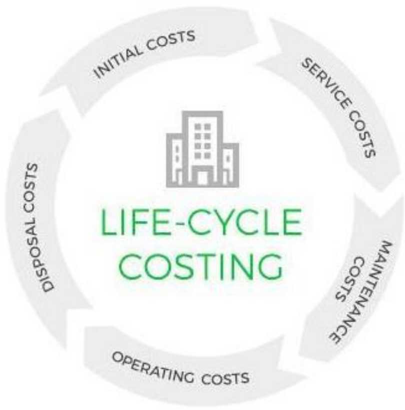


Figure 22: Life Cycle Costing Analysis (OneClickLCA, n.d.)

In the context of AM, the Refuse, Reduce, and Rethink set of measures imply that when bridges are selected for potential decommissioning based on functional grounds, it must first be assessed if the functional change is necessary (refuse), if restricting heavy vehicles can solve the problem (reduce) or if the traffic around the bridge can be redirected to a stronger bridge (rethink). These are examples that could dismiss the case of decommissioning or delay the decision, thereby extending the structures functional lifetime. These measures are not always possible but should be considered first. Secondly, contradictory to the framework, Repair or Renovation/Refurbish (enhancement) should be considered to extend the asset's lifetime by modifying the asset such that it can serve under the new functional purpose with sufficient lifetime to make it a profitable investment. In doing so, postponing the replacement task and (generally) using less resources in the process but increasing the maintenance activities for the remainder of the asset's lifetime.

Replacement is often the last option, this involves demolition or deconstruction of the asset and rebuilding a new bridge on the same location to maintain the accessibility of the network. In this process, Reuse has the largest priority, followed by Recycle and Recover. Despite the high recycling percentage in the construction industry, this method is actually not sustainable for a CE, as noted in section 2.2. Which route is the best to take depends on the Life Cycle Costing Analysis (LCCA) outcome, see Figure 22. LCCA has been defined by ISO15686-1:2011 as "a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial costs and future operational costs" (International Organization for Standardization, 2011). LCCA is an objective method for measuring and managing the lifetime costs of any project or asset. In construction, it enables more robust design options to be compared from a lifetime perspective to reduce overall lifecycle costs compared to Return on Investment based calculations (OneClickLCA, n.d.). The three options for asset managers are displayed in Figure 23.

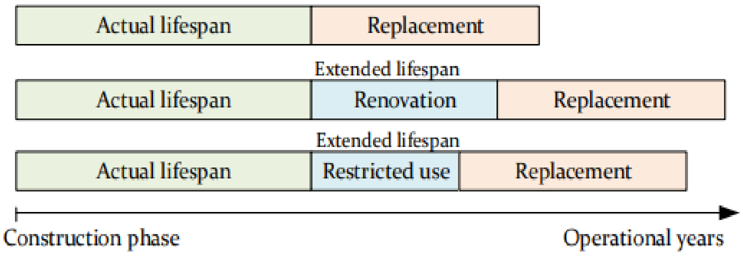


Figure 23: EoL options for asset managers

Based on conversations with practitioners, the current strategy for assessing the acreage can be generalised by the following steps:

1. Periodic inspections of assets (often not frequent enough considering structure's age).
2. Annual assessments of the entire acreage using inspection reports.
3. Note down the assets with alarming characteristics (functional reasons, poor condition, low remaining lifetime, etc.) within the next 3-years.
4. Make plan for the most urgent replacements or renovations.
5. Repeat.

Even when applying the 10-R framework properly, it is easy to see why this strategy will cause problems if maintained: the problem is only delayed and once the decommissioning peak comes it is too late to get the funding or capacity to tackle the task, causing unavailability of infrastructure or unsafe situations. In many cases of replacement, the technical design lifetime (i.e., ~80 years, until the asset becomes unsafe to use as deterioration is too severe to maintain as per design) is not completed due to changes in functional requirements. It is estimated that approximately 70-80% of the bridges currently nominated for decommissioning within Rijkswaterstaat's acreage, have not yet reached their design lifetime, meaning that there is still plenty performance left in the structure (Offenbeek, 2022) (Nicolai, 2019). Figure 24 shows an average remaining lifetime of 30-40 years when assuming an 80-year design lifetime (standard before 2005, now 100y (Wouter Truffino, 2013)), proper maintenance, and limited additional degradation due to functional changes. This remaining lifetime even increases when the bridge (element) is reused on a location with a lower loading profile.

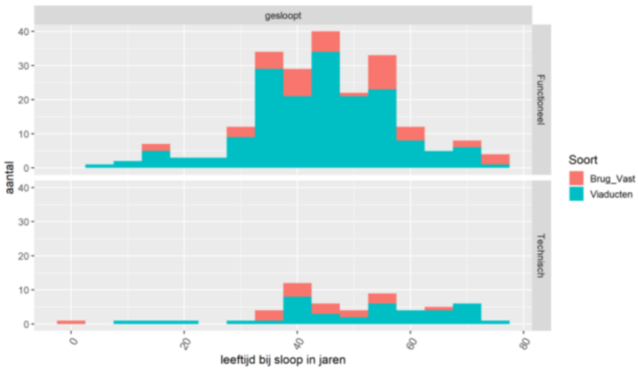


Figure 24: Lifetime bridges (Nicolai, 2019)

The important question remains how many years of the design lifetime are reduced because of this increased loading over time. The answer requires structural recalculations for vehicle bridges, while for foot- and cycling bridges degradation models based on inspection data will suffice as the loading profile has not changed much (Janssen, 2022). These recalculations can be conducted on different levels of detail, each level requiring more accurate asset data (Janssen, 2022), once again highlighting the importance of good asset data quality and documentation on the structures' condition, geometry (drawings), material, construction details, and actual load cases compared to what it was designed for.

With this information, the remaining lifetime of the individual elements can be estimated more accurately, which is essential information for the LCCA of the different EoL alternatives previously discussed. In doing so, a better overview of the activity timeline for renovations and replacements can be obtained which could lead to valuable insights for allocating capital and decision making on when to execute apply the restrict, renovate, or replace strategies to flatten the peak.

To conclude, with the knowledge on the remaining technical performance of the structures and their expected decommissioning dates, a door is opened for the exploration of reusing elements in case of functional replacement and the technical performance is sufficient to make a business case. However, technical replacement does not always imply that the entire structure's elements are at their technical EoL, as the changed loading profile mainly affects the main load bearing system (deck + girders) (Janssen, 2022), leaving an opportunity for substructure reuse, more on this later. Without accurate technical information on the asset, a business case cannot be made due to the uncertainty involved and potentially costly consequences of structural failure (Copper8, 2022) (Delgado & Oyedele, 2020). Reuse of bridge elements will play a key role in the R&R-task, as most of the replacements will occur between 2040-2060 and the construction industry should already have realised at least a 50% reduction in primary material usage by then according to the CE-goals (Rijksoverheid, 2016). Even more so, as upcycling of construction materials on a large scale are far from reality currently (Bułhak, Karp-Kręglicka, Krysiak, & Boruc, 2022). Because of this importance of reuse, quality asset data should become a top priority for asset managers.

2.3.3. Reuse barriers CE

The Netherlands is widely regarded as the 'champion' when it comes to realising the CE. This status originates from their dependency on raw materials which makes them vulnerable (68% import) (CBS, 2012), but also because of a government push and a willing market (Rijkswaterstaat, 2022). As already determined in Chapter 2.1, the problem with realising this is often that the companies don't know how to put innovative circular theories into practice or are constrained by the client's requirements and their own profit margins (Copper8, 2022) (Delgado & Oyedele, 2020). As of now, not many reuse activities are executed as it involves a lot of risk, research and costs compared to traditional practices (Kanters, 2022). However, some flagship reuse projects lead the way such as the bridge in Vianen (Teeuw & Dijcker, 2017) or the Van Brienenoord bridge (Delrue, 2022) while other smaller projects have implemented reused elements already too. Furthermore, Rijkswaterstaat initiates Small Business Innovation Research (SBIR) competitions for improving reuse in bridges and the ministry of infrastructure has developed a multi-year programme for infrastructure spatial development and transport with respect to the CE-transition (Transitieteam Circulaire Bouweconomie, 2022). Despite these initiatives, it can be concluded that reuse is far from standardized as an option when decommissioning is announced, this is caused by the obstacles discussed in this section (in addition to those mentioned in Chapter 2.1).

In the context of this study, the adoption barriers for realising reuse in practice are important for understanding the underlying problem as well as contributing to defining the solution space for the development phase. The obstacles for reuse can be summarized into four main categories: lack of knowledge & incentives in practice, lack of data, unbalanced supply and demand, and limited application methods of elements (Brouwer, 2022). Figure 25 provides a synthesis of the full analysis with sources in Appendix: C, where each category is subdivided into items contributing to the overarching obstacles. This analysis aimed to capture the problem as accurately and completely as possible within the scope of this research and the Dutch construction industry. However, it is noted that this is not a complete in-depth analysis of all the contributors to this problem.

Lack of knowledge & incentives in practice	Lack of data
- Not standardized part of design methodology to integrate 'imperfect' elements. - Reuse is perceived as more risky, costly, and time consuming for contractors. - Transportation and storage constraints. - Financial attractiveness of demolition as existing structures are not designed for deconstruction. - Reused elements often incompatible with existing design standards. - Lack of incentives for reuse through tender criteria & contracts.	- Insufficient details/data on elements in reuse databases. - Absence of exact geometry and modelled elements in design software. - Lack of accurate data on condition & structural state due to functional changes over time. - Missing maintenance records over time. - Uncertainty on time-of-availability of elements.
Unbalanced supply & demand	**Lack of applications**
- Unpredictable supply due to lack of data and costs involved to obtain this data. - Low demand due to unfamiliarity with designing around reusable elements. - Lack of standardization in projects limits demand. - Organisations tend to limit to intra-organisational reuse. - Over-supply makes it not financially attractive for AM to obtain quality data. - Over-demand results in skyrocketing prices for reused elements, making exploration financially unattractive.	- New field of research, currently limited to girders. - Most bridge elements are limited to reuse with the same functional purpose (high-value reuse). - Lack of low-value applications for elements. - Over-dimensioning of structural elements is a waste of material. - Low demand limits the applicability of elements.

Figure 25: Overview adoption barriers for reuse

One barrier that is discussed further here concerns the state of reuse/material databases, as this can be highly dependent on country. At the time of this research, the author has identified three existing platforms for (bridge) reuse in the Netherlands, while more are currently under development (e.g., Revelop by SWECO (2022)). The largest database is MADASTER (2023) this platform is a central database for material passports and can in the future function as an exchange platform/market for materials. However, this is currently not a reality and does not offer intuitive reuse opportunities for project designers. The other two databases are purposely designed to realise reuse and are therefore of interest to this study, these are (Bruggen bank, 2023) and (Duspot, 2023). Duspot is a matching tool for supply and demand for any reusable element, while Bruggenbank is an open database explicitly aimed at bridge infrastructure elements. Therefore, Bruggenbank provides the most representative perspective on the current state of information supply for such databases. At time of research – March 2023 – a total of 22 entries were in the database, ranging from smaller sets of girders to smaller bridges and varying availability timeslots, see Figure 26. After analysing this database, it was observed that information supply lacked for the majority of these bridges. Material input included: length, width, material, fixed/moveable, time of availability, and photos. For two entries, a picture of a 3D model was included which would hint at more detailed information upon request. This brief analysis confirms the study's findings and highlights a need for more detailed asset data for reuse realisation.

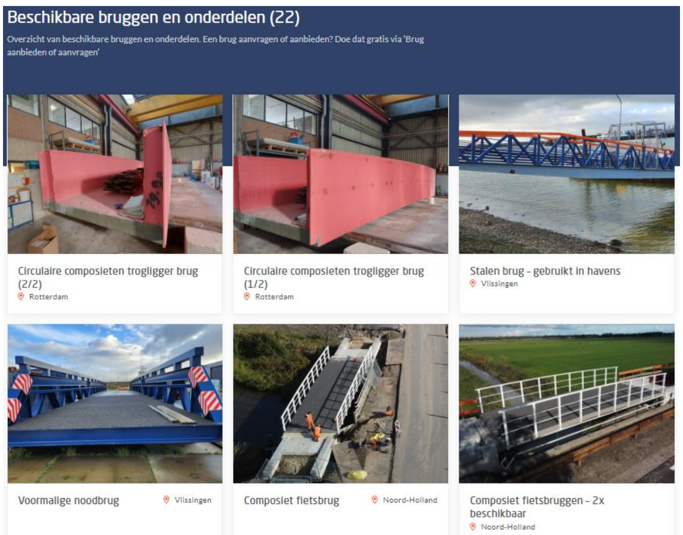


Figure 26: Bruggenbank reuse offers snapshot March 2023

2.3.4. Reuse methodology for AM

The previous section has displayed the many obstacles that need to be overcome to realise an efficient reuse economy. One of the key barriers being the lack of high-quality asset data originating from AM. This section aims to translate these barriers into concrete actions that need to happen from the AM perspective from a theoretical point of view to enable more reuse in practice. To do this, the 'Close the Loop' concept developed by NEBEST and Van den Berg (2019) was adopted as primary inspiration, see Figure 27. This concept was expanded on to address the needs for the R&R-task.

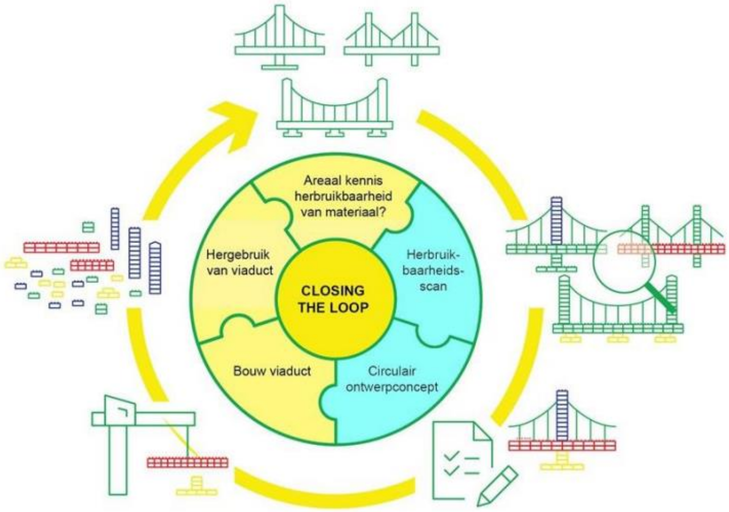


Figure 27: Closing the loop framework (NEBEST, 2021)

This concept was selected because of its focus on bridge infrastructure, and it addresses what is mostly missing in current roadmaps and literature (see Section 2.5): the front-end AM inventorying of asset data. Moreover, it aligns with the needs for the previously described R&R-task, which also requires inventorying of assets and structural assessments of ageing assets. This section will present a brief overview of the steps for realising a reuse economy within an asset-owning organisation. Appendix: D provides notes on each step with more explanation on the processes and outputs, as well as some nuance to the steps with respect to practice. This concept is also used for the roadmap in Chapter 6.

1. Inventorying the circularity potential of the acreage

The first step (on top in the chart) is about gaining knowledge on circularity potential of materials and elements within the acreage.

i. A framework is to be constructed on how certain elements can be reused, recovered, and recycled in theory, to execute step two consistently. A similar effort has already been initiated in this study for concrete bridges in section 2.3.2. this framework concerns deconstruction practices, as well as logistics and applicability of construction elements.

ii. Next, the acreage needs to be inventoried in greater detail with respect to the actual decompositions of assets and characteristics, preferably with geometry data (3D models). Based on this data, step 2 can be executed.

iii. Centrally documenting the asset data (preferably in 3D) obtained in the previous point to improve data accessibility and traceability for step 2 and communicative purposes.

2. Reusability scanning

The second step concerns the execution of reusability scans on the assets using the asset information obtained in step 1. Tools are currently in development to efficiently assess the circularity potential of individual elements (Sykes, 2023). The better the data quality of the asset, the more certainty can be attributed to this scan. Potential elements can be identified by using the framework developed in step 1. For reusability, it could be that additional tests are required to gauge the remaining strength by means of structural recalculations (potentially including site tests, depending on data quality) or degradation models. The steps for this stage are summarized in the three items:

i. Reusability scans based on design characteristics, inspection data, maintenance history, and degradation models.
ii. Structural recalculations/degradation modelling for bridges with altered function requirements to obtain more accurate insights on remaining strength/lifetime valuations of the assets for reusability purposes.
iii. Reusable elements' data should be uploaded to reuse databases to improve the link between supply and demand, such as Bruggenbank, Duspot & Madaster.

3. Circular design concepts in projects

The third step is making sure that reuse is part of the design methodology of all construction projects. For clients (and contractors/designers/engineers as an extension of that) the following initiatives should be standardized:

i. Incentivizing reuse in tender specifications/criteria and contracts. Shifting from cost-dominated awarding criteria towards environmental/sustainability-dominated awarding criteria. Using ECI-values to quantify environmental benefits by subtracting a fictional amount from the bid, specifying a set amount of reused material share (Transitieteam Circulaire Bouweconomie, 2022).
ii. Revising the risk allocation standards proportional to the party's ability to carry the increased risk involved in projects with reused elements (Bao, Lu, Chi, Yuan, & Hao, 2019).
iii. Implementing Early Contractor Involvement models to improve the feasibility of circular design solutions (Kreike, 2022).
iv. Standardizing reuse exploration in the design phase as an iterative process where elements from reuse databases are (attempted to be) integrated in- and adjusted for the design. (Kanters, 2022).
v. Conducting Life-Cycle-Costing Analyses (LCCA) to assess whether reuse is the best option for the functional purpose of the asset (Heralova, 2017).
vi. Centralise Industrial, Flexible and Deconstructable (IFD) methodology in the design, to optimize construction, replacements, and deconstruction at EoL (NEN, 2022).

4. Construction & reuse

The construction of one project is closely intertwined with the decommissioning of another where the elements are harvested. The dismantlement date of the existing structure generally occurs 1-3 years after the decommissioning announcement, this is because a replacement must be tendered out and be ready for construction to maximize availability of the asset. As for the new (other) project, the construction can start the earliest when the elements become available (and have been maintained & adjusted if necessary), this is represented by the red arrow in Figure 28. Below four processes are listed that require change.

i. Scheduling decommissioning dates sufficiently ahead of time to ensure availability for users.
ii. Active communication lines and trust between asset owner and project manager should be maintained to minimize unexpected delays.
iii. Setting up local material depots for harvested elements to ensure longer availability for projects.
iv. Transport (permitting), maintenance/repair, potential adjustments, and storage to connect the element from its harvested location to its new purpose.

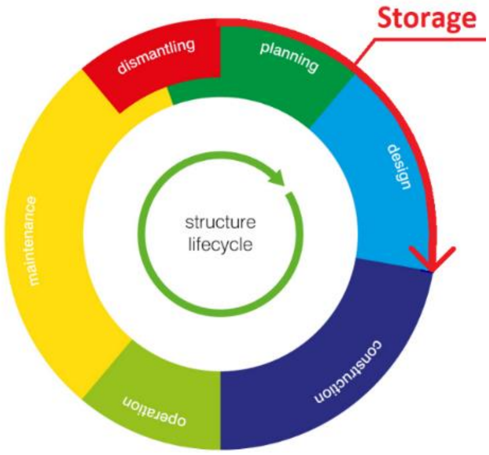


Figure 28: Overlap of storage for reuse realisation

2.4. Asset management in practice – past, present & future

The previous two sections have uncovered an urgent information need on existing infrastructure to better manage the CE-transition and R&R-task. This study has shown that AM is intertwined in both challenges. Here, the cause for this lack of asset data is discussed, followed by a discussion on what the future holds for asset management practices and how this transition might impact current-day decision-making. The findings in this chapter are based on literature and expert knowledge, the subsequent chapter will aim to validate this with practice through interviews.

2.4.1. Asset management tasks

Infrastructure Asset Management (AM) is defined by Christiansen (2020) as "the process of organizing the step-by-step method of developing or obtaining, operation and maintenance, renewal or upgrading, and disposal of an organisation's assets" (Christiansen, 2020). AM can be summarised in two main tasks: asset procurement/disposal and asset tracking & maintenance. Asset procurement involves the initiation for new assets, replacements (including disposal), or renovations. Once the projects are completed, the handover of construction data is to be documented in the AM system of the organisation. That is when the operational phase of the asset commences, where the goal is to maintain peak performance throughout the asset life cycle, with minimal downtime (Tyrrell, 2022). Activities include ensuring that all assets are inspected periodically according to what is prescribed by standards, monitoring its condition (including remaining lifetime), overseeing maintenance activities based on these inspection reports, and documenting & updating the data in the AM system. In addition to these tasks on an individual level, AM also includes managing the asset portfolio. For example, the previously discussed R&R-timeline for bridges to decrease the expected decommissioning peak or planning and executing the long-term vision for the acreage. The quality of AM entirely depends on the asset data availability and how this data is documented and maintained over time, as this influences the decision-making. Next, an analysis is provided on the cause for this absence of asset data when its use is evident.

2.4.2. Digitization transition for AM

Starting by looking back in time, design and construction methods have changed quite a bit throughout the last centuries. 200 years ago, construction drawings were made by hand in 2D, the construction time was often years, and the materials were procured as was required on site. 100 years ago, not much had changed besides increasing experience in construction resulted in lower construction times and materials were estimated using the 2D drawings, still very inaccurate but it decreased the lead time (Quirk, 2012). Since the 1980's, 2D Computer Aided Design (CAD) software was adopted by the market, replacing hand drawings (Digital school, n.d.). Starting in the 1990's 3D modelling was introduced, but to date it has not fully replaced 2D drawings due to various reasons (Creative Mechisms, 2015). In the 2000's, BIM slowly started making its introduction to improve both the design phase and asset documentation quality for the operational phase (Wierzbicki, de Silva, & Krug, 2011). Based on this brief overview, the digitization trend is clearly visible, however the technology adoption generally takes a long time compared to other industries due to its conservativeness (Easen, 2017). Both the design- and documentation changes over time are visualised in Figure 29.

Nowadays, it is evident that more data (digitization) allows for better informed decision making and management, automation possibilities, condition monitoring, and the list of potential benefits goes on as studied by (Ghaffarianhoseini , et al., 2017). The extra effort that is required to measure and digitally document data during the design and execution phases are paid back by the benefits obtained over the operational lifetime and EoL of the asset (a positive return on investment) (Giel & Issa, 2013).

Guzzetti et al. (2021) state that BIM is an extremely advanced and necessary method for the digitization process in the construction sector and its considerable diffusion is evident. This transition was perpetuated by the COVID pandemic, where remote management was asked, requiring digitization of project information and data (Orzeł & Wolniak, 2022). Besides the digitization pull due to COVID, another factor that plays a role is the context of sustainability. As found in the previous chapters, this transition requires a lot of asset data that tracks all the materials over time. This demand for data also pulls the market towards recording, measuring and documenting data with benefits for management, operation, maintenance and EoL. However, the products of the digitization transition are predominantly applied on 'new' projects, not on existing asset data (Guzzetti, Anyabolu, Biolo, & D'Ambrosio, 2021). This causes an ever-growing gap between AM quality of existing structures and new ones.

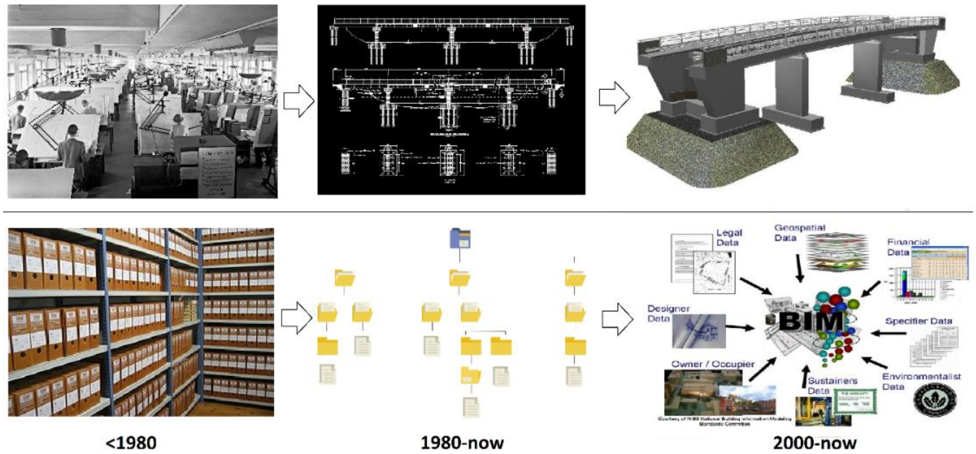


Figure 29: Overview of asset documentation standards over time

2.4.3. Lack of data documentation

Before the Brundtland report in 2000, sustainability and circularity had little priority in projects as reflected by the principles, standardizations, and applications in place (Krigsvoll , Fumo, & Morbiducci , 2010). Because of this, it did not matter how much, or what type of material was used, as there was no sight on resource scarcity or repercussions for the environment, as long as the requirements were fulfilled with the lowest possible costs. Similarly, asset documentation for improved monitoring, asset durability, and EoL-value was of limited importance, as structures were designed and constructed with the perception that most materials would end up in landfills once they were deemed unsafe and unfixable within reasonable costs (Yang, 2022). Moreover, tools to efficiently measure and document all this data were simply not available at the time, making it a lot of effort for something that would be used minimally. Until the recent CE-transition, this detailed data was also not requested by the client as AM is mainly focused on the short-term by adopting a reactive maintenance strategy based on periodic inspections (Lunenborg, 2022). Moreover, the construction sector is generally known for its small margins and high competitiveness, this also did not allow for extra costs without certain (short-term) benefits.

As the previous paragraph indicates, there was no incentive or possibility to document the information demand required today. This leaves the asset owners of structures built before 2000 generally only with 2D drawings, either by hand or computer, project specifications, and sometimes asset databases with historical maintenance data (Abdirad & Sturts Dossick, 2020). This documentation ended up in an archive (perhaps more recently in a digitised form in an online database), with little intention to be used. With time and many asset manager changes, a lot of (tacit) information was lost compared to what was known or could have been measured during construction (Lunenborg, 2022). It could be that additional information was collected through maintenance activities, however due to the often already poor documentation strategy this information was often also lost. Despite its clear need, very little is published in research and practice that addresses the methods for collecting and updating reliable and verifiable data for assets in existing facilities and infrastructure (Abdirad & Sturts Dossick, 2020). The author furthermore suggests that the existing infrastructure needs to be upgraded to BIM, with data collection practices to fill the information gaps. In the future, Artificial Intelligence (AI) can play a role in generating and using this data, however this is still in the future (Rampini & Re Cecconi, 2022).

The graph in Figure 30, emphasizes this lack of data availability. The figure represents Rijkswaterstaat's Data Informatie Systeem Kunstwerken (DISK) for the types of main load bearing systems within their acreage, it can be derived that for 50% of its bridge structures this information is lacking. Considering that it is widely accepted that Rijkswaterstaat has one of the best documentation standards among the administrative layers in the Netherlands, there is cause for concern (Visser, 2022). Brouwer (2022) has also conducted interviews with Dutch industry experts and asset owners, this showed that that there currently is a lack of overview on both currently stored elements/materials in infrastructure assets as well as when these become available. Due to the highly distributed management system in the Netherlands, it is very likely that there are large variations in management strategies and systems among them, making large scale data studies even more complicated. There is still a large task ahead for the industry to upgrade its existing asset data. Especially for bridges in the lower road networks, often designed for the lower load classes and maintained by municipalities, the documentation is missing (Harrewijn, 2019). This brief assessment has shown the cause for the lack of information documentation, that being an absence of information need at time of construction and lack of technology to cost-efficiently document this data, with the former being most dominant. The minimalistic approach of asset owners now causes problems for current CE- and R&R-task challenges.

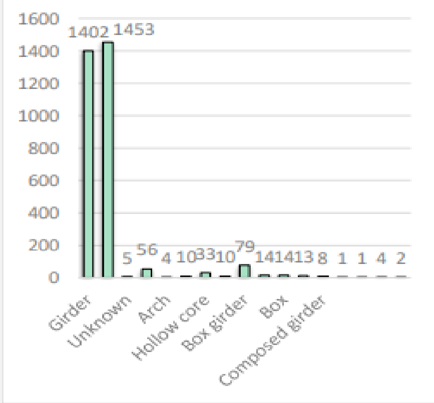


Figure 30: RWS MLBS types (Brouwer, 2022)

2.4.4. Digitization transition for asset management practices

As was proven in the previous section, the digitization transition has heavily impacted the construction industry and AM practices. Digital technologies are considered enablers of CE implementation in the built environment (Cetin, Gruis, & Straub, 2022). While literature mainly focuses on conceptual or review studies examining the role of digital tools (e.g., material passport and BIM) to close the material loops, there is a lack of understanding of how digital technologies are implemented in real-life and whether they offer value to the industry actors (Cetin, Gruis, & Straub, 2022). This section aims to look at the current digital developments in relation to AM and the CE-transition in the construction industry and how they might play a role in the future, putting the findings of the previous section in perspective.

2.4.4.1. 2D centralised asset management

Digital tools are constantly being developed and enhanced to improve AM efficiencies and decreasing the traditional issues in the construction industry surrounding data documentation and communication (Roberts, Pärn, Edwards, & Aigbavboa, 2018). The current standard for AM tools is described in this research as '2D-centralised AM', as will be elaborated below. This description concerns the current potential and objective of most asset managers using the tools currently available, it is by no means a representation of the average AM practice in the Dutch industry. Most organisations in the Netherlands use the example tool or something similar but cannot use it to its potential due to data incompleteness and fragmentation (Halfawy, 2008).

2D centralised AM requires all asset data to be stored in a single cloud-based system, (e.g.: IAsset) see Figure 31. Assets are characterised by dots on the map which can be accessed via the register on the left or from the 2D map. Each asset has a material passport tab that displays the basic data conform to the user's needs (for example: general information, coordinates, classification, photo's, comments, inspections, maintenance, and archive). Besides that, there are tabs for maintenance history and scheduling of the entire acreage, decomposition of the assets and acreage, and a directory for technical drawings (2D or 3D) and specifications. However, these tabs are often found empty. Additionally, an analysis tool needs to be implemented to conduct data analyses across the entire asset portfolio (e.g., for maintenance operations optimization). This functionality is often still missing in the existing platforms but can be executed using third-party tools (e.g., Excel). With this approach, the essential AM tasks discussed previously can be executed.

Figure 31: 2D centralised asset management – IAsset (IAsset, 2022)

2.4.4.2. *BIM & digital twins*

The main development in the construction industry regarding the digitization transition concerns BIM (already introduced in Chapter 2.1 and Appendix: A). BIM is increasingly standardized within the industry and is now mainly applied to the design- and construction phases. AM is now progressively gaining considerable academic and practitioner interest particularly in terms of exploiting the beneficial implications of BIM implementation (Roberts, Pärn, Edwards, & Aigbavboa, 2018). Pärn et al. (2017) suggest that BIM is displacing traditional construction industry practices and replacing them with virtual communities of practice. This is particularly relevant for AM organisations that see technological development as a vehicle for delivering increased efficiency and value (Love, Jingyang, Matthews, & Harbin, 2016). Mohandes et al. (2014) contend that the data management potential of BIM affords a panacea to AM issues inherent within the ever-increasing quantity and complexity of information gathered throughout a structure's lifecycle.

The main difference for AM concerns the data quality at handover, which is a 3D model filled with object data instead of large folders with (often unorganised) 2D drawings and project specifications (Visser, 2022). When the 3D BIM is updated with as-built information after construction finalisation, the model can be considered a digital twin, or: a digital representation of the physical structure. Figure

32 displays an overview of the benefits digital twins bring to the table. The concept of a digital twin can be enhanced by integrating sensors in the structure that help monitor the condition and allow simulations based on real-time data, e.g., for preventive maintenance (IBM, 2022). Currently, the development of digital twins within the construction industry is still in its infancy compared to manufacturing or automotive industries (De-Graft , Perera, Osei-Kyei , & Rashidi, 2021). This can be explained by the facts that BIM is generally only applied in new projects where all information is available (Mohandes, Hamid, & Sadeghi, 2014), it requires upfront capital that is not always available, and there are only a limited number of new projects per year as structures are designed for very long lifetimes. Consequently, there is low supply of digital twins for asset managers. Asset managers have two options: to use separate AM strategies for new structures with BIM and existing structures, or ‘dumb down’ the BIM to traditional 2D AM practices and thereby disregarding a lot of valuable information stored in the BIM.

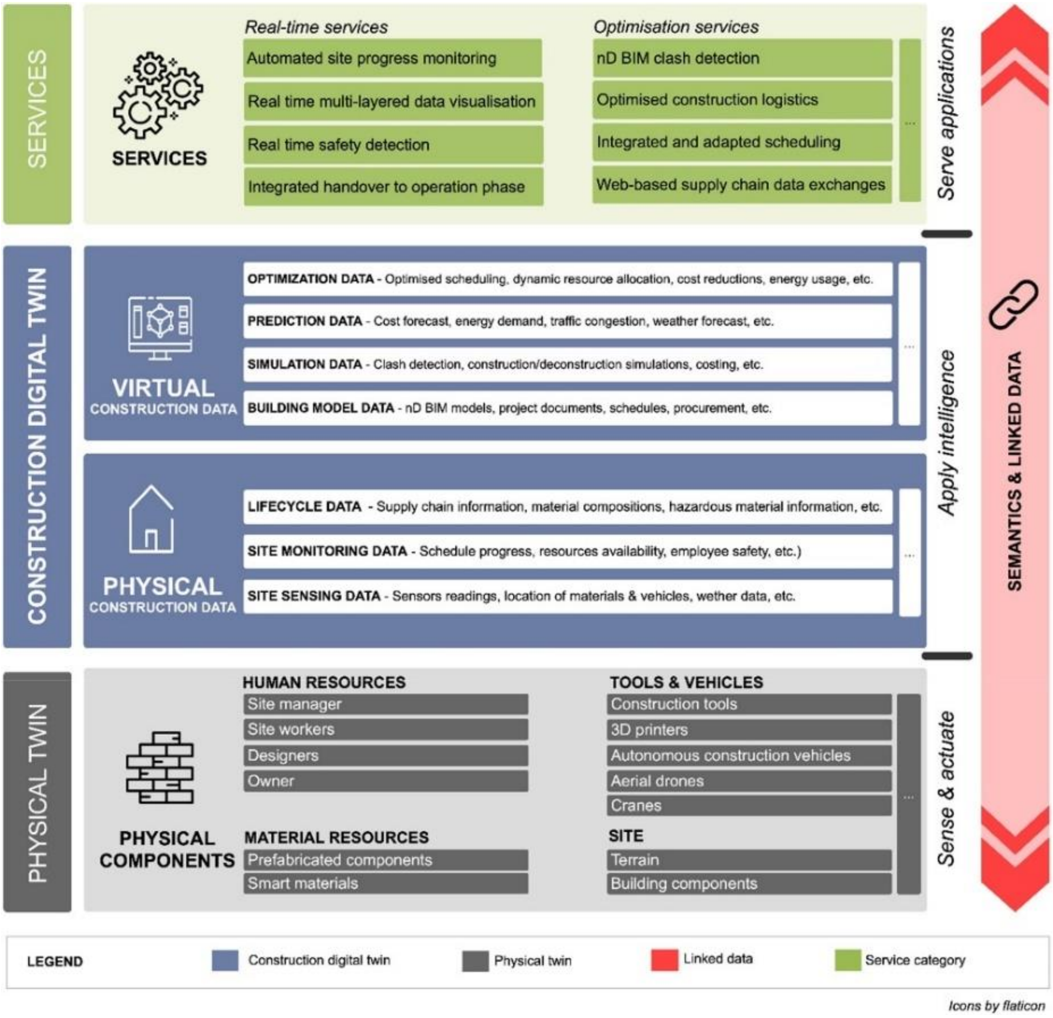


Figure 32: Digital twin benefits (Boje, Guerriero , Kubicki , & Rezgui, 2020)

2.4.4.3. 3D centralised asset management

With time, the supply of digital twins will increase to a point where a new management system will need to be adopted to leverage the benefits of these digital twins. For simplicity, this new management system is called 3D centralised AM, as the strategy revolves around the 3D – digital twins – of assets integrated in a single centralised environment, instead of in dots in a 2D space. Before such a transition can be made, the majority of the assets need to be in 3D. Considering the 80–100-year lifetime of structures, this tipping point can take a very long time while the information need is already there for existing structures. To bypass this issue, the existing built environment should be upgraded to semi-accurate digital twins based on the existing data (2D drawings + specifications) or scanning technology. Naturally, these 3D models will not yield the same benefits as a digital twin, but the need for geometry and more detailed asset data has already been highlighted in the previous chapters. The purpose would be to saturate the 3D AM system with existing infrastructure and accelerate the digitization adoption process within public entities and acquire benefits earlier. A 3D environment allows physical assets to be selected for material passports, and attribute data (including condition data, maintenance history, etc.) to be linked to the individual physical elements, as opposed to in a list-like decomposition format in 2D systems. Below, more benefits of the 3D centralised asset management system are described. Figure 33 displays a how such an environment might look in the future. As there is currently not a big enough market for these systems, to the authors knowledge there is not yet a diffused software system that is optimized for this purpose.

Figure 33: Example digital twin city (Hollings, 2019)

The ambition for such a 3D centralised AM system is not only confirmed by literature through the extensive coverage of the benefits of digital twins, but also in practice. In the Netherlands, the three biggest cities (Amsterdam, Rotterdam & The Hague) have started an initiative 'Totaal Driedimensionaal' (T3D) that aims to capture, register, and use 3D object data within their acreages in their AM strategies (T3D, 2022). With this, they aim to expand the municipal perspective on the development of geospatial registration systems and utilize this development in aspects like the energy transition, climate adaptation, environmental & planning acts, and improve the mobility of the city. Similarly, Rijkswaterstaat has realised that the acreage needs digital twins for effective renovations, most recently in tunnel infrastructure (Cobouw, 2022). Figure 34 shows a snapshot of the result as of 2022 year-end in the The Hague's system, where a bridge is integrated within the CityGML model. In the figure, the material passport for the bridge deck highlighted in blue is shown upon selection with some basic attributes. After completion, the organisation will openly publish a toolkit including tools, guidelines, and research reports.

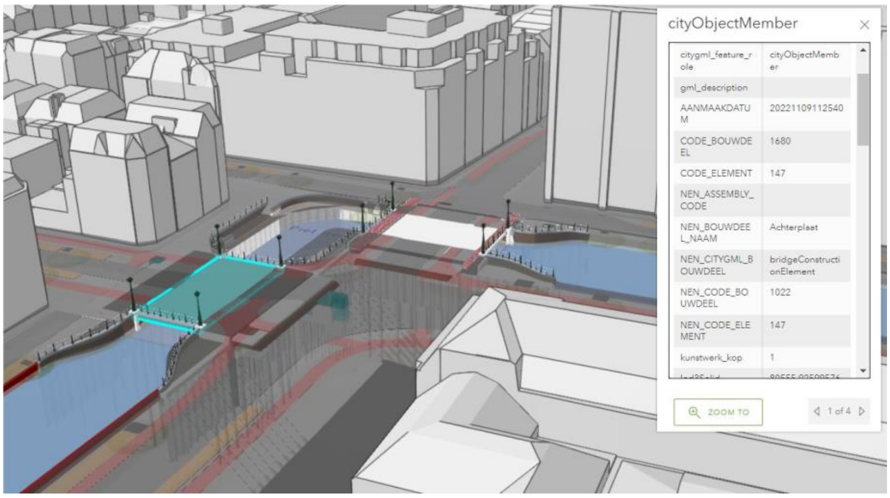


Figure 34: Snapshot of CityGML with bridge - municipality The Hague (Kampinga, 2022)

The first step in developing such a system is to create rough geometry with laser scanning technology (T3D, 2022). Subsequently, the individual structures can be integrated to create an increasingly data-rich model that can be used for a variety of purposes. For this step, more detailed laser scanning technologies can be used as well. However, to do this for each structure individually will quickly drive up the costs, which is unlikely to be justified by the benefits it generates. So, what is the added benefit of developing 3D models for existing structures? Considering the scope of this research (fixed bridges), this question becomes even more relevant with the upcoming R&R-task where many structures are nearing their EoL. Below the benefits are briefly described in 7 points, due to the novelty of such a strategy, literature cannot be provided for each point. This is replaced with the author's personal industry experience and expert knowledge from W+B.

1. All data surrounding the assets is documented and visualised in a single environment, thereby **increasing data accessibility, improved understanding of the acreage, and allowing more efficient communication** of data within the organisation and to external parties (Royal Haskoning DHV, 2022). Moreover, it enhances spatial planning and overall decision-making.
2. By creating a (semi-accurate) 'digital twin' of the asset, **attributes (including condition and maintenance data) can be directly linked to physical elements**, thereby significantly improving monitoring of the asset through better accessibility and traceability of data compared to 2D (cluttered) data storage for elements/components using Excel.
3. **Improved workflow for executing reusability scans**, driving down consultancy costs. Reusability scans require attribute, condition, and maintenance data for the individual objects of interest, geometry data with element connection insights omit the need to go on site for data gathering (Sykes, 2023).
4. Element geometry and its metadata from the 3D models and reusability scan output can be used as **improved communication medium in intermediary reuse databases to improve the linkage of supply and demand.** More accurate data increases the likelihood of reuse realisation by decreasing risk for the demand party. The 3D element can directly be integrated in the design software for a more streamlined design process. As a result of increased reuse, the asset value increases through compensation or indirectly in reduced project costs and emissions.
5. **Improved maintenance operations**, as the exact location of the asset can be traced digitally and the maintenance task can be prepared accordingly (equipment selection, workflow, etc.), thereby saving time and costs.
6. Asset & environment visualisation can **improve the preparation process of demolition/ deconstruction practices**, reducing the need for site visits. Potential improvements can be achieved in risk identification & management, site safety, work-breakdown-structure development, locating (hazardous or important) materials/elements on site, equipment requirements & placement, material storage and waste stream optimization on site, and deconstruction strategies. For certain structures, a 4D deconstruction simulation can be improve workflow efficiency, but not all (Van den Berg, 2019) (Goorhuis, 2020) (Rivero & Garcia-Navarro, 2020) (Designbuildings, 2021).
7. **Higher efficiency in setting up structural models** by directly extracting the correct dimensions and available material properties from the BIM-model using IFC-exports into the structural software (e.g., SCIA), thereby increasing the reliability and decreasing the costs of traditional workflows on recalculations (Lai, 2023). It also provides future potential for directly using the 3D models in software packages like Autodesk Robot Structural or Tekla Structures for automatic recalculation (when models are of sufficient Level of Detail).

Despite the short remaining lifetime of many bridge structures (~10-15 years), the upgrade can prove beneficial. AM efforts and maintenance operations generally increase in the last phase of the asset lifetime, meaning that there is still a large opportunity when acting fast. Based on this analysis, the view is adopted that 3D is a necessary development once 2D centralised AM is (fully) realised. The timeline for this upgrade is projected to be 2023-2030, in line with the current goal to have the entire built environment inventoried (Dutch: inzichtelijk) (Transitieteam Circulaire Bouweconomie, 2022). Until now the realisation of this 3D environment, more specifically that of upgrading the existing built environment, is infeasible due to the large costs of scanning technologies and manual modelling. Because the upfront investment for this upgrade is significantly large for public organisations, new technologies need to be developed that help reduce this threshold. The sooner the transition is made, the longer the benefits can earn back the investment and become profitable.

2.5. Theoretical framing of CE-transition

To conclude this literature study, a brief review of the state-of-the-art is revisited to put the findings in perspective. The main findings of this study include:

1. From the overview of the main barriers & initiatives of the CE-transition in leading Dutch roadmaps, it was found that most initiatives are focussed on realising a future circular built environment, without many concrete solutions on the lack of data on existing assets to enable short-term circularity.
2. Input uncertainties in Material Flow Analysis (MFA) studies, especially for civil infrastructures, impact the reliability and accuracy of CE-transition roadmap timelines and interventions, negatively impacting either the environment or the economy.
3. There is a lack of centrally stored high-quality physical asset data available at public organisations to conduct reusability scans and structural assessments on existing structures, this disincentivizes reuse realisation in practice as there is generally too much risk involved for demand parties and complicates the management of the activity timeline (maintaining/ renovating/replacing) to flatten the expected decommissioning peak in the R&R-task.
4. Asset Management (AM) is transitioning towards a 3D-centralised strategy in line with Building Information Modelling (BIM) technologies, while existing assets are still (and will be until decommissioned) in 2D with incomplete and fragmented data documentation.

To review these findings, a literature review was conducted with key terms ‘Circular Economy transition’, Çlosing the loop’, ‘Initiatives/enablers’, ‘Infrastructure’, ‘(Existing) Built Environment’, ‘Construction industry’, Digitization’, ‘Digitalisation’, ‘Industry 4.0’, ‘BIM’, ‘MFA’, ‘Material stock’, and ‘Asset Management’ that were combined while limiting the search to articles published after 2017. This resulted in approximately 20 articles that most related to the above statements. Below, the findings of these studies are used to reflect on the findings of this study. This theoretical framing will exclude the CE-transition barriers, as these were previously synthesized in Chapter 2.1 based on the literature findings in Appendix: A and Chapter 2.3.4 based on Appendix: C. This section will instead focus on the initiatives and enablers of a CE in the context of the construction industry.

2.5.1. General remarks

The CE-concepts/initiatives recommended by the state-of-the-art literature are summed up below: ***Encourage stakeholders to develop knowledge & skills, incentivize organisations to explore circular concepts, develop supporting policies, implement regulations, providing more evidence-based circularity, standardize CE-processes, measuring circularity methods, integrate 10-R ladder, Design-for-X concepts, circular business models (e.g., Product Service Systems), long-term partnership models & intense collaboration along the value chain, centralising management of asset and***

***material information, and leveraging digital technologies (BIM, AI, Blockchain, Internet of Things, Digital Twin, digital exchange platforms & big data analytics, and Material Passports)**.*
(Hart et al. (2019); Shooshtarian et al. (2022); Ghufran et al. (2022); De Mattos et al. (2018); Debacker et al. (2017); Zandee et al. (2022); Charef et al. (2022); Elghaish et al. (2022)).

Comparing the previously stated initiatives with the findings in section 2.1, it can be concluded that there are large similarities between these studies and the developed roadmaps in the Netherlands. From the analysis of these articles, it was concluded that there is a general lack of applicable practices as the articles remain on a rather conceptual level. A similar conclusion was drawn by Elghaish et al (2022), stating "Most of the existing bodies of research provide conceptual solutions rather than developing workable applications for the future of smart cities.". Whilst the theoretical knowledge on what needs to change systematically is important to create awareness and direction for the transition, more evidence-based research on potential solutions to overcome these barriers is required. Additionally, it was observed that the majority of the articles 'ignore' one of the most prominent barriers that limits reuse currently in their recommendations: the lack of data on existing structures and tools for visualising, identifying, and classifying potentially salvageable materials (Akinade, et al., 2020). Asset data governs the potential for reuse realisation for the coming 30 years as the existing structures are the material banks, not those that will be built with all the abovementioned circular concepts integrated in the project. This observation highlights an issue with the state-of-the-art literature on CE-initiatives: AM is hardly targeted in the initiatives compared to the attention that the CE-concept receives in academics. For this reason, the Closing the Loop concept was elaborated in greater detail in section 2.3.5 as this aims to tackle this problem (Van den Berg, 2019). Below, attention is paid to some state-of-the-art studies that aim to solve this problem.

2.5.2. Material flow modelling studies

Focussing on the scope of this research, multiple studies have been conducted on the significance of material flow modelling of the existing built environment. This domain adds to the predictability of material flows over time used in transition roadmap development as discussed in Chapter 2.2. Lanau & Liu (2020) and Honic et. Al (2023) reiterate the lack of detailed knowledge on material quantities, type, and distribution of secondary materials, and call for the development of a 'global' resource CADASTER, see Figure 35. Lanau & Liu (2020) conducted a case study of the city Odense in Denmark using geo-localised bottom-up material stock analysis based on building material intensity coefficients. The developed resource CADASTER at high resolution can inform stakeholders along the value chain to better plan for materials and component recovery and improve waste management. While the uncertainty remains high by adopting coefficients, a valuable model can be built using this approach for CE-purposes. Reflecting on the digitization transition and 3D centralised AM, these developments can be valuable complete one another.

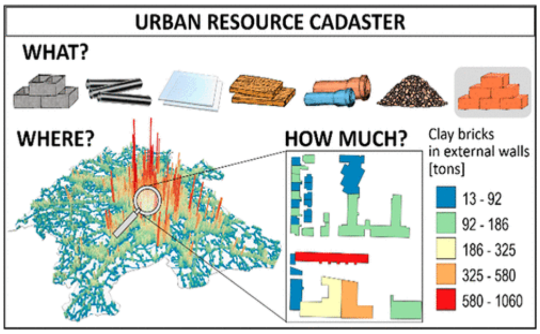


Figure 35: Resource CADASTER model (Lanau & Liu , 2020)

A second state-of-the-art approach by Honic et al. (2023) concerns the use of BIM and Geographic Information System (GIS) to assess material quantities. This approach combines two tracks to obtain the material quantities: (existing) planning documents, laser scanning and site visits to create a BIM, as well as using both 2D and 3D GIS models to approximate gross material volumes of the asset. However, this study is limited as it adopts archetypes (e.g., construction period of a type of housing) and extrapolates these findings to structures that fit this archetype. This results in uncertainty as well as limitation by design as it requires a complete set of archetypes that cover the entire built environment. Once such a database expands and is validated, this proves to be a promising method.

Both studies show the need for bottom-up material modelling of the existing built environment, while providing potential solutions by extrapolating real-data using geospatial information, primarily applicable for the building sector. Similar findings were concluded in section 2.2. However, putting such studies into perspective, Shojaei et al. (2021) have investigated the potential advantages of CE-based blockchain technology for the construction industry. This study found that blockchain allows for a fast, secure, and accessible information network by providing a decentralized ledger where construction materials and products can be traced from source to EoL. In doing so, providing opportunities for early planning of reuse/recycling, and optimizing the waste supply chain. However, construction CE solution-based blockchain requires further studies on a larger scale to be validated, moreover, it will require the data from studies above to function properly.

2.5.3. Digital technologies & CE

From the analysis of a wide range of recent bodies of research on the CE-transition, a common theme was derived: the linkage between digital technologies and the CE. Okorie et al (2018) observed an increase in research attention that combines these topics. Cetin et al. (2022) stated that digital technologies are the enablers of the CE by providing an analysis on 10 enabling technologies, while Antikainen et al. (2018) concluded that digitalization could help close material loops through more accurate information representation on availability, location, and condition to increase resource efficiencies. However, there are still large challenges to be overcome before these desired benefits can be realised. Taking this a step further, Elghaish et al. (2022) have conducted a larger body of work that reviews the existing research on digital technologies and the industry 4.0 concept in relation to the CE and identifying the gap to what is currently possible. Common technologies named in previously mentioned studies included: BIM, AI, Internet of Things, Blockchain, 3D scanning technology, Digital Twin, digital exchange platforms/marketplaces combined with big data & analytics, cloud technology, and Material Passports. While many of these innovations depend on a situation where there is sufficient asset data available, some (AI, BIM, 3D scanning technology & Material Passports) aim to address the current problem of existing information availability.

Dang et al. (2018) propose a new approach to bridge asset maintenance that leverages 3D scanning technology and alignment-based parametric modelling to create a 3D model of the asset with automatic detection of cracks and other defects. These generated 3D models can then be armed with attribute data (condition, environmental data, etc.) of specific elements to create BIM models or digital twins, which in turn provides the basis for material passport generation (Charef & Emmitt, 2021). Using AI and big data analytics, future performance of a structure can be predicted by damage records of similar structures under different environmental conditions (Dang, Kang, Lon, & Shim, 2018). This example shows a potential solution for the lack of asset data that could result in more short-term circularity. However, Rashidi et al. (2020) state that the higher costs remain a barrier for adoption, while costs are projected to decrease over the coming years. These upfront costs can be offset against traditional (more frequent) manual inspections by its higher level of detail and longer-term benefits. Ramadoss et al. (2018) introduce another method that aims to optimize monitoring of reusable elements through low-cost sensors combined with AI for analysis, providing a lower threshold option. Akanbi et al. (2020) proposed a deep learning model to estimate the salvage value of building materials before demolition, which supports decision-makers to determine the monetary value of materials to be recovered. To integrate all these technologies properly for optimized impact, a digital ecosystem should be developed where information is interlinked through IoT and blockchain for asset tracking (Damianou et al., 2019; Rahimian et al., 2021).

With the insights from the state-of-the-art, this study's literature findings can be put into perspective. It can be concluded that the 3D centralised AM proposed in section 2.4 is inevitable with the digital technologies in the pipeline and its linkage to realising a CE. While there is a large potential in these developments, more R&D is required on a large-scale adoption before they can become practicable and affordable to solve or accelerate the problems found in this literature study. At the heart of all the initiatives from literature, is a data-rich environment of the (existing) assets that will then allow reuse realisation empowered by political, contractual, collaborative and technological changes. Obtaining this data should be a more prominent research topic if we want to reach the CE-goals of 2030 and 2050 (Rijksoverheid, 2016).

2.6. Concluding remarks literature study

This literature study is summarized in Appendix: E. Figure 36 shows a simplified overview of the findings. Each of the industry challenges covered in this study can (in part) be traced back to AM and the lack of quality data registration on existing assets and lack of funding to upgrade this data to the required BIM level of information need that is provided in newly constructed assets. Considering the number of assets (materials & value) and the short-term need for solutions to manage the challenges (increased reuse realisation, accurate CE-roadmapping, effective R&R-timeline management & AM practices), neglecting existing assets until they are replaced (with BIM at handover) has large environmental impacts that can be mitigated with smart engineering solutions to obtain semi-accurate BIM against reduced costs compared to existing methods to better navigate the industry challenges.

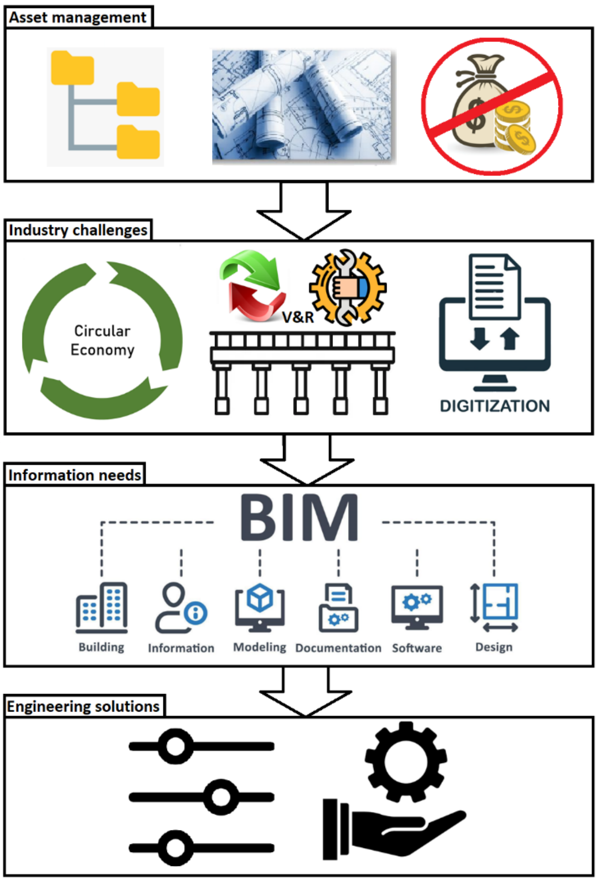


Figure 36: Overview of literature study findings

Chapter 3: Interviews data availability at industry parties

The literature study has provided a theoretical perspective on the changes happening in the construction industry, the problems and opportunities that come with them, and what information is to be required to tackle these transitions effectively. Considering the novelty of the CE- and 3D asset management transitions and the traditionally conservative tendency towards innovations in the construction industry, the proposed changes were introduced to various industry players to gauge their readiness and willingness for adoption. In doing so, various concepts discussed in the literature study were attempted to be validated to further establish the need for urgent changes.

The method used for acquiring these insights comprised of conducting semi-structured interviews with asset owning organisations across administrative layers and informal interviews with a variety of experts from an engineering consultancy. Parties included in this analysis were municipalities of Deventer and Almere, the province of Overijssel, and Witteveen+Bos (W+B). Rijkswaterstaat was excluded from the interviews, as much information regarding their ambitions and data documentation standards was already found in online publications and from W+B experts deployed there. The questions of the interviews were divided into the following topics, in which W+B experts answered these from the perspective of the consultant:

- Current level of data quality & documentation for (bridge) infrastructure at public entities.
- Inspection & maintenance documentation.
- Current efforts to improve data quality & documentation.
- Representativeness of organisation's answers for comparable entities.
- Cause for lack of complete data centralization.
- Circular economy efforts within the organisation.
- Ambitions for upgrading to 3D centralized asset management.
- Hypothetical implementation of the developed design tool in organisation.

The interview findings are summarized in matrix format, to be found in Appendix: F. The findings are based on the takeaways generated from the interview transcripts. Below, the main conclusions of the interviews are briefly discussed. From the interviews, it can be concluded that the literature study findings are in line with practice and are therefore validated.

1. **Incomplete asset data in a centralised environment.**

   Most organisations do not have complete material passports for their assets compared to what was discussed in Chapter 2.1, only the basic information such as construction year, design lifetime, surface area, and asset type are consistently documented and linked to their location in a GIS platform. For some assets, a photo and traffic class are attached. 2D drawings and project specifications were documented but are currently lost at many organisations, it will require large efforts to retrieve this data and link them to the specific assets. It is likely that not all data will be retrieved, and site measurements will be necessary to obtain physical information on the asset. Furthermore, there is no data on material quantities of the assets.

   The main reasons for this data unavailability are the lack of need for the information over the first part of the asset's lifespan, change in personnel causing knowledge loss, and changing asset management systems over time. These findings confirm the lack of asset data quality, completeness, and centralization, as discussed in the literature study. The lack of data resulted in limited overview of the assets and material flows, information traceability and communication to external parties.

2. Inefficient condition monitoring & maintenance operations.
Inspection findings are generally stored in standardized reports where there is a lot of noise that limits the traceability efficiency of information for the purpose of monitoring or maintenance activity management. Often, a maintenance register is lacking for overviewing all activities to allow for operations optimization. Monitoring conditions of specific elements over the entire acreage is either inefficient or (more often) completely lacking.

3. Larger organisations tend to have higher quality data & documentation standards.
Asset data quality and organisation standards are generally better organised at larger organisations due to larger capacity and budget. The impact of poor management strategies is significantly larger compared small organisations, where civil artworks received less attention due to lower asset counts and maintenance requirements at the first part of the asset lifetime. Especially smaller organisations are waking up now and trying to achieve a complete centralised asset management environment by gathering data to be able to manage the upcoming R&R-task.

4. Reuse realisation lacks standardized methodology & asset data to become a business case.
Reuse is often an ambition that is currently very difficult to realise with the limited data that is available. At public organisations, reuse is by no means a standard part of the EoL methodology due to a lack of knowledge and practices. The current reuse initiatives predominantly regard low-value reuse of beams and planks from timber (foot/cycle) bridges. There are ambitions of setting up local reuse-databases and material depots, however this currently lacks the required data inventory of assets and elements. From the project perspective, a lack of quality supply for reusable elements is observed, constraining the integration of reuse in designs. The interviews confirmed the findings in literature where there is lacking knowledge for integrating reuse, data, reuse applications, and supply of reusable elements. Most barriers can be traced back to a lack of data on existing infrastructure.

5. Widely shared ambition for 3D asset management in the future, constrained by budget.
All parties agree that 3D asset management & digital twins bring many benefits on asset management and circularity grounds and will become the standard in the asset management realm, however this is perceived as a future too far away to worry about now. Upgrading the existing acreage from 2D to 3D will first require a complete 2D asset management system, which is the priority now. The focus for most (smaller) organisations is still short-term asset management, thereby disregarding or postponing the long-term problems and costs like the R&R-task (recalculations, renovations & replacements). In doing so, costs will only pile up, making the budgeting problem even larger. Despite this mindset and awareness of the R&R-task, the budget constraint remains a limiting factor in realisation, even when the users are convinced of the business case. (Innovation-) budget allocation needs to be reviewed higher up, where short-term profits and ROI-certainty play a large role. By providing more certainty on the business case of upgrading the acreage to 3D and reducing the investment threshold, parties are more likely to reassess their shorter-term perspective on this transition. The ambition is particularly interesting for concrete vehicle bridges as these have the largest reuse value, timber is often constrained to low-value reuse, and steel has promising sustainable (high-value) recycling potential. Foot/cycle bridges are often constrained to low value reuse as technical replacement is more likely.

Chapter 4: Opportunity analysis

This chapter comprises the analysis of an opportunity concerning the call for more cost-efficient modelling methods for existing (bridge) infrastructure in the context of the CE-transition, R&R-task and digitization transition within AM, arising from the literature study and interviews with industry experts. First, the development statement is presented, followed by a gap-analysis that includes an introduction to Parametric Engineering & Modelling (PEM) as well as a market analysis on the current state of the field in the context of the development. Then, a Cost Benefit Analysis is performed on the upgrade from 2D to 3D centralised AM system based on conventional manual modelling practices, to display the business case and lay a foundation for assessing the value of the tool later. Subsequently, a risk assessment is conducted on the business case by means of analysing the to-be-developed tool's leap of faith assumptions to ensure the robustness of the business case. Next, fixed bridge infrastructures are assessed on reusability, first to identify the most promising category followed by individual elements of that bridge category. These findings are used for determining the desired Level of Detail (LOD) of tool development, in combination with an analysis of the end-use of the tool-output. Through these analyses, the tool can be justified, and the chance of wasted effort is minimized.

4.1. Development statement

In the context of the CE-transition, R&R-task and digitization transition, there is an urgent need for 3D BIM models of existing structures. Although bridges are only part of the larger problem (i.e., all infrastructure assets), fixed bridges have a large impact on each of the three previously mentioned challenges and provide the opportunity for parametric tooling to reduce the investment threshold for public organisations in obtaining this data. The development statement therefore becomes:

> *Developing a design tool for fixed beam- & slab bridge infrastructure using modular Parametric Engineering & Modelling methods to significantly decrease the design efforts and costs for obtaining 3D BIM models from 2D data at public organisations.*

In doing so, accelerate the digitization transition at public organisations, increase circularity realisation for bridge infrastructure, provide more accurate bottom-up material quantity data for CE-transition roadmap development, and improve data quality for the upcoming R&R-task. To achieve this outcome, some steps were be followed:

- *System analysis.* Understanding the solution space and why this development needs to take place. This will be tackled in this chapter.
- *System requirements.* Describing what functionalities this tool at least should provide, using which tools, and in what timeframe. This will be done in the next section.
- *System synthesis*. Here, the tool will be developed until the set requirements are fulfilled, using a specified approach. First, the approach will be justified, then the tool will be described.
- *System validation & evaluation.* Lastly, the tool's requirements are verified, and its performance is both quantitatively and qualitatively analysed.

4.2. Gap analysis

The literature study described the need for a cost-efficient method for upgrading the existing asset data to higher quality 3D-BIM data. The existing methods include hiring an engineering firm to manually model the structure based on the 2D drawings or leveraging 3D scanning technologies to compute a 3D model from points clouds. Bridges represent the most impactful infrastructure type (excl. roads) using count, total material volume, and R&R-task challenges as metrics. The traditional modelling methods are perceived as too expensive for public organisations to employ on a large scale, while cost reductions for 3D scanning technologies are uncertain. Considering the characteristics of Parametric Engineering and Modelling (PEM), the author identified a large opportunity in fixed bridge infrastructures to significantly reduce the modelling time and costs.

4.2.1. Parametric bridge modelling

Parametric modelling is a modelling process with the ability to change the shape of the model geometry by modifying a predefined parameter value (Fu, 2018). In other words, the modelling effort changes from physically drawing lines and shapes to defining them with adjustable parameters based on mathematical functions and relationships. This omits the need to completely model a structure from scratch or re-do design aspects influenced by a certain rework, as the design is predefined and parameterised. When the parametric model is used for multiple projects, the upfront effort of parametrizing the design can be recouped by this decreased design effort. Similarly, in highly dynamic or complex projects with many reworks/design changes over the course of the project, significant design efforts can be saved. Parametric modelling is made accessible for designers through visual programming, which is shown in Figure 37. Each node represents a function, or tool, requiring predefined input and producing a set output. Behind this node is Python code that allows the functioning of the node without requiring the programming knowledge for the designer. By connecting nodes, a link is created of the output of one node to the input of another. This way, it is possible to create interrelatedness between parameters and elements.

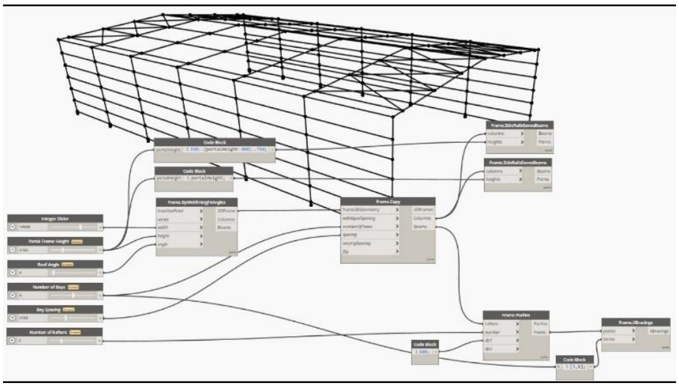


Figure 37: Dynamo interface for parametric modelling

Bridges are often very similar in nature, which makes them interesting for parametric modelling, this has multiple grounds. Firstly, bridge design is highly influenced by design codes and standards (Yang, 2022). Because of this, and their functional purpose which requires them to be structurally robust and maintain high serviceability, bridges generally leave little space for architectural influences which are more expensive. Secondly, there are a limited number of bridge types, as shown in Figure 23 in section 2.3. Each of these types can be decomposed into a limited set of elements and components. These elements and components can then vary from one another in design, dimensioning, and material. Moreover, due to the large number of bridge structures in the Netherlands (but also in general), many similarities can be expected between the structures as there are limited designs practicable with costs as the restricting factor. These characteristics of bridges make them suitable for PEM.

4.2.2. Market analysis

With this potential opportunity of using PEM to improve conventional modelling practices, it is mandatory to be aware of existing models or tools to avoid developing an existing tool. To do so, a market analysis was conducted that aimed to uncover the current availability of such tools, their purpose, scope, limitations, and relation to the problem at hand. Three search engines were consulted in this study: Youtube, Google, and Google Scholar. Additionally, W+B was internally consulted on the existence of similar tools already developed or in development. The findings are discussed using a distinction between software and stand-alone models. Recurring search terms in this analysis included:

iv. Parametric modelling bridge
v. Parametric design tool bridge
vi. Bridge design dynamo/grasshopper
vii. 3D model from 2D drawings

Discussion on findings

Software

Multiple software packages were discovered that allow more accessible and efficient parametric modelling for bridge infrastructure compared to visual programming like Dynamo/Grasshopper, such as Allplan bridge (Allplan, n.d.) or Sofistik (Sofistik, n.d.). These tools still require considerable manual labour and input when it is to be used for existing structures as they cannot easily interchange predefined design elements to account for minor (or major) changes between structures, which is desired for modelling large quantities of existing structures.

Models/scripts

The analysis has also shown that there are little freely available parametric models of bridges as it is often intellectual property. Those that are freely available or replicable generally require highly detailed input, which is not easily extractable/available in drawings, or desired given the context of the development. Moreover, most tools concern highly complex, architectural structures with organic shapes, as these are complicated to model manually (mostly for arch-type bridges). A limitation of such models generated by either Grasshopper or Dynamo is that the design itself is defined and cannot easily be changed outside of its parameters (e.g., length, height, etc.). When one element is different in design, the model is already unusable or requires manual interference. This characteristic makes parametric modelling currently unattractive for 3D modelling existing structures, even more so considering the low frequency of such tasks (one bridge at a time instead of in bulk, making parametric tooling interesting). W+B designers confirmed this, showing that little to no attention is currently paid to developing tools for generating 3D models for large quantities of existing bridges.

A potential solution to this would be to develop a database of parametric models to account for different designs/structures, thereby decreasing the manual effort to account for minor changes. However, this requires a lot of development effort and requires a lot of designers to familiarise themselves with the scripts to be able to model the entire bridge infrastructure acreage in the Netherlands. This is an inefficient workflow and above all not realistic as there are too many design details to account for, especially when implementing higher levels of detail in designs. As established in the literature study, not all elements require similar level of detail due to their reusability potential. For this reason, a modular approach where a database of parametric elements (sorted by element type) is developed to account for the variations in elements could be promising.

4.3. Cost-Benefit-Analysis 3D upgrade

Now that the opportunity is exposed, the business case needs further analysis before moving on to the development phase. In this research was opted for a Cost-Benefit-Analysis (CBA) considering the role costs play in the problem at hand. This CBA uses the current situation of traditional modelling practices (hiring an engineering firm) for upgrading the 2D AM system to 3D, to draw a baseline for costs that can be used as a benchmark for the to-be-develop tool's performance. For simplification reasons, it is assumed that the 2D centralised AM system as described in section 2.4 is the standard practice. This simplification is logical as most organisations aim to, or already working towards, realise this strategy at the time of research. With this simplification, the costs for data gathering on 2D drawings is not included considering the differences in documentation standards between organisations. For this reason, the benefits that are generated by centralizing the asset data in a 2D environment compared to current (fragmented, decentralised & inconsistent) work-practices are not included either. An exception is made for the case where drawings cannot be retraced, in which case costs are made for making measurements on site specifically for this upgrade to 3D. The CBA is limited to the quantification of costs and some benefits, as not all can be quantified at this stage due to the novelty of the transition. For the benefits that are included, assumptions were combined with real data. To account for uncertainty, bandwidths for both costs and benefits were included. First, the costs and benefits are (re)introduced.

4.3.1. Costs (for bridge infrastructure):

1. Conducting site measurements for the geometry in case there are no drawings to be found.
2. Costs for manually modelling a 3D model from (organised) 2D drawings or site measurements.
3. Transitioning to the 3D supporting AM environment, including setting up the initial environment, integrating the models (with attributes).

The general assumption for upgrading to higher quality asset data is that this directly implies more registration and documentation work for the asset managers (Lunenborg, 2022), which are indirect costs. While this is true to an extent, the author adopts the view that this effort is already required to a large degree for 2D centralised AM. Moreover, the time savings generated by the upgrade (e.g., improved data traceability and communication quality) could counterweigh the effort, especially when an efficient methodology for data management is implemented within the organisation.

4.3.2. Benefits (summarized from Chapter 2.4):

1. A centralised file for all asset information that improves decision-making and communication.
2. Direct linkage of attribute data on all levels of the decomposition for improved information accessibility and monitoring of assets.
3. Maintenance operation optimization based on more accurate and visualised task descriptions.
4. Reduced efforts for reusability scans.
5. Better linking of supply and demand for reusable elements. 3D object geometry with its metadata can be used as communication medium in intermediary databases for increased reuse realisation in projects, increasing the asset value and reducing emissions.
6. Improved preparation processes for demolition/deconstruction practices.
7. More efficient information gathering and potential automation for recalculation tasks.

4.3.3. Analysis

To be able to conduct the analysis, a case is constructed based on real data from the municipality of Deventer, supplemented with fictive (yet realistic) assumptions. The municipality of Deventer is an average sized municipality, making it representative for most municipalities in the Netherlands. The municipality has 163 fixed bridges/viaducts in its acreage (Lunenborg, 2022). For simplicity reasons and lack of concrete numbers (as most municipalities do not know yet), it is assumed that an average of approximately 10% of bridges in the acreage lack the technical drawings and specifications. Moreover, it is assumed that 100% of bridges within the acreage will be manually modelled (excluding the possibility for 3D scanning technologies). For reuse, 10% of bridges are assumed to provide a potentially reusable element with 30 remaining that is reused within the organisation so that the cost savings for the new project are for the owner. Finally, it is assumed that by the time there are enough 3D models to fully make the transition to a 3D centralised environment, a software package has arisen that has sufficient out-of-the-box that requires minimal customization efforts.

4.3.3.1. Costs

Measuring dimensions on site:

- 500 EUR/asset for an average municipal bridge when it is combined with a routine inspection, or 25% on top of inspection cost (2000EUR average) (Sykes, 2023).

3D (manual) modelling:

- Average (municipal) bridge: 1500-2500EUR/bridge (Wolbrink, 2023).

Setting up data environment and integrating data:

- 50-100h to familiarise and customize with software package (assumption).
- 1h/asset to integrate in environment and set up passports (Visser, 2022).
- Assumed rate of 70EUR/h for asset manager.

Total costs:

- To obtain measures (combined with inspection): 500EUR x 163 x 10% assets = 8k EUR.
- To upgrade to 3D (manual modelling): 163 x 1.5-2.5k = 244.5-407.5k EUR.
- To set up 3D environment: 50-100 x 70 EUR + 163h x 70 EUR = 14.91-18.41k EUR.
- Total costs: 8k + 244.5-407.5k + 14.91-18.41k = <u>270.4-444.1k EUR.</u>

4.3.3.2. Benefits

The benefits that are included in this study are those that can be linked to actual costs, most benefits relate to time savings or improved quality of work which is not possible to accurately quantify nor monetize. The following assumptions were made for reuse scanning and reuse:

Reuse scanning:

- Average costs reusability scan: 1000EUR/asset (Sykes, 2023).
- Time savings with a 3D model including element specific attribute data: 25-50%.

Cost saving for using reused elements in projects (reference element used: bridge deck):

- Average municipal bridge: 12x6m=72m2 (Wolbrink, 2023).
- New value of in-situ slab or composite girder bridge deck with 100y design lifetime: 1000-1500EUR/m2 (Bakker, 2023).
- Value = price new element * (remaining technical lifetime reuse element in new function / design lifetime new element)

Savings:

- Reusability scan savings: 163 x 250-500EUR = 40.75-81.5k EUR
- Reuse savings: 163 x 10% assets x 300EUR*72m2- 450EUR*72m2= 387.3-580.1k EUR
- Total savings: 40.75-81.5k + 387.3-580.1k = <u>428.05-661.1k EUR</u>

4.3.3.3. Discussion

1. **Optimistic outlook on reuse realisation.**

Looking at the final bandwidths for costs (<u>270.4-444.1k EUR)</u> and benefits (<u>428.05-661.1k EUR)</u>, the Return on Investment (ROI) looks profitable. However, there is a large uncertainty involved in the quantification of the benefits while this uncertainty is limited for costs. For this analysis, an assumption was made for bridge deck reuse in 1/10 bridges. This assumption might seem very optimistic considering that it is still unknown what ratio of technical/functional replacements will be. However, while the current perception on bridge reuse is often limited to the main load bearing system (girders/deck), this research has shown that other elements can also be suitable for reuse (both low- & high value) when they are armed with quality data. Although these elements might be worth less, value is still to be captured. The bridge deck reference shows that construction elements are highly valuable even with decreased lifetime and can certainly win back part of the investment, if not make profits. Considering the growing number of functional replacements (70-80% in RWS's acreage

(Offenbeek, 2022)), it is very plausible that in more than 10% of bridges some elements are reused. Although 3D is not a prerequisite to harvest elements, it is essential in improving the connection between supply and demand as this research has shown the lack of demand is (partly) caused by low quality of data supply causing undesired uncertainty in the design process.

2. **Qualitative benefits of the upgrade are not included in study.**

More importantly, most benefits of the upgrade to 3D are not included in this analysis, for example improved maintenance/decommissioning operations, information traceability & exchange, condition monitoring, and indirect benefits (see Appendix: G). These activities can save time or improve the quality of project outcomes through decision-making, as was explained in section 2.4. Although their magnitude cannot be quantified, it can reasonably be assumed that decisions can have large financial, social, and environmental consequences, especially considering the scale of the construction sector. Additionally, considering the ambitions stated in the Transitie Agenda (2022), 'requiring' the entire built environment to be *transparent* (Dutch: inzichtelijk) before 2030, the investments are inevitable. By making the upgrade earlier, the benefits can recoup the investment for a longer duration.

3. **High upfront investment remains the largest barrier.**

The downside of the business case remains the high upfront investment costs. As determined in the interviews, this funding is generally not available unless an innovation fund is used. However, putting the costs into perspective, a structural recalculation for an average concrete bridge can already amount to 10-50k (depending on the data availability and level of detail required and excluding additional site experiments), and a new bridge can easily cost over 1 million EUR (Janssen, 2022). Large amounts of capital need to be allocated to the bridge R&R-task in every organisation, considering the scale of costs that will be required here, the costs for the 3D upgrade can be justified more easily. The cost analysis was conducted with the assumption that traditional modelling practices were used, which accounts for the majority of the costs. If the average modelling time required per asset were reduced, significant costs can be saved, making the transition more attractive for asset managers.

4.4. Leap of faith assumptions

The last element in analysing the business case of developing a tool for optimizing the design 3D process concerns a method by Eric Riess' book the Lean Start-up (2011): the leap of faith assumptions. This aspect is an important step in any innovation as it exposes the risk and dependencies of the development. Leap of faith assumptions concern statements that 'must' be(come) true in order for your innovation to make sense and succeed. Not all assumptions can/are be checked before starting the development phase or investment and therefore expose the risk. Below, a list of assumptions is shown for the to-be-developed tool.

1. Asset managers face problems with the fragmented documentation on assets and would benefit from a single file with all/most asset information documented. **(Already validated)**
2. Asset owners want to have 3D models for reuse/maintenance purposes and there is ambition for a 3D centralised asset management. **(Already validated)**
3. 3D scanning technologies will not become cheaper in the near future (<10 years).
4. Organisations can obtain 2D drawings and project specifications of the majority of their assets.
5. Once 2D centralised AM is completed, the only obstacle that remains is the costs for upgrading.
6. Smaller organisations can get the funding to upgrade their existing bridges to 3D.
7. Asset owners want to invest in upgrading bridge data that will be decommissioned in 10-20y.
8. A 3D centralised AM software will have been developed by the time organisations have sufficient data to make the transition.
9. Similar efforts (3D upgrades) are being executed for other asset types (and buildings).

10. Demolition contractors will use the 3D models to optimize preparation and harvesting.
11. Asset managers will actively share and maintain the newly obtained basic asset data in centralised registration systems like BGT to help achieve a more efficient CE transition.
12. In the future, organisations will explore interorganisational reuse by using third party databases and expanding the applicability of their products to increase asset value.

After analysing these statements, it was concluded that the largest risks for the business case were the data gathering timeline and completeness for the transition to 2D as this determines the potential adoption rate for the tool, and whether funding can be made available within organisations to explore the upgrade to 3D (even with cost reduction through the tool). From the interviews it was made clear that the 2D data was not lost permanently (yet), but the effort to for the data-gathering and organisation process is simply too large for the time being. Moreover, considering the broadly shared ambitions of the asset managers to transition to 3D centralised AM, the funding is perceived as a matter of time. This assessment excludes the technical risks & limitations in the development process.

4.5. Bridge reusability analysis

To narrow the scope of the to-be-developed tool, the most promising bridge types and elements were determined by means of ‘high-level’ analyses. This means that some simplifications have been made throughout the process to be able to arrive at conclusions faster, thus carrying some uncertainties. First, the types of structures, materials, loading profile, volatility of the acreages, and reuse value are analysed to identify the most promising bridge category for reuse exploration. This scope reduction then allows a deeper dive into analysing the individual bridge elements on their reusability to be able to conclude if bridge reuse is worth pursuing and if so, where the focus should be. Due to the newness of the field of reuse in the construction industry, there is limited validation of the findings in the five discussion points in literature, this should be considered when reading this section. Expert knowledge from W+B was consulted to reduce uncertainty.

4.5.1. High-level reusability analyses bridges

From the extensive analysis in Appendix: H, the following conclusions were drawn on bridge reuse:

1. Beam bridges have the largest potential for reuse followed by ‘dry-connected’ slab or plate bridges, and lastly, arch bridges (depending on material and size). See Figure 38 & Figure 39.
2. Concrete, steel, and composite structures the most promising material for high value reuse, with concrete having the largest impact considering the material distribution in bridges, emission-free upcycling potential of steel, and low probability of high-value timber reuse.
3. Rijkswaterstaat (RWS) and provincial bridges are more heavily impacted by increased loading over time as freight transport predominantly uses these networks, resulting in higher degradation. Therefore, municipal bridges have a higher relative durability.
4. Volatility of the acreage causing functional changes is most common in municipalities, though recently many RWS bridge had to be replaced/renovated due to increased traffic intensity.
5. RWS bridges have the largest potential for high value reuse, followed by provincial and municipal vehicle bridges. However, RWS bridges are most easily over-dimensioned as the provincial bridge count is relatively low. Provincial bridges have a large pool of municipal bridges where they can be applied. Though municipal vehicle bridges have the highest potential as they can be applied on lower loaded municipal bridges or foot- & cycling bridges. Last mentioned have the smallest probability of high value reuse considering their limited applicability and low probability of functional replacement.

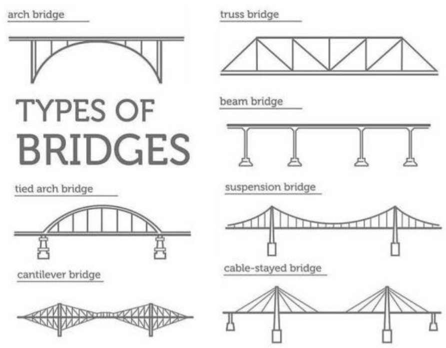


Figure 38: Bridge structure types (Yashavsi, 2022)

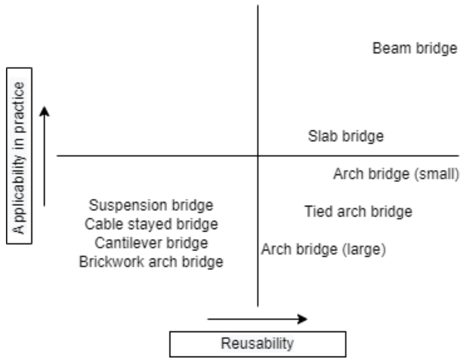


Figure 39: Overview reusability bridge structures based on analysis.

Figure 40 summarizes the previous statements by means of a flowchart for bridge reuse, above the flowchart are the influences on the bridge reuse process. Based on this high-level analysis of bridge reuse, it can be concluded (municipal) beam & slab vehicle bridges made of concrete (or composite) have the largest impact on the R&R-task and CE-transition and should therefore be evaluated further.

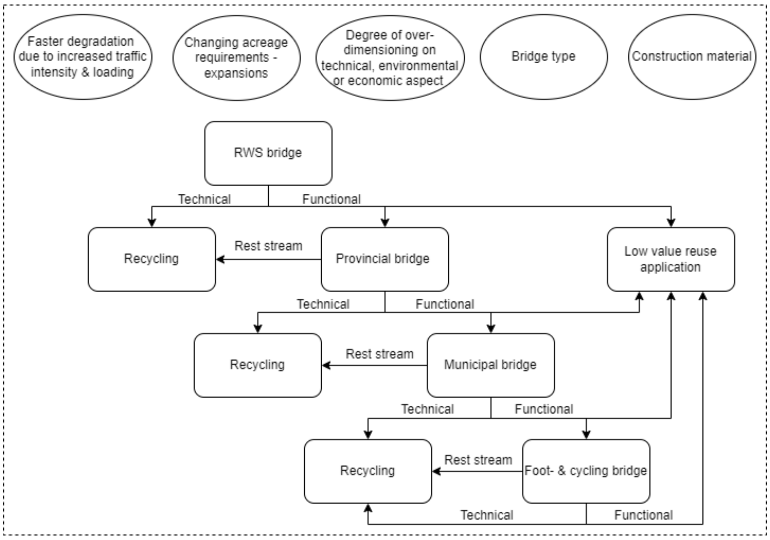


Figure 40: Flow of bridge materials at EoL

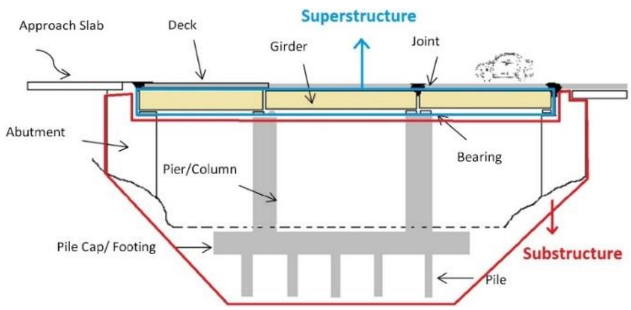


Figure 41: Bridge element definitions (Bektas, Carriquiry, & Smadi, 2013)

4.5.2. Reusability of bridge elements of vehicle beam/slab-bridges

Using the conclusion from the previous section, an analysis was conducted on the reusability of the most common/important bridge elements of beam- and slab bridges. In this report, only the conclusion of the more in-depth study in Appendix: I is presented. There, more detailed explanations can be found as to how the pros and cons were generated. An inspiration for this study was the framework developed by (Brouwer, 2022). Figure 41 displays the common bridge lexicon for concrete bridges was used in this study. It should be noted that asphalt is not considered as part of the bridge structure as it belongs to the road and is managed differently to civil works. Considering the newness of this field, and the limited studies on individual elements, it is likely that the possibilities (and therefore findings) will be expanded due to the increase in research and awareness in recent years (Wind, 2022). This section should therefore only be used as knowledge base and not as limitation of reuse in bridges. An important definition that was used in this study concerns the reuse value score of an element. This score is affected by three indicators: Structural, Economic and Environmental. The structural value depends on the extent of over dimensioning of the element in the context of its new function, the economic value depends on cost differences with other alternatives, and the environmental value depends on the environmental emissions compared to other alternatives (Brouwer, 2022). Low-value reuse concerns reuse of an element that is in a different function than what it was designed for, whereas high value reuse is using the element in a similar purpose.

Table 9 in Appendix: J shows an overview of the findings in Appendix: I. From this, it was concluded that that girders are most suitable for reuse at another location (high value), followed by railings & barriers, curbs, tiles, standard columns, supporting beams, and dry connected slab decks (with limited size). Furthermore, the substructure elements are suitable for extended lifetime at the same location, supported by structural enhancements if need be. The concept of reusing bridge elements is still very new and far from optimized, meaning that more elements can be deemed reusable in the future. These findings will be used in the tool development process to ensure higher accuracy for these elements as they provide potential for reuse. This is not to say that the other elements can become inaccurate, only that small details/inaccuracies can be accepted for now to reduce the scope.

4.6. Purpose & LOD analysis

Finally, it is important to establish the Level of Detail (LOD) that the tool output needs to have to leverage the desired benefits. This will be analysed in this section. A distinction is made between LOD for geometry/modelling and information detailing (attributes). Bertin et al. (2020) has provided a BIM-based framework for the LOD of load bearing systems in the context of reuse, which will be adopted for this research. Figure 42 shows this framework with a high rise building as an example. Another widely adopted framework was developed by BIMFORUM (2019), which provides similar descriptions for the levels. Up to LOD500, the geometry accuracy gradually improves in line with the design stage. LOD600 and LOD700 concern the use phase and decommissioning/reuse, where attribute data (information) becomes more important. Throughout the literature study and interviews with asset managers, the need for higher quality asset information has been discussed. Below, the purposes of the individual 3D models for asset managers are briefly revisited, collectively they determine the required LOD for the tool. These functions are divided into three groups: asset management, providing a data foundation for reusability scanning & structural assessments, and material quantification.

1. **Asset management**

The key activities in AM include spatial planning, communicating asset data to stakeholders, condition monitoring, maintenance planning, and decision making for EoL. Moreover, inspections, maintenance and decommissioning activities need to be executed. These activities require a semi-accurate 3D model of the asset with distinctive elements to the degree in which they are managed/inspected, excluding minor details that don't impact the spatial/functional aspect of the asset. Additionally, customizable element specific attribute data storage is necessary based on user preferences. Lastly, the model will require information (visualised or attribute) on element connections.

2. **Providing a data foundation for reusability scanning & structural assessments**

For the realisation of reuse and better management of the bridge R&R-task timeline, reusability scans need to be conducted on assets and structural assessments on a select group of assets. In addition to the previously mentioned requirements, this will require a higher accuracy of model elements that have a high reuse potential (see section 2.3.) such that they can be represented in reusability databases and provide accurate information for the structural assessments that might be required. Condition data (cracks, deformations, degradation, etc.), material specification, loading profile, and reinforcement profile all play a vital role in reusability scanning and structural assessments. It is important that these attributes can be stored efficiently on element level, as well as the findings.

3. **Material quantification**

As discussed in section 2.2, material quantities of the individual assets are valuable information for the material flow models, especially for civil structures as there is large uncertainty in the current models. These material quantities can be derived directly from the geometry (volume). To ensure that this data can be used properly on a local scale, a bandwidth value of 95-105% of the total asset volume is aimed for, which then results in the material mass when using the material specifications. This allows space for detail errors that go beyond the scope of the 3D purpose yet remain accurate enough for local material flow studies. Reinforcement is not specifically required to be modelled but does need to be represented using attribute data.

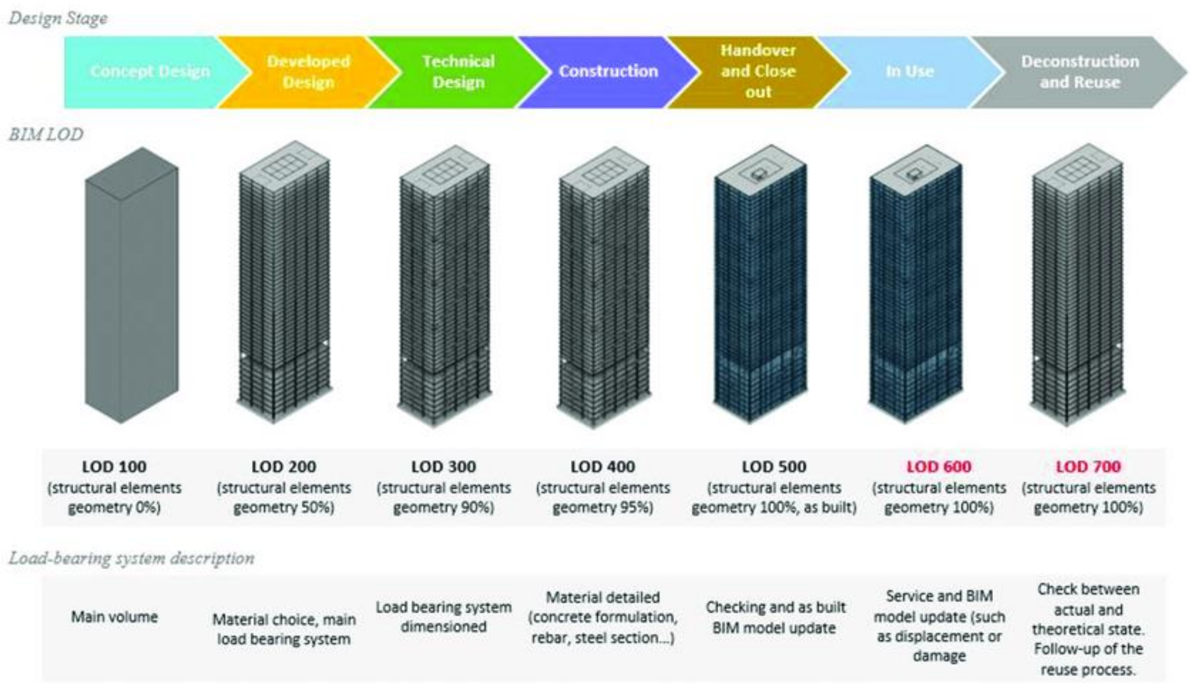


Figure 42: LOD levels (Bertin, Mesnil, Jaeger, Feraille, & Le Roy, 2020)

4.6.1. Level of Detail conclusion

From this requirements analysis based on the use-purposes of the tool output, it can be concluded that a geometry is to be constructed that has distinctive elements where attributes can be customized based on user preferences. High-potential reusable elements are required to have more customizability through parameters to account for more details (incl. connections to neighbouring elements) and resemble the actual elements as accurately as possible. Insignificant (architectural) details or components can be excluded when it does not impact the spatial or functional purpose of the element or the reusability assessment. A volume resemblance rate of 95-105% of the actual structures should be achieved. Lastly, reinforcement formwork can be excluded from the scope as it is highly complex to parameterize and is often modelled in separate software when conducting recalculations. Before concluding the LOD, the information input scenarios need to be considered in the assessment. These scenarios are 2D drawings or site measurements (both including pictures of the asset). As it is expected that for the majority of structures the drawings will be recovered, this scenario is taken as a baseline as more information is available on the elements. Based on the performance requirements and information input limitations, the desired tool-LOD can be established as follows:

The tool should LOD400 as a baseline, and LOD500 (excl. reinforcement) for reusable elements. The tool should facilitate the LOD700 level of information documentation.

Chapter 5: Tool Development: Bridge RE-design tool

This chapter comprises the development of the design tool that has been deemed necessary and makes sense in the market according to the previous chapters. First, the design scope for the tool is introduced using the findings of the opportunity analysis. Then, two potential solutions are introduced, and a final approach was selected using a Multi-Criteria-Decision-Analysis (MCDA), after which the tool functionality is described. Next, the results will be presented alongside the user's guide and whitepaper for policymakers. Finally, the tool's value and position are analysed to put the tool in perspective.

5.1. Development scope

- Time spent for development: 1-1.5 month.
- Target group: asset owners (mainly public organisations).
- End-user: designers.
- Bridge types: beam & slab bridges.
- Input: 2D (as-built) drawings or site measurements of elements.
- Baseline LOD400, with high-potential reusable elements LOD500 (excl. reinforcement).
- Tools used: Revit & Dynamo 2023, Excel.
- The development process will be restricted to creating a working principle/prototype to show the potential of the tool. In doing so, limiting the number of design variations of individual elements that will be included.
- Only the fundamental elements of bridge design and high-potential circular elements will be included in the prototype to limit the complexity of the tool, see below.
- The prototype will be limited to facilitate the most common/basic design choices to allow modelling of the majority of the bridges in practice.

Below, the decomposition for beam/slab bridges is depicted, inspired by the NEN-2767 standard. Here, only elements are included that are managed individually in AM and grouped elements under substructure, superstructure, and support elements. The lowest level elements are the objects that are managed in practice. This decomposition was used to develop the script. Each element has been colour coded representing their role in the tool: green is included in the model (see Figure 45), blue elements are modelled as one object under the element above due to scope/complexity reasons, orange is not yet included but can/will be included later, and red will not be included considering the purpose of the tool. A larger depiction of the decomposition can be found in Appendix: K.

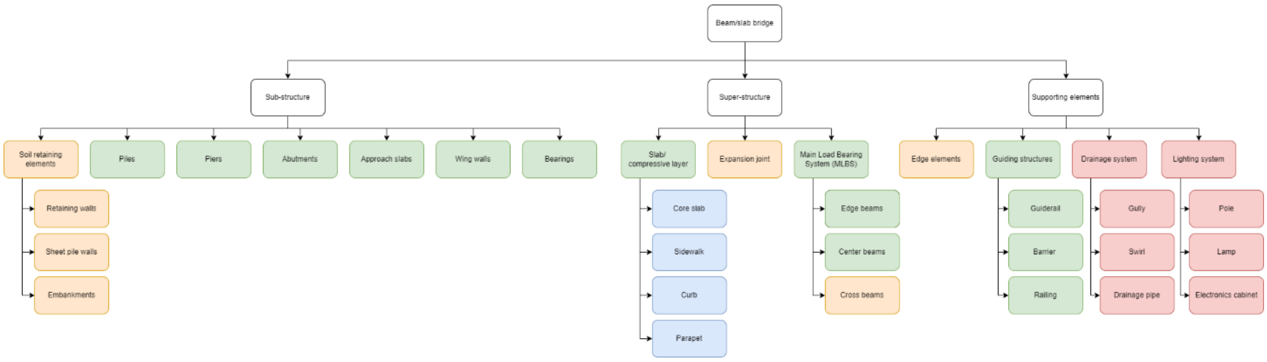


Figure 43: Scope bridge decomposition

The tool prototype must adhere to the following requirements:

1. Must be able to model beam- and slab (plate, dry connected) bridges within the same script.
2. The tool must have distinctive elements considering the level of detail in which they are managed in practice. The elements displayed in green in Figure 43 must be included.

3. The tool must facilitate automatic attributes assignment to element categories and be adjustable by the user based on their needs.
4. High circularity potential elements need to have LOD500 design optionality (girders, railings, barriers, columns, dry connected slab decks, etc.)
5. The model must be able to interchange design variants instantly without running into errors.
6. Element parameters must be adjustable within the model.
7. Elements must be manually manipulable to account for changes after running the model.

5.2. Potential solution assessment

As part of the double diamond model, the acquired knowledge is used for the development of potential solutions. Here, the potential solutions for this study will briefly be introduced. Then, a final decision is made on the solution that will be developed in greater detail, by analysing the characteristics of the potential solutions considering the research context, development statement and scope.

5.2.1.1. Option A: multi-script tool

Design Dynamo scripts for individual bridge elements that can be ran in series using DynamoPlayer within the Revit interface, for example: abutments-piers-bearings-girders-deck-piles-etc. Standard preconfigured families can be used as input, faces/elements can be selected to coordinate the placement points of the elements to build the model like LEGO blocks. Figure 44 displays an example view of what it would look like for placing girders using a Revit family type and the bearings (start and end). Family instance parameters (e.g., height girder) are to be adjusted manually in the properties window by selecting the elements after placement.

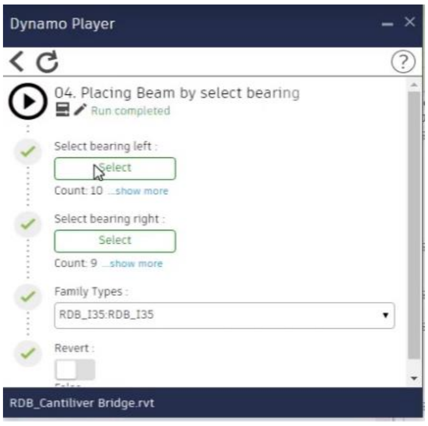


Figure 44: DynamoPlayer script

5.2.1.2. Option B: single script tool

Developing a complete script that instantly models the entire bridge using the road line as a guiding element. This approach would be coded in a single dynamo script that can be ran multiple times to test out different design variants for individual elements, parameters, and design functionalities without any manual design efforts. The elements are placed using relationships and hardcoded parameters for the faces to ensure a structurally sound design based on what is seen in practice. This way, more design functionalities can be included in the model to account for the variation in bridges, despite their similarities on a high level.

5.2.1.3. Analysis

A Multi-Criteria-Decision-Analysis was conducted using 5 performance metrics. Table 2 shows the results based on the analysis of the general characteristics of the options. Below, some general remarks on the analysis are provided.

Table 2: Multi-Criteria-Decision-Analysis design options

	Option A	**Option B**
Robustness output	+	++
Model accuracy	++	+++
Modelling time	+	++
Adoptability for users	++	+
Adaptability potential	-	++

Option A would be limited in robustness as the stand-alone scripts do not allow for much customization and dependencies among elements. This also impacts the potential model accuracy that can be obtained, however this can in part be solved by a large element database. To compensate for this, either a lot of inputs are required which decreases usability, or a lot of scripts are required to account for all the variability of designs in practice. Moreover, option A does not allow for quick changes that affect the rest of the model, as all elements will need to be redone. This approach is not beneficial considering the context of the tool as the data gathering is an ongoing process that will gather more data over time. Option B provides the opportunity to get higher levels of detail by adding more complex design options that have dependencies with other elements within the model. Most importantly, option B provides for more opportunities for further optimizations and roles in other contexts. This assessment leads to the selection of option B to further develop.

5.3. Tool description: RE-design

After starting up the Dynamo script, the following screen should be displayed. Red text was added to help the user navigate the script. Each group of nodes (displayed in green blocks) represents a modelling element (from Figure 43) or feature (e.g., bearing distribution).

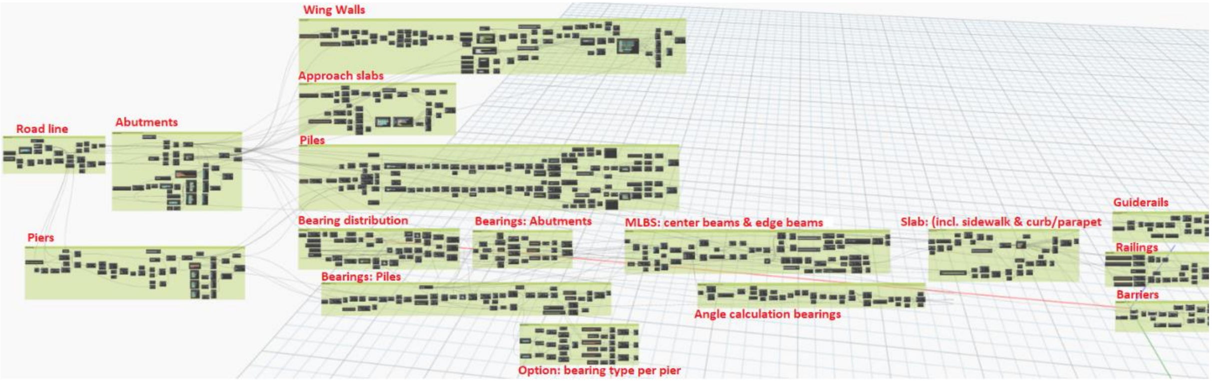


Figure 45: Script overview

The tool works as follows. The entire bridge is created using the bridge's road line (Dutch: 'weg-as'), and the relationships between individual bridge elements using their 'faces' and 'edges'. Each bridge element is a pre-modelled parametric family developed in Revit. These elements are consisting of 'faces' that collectively make up the exterior of the element. Each face can be deconstructed into its perimeter curves (or lines), which can consequently be used to define new lines of points for the placement of other elements. Using these relations, a bridge can be constructed. Each family 'instance' (or: element) can be customized by defining its parameters within the model. Moreover, some customization features have been built into the model using Boolean operators to account for the variation in bridge designs (e.g., beam bridge or slab bridge). Every time the model input is changed, all its dependencies will be updated automatically. All element categories are automatically assigned a set of (general & specific) attributes that can be filled in to allow element specific information storage for AM, reusability scanning and structural assessments. The attributes are customizable to the user's needs via an Excel file. The preconfigured 'out-of-the-box' attributes included in the Excel file are based on BIM-theory and expert knowledge, see Appendix: L.

5.3.1. Design options

Below, the design options integrated in the tool prototype are listed. For more context on their functionality, visit the handbook provided in Appendix: M.

1. Road line input.
2. Interchangeability of bridge elements with other variants.

3. Beam bridge or slab bridge design.
4. Abutment footing alignment.
5. Setting the pier locations.
6. Rotation for abutments & piers tangent to road line or set manually.
7. Wing wall customization (rotation, placement, thickness & extrusion direction).
8. Pile configuration per footing.
9. Bearing configuration & edge beam option.
10. Option for different bearing types per pier.
11. Railings at curb or side of curb/edge element & distance between poles.

5.3.2. Limitations

The limitations of the prototype version of the design tool are described below. It is important to note that these limitations are predominantly influenced by scoping of the research. After deliberation with designers, no limitations were identified that cannot be realized, however adding functionalities will impact the runtime of the model. There is ambition to increase the LOD & address the limitations in further research, which likely results in the discovery of more limitations. Only the most governing limitations are discussed, some limitations are addressed simultaneously as they are correlated.

5.3.2.1. Limited design elements & variants.

As Figure 43 shows, the orange elements were not included in the prototype, these being the embankment, cross beam, expansion joint, edge element, retaining walls and sheet piles. For a complete tool, these elements will be required to model bridges semi-accurately, as will be exposed in the validation process. Secondly, a limitation in design variants of the included elements was set to 2/3 due to time required for setting these up. However, with the guideline provided in Appendix: M, this time is now minimized. Moreover, with an expanding database, the likeliness of needing to model a new variant becomes smaller. Lastly, due to these limitations, there will be some errors in total material quantities even in the elements that are modelled. For example, the drainage pipes and reinforcement would normally be subtracted from the concrete volume.

5.3.2.2. Automated material passport filling & material database

One of the reasons this modelling approach was selected concerned the ability to use functions within the script to manipulate the outcome. One of the current limitations is that while the attributes are assigned to the elements, the inputs are still empty. Manually putting in this information can be a time-consuming job considering the number of elements in a model, especially as many inputs will be the same (for all, or within the category). This could be implemented within the script or using a separate script to keep a better overview and limit unnecessary runtime during the modelling process.

5.3.2.3. Adaptive component design

A known 'headache' among Revit users concerns the use of Adaptive Component families, used for the bridge deck, railing, barrier, and guiderail. The modelling approach is different to Generic Models, and often results in design difficulties or unknown errors. Due to a limitation in experience of the author, the design variants were limited. W+B designers have provided assurances on fixing this limitation.

5.3.2.4. Bridge deck/girder limitations

The bridge deck and girders are one of the most important elements in the bridge, specifically because of their reusability potential. The bridge deck element is currently composed of the slab/compressive layer, sidewalk, and curb/parapet in one. In the future, the latter two are required to be separate elements. Consequently, the sidewalk & curb are now constrained by the road line direction and cannot derive from this without manual intervention. Secondly, the deck element is still a continuous element over the entire bridge, in practice it can also be discontinuous at pier locations when there are expansion joints to allow more movement. Girders are currently placed using the global z-coordinate for placement. In practice, when the bearing seat and bearings have a slope (red line) the girders should have a similar slope while this is not yet possible (blue line for indication), see Figure 46. Lastly, girder/deck elements cannot yet have a camber in longitudinal direction, nor is it currently possible to have a varying height over the span (see Figure 47).

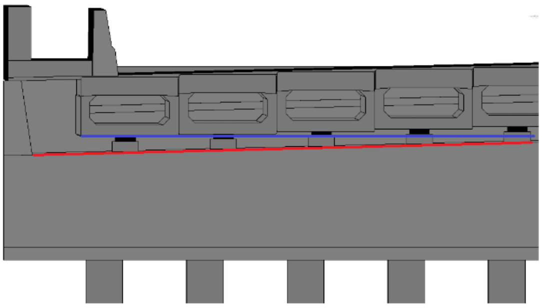


Figure 46: Angle setting for girders

Figure 47: Varying girder height example

5.3.2.5. Bearing customization

An element with many exceptions and design variations is the bearing component. The prototype facilitates some standard customization, but not all. For example, it is currently impossible to remove the bearing for the edge beams while this might be the case in practice. Secondly, different types of edge beams have different positionings for the bearing which is currently predefined. Bearings are placed using the girder width parameter for distances, this excludes the small joint width that is normally there. Lastly, bridges can have variation in bearing types (e.g., roller & pot bearings) within the same row on a support. For this prototype, only variation per support (abutment/pier) is facilitated.

5.3.2.6. Miscellaneous

To conclude, some (minor) limitations for design detailing have been identified. To start, piles cannot be set at an angle, see Figure 48. Secondly, wing walls cannot be curved (as displayed in Figure 49) nor can the wing walls be 'inverted' individually, see Figure 92 in the handbook in Appendix: M for explanation on 'inverted'. Lastly, approach slabs are currently a solid object while in practice the slab can be subdivided into multiple elements, see tool results on the next page for visualisation of this.

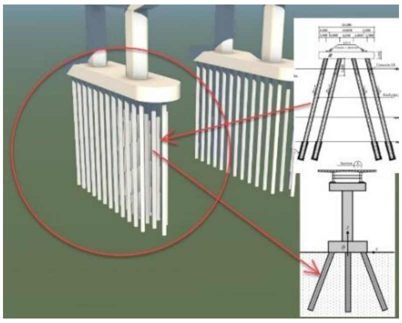


Figure 48: Pile inclination

Figure 49: Curved wing walls

5.4. Tool results

With these limitations in mind, the final prototype of the RE-design tool was validated using real project data. The validation process was divided into two categories, qualitative and quantitative. For both categories, multiple W+B designers were consulted for feedback to support these findings. The results are shown below. For each project, the RE-design generated model is shown on the left, the actual model excluding elements outside of the scope is presented in the middle, with the entire model shown on the right. Table 3 shows some basic project characteristics.

Project A:

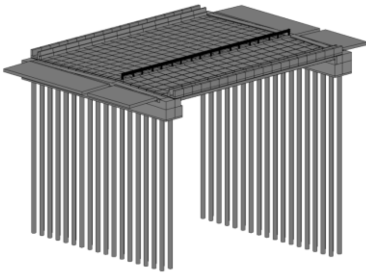


Figure 50: RE-design tool

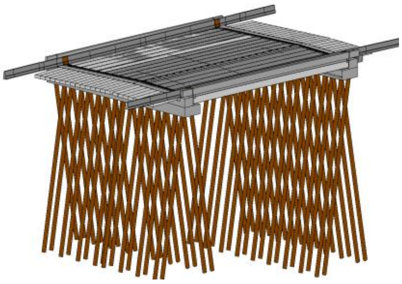


Figure 51: Scoped elements validation

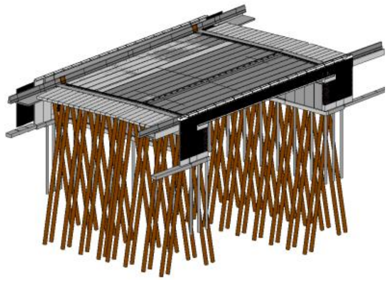


Figure 52: Entire project

Project B:

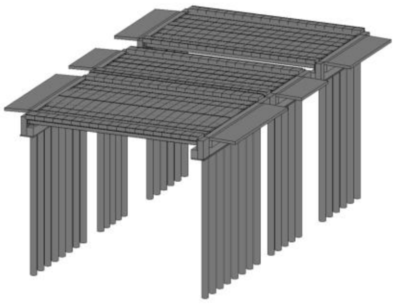


Figure 53: RE-design tool

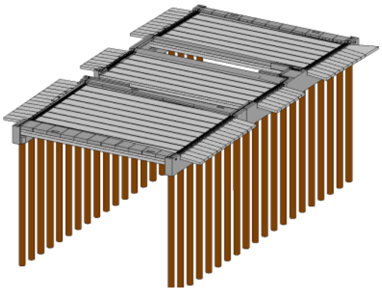


Figure 54: Scoped elements validation

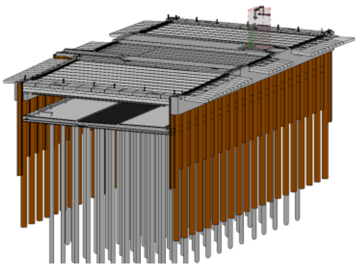


Figure 55: Entire project

Project C:

Note: approach slabs do not show in supplied 3D models

Note: Barriers before/after bridge not part of scope

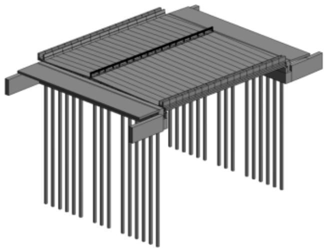


Figure 56: RE-design tool

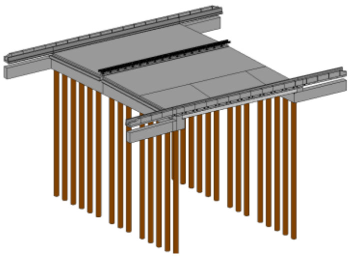


Figure 57: Scoped elements validation

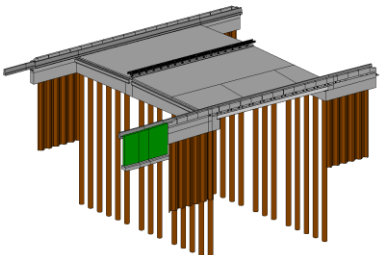


Figure 58: Entire project

Project D:

Note: Barriers before/after bridge not part of scope

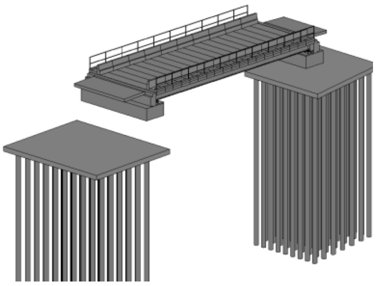


Figure 59: RE-design tool

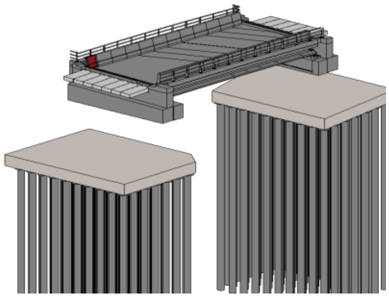


Figure 60: Scoped elements validation

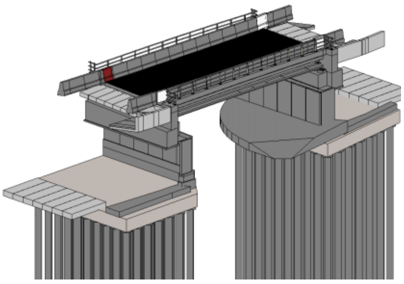


Figure 61: Entire project

Table 3: Project characteristics

	Project A	Project B	Project C	Project D
Left out of scope:	L-wall, retaining walls & piles, sheet piles, edge elements.	Station & lift, exit station between abutments, sheet pile wall.	Green wall, sheet pile wall.	Retaining walls, cross beams, additional footing, extra approach slabs.
Data quality	Good	Excellent	Medium	Good
Size	30x28m	20x(18-8-11)m	21x32m	25x10m
Complexity	Low-medium	Medium-high	Low-medium	Medium

5.4.1. Quantitative metrics

The tool was tested against the following performance metrics:

- Obtainable model accuracy without requiring manual design adjustments.
- Average time required to model the bridge using 2D drawings.

Method:

To test the tool, real projects have been used to validate these metrics. Due to data gathering difficulties with municipalities, only projects from W+B could be used in this process. Moreover, due to time constraints, the author conducted the testing instead of the intended designers, this has impact on the obtained modelling time which will be a topic in the discussion chapter. For context, 3 out of 4 projects are from the same contract and therefore have some similar design principles integrated in them. All bridges are beam bridges as shown on the previous page. The projects are all recently designed, which implies a higher standard of design drawings compared to structures constructed before 2000. To simulate the tool's future use, first the 2D drawings were studied to obtain parameter values and design characteristics of the structure, with this knowledge the bridge RE-design tool was used to generate the model. The development process of element variants was not included in the modelling time, to better represent the future average performance of the tool considering that the design variant database will be saturated by then. The obtained element quantities were individually compared with the 'actual' 3D model (limited to scoped elements) from the drawings using the individual element volumes to obtain a resemblance percentage as shown in Table 4. The weighted total was calculated using eq. 2, the average accuracy of an element type was calculated using eq. 3.

$$Weighted\ Total = \frac{\sum V_{R,i}}{\sum V_{A,i}} \times 100\% \tag{2}$$

Where:

- $V_{R,I}$ = Volume for all objects of element type I as modelled by the RE-design tool.
- $V_{A,i}$= Volume for all objects of element type I as modelled by the actual design.

$$Average\ accuracy = \frac{\sum \rho_n}{n} \tag{3}$$

Where:

- ρ_n = the model accuracy for the element in project n
- n = the number of projects included

From these results, it can be derived that abutments have the largest impact on the overall accuracy given its size. It must be noted here that the accuracy does not represent the physical resemblance of the element and its details. For this, more advanced model compare tools will need to be consulted. Nonetheless, the results look promising despite the limited design variant database.

Table 4: Model accuracy (volumes) performance

Element[1]/project	Project A	Project B	Project C	Project D	Average
Abutments[2]	99%	89%	95%	96%	94.75%
Wing walls	N/A	N/A	99%	N/A	99%
Piers	N/A	N/A	N/A	N/A	N/A
Bearings	100%	100%	100%	100%	100%
Girders	100%	100%	100%	100%	100%
Deck/compressive layer	100%	100%	100%	100%	100%
Sidewalk[3]	91%	85%	100%	100%	94%
Curbs/parapet[3]	100%	93%	100%	100%	98.25%
Piles	96%	100%	100%	100%	99%
Approach slabs	100%	100%	N/A	100%	100%
Railings[4]	N/A	N/A	N/A	75%	75%
Guiderails[4]	83%	N/A	83%	N/A	83%
Barriers	100%	N/A	100%	100%	100%
Weighted total	98.37%	93.61%	98.56%	99.12%	97.41%

[1] Note that elements are measured by element volume, this is not equal to geometric accuracy.
[2] Abutments were modelled only using 2 design variants, severely limiting the accuracy potential.
[3] Sidewalk and curb/parapet are still modelled as one attached to the bridge deck.
[4] Railings and guiderails only have 1 standard type included for now, see limitations.

To assess the required time for obtaining a 3D model, the effort was measured for both the desk study which included studying the drawings, selecting the design variants in the handbook, assessing the parameter values of the design variants, and determining the design options. The modelling time represented the time required to translate this information using RE-design into a 3D model. This excluded the time required for assigning data to the attributes of the elements. The results are shown in Table 5. These are bandwidth values to account for inaccuracies and distractions during modelling.

Table 5: Required modelling time

	Project A	Project B	Project C	Project D	Average
Desk study time	120-150min	90-120min	90-120min	60-90min	90-120min
Modelling time	15-30min	30-45min[1]	15-30min	15-30min	18-33min
Total	135-180min	120-165min	105-150min	75-120min	108-153min

[1] Project B consisted of 3 bridges next to one another and therefore required more time for modelling.

For comparison: it was estimated by W+B designers that municipality bridges would require between 12-20 hours to model using traditional practices (also from 2D drawings). However, this is at a slightly higher level of detail and includes the remaining elements that were left out of the scope for this prototype. Given the uncertainties involved in this process, the results will be nuanced in the discussion.

5.4.2. Qualitative metrics:

The qualitative metrics included for this tool are as defined as follows:

- *Adoptability*: measures the user-friendliness and required knowledge threshold for operating the tool.
- *Robustness*: measures the share of bridges (within scope) that can be modelled with the tool.
- *Adaptability*: measures the potential functionalities of the tool beyond its current set of requirements.

5.4.2.1. Adoptability

Adoptability of the tool is very important in reaching the desired outcome of the tool: to be used across organisations and improve the CE- and R&R-challenges and accelerate digitization. To do so, a user's guide was developed that shows a step-by-step process on how to operate, manipulate, and customize the tool to achieve the desired model. To ensure interoperability, development guidelines have also been included. No modelling experience is required to use the already existing database of elements and design options. However, to improve the tool and its robustness, this skill is required. As the tool is fully embedded in Revit, the standard design tool for infrastructure, it is very likely that designers also have (basic) understanding of the functionality of Dynamo and can therefore also manipulate/improve the script. Due to the modular approach, the degree of difficulty for understanding the logic behind an element is also contained, making troubleshooting significantly easier. One skill that is required is the ability to derive information (quickly) from 2D drawings, this might take more time for inexperienced users. Overall, it can be concluded that the entry level for knowledge/experience is low and, while the level of knowledge for further expanding the robustness of the tool is moderate. Moreover, to ensure minimal errors for future use, no additional add-ins or packages were used in the development.

5.4.2.2. Robustness

The robustness metric was tested using a database of bridges of the municipality of Gouda, containing over 150 bridges. It was concluded that the tool design can become very robust once the previously identified limitations are solved, the remaining elements (excluding drainage and lighting) are included, and the element variant database is expanded with elements parametrized elements from practice. From this assessment, no beam or plate bridges were identified that fall outside of the potential of this tool, given the previously mentioned developments. However, the status of the prototype does not offer this robustness as only limited design variants have been included. Due to the limited reference material for this assessment, certain figures cannot be provided at this time. However, a safe assumption would be that the tool will be able to model >90% of all beam and plate bridges (this excludes integral bridges) in the future, judged by the characteristics and potential shown by the prototype.

5.4.2.3. Adaptability

Lastly, the adaptability of the tool. This metric captures the full potential of the tool and method in different contexts and requirements compared to this research. Below, some are introduced, however they will not be further discussed here.

- The tool's method can be applied to other types of infrastructure like locks, culverts, or road elements (lighting, barriers, guiderails), for similar purposes.
- Once the tool's LOD is increased, structural calculations using software like Autodesk's Robot Structural (or something similar) can be explored using the tool's output and potentially using optimization strategies for the design phase.
- The tool output geometry can be used for reverse engineering reinforcement in elements (Harrewijn, 2019).
- The tool can be used in optioneering processes at the start of design/exploration phases to quickly visualise the possibilities.
- Integrating circularity databases/tools with information of what is the most likely EoL purpose of materials in the structure (which can then be documented in the element MP's).
- Directly linking the tool's output (Revit model) to the AM software and reuse databases using third party tools (e.g., ANT (CollaborAll, n.d.)), to decrease manual labour of updating the same information.

5.5. User guide & white paper for implementation strategy

This section comprises of a summary of the user's guide, or design tool handbook, that can be found in Appendix: M. This handbook ensures that anyone with moderate design skills in Revit can operate the script and obtain similar output, expand the family database to increase robustness of the tool, and manipulate the material passport setup for the end user (generally the asset manager). The handbook describes the design protocol (also simplified in a schematic in Figure 62), provides troubleshooting guidelines & tips, explains how to adjust the MP document for customization, elucidates the design options integrated in the model and how to adjust them, sets the design rules for creating new design variants for elements, and shows the existing design variants and their parameters (visualised) sorted by element type. Moreover, the guide provides inspectors with tangible requirements for making measurements on site in case no drawings could be obtained.

In Appendix: N, a whitepaper is provided for policymakers. This whitepaper neatly shows what the problems are in the context of their organisation, how the bridge RE-design tool can be the solution, what their benefits could be and how this would look in practice. This whitepaper can be used by practitioners to convince their superiors to actively make the transition and free up funds.

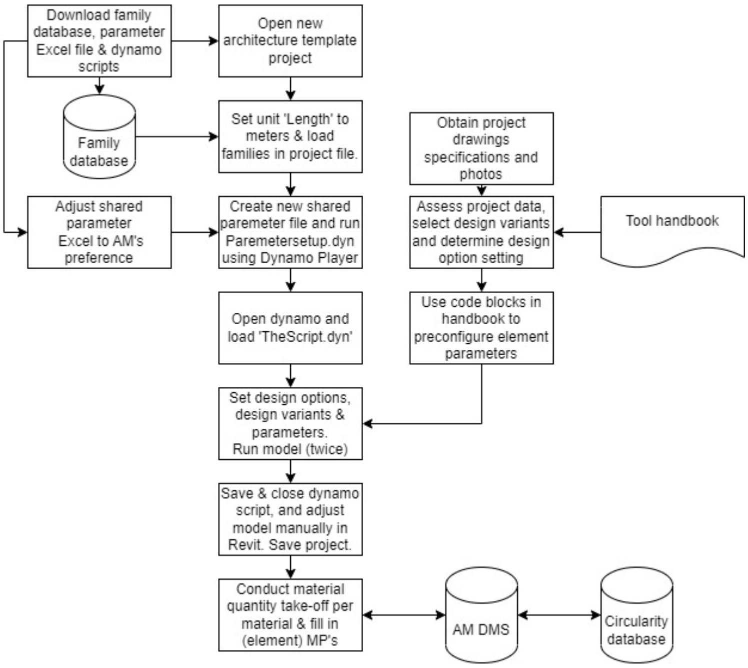


Figure 62: Process flowchart simplified for RE-design tool

5.6. Position RE-design in practice

5.6.1. Context

As shown in the literature study, one of the main enablers of the CE are digital technologies. On the other hand, one of the key barriers is the lack of asset data visualisation, quantification, and centralisation of existing infrastructure objects. Many of the enablers and initiatives presented in both CE-transition roadmaps and state-of-the-art literature depend on this data availability, while there are little efforts or solutions to actively tackle this issue on the short-term. Current practices include manual 3D modelling using 2D drawings and project specifications (labour intensive and costly) or laser scanning and post-processing to obtain 3D models (very expensive, decreasing in costs). Taking into account the limited funding availability at public organisations and asset manager priorities obtained from interviews, this digitization transition is likely to take place in the distant future despite the potential benefits found in the literature study. Looking at the data quality of newly constructed assets, 3D-BIM models are supplied with information attached to the individual elements, allowing more accurate tracking/monitoring of information of the remainder of the asset lifetime. Currently, assets are registered using a single 'material passport' linked to a dot on a map with generally very basic asset information attached to it and a photo. Given that many assets are entering the final phase of their lifecycle, more specific insights are required for monitoring the condition of individual elements, reusability scans & structural assessments (LOD700). These insights can currently only be stored using very cumbersome methods (e.g., Excel) as this is not supported by current AM software. Moreover, current practices for bottom-up material quantification are very uncertain due to assumptions and extrapolation, or labour intensive to obtain for AM physically using asset characteristics and statistics.

5.6.2. Value

This is where RE-design comes into play, by providing a more cost-efficient method to generate 3D-BIM to efficiently store element specific asset data compared to manual modelling and 3D scanning technologies, allowing for a faster transition to digitize the acreage (3D centralized AM) and reap benefits for a longer duration. For the bridges constructed between 1960-1980, this means another 20 years of AM (on average), making it a worthwhile investment considering the AM benefits it provides (see section 2.4). While 3D-BIM level of information supply is not a prerequisite for reusability scans and structural assessments, it does provide a more streamlined process by centralising (the available) data and providing a better overview of the asset to reduce structural modelling time. Structural assessments currently also require similar data supply, reducing the threshold for the data gathering effort. By conducting these assessments earlier (through a collective data gathering effort), earlier insights into the reusability of assets and actual EoL dates of assets can be obtained for increased reuse potential and R&R-task timeline management. Moreover, the 3D-BIM can function as a medium for improving the data supply quality in reusability databases. As a by-product, the tool allows earlier bottom-up material quantities for MFA to improve the reliability of CE-roadmaps (once reinforcement approximations are added). Finally, as the tool generates centralised high(er) quality data storage of assets, AI & big data can be leveraged sooner to use this data for optimization of AM, as shown in section 2.5. The value of this tool lies in the combination of benefits and its potential for further development on automated (parametric) structural/reusability assessment and (preliminary) design applications. However, the degree to these benefits depends on the quality of information supply.

5.6.3. Data availability for tool implementation

This data availability at public organisations can be distinguished in three scenarios.

1. **2D drawings & project specifications readily available and organised.**

This is the ideal scenario for the RE-design tool. This level of data availability is currently predominantly reserved for larger organisations, according to the interview findings. With this level of information supply, a large contract can be drafted to develop 3D-BIM asset data. The RE-design tool (once fully developed) can be used to model the beam- and slab bridges within this contract with reduced effort. In the future, other bridge structure types can be explored with similar tooling to also reduce the modelling effort. Bridges outside of the scope should be either manually modelled or laser-scanned when the design is too complex.

2. **Temporarily lost project data.**

In this case, the organisation needs to conduct a central effort to recover the project specifications and drawings where possible. When acquired, see scenario 1. If not, see scenario 3. During interviews with industry asset managers, some reluctance to this task was observed. However, considering the need for reusability scans and structural assessments of assets, this data will be required for a large share of the assets. Current strategies limit this search to the asset that is required in the particular moment while this can be optimized by organizing all asset data at once.

3. No data can be retraced after recovery efforts.

In case no additional project data can be recovered, the RE-design tool can still be utilized. In this scenario, which is likely to be the case for at least a minor portion of the assets especially at smaller organisations, the RE-design tool can be employed in combination with manual inspections. During inspections, data can be obtained using the developed handbook's visualised element database and design options to still quickly generate the design. This model can be improved and supplemented with data obtained throughout the remainder of the lifecycle. When the structure is outside of RE-design's scope, 3D scanning practices are advised.

5.6.4. Implementation & future practice

Below, a simplified timeline is presented for the implementation of RE-design in practice.

0-2 years: tool finalisation, refinement & database development using real projects. Exploring the potential for streamlining the structural assessments within engineering firm. Convincing public organisations of the urgency and need for upgrading existing assets to 3D using the white paper and sampling strategy at various public organisations.

2-5 years: collective data gathering effort of *all* assets at public organisations. During this time, the early adopters (predominantly large organisations) can use RE-design either in-house or via an engineering firm to digitize the bridges within scope. RE-design can also be implemented for reusability scanning projects or as optioneering tool in the early design phases. During this time, the automation of using the 3D models for structural assessments needs to be developed when deemed possible. AI & big data or reverse engineering approaches need to be consulted for reinforcement approximation in the model for material quantification. In case of demand, expand concept to other infrastructure types.

5-10 years: large scale adoption of RE-design for digitizing the existing acreage (fixed beam & plate bridges) using data scenarios 1 & 3. Structural assessments use the generated 3D-BIM (including linked condition data) for their 2D model development and document the data in this. With time, the 3D-BIM is used as source for structural assessments by directly linking the model to software.

10-20 years: the tool can be further developed as a design tool that is automatically linked to the structural software to run optimizations for geometry, like Karamba3D for Rhino/Grasshopper. The design variant database is supplied with standardized elements according to the IFD framework. In this period, the digitization transition will be well underway and 3D scanning technology will become competitive in costs and offer more quality with respect to inspection data.

5.6.5. Industry perspective

From the interviews with various asset managers and personal conversations with W+B experts, a final perspective on the tool's value is obtained. **Asset managers:**

- Transition is likely to occur in 5-10 years. Data & funding are short term obstacles. While current software infrastructure is also far from ready to support 3D centralized AM.
- More evidence is required on the benefits, larger organisations can provide this (e.g., T3D).
- Clear ambitions for upgrading to 3D at some point, providing demand for RE-design tooling.
- Demand targeted at assets listed for functional replacement or structural assessments.
- Before making the switch to 3D centralized AM, the majority of the assets need to be in 3D, explaining the reluctance for upgrading as it would require a large investment at once.

W+B experts:

- Integration in reusability scanning workflow and as optioneering tool in initial design phase.
- More robustness is required before adoption becomes viable/competitive due to details.
- Potential application for using the output for parametric 3D structural assessments to further drive down costs. Current (2D) methods are mainly kept in place due to standard practices.

Chapter 6: Recommendation – Asset management roadmap

This research has shown the need for upgrading the existing infrastructure to 3D, as well as a tool to do so more cost-efficiently. However, this tool can only be implemented when the 2D drawings have been retraced and the foundation has been laid. The goal of this recommendation is to provide the asset managers with a roadmap towards 3D centralised AM for improved R&R-task management and reuse realisation in the future. The roadmap uses logical steps based on the CTL concept, expert knowledge, authors previous work activities within W+B, (Brouwer, 2022), and the guideline to reuse developed by the Nationale Bruggenbank (Van Offenbeek et al., 2021). The target group for this recommendation is therefore also asset managers at public organisations in the construction industry. Each of the included 9 steps are briefly discussed and substantiated with tangible actions, examples, and options where applicable. An overview of the steps is provided in Figure 63.

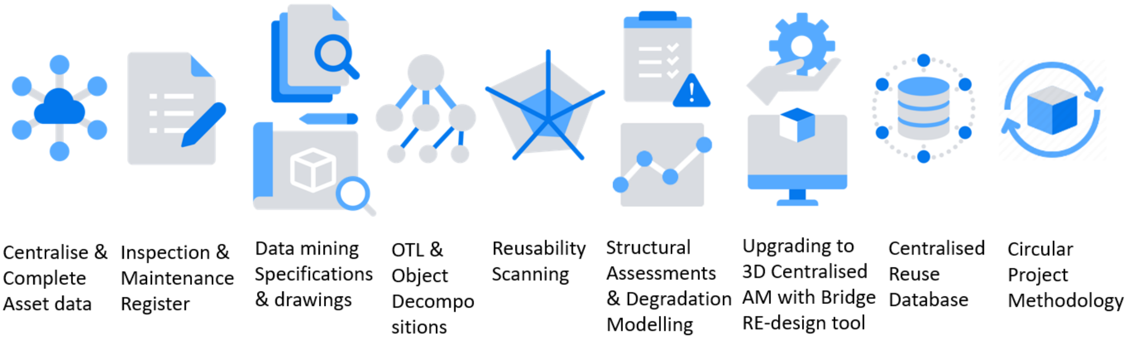


Figure 63: Roadmap overview

1. **Completing & centralising asset data.**

AM is the root of reuse, as the previous chapter has shown. Quality AM starts with proper data quality and centralized documentation. This is a mandatory step that all organisations must take. An AM platform of choice can be selected for this (e.g., IAsset, DISK, GBI). In this platform, a material passport on the highest asset level should be completed for each asset. Figure 64 displays a representation of such a material passport for an example viaduct case with imaginary input. The environmental data section is included for new structures, whereas for existing structures this information can (partly) be obtained only when the geometry and materials are known. The peculiarities section can be used for any comments on the condition, reusability, or even deconstruction. This MP example is not meant to represent a complete list, as different organisations can have different information needs, but it does provide a framework of what should be documented minimally in line with the findings of this research and Platform CB'23's guide for material passports.

General information			
Obtject name	Wicher Lemstra viaduct		
Object code	12345		
Construction year	1975		
Asset owner (manager)	RWS (Mun. Sneek)		
Contractor	BAM		
Asset type	Viaduct		
Asset category	Vehicles + bicycle		
Main material	Concrete	Environmental data	
Length	25m	% Primary input (renewable %)	60% (0%)
Width	7m	% Secondary input (renewable %)	40% (10%)
Height	5m	% Reusable output	35%
Surface area	175m2	% Recyclable output	61%
Volume	150m3	% Incinerated output	0%
Material quantity	360 metric tonnes	% Landfilled output	2%
Condition	Good	% Lost materials	2%
Upcoming inspection	2023 - Witteveen+Bos	Harmful substances presence	None
Recent maintenance activity	2018-04 - crack maintenance beam A12	ECI-score	10000EUR
Upcoming maintenance activity	2025-06 - Replacement barrier	Asset specific information	
Location	E23 - N7	Traffic class	C250
Design lifetime (remaining)	80y (23y)	Number of spans	2
Expected decommissioning date	2055	Number of lanes	2
Peculiarities (Dutch: bijzonderheden)	Railing is reused.	Structure type	Beam bridge

Figure 64: Material passport for asset example

2. Inspection & maintenance registers.

Secondly, separate tabs are required for maintenance and inspection registering. These tabs display the executed and upcoming maintenance or inspection tasks and have the reports attached after finalisation. Historical maintenance activities need to be retraced, if possible, this is important for assessing the remaining lifetime of elements. Once the reports are received, the key results are to be documented in the register, as displayed in Figure 65. A larger picture can be found in Appendix: A. This register is based on the PRINCE2 (PRINCE2, n.d.) project management methodology and expanded with AM needs. Each asset should have an individual tab with just the reports and register items for that asset, synchronised with the global condition & maintenance register. When such a register is not possible in the AM tool, Excel can work as long as it is centrally documented in the cloud with access to all involved parties (including contractors and inspectors) to update the register after jobs. Confidentiality breaches can be circumvented by providing external parties with standardized formats that need to be filled in, which can then be manually copied into the database. Such a database then allows better management of activities and condition monitoring, without needing to open reports and missing crucial information. When an element receives an update on its condition or metadata, its MP should be updated directly by linking the register to the MP. When this information is still documented in a 2D object decomposition (see step 4), they need to be updated manually. Lastly, it is advised that for inspections, the CUR117:2020 method is adopted (as opposed to NEN 2767-4), as this provides more accurate representations of the actual condition of the elements (Lunenborg, 2022).

ID	Description	Condition score	Issuer + Date	Asset type + ID	Object type + ID	Link to model	Inspection report	Inspection date	Priority	Severity	Status	Activity	Activity window	Activity owner	Maintenance report	Closure date	Last update + name	Comments
0	Starting corrosion	5	REIC6 1-1-2023	Bridge 0013	Barrier A12	Link	Download Link	22-11-2019	Low	Medium	Open	Protection layer	2023-2024	TBD		Download Link	REIC6 1-1-2023	
1	Replacement advised	1	REIC6 1-1-2023	Culvert 0213	Pipe 1	Link	Download Link	10-5-2020	Urgent	High	Closed	Replacement	okt-20	BAM	1-11-2020	Download Link	REIC6 1-1-2023	
2	Cracks found	3	REIC6 1-1-2023	Bridge 0163	Deck 1	Link	Download Link	22-11-2019	High	Critical	WIP	Active monitoring	2019-2022	Mun. Deventer		Download Link	REIC6 1-1-2023	
3	Broken streetlamp	0	REIC6 1-1-2023	Viaduct 0015	Lamp post A123	Link	Download Link	18-9-2018	Medium	Low	On hold					Download Link	REIC6 1-1-2023	Might be replaced in new project
...																		

Figure 65: Condition & maintenance register

3. Technical drawings data mining.

Thirdly, technical drawings and project specifications need to be gathered, organised, named, and linked to the assets/elements. These documents are important for the generation of the 3D data. In case the drawings are still on paper, they need to be scanned. When the drawings cannot be retraced, site measurements will be required. These site measurements can be combined with an inspection. The RE-design tool's user guide provides a guideline for the required measurements for individual elements as well as what needs to be known for the design options, which can be used by inspectors on site. This will result in accuracy limitations for the 3D model compared to 2D drawings. It is advised to execute a central effort for data gathering instead of one-by-one to decrease costs.

4. Object decompositions.

As part of the 'inventorying the acreage'-step from section 2.3, an Object Type Library (OTL) should be developed for all assets. An OTL ensures consistent data registration across all existing and future assets (per type) within the acreage by describing what elements and components each asset type can be decomposed to, and what attributes need to be documented per object type. The OTL is the framework that is used for each asset to develop the decomposition, a decomposition is then a representation of this framework applied on a certain asset. The difference is highlighted in Figure 66, in grey shows a simplified (incomplete) example of an OTL for a bridge where the lowest level is generally where attributes are documented. Considering an actual bridge, there will generally be two abutments that are not necessarily the same (e.g., different condition). Each abutment is documented separately with similar attributes but different inputs, as shown in red. These attributes are highly object-specific and need to be tuned to the asset manager's demands. As a guideline, the Material Passport Guideline developed by CB'23 can be consulted to find attributes (Platform CB'23, 2020).

So, first an OTL is to be set up for each asset type (Dutch: beheerobject), for civil structures the recommended standard is the NEN2767-4. However, it is recommended to make adaptions and/or additions according to the organisations wishes to make this standard more in line with practice. Secondly, all assets within the acreage need to be inventoried to create a database of object decompositions. There are two routes to take for developing such a database:

1. 2D, using software like Relatics to create a list-like format with different layers, where each object has an attribute window where the values can be registered. The decompositions can then be imported in the AM software if the software allows. This is generally a labour-intensive task and becomes a large file that is difficult to manage. However, it is a sensible steppingstone towards 3D centralised AM.
2. 3D, in step 7 the geometry of the asset will be generated from the 2D drawings. Using this geometry and the individual elements, attributes can directly be attached to the physical elements in the 3D model. The 3D model can then be exported to a more accessible format like Industry Foundation Classes (IFC) to make the information more accessible while still maintaining 3D. Alternatively, the information can be exported and manually linked to the 2D system as an intermediate solution while the 3D system is being set up.

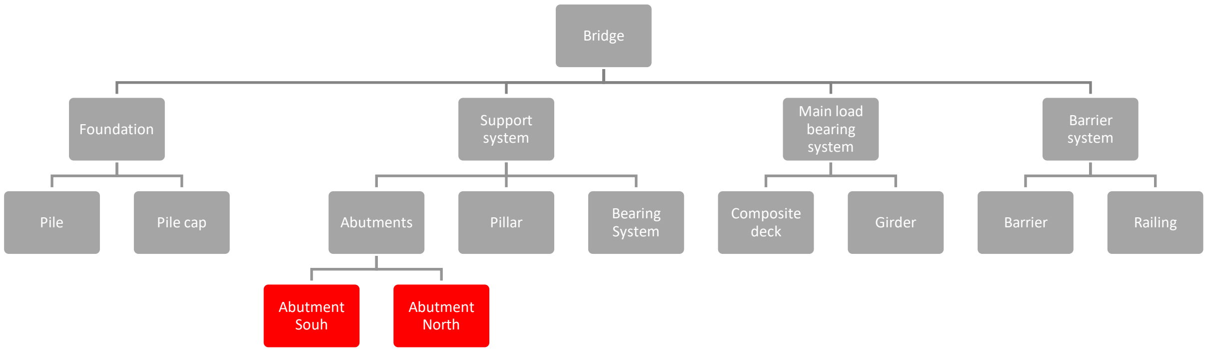


Figure 66: Object type library vs asset decomposition

5. Reusability scanning.

The next step is conducting reusability scans on the assets that with the data gathered up to this point. All assets should be analysed on their reusability potential, as was done for beam- and plate bridges in Chapter 2.3. Then, a selection should be made for assets that are most likely to be replaced before they reach their design lifetime, as there is reuse potential. For this, land-use plans, and mobility developments of the acreage should be studied along with the condition data and remaining lifetime estimates of structures. The output from reusability scans is to be documented in the MP's of the asset and individual elements where needed, and when there is potential also in a reusability database. This should be a continuous process. To create a reusability report, the following data should be gathered and centrally stored:

- Land-use and mobility development plans.
- Material passport of asset/elements.
- Object decompositions with attributes.
- Maintenance records – linked to objects.
- Inspection reports – linked to objects.
- Drawings & project documentation.
- If available: 3D model of structure.
- For new structures: Environmental Assessment Report.

6. Structural state assessment.

Reusability scan output can be enhanced when the data certainty on the structural state of the asset and its key elements is higher. Moreover, it is essential information in making decisions on the fate of the asset: (premature) replacement, renovation, or maintaining/extending. Currently, this strength is estimated based on the degradation expectations made during the design, with conservative (based on safety factors) assumptions for mobility developments and environmental changes (IV Infra, n.d.). These conservative estimates can severely impact the reusability business case by underestimating the remaining strength, resulting in unnecessary decommissionings, resource consumption, and costs (Janssen, 2022). Two methods can be applied on assets where the loading/environment deviates significantly from the designed enough to alter the remaining lifetime:

1. Degradation modelling based on design specifications, maintenance history, inspection reports and expected future loading.
2. Structural recalculations based on drawings, material specifications, and loading profiles (design, actual, and future). Potentially requiring material testing and/or reinforcement validation, depending on the desired level of detail. Using Richtlijn Beoordeling Kunstwerken (RBK) or NEN8700.

The literature study and interviews have shown that large costs can be expected in 10-15 years concerning recalculation costs, recalculations are predominantly required for concrete vehicle bridges due to the increased loading over time and reuse potential and can quickly accumulate in costs – ~25k on average, depending on size and level of detail, excluding additional material or reinforcement studies. The interviews also revealed the tendency of owners to execute these only when necessary, likely when it nears EoL, potentially resulting in immediate decommissioning. The first step is to inventory which bridges require structural assessments and which can do with revised degradation modelling. It is highly recommended to start recalculating concrete vehicle bridges sooner rather than later to decrease this peak. Combining multiple assets in one contract could save significant costs.

7. Geometry of structure/elements/site

In parallel with reusability scanning, the development of the 3D environment is to be developed. First, laser scanning technologies or Google Maps 3D should be employed to create a rough outline of buildings, roads, and waterways. Then, there are two routes to take to start filling this environment with individual asset 3D models. The first being to hire designers (in-house or via consultancy firm) to manually model structures based on drawings/measurements, and the second is to employ digital scanning companies to scan structures (e.g., LIDAR, drone scanning, etc.). The method selection depends on the following factors:

- Complexity of the structure.
- Reuse potential – impacting the required level of detail of elements.
- Data availability for modelling.
- Budget – Laser scanning is significantly more expensive.

As established previously, not all structures (or elements) have the same potential for reuse. Therefore, the level of detail for these structures can be lower. Moreover, if a structure only has 2 years until replacement and has no reusable elements, modelling would be pointless considering a new model will be generated for the new structure. In general, laser scanning is best applicable for highly complex and architecturally dominant infrastructure or buildings, or when it is difficult or not cost-efficient to obtain measurements for manual modelling. Otherwise: manual modelling. With this knowledge, a list can be developed for assets to document the desired LOD, most modelling suitable method, and priority. From this, an execution plan can be developed to upgrade to 3D assets.

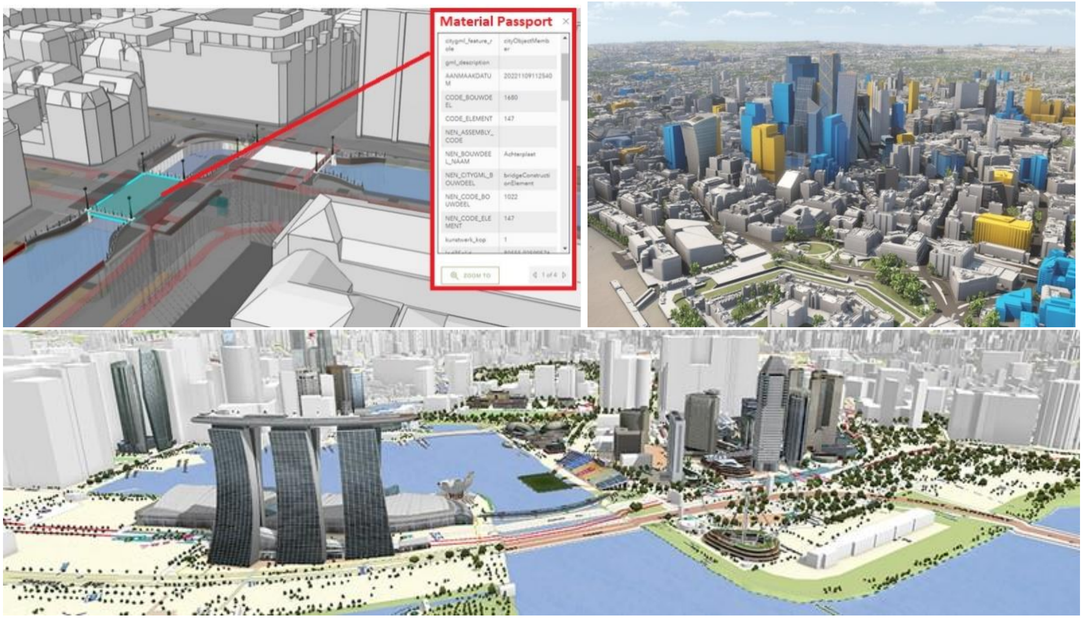


Figure 67: 3D centralised Asset Management

Tips:

1. To minimize costs, it is advised to employ RE-design tooling for bridges.
2. Combine site measurements with inspections in case there are no drawings.
3. Organise large contracts for modelling/scanning multiple assets at once to decrease costs.
4. Create a link via a third-party software (e.g., ANT) from the 3D model to the AM system for exchanging and updating MP information. Similarly, connect the reuse database inputs with the 3D-BIM as well to avoid repeated tasks when an update is required.

8. **Information needs for reuse realisation.**

Here, recommendation is made to ensure a more efficient reuse economy. This item concerns the information registration of reusable elements in reuse databases as well as the information requirements for project developers, see Table 6. The former being for asset managers aiming to reuse their elements (supply), while the latter is for projects with reuse ambitions (demand). With this information, the designer can analyse the transportation, storage, maintenance, and adjustment/enhancement aspects per element for the life cycle costing assessment.

Table 6: Information needs reuse

Information registration AM	**Information requirements designer**
Location (of asset or storage depot)	Desired geometry characteristics
Element geometry & attributes / picture	Desired lifetime of new asset
Remaining lifetime based on loading profile	Local design guidelines/building codes
Uncertainty score of model accuracy & performance	Development planning of area
Maintenance requirements after harvesting	Site accessibility
Condition	Execution window of project
Decommissioning window (expected)	(Future) loading profile of object
Risk score deconstruction	
Desired compensation	

9. Reuse realisation framework for practice.

Lastly, a framework (Figure 68) is provided to increase understanding of circular project methodology (bottom) compared to traditional linear project methodology (top). The chart displays the interrelatedness of assets and parties throughout their whole lifecycle and can be used as a guideline to understand the changes that are required for realising a circular construction economy. The chart represents a typical project where an asset is replaced (Asset A, as highlighted in purple), also called a brownfield project. However, it can also suit a greenfield project by excluding the purple elements. In the circular project methodology, another asset is introduced: 'Asset B' – representing the asset where the reused elements are harvested. This adds significantly more complexity to the construction project for both project manager and asset manager, as represented by the chart. A few notes on the chart:

1. Central to the process is the decommissioning date of the to-be-harvested asset (asset B). This date determines when it is beneficial to deconstruct the existing asset on the project site as too early would mean that the construction has to wait on the harvested elements. In case Asset B is already harvested, there are no limitations.
2. The yellow nodes in the chart are highlighted as they are only executed once for the existing assets and represent the data gathering and asset studies that allow reuse realisation.
3. After realisation of new projects, digital twins should be used to continuously store the data and manage the asset, hence the arrow back to the asset manager.
4. The details of the various design stages (preliminary, detailed, technical, etc.) are intentionally left out and summarised in 'Life-cycle-costing analysis & finalising design'. This is because there are no other data streams required for this process besides engineering, unless the design returns to concept level (e.g., element becomes unavailable), represented by the arrow back to the design phase for concepts.
5. The decommissioned asset (asset B) is split into 2 steams: the harvested element(s) and Construction Demolition Waste (CDW). Ideally, both are developed into secondary materials, however it is likely that some of the CDW is landfilled (despite the landfill ban).
6. The model focusses on the processes where materials play a role direct within the project, aspects such as tendering, quality assurance, risk management, etc. are not included.

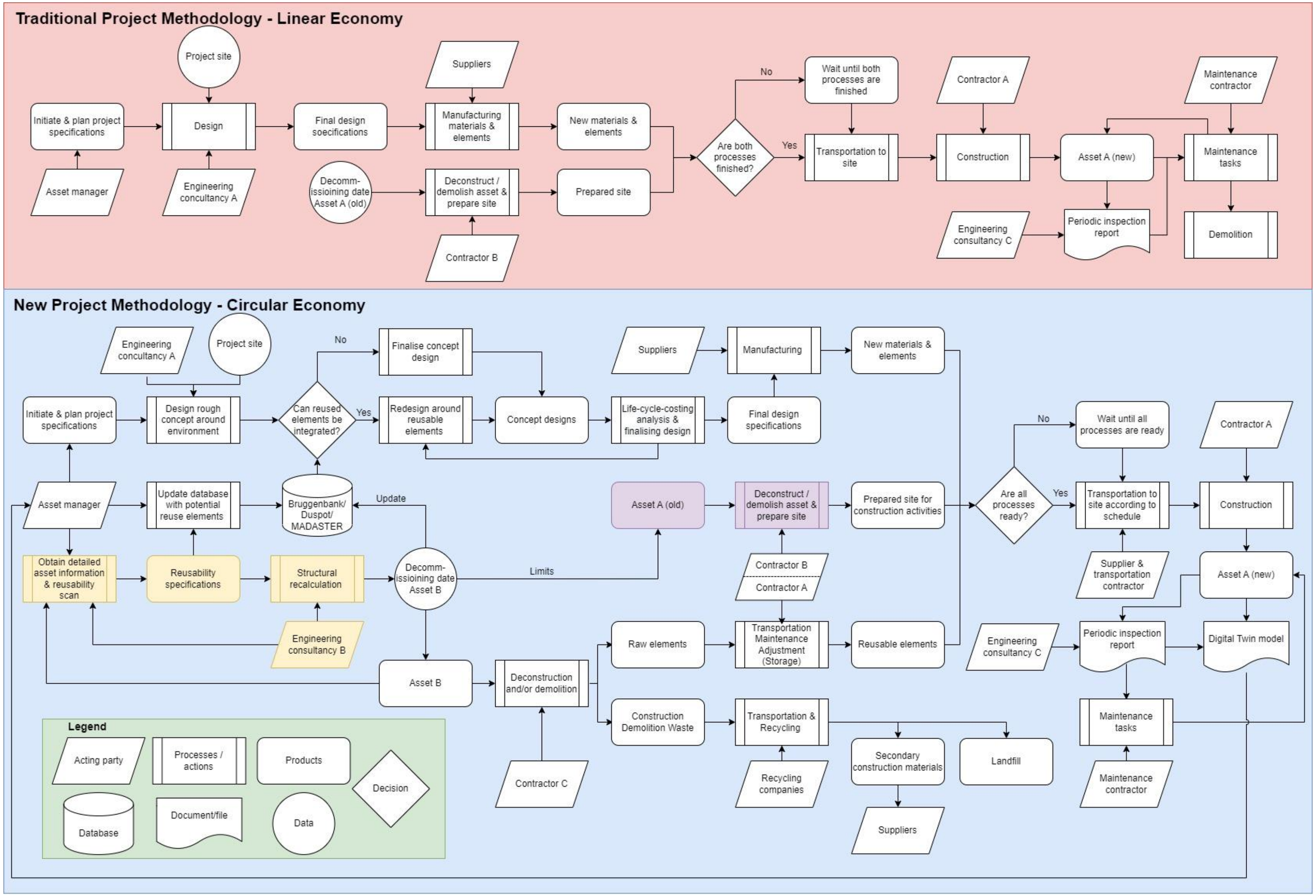


Figure 68: Reuse project methodology

Chapter 7: Conclusion, Discussion & Further research

7.1. Conclusion

In this section the conclusion of the research is formed using the drafted research questions.

1. What is the impact of the lack of available high-quality asset data on existing infrastructure on the CE-transition and the R&R-task?

The literature study has shown that material flow models are used in Dutch CE-transition roadmap development for setting goals & timelines. For civil infrastructures, this data input proved very unreliable as the centralised data location is not maintained by asset managers and rough assumptions had to be made on the characteristics of assets due to lacking asset data. This implies that the model output is also highly unreliable, impacting the accuracy of CE-roadmaps. Overestimation of the existing material stock equals larger secondary material potential and therefore lower raw material requirements in the future to meet construction demand, resulting in more conservative goalsetting. Conversely, implementing strict reuse/recycle regulations caused by overestimation of the material stock will significantly impact the construction industry and economy. Accurate bottom-up modelling of material quantities is paramount to enable and improve local and global CE-strategies.

The bridge R&R-task will require asset managers to make knowledgeable decisions on whether to replace, renovate, or maintain (extend) assets and when it is best to do so considering the large decommissioning peak that is expected in the upcoming decades and the limited (capital) resources available. The challenge arises from the demand for high quality asset data to make such decisions effectively or conduct structural assessments to obtain this information. Similarly, literature showed that one of the main barriers to reuse realisation also concerned the lack of data quality (condition & structural performance) and visualisation (communication) of assets and elements, making the risks for the demand party too high or costly to investigate, affecting the feasibility of CE-goals. Considering the ageing bridge infrastructure, an opportunity for reuse arises in the upcoming decades.

2. What are the current standards for data availability and documentation, what led to this present lack of asset data, and what future developments can be expected in AM?

Interviews with asset managers of a variety of public organisations have shown that asset data is often incomplete, fragmented over multiple systems, limited to some basic characteristics of the asset, and inspection reports. 2D drawings and project specifications are generally (temporarily) lost, requiring significant efforts to recover if possible. Moreover, asset documentation strategies vary across organisations, with larger organisations generally having more capacity and funds to organise their systems and upgrade their data. The most dominant causes for this lack of asset data derived from literature & interviews with stakeholders relate to the absence of technology at time of construction, changing asset managers over time causing loss of (tacit) knowledge, low priority for reuse realisation, and lack of demand from the client/asset manager to document the information for the operational lifetime. With the ongoing digitization transition, CE-transition, and R&R-task, more data is required, calling for BIM and digital twins to be adopted in AM. This results in an increasing data gap between newly constructed assets and existing assets. At some point, the AM strategy will be shifting to 3D centralised AM to better leverage the potential benefits that these 3D-BIM bring, calling for an upgrade of existing assets to 3D. While organisations have ambitions to do so, the lack of funding and capacity to effectuate the upgrade of existing assets stagnates the digitization transition and its benefits.

3. What is the potential performance and impact of a modular parametric design tool for fixed bridge infrastructure on the digitization transition at public organisations?

To counter the need for higher quality information on existing infrastructure for improved AM and facilitating circularity realisation and better management of the R&R-task timeline, a solution is required. Manually modelling assets from 2D drawings is labour intensive & expensive and 3D scanning technologies are expected to remain even more expensive over the coming years. The gap-analysis exposed the need for a modular approach to parametric modelling of fixed bridge infrastructure to reduce these costs and allow accelerated digitization at public organisations. The preliminary Cost-Benefit-Analysis showed that upgrading assets to 3D could yield potential profit on the long term, however this included large uncertainties and limited benefits. Moreover, through risk-analysis it was found that the successful adoption of such tooling would depend on the data availability at public organisations, their willingness to recover this data, and funding. The desired LOD for the design tool's output was analysed using three purpose categories: AM, reusability scanning & structural assessments, and material quantification. From this analysis, LOD400 was selected as a baseline for geometry output, and LOD500 for high reuse-potential elements.

Tool testing with 4 beam bridge projects showed promising results to obtain high accuracies (>97%) for modelling volumes and high potential for reducing the required modelling time compared to manual modelling practices from 2D drawings (1.75-2.5h vs 12-20h). From preliminary analysis, no beam or plate bridges were identified that could not be modelled with the RE-design concept in the future, speaking to the robustness potential of the solution. However, more user validation is required to confirm the exact figures for accuracy, cost-reduction, and applicability. To accommodate further use of the tool output, customizable attributes are automatically assigned to element categories for AM and reusability/ structural assessment needs (LOD700) based on BIM-theory and expert knowledge (W+B). Thereby providing designers and asset managers with the opportunity to document and monitor asset data from available sources, reports, and assessments more accurately per element. With more development, the prototype also provides the opportunity for playing a more prominent role in structural recalculations and design practices in the future. To ensure its large-scale adoption potential, a user's guide was developed for designers to decrease the entry barrier for the tool and facilitate inspectors with visualised information requirements for making measurements on site. Moreover, a white paper was designed to increase awareness among decision-makers and incentivize investments into transitioning towards 3D centralised AM.

4. What are the practical implications of the research findings on the construction industry and asset management in the context of the digitization-, CE-, and R&R-challenges?

The upgrade process of current data quality towards 3D-BIM and the following steps to leverage this information has rather significant implications for AM practices. To put these implications into perspective, a transition roadmap was developed that visualises the required steps for organisations to first get towards 3D centralised AM and consequently reuse project methodology and effective R&R-task management in practice. This resulted in 9 steps presented in Figure 69, provided with information needs and recommendations for execution. The sooner the data-gathering is initiated, the better.

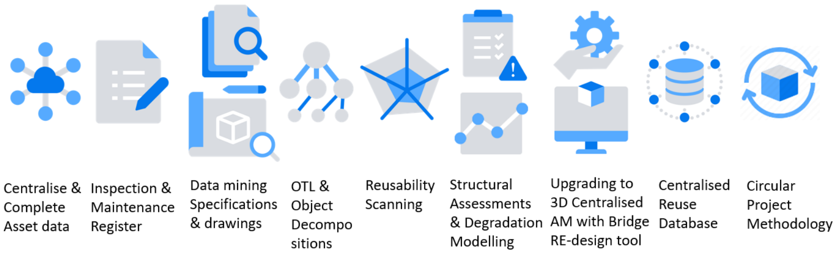


Figure 69: Roadmap for AM

How can centrally stored, quantified, and visualised asset data of existing infrastructure impact the CE-transition, bridge R&R-task efficiency, and AM practices?

High-quality asset data on existing assets is important for multiple reasons. The first being that it provides the input for MFA models which are consequently used in CE-transition roadmap development to make timelines for interventions (regulations, investments, etc.). Secondly, physical asset data is important for the realisation of reuse as at least the geometry, material, design load/strength, condition/degradation, and date of availability need to be known for demand parties to reduce their risk profile and have seamless integration of the available elements in their design. Lastly, for the R&R-task management the structural state of the asset needs to be known to determine whether to replace, renovate, or extend the asset, taking into account the decommissioning peak.

From interviews, it was observed that asset data is generally incomplete, fragmented, and divergent across public organisations. By centralising the asset's data into a single file, all the available data for reusability & structural assessments can be extracted from- and documented in a single source for more streamlined processes. The visualised asset (3D) automatically generates the material quantities for material flow models, given accurate attribute data. Finally, visualised asset data allows for more specific asset data documentation and monitoring on element level, improves information traceability & communication, maintenance & decommissioning preparation, and enhanced spatial planning decision-making. Moreover, potential benefits can be generated from the increased data storage potential and information availability through AI and other digital technologies in the future. From these findings, it can be concluded that centralised, quantified, and visualised asset data directly improves AM practices and MFA input accuracy, and indirectly influences the CE-transition and R&R-task management by providing a better data foundation for reusability & structural assessments.

Knowing this, and the cost-barrier at public organisations, a design tool prototype was developed using parametric modelling to reduce the upfront investment costs for developing 3D-BIM to centralise, quantify, and visualise existing fixed bridge infrastructure. Despite limited validation and scope, the tool showed promising potential to reduce costs and calls for further development and testing to improve robustness, while also having potential for playing a more prominent role in reusability & structural assessments. The degree to which the AM-benefits and potential role it can play in these assessments is governed by the availability and quality of asset data at public organisations.

7.2. Discussion

This section discusses the results of this research, as well as the most important uncertainties, assumptions and limitations that impacted the outcome of this research, grouped by theme.

7.2.1. Academic contribution

This study highlighted the limited attention in concrete initiatives/recommendations to overcome the urgent information need for existing infrastructure assets to enable short-term circularity realisation in both Dutch CE-transition roadmaps (Transitieteam Circulaire Bouweconomie, 2022) (Circulaire Bouweconomie, 2018) and state-of-the-art literature (as found in references in section 2.5.1 on page 40). Most of these initiatives and recommendations are positioned in the scenario where assets have this information readily available, while this is far from reality for most of the assets for at least the upcoming two decades. It is not meant to imply that researchers and industry players alike have been oblivious to this lack of data, but merely to point out the need for more evidence-based research and initiatives that will help 'convince' industry players to pull the trigger and tackle this problem. This study has taken a step in the right direction by calling for urgent action on upgrading the existing asset's data quality for increased potential for reuse realisation and R&R-task management, in addition to improved AM possibilities. This is effectuated using three developed products: a roadmap towards 3D centralised AM and reuse, a proof of concept for RE-design to reduce upgrade costs, and a white paper to increase awareness at public organisations on its urgency and benefits. While the tool itself does not generate all the data required to address these needs, it allows centralised storage of all the available information that is currently fragmented over multiple systems to better facilitate the actions required (reusability & structural assessments). Much of the data that is required as input is also needed for such assessments, thereby theoretically limiting additional efforts. Moreover, RE-design can accelerate research applications of digital innovations (e.g., AI) for CE through data centralization.

In the literature review, the Closing the Loop (CTL) concept for bridges & viaducts was selected as a starting point as this was one of the few encountered concepts that addresses the required front-end AM needs to enable short-term circularity to meet the 2030 and 2050 CE-goals, compared to the predominantly political, regulatory, financial, collaborative, and design concepts proposed by literature and transition roadmaps (as referred to in previous paragraph). The CTL concept calls for large-scale inventorying- and reusability scans of the acreage. However, inventorying and reusability scans alone are insufficient for reuse realisation. The concept was therefore built upon in this study by adding 3D modelling for documenting the data required for reusability scanning and structural state assessments. This concept serves as a bridge towards a complete CE where assets are represented in digital twins with high-quality asset data allowing for more accurate assessments and planning of circularity. This bridging period is expected to take 20-30 years before most of the bridges constructed between 1960-1980 are decommissioned. Despite the perception that this is a short period for such large investments, significant value can be captured with large impacts on the CE-transition.

7.2.2. CE-transition roadmapping

The significance of the uncertainty involved in MFA inputs for civil structures is still unknown, and therefore also the impact this has on roadmap development and the CE-transition, putting doubt to the urgency of obtaining more accurate data. There is also little incentive for AM to invest in obtaining material quantity data using statistical models & site observations and actively maintain the central databases (e.g., BGT) for the benefit of these MFA studies and transition roadmaps. This threshold is aimed to be lowered with RE-design by combining other incentives with this problem. However, the tool is for now limited to object volumes and lacks reinforcement approximation.

7.2.3. R&R-task and bridge reuse

One of the most important themes in this research concerns bridge reuse. First and foremost, it is still unknown what share of the bridges will be ‘functionally replaced’, due to uncertainties on accelerated degradation from functional changes and concrete hardening of bridges. Less functional replacements would decrease the potential benefit of upgrading to 3D due to lower potential for reuse realisation and consequently earning back some of the costs. Even with high-quality asset data and structural assessments, significant risks will remain for the demand party. This will require new incentives, business models, and risk management strategies in the future. In the analysis for the identification of the most promising group of bridges and elements, numerous assumptions and simplifications had to be made considering the newness of the field providing little precedent or research, lack of large bridge datasets, and scope considerations of this research. In principle, all bridge types have potential for reuse. However, more research is required on the potential for reusing elements outside of girders and railings, which are the primary focus currently. 3D-BIM elements could help benefit this research and expand the supply in reuse databases. Lastly, it is still a relatively unexplored field to value reusable elements to create a functioning market that also incentivizes AM to record data and explore reuse.

7.2.4. Data availability at public organisations

The main risk for successful large-scale adoption and impact of RE-design concerns the data availability and willingness to obtain data at public organisations. This data concerns 2D drawings and project specifications. Interviews with asset managers have shown that especially smaller sized organisations are unsure to what extent this data can be recovered due to their fragmented data documentation standards and changes in asset managers over time, making it a very large task to gather, organise, and scan the drawings. Moreover, smaller organisations currently have no spare capacity to conduct this task, due to the increasing management load and costs required by the R&R-task. Such efforts are likely required to be funded by the digitization/digitalisation-departments (often disconnected from AM) or innovation funds within the organisations. However, more interviews are required to obtain a more robust assessment on the availability of data and willingness to recover it.

Two alternatives are presented in case there is no data. The first being to employ 3D scanning technologies, despite continuous cost-reductions this solution is projected to remain very expensive in the coming 5 years at least. The cheaper alternative is to conduct site measurements during inspections using RE-design's handbook with visualised parameters of elements in the database and design options to develop the model. However, this would limit the accuracy of the model to above ground/water only, with approximations for the remaining dimensions. The latter option being favoured at smaller organisations. Key in this process is to convince industry stakeholders of the urgency and benefits of upgrading to 3D centralised AM. Especially considering that Dutch CE-transition roadmaps will 'require' the acreage to be fully 'transparent' (Dutch: inzichtelijk) by 2030.

7.2.5. Tool performance

Due to unforeseen circumstances the validation process was limited to a set of 4 'new' projects with current-day standards of design drawings, which can significantly differ from the data quality of bridges constructed before 2000. Testing was limited to modelling the geometry of the asset, thereby excluding the time that would otherwise be required for extracting and assigning attribute data to the individual elements. Lastly, due to time constraints, tool testing was conducted by the author instead of independent designers. To what extent these circumstances impacted the modelling time is uncertain. Conversely, it can be assumed that designers leverage their experience to assess drawings faster than to the author but might struggle more with the process at first. Given that the most dominant modelling aspect concerns the desk study of drawings to extract parameter values, it is plausible that designers can obtain better results given a saturated element database and practice with the tool. Comparing the results to current practices (~12-20 hours for municipal bridges (Wolbrink, 2023)), cost-reductions for modelling efforts seem very probable, despite the lower LOD and missing elements of the prototype's output. However, more testing by designers will be required for more reliable and consistent assessments on time-savings.

Testing also showed a high potential for model accuracy. However, the current element database and tool limitations resulted in some inaccuracies on details. An uncertainty score attribute will help with this problem to provide caution for future users of the model. Once the database expands, the model accuracy metric will perform more consistent across projects. The robustness performance metric was validated using a bridge dataset from the municipality of Gouda which contained only few beam and plate bridges, requiring a larger database to improve the validity of the robustness metric. The author and W+B designers did not identify any permanent limitations, however with further development comes more complexity. Nonetheless, this is a promising observation with respect to increasing robustness (expanding element database and design options) and exploring 3D structural assessments with the model output to further streamline this process. Moreover, improvements with respect to reinforcement approximation using statistics or reverse engineering methods require further research.

7.2.6. Scope & outcome

The scope of this research was very broad with the inclusion of three grand challenges: CE-transition, R&R-task, and digitization. While this study aims to contribute to each of these challenges either directly or indirectly, only a limited impact can be obtained with the outputs of this research: a roadmap for AM to better navigate the CE-transition and R&R-task, as well as a design tool prototype (RE-design). The roadmap was developed with bridge assets as a reference point but is recommended to be applied as a general strategy for AM of any scale of organisation. Considering the differences in data availability and capacity between organisations, the roadmap might prove more applicable to larger organisations on the short-term as they will need to take the lead to provide evidence of the benefits before smaller organisations will risk the investments. To accommodate for differences and preferences of organisations, exact methods, software, timelines, and other details have been excluded from the roadmap or posted as a suggestion.

This research only provided a proof of concept for potential cost reductions in upgrading existing fixed bridge infrastructure to 3D-BIM as part of this roadmap, therefore requiring more development before being able to obtain the desired industry impact. The subsequent impact and adoption are entirely dependent on the data availability or recovery and budget at public organisations while the outcome is limited to providing a data foundation for the R&R-task and reuse realisation efforts, not solve these challenges entirely. Waiting until 3D scanning becomes the prevalent (and cost-effective) solution loses significant value and opportunities. Similar efforts are required for other types of infrastructure to have the desired large-scale effect on the CE-transition and effectuate the digitization transition.

7.3. Further research

For my fellow researchers & designers, I have identified the following points for further research.

7.3.1. Study data availability potential at public organisations

To start, it was concluded that the main uncertainty regarding large-scale tool adoption concerns data availability of 2D drawings & specifications at public organisations. While stakeholder interviews provided hopeful indication that this data can be recovered to an extent, more research should be conducted on more accurate estimations on the extent to which this data can actually be recovered on a large scale, the willingness of organisations, as well as costs vs benefits and costs to do so.

7.3.2. Expand tool robustness and explore similar opportunities for other asset types

Considering the preliminary results shown in this research for the cost-reduction potential that modular PEM tooling can provide for fixed beam- & plate bridge infrastructure compared to manual modelling and current scanning technologies, the RE-design prototype should be further developed with respect to robustness (including remaining elements, database expansion & script optimization) and validation in practice. Additionally, similar opportunities can be explored for other types of (bridge) infrastructure to further accelerate the digitization transition and improve overall AM quality.

7.3.3. Reinforcement modelling & automation of 3D-BIM in structural assessments

One of the shortcomings of RE-design concerns the lack of reinforcement modelling. Following the example set by Harrewijn (2019), similar scripts could be developed for other design elements to parametrically model reinforcement using element geometry and construction period as input, these can then be applied on RE-design's output. Such studies are very extensive and complex, calling for a top down initiated & funded effort to achieve the desired effect. Moreover, automation of integrating 3D-BIM in structural assessments to streamline the workflow for structural engineers and lower the costs require more research. Here AI can play a role as introduced by (Dang, Kang, Lon, & Shim, 2018).

References

Abdirad, H., & Sturts Dossick, C. (2020). Rebaselining Asset Data for Existing Facilities and Infrastructure. *Journal of Computing in Civil Engineering, 34*(1). doi:http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000868

Abrelpe. (2018). *PANORAMA dos residuos no brasil.* ABRELPE.

Adams, K., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: currentawareness, challenges and enablers. *Waste and Resource Management, 170*(1), 15-24. doi:https://doi-org.tudelft.idm.oclc.org/10.1680/jwarm.16.00011

Ajayabi, A., Chen, H., Zhou, K., Hopkinson, P., Wang, Y., & Lam, D. (2019). REBUILD:regenerative buildings and construction systems for a circular economy. *IOP Conf. Ser. Earth Environ. Sci. 225.* doi:https://doi.org/10.1088/1755-1315/225/1/012015

Akadari, P., & Fadiya, O. (2013). Empirical analysis of the determinants of environmentally sustainable practices in the UK construction industry. *Construction innovation, 13*(4), 353-373.

Akanbi, L., Oyedele, L., Omoteso, K., Bilal, M., Akinade , O., Ajayi, A., . . . Owolabi, H. (2020). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *Journal of cleaner production, 223*, 386-396.

Akinade, O., Oyedele, L., Oyedele A, Davilla Delgado, J., Bilal, M., Akanbi, L., . . . Owolabi, H. (2020). Design for deconstruction using a circular economy approach: barriers and strategies Industry 4.0 digital technologies for improvemen. *Production planning and control, 31*(10), 829-840.

Ali, A. (2019). Mapping a Resource-Based Design Workflow to Activate a Circular Economy in Building Design and Construction. *IOP Conference Series: Earth and Environmental Science*. doi:doi:10.1088/1755-1315/225/1/012010

Allplan. (n.d.). *Allplan bridge*. Retrieved February 2023, from Allplan: https://www.allplan.com/products/allplan-bridge/

Antikainen, M., Uusitalo, T., & Kivikytö-Reponen, P. (2018). Digitalisation as an Enabler of Circular Economy. *Procedia CIRP, 73*, 45-49.

Arora, M., Raspall, F., Cheah, L., & Silva, A. (2020). Buildings and the circular economy: Estimating urban mining, recovery and reuse potential of building components. *Resources, Conservation and Recycling, 154*. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.resconrec.2019.104581

Attencia, G., & Aperacida de Mattos, C. (2022). Adoption of digital technologies for asset management in construction projects. *Journal of Information Technology in Construction, 27*, 619-629.

Bakker, H. (2023, january). Costs for bridge elements. (C. Reit, Interviewer)

BAMB. (2020). *Enabling a circular building industry.* Retrieved nOVEMBER 2022, from https://www.bamb2020.eu/

Bao, Z., Lu, W., Chi, B., Yuan, H., & Hao, J. (2019). Procurement innovation for a circular economy of construction and demolition waste: Lessons learnt from Suzhou, China. *Waste Management, 99*, 12-21. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.wasman.2019.08.031

Bektas, B., Carriquiry, A., & Smadi, O. (2013). Using Classification Trees for Predicting National Bridge Inventory Condition Ratings. *Journal of Infrastructure Systems, 19*(4).

Benachio, G., & Freitas, M. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of cleaner production, 260*. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.jclepro.2020.121046

Bertin, I., Mesnil, R., Jaeger, J.-M., Feraille, A., & Le Roy, R. (2020). A BIM-Based Framework and Databank for Reusing Load-Bearing Structural Elements. *Sustainability, 12*.

Bhaskar, A., Abhishek, R., Assadi, M., & Somehesaraei, H. (2022). Decarbonizing primary steel production : Techno-economic assessment of a hydrogen based green steel production plant in Norway. *350*. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.jclepro.2022.131339

BIMForum. (2019). *Level of Development specification.* BIMForum.

BIS . (2013). *Supply chain analysis into the construction industry: A report for the construction industrial strategy.* London: Department for Business, Innovation and Skills.

Bleijenberg, i. (2021). *Instandhouding civiele infrastructuur - Proeve van landelijk prognoserapport vervanging en renovatie.* TNO. De bouwagenda. Retrieved February 2023

Boer, P. A. (2022). Asset management in practice at public organisations. (C. Reit, Interviewer)

Boje, C., Guerriero , A., Kubicki , S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction, 114*. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.autcon.2020.103179

Bouwend Nederland. (2022). *Kengetallen uit de bouw en infra*. Retrieved February 2023, from bouwend nederland: https://www.bouwendnederland.nl/service/feiten-en-cijfers#:~:text=Bouw%2D%20en%20infrabedrijven%20hebben%20een,van%20ruim%2082%20miljard%20euro

BouwTotaal. (2022, November 3). *Bouwvrijstelling stikstof van tafel: 'drama voor de bouw'*. Retrieved December 2022, from Bouwtotaal: https://www.bouwtotaal.nl/2022/11/bouwvrijstelling-stikstof-van-tafel-drama-voor-de-bouw/#:~:text=De%20bouwvrijstelling%20stikstof%20voldoet%20niet,gebruikt%20mag%20worden%20bij%20bouwprojecten.

Bridgeweb. (2021). *Study finds a tenth of German bridges in poor condition*. Retrieved March 2023, from Bridgeweb: https://www.bridgeweb.com/Study-finds-a-tenth-of-German-bridges-in-poor-condition/8590

Brouwer, J. (2022). *Reusability of viaduct girders.* Delft: TU Delft.

Bruggen bank. (2023, March). *Beschikbare bruggen en onderdelen*. Retrieved February 2023, from Bruggenbank: https://www.bruggenbank.nl/bruggen/

Bruggencampus. (2022). *Bruggencampus*. Retrieved October 2022, from https://bruggencampus.nl/

Brunner, P. (2011). Urban mining A contribution to reindustrialising the city. *Journal of industrial ecology, 15*, 339-341.

Bryde, D., Broquetas, M., & Volm, J. (2013). The project benefits of Building Information Modelling (BIM). *International Journal of Project Management, 31*(7), 971-980. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.ijproman.2012.12.001

BSI. (2021, July 21). *Why construction standards are crucial in the built environment*. Retrieved November 2022, from Knowledge BSI group: https://knowledge.bsigroup.com/articles/why-standards-are-crucial-in-construction-and-the-built-environment

Bułhak, T., Karp-Kręglicka, E., Krysiak, H., & Boruc, J. (2022). *Upcycling in construction. Recycling with added value*. Retrieved February 2023, from Greeneuropetoday: https://greeneuropetoday.com/upcycling-in-construction-recycling-with-added-value/

Cao, W. (2022). *Getting it straight - bridges are becoming circular*. Retrieved October 2022, from TUDelft: https://www.tudelft.nl/en/ceg/research/stories-of-science/getting-it-straight-bridges-are-becoming-circular

Capelle, T. (2019). *Buildings as Material Banks, H2020 Innovation Project, Pilot Projects- circular economy.* BAMB.

Carvalho, J., Braganca, L., & Mateus, R. (2019). Optimising building sustainability assessment using BIM. *Automation in Construction, 102*, 170-182. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.autcon.2019.02.021

CBS. (2012). *Bulk van grondstoffen uit Europa*. Retrieved from https://www.cbs.nl/nl-nl/nieuws/2012/46/bulk-van-grondstoffen-uit-europa#:~:text=Nederland%20haalt%2068%20procent%20van,twee%20derde%20uit%20Europese%20landen

CBS. (2012). *Bulk van grondstoffen uit Europa*. Retrieved March 2023, from CBS: http://www.cbs.nl/nl-NL/menu/themas/dossiers/eu/publicaties/archief/2012/2012-3726-wm.htm

Cetin, S., Gruis, V., & Straub, A. (2022). Digitalization for a circular economy in the building industry: Multiple-case study of Dutch social housing organizations. *Resources, conservation & recycling advances, 15*. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.rcradv.2022.200110

Charef, Lu, & Hall. (2022). The transition to the circular economy of the construction industry: Insights into sustainable approaches to improve the understanding. *Journal of cleaner production, 364*.

Charef, R., & Emmitt, S. (2021). Uses of building information modelling for overcoming barriers to a circular economy. *Cleaner production, 285*.

Charef, R., Morel, J.-C., & Rakhshan, K. (2021). Barriers to Implementing the Circular Economy in the Construction Industry: A Critical Review. *Sustainability, 13*(23).

Christiansen, B. (2020, November). *Construction Asset Management: Tracking and Maintenance Basics*. Retrieved january 2023, from Limble: https://limblecmms.com/blog/construction-asset-management/

Circulaire Bouweconomie. (2018). *Transitie Agenda Circulaire bouweconomie.* Retrieved October 2022

Cobouw. (2022). *Zonder digital twin wordt er geen tunnel meer gerenoveerd*. Retrieved January 2023, from cobouw: https://www-cobouw-nl.tudelft.idm.oclc.org/302415/zonder-digital-twin-wordt-er-geen-tunnel-meer-gerenoveerd

CollaborAll. (n.d.). *ANT*. Retrieved March 2023, from CollaborAll: https://collaborall.net/ant/

Copper8. (2022). *Materialen Expeditie - geleerde lessen rondom hergebruik tussen projecten en organisaties.* Bouwend Nederland.

Cramer, J. (2014). *Circular economy - from wish to practice.* Utrecht: Council for the environment and infrastructure.

Creative Mechisms. (2015). *The History of Design, Model Making and CAD*. Retrieved January 2023, from Creative Mechisms: https://www.creativemechanisms.com/blog/the-history-of-design-model-making-and-cad

Damianou, A., Angelopoulos, C., & Katos, V. (2019). An architecture for blockchain over edge enabled IoT for smart circular cities. *15th international conference on distributed computing in sensor systems* (pp. 468-472). IEEE.

Dang, S., Kang, H., Lon, S., & Shim, C. (2018). 3D DIGITAL TWIN MODELS FOR BRIDGE MAINTENANCE. *10th International Conference on Short and Medium Span Bridges.* Quebec.

Davis, N., Sanayei, M., Hoomaan, E., & Jalinoos, F. (Journal of Bridge Engineering). Foundation Reuse in Accelerated Bridge Construction. *Journal of bridge engineering, 24*(10). doi:http://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0001455

De bouwcampus. (2022). *V&R transitie dashboard*. Retrieved February 2023, from https://portfolioaanpak.debouwcampus.nl/aanleiding

De Mattos, C., & Meira De Albuquerque, T. (2018). Enabling Factors and Strategies for the Transition Toward a Circular Economy (CE). *Sustainability, 10*(12).

Debacker, W., Manshoven, S., Peters, M., Ribeiro, A., & de Weerdt Yves. (2017). Circular economy and design for change within the built environment: preparing the transition. *International HISER Conference on Advances in Recycling and Management of Construction and.* Delft.

De-Graft , J., Perera, S., Osei-Kyei , R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering, 40*.

Delgado, M., & Oyedele, L. (2020). BIM data model requirements for asset monitoring and the circular economy. *Journal of egineering design and technology*. doi:http://dx.doi.org/10.1108/JEDT-10-2019-0284

Delrue, S. (2022). *Circular Economy inspires renovation of Netherlands busiest bridge, extending lifespan by another 100 years*. Retrieved December 2022, from Arup: https://www.arup.com/projects/van-brienenoord-bridge-renovation

Designbuildings. (2021). *Decomissioning buildings- preparing a scope of work*. Retrieved january 2023, from designbuildings: https://www.designingbuildings.co.uk/wiki/Decommissioning_buildings#Preparing_a_scope_of_work

DesignBuildings. (2022, March 28). *Consumption in the construction industry*. Retrieved from Designbuildings: https://www.designingbuildings.co.uk/wiki/Consumption_in_the_construction_industry

DesignCouncil. (2019, May 17). *Framework for Innovation: Design Council's evolved Double Diamond*. Retrieved from Designcouncil: https://www.designcouncil.org.uk/our-work/skills-learning/tools-frameworks/framework-for-innovation-design-councils-evolved-double-diamond/

Digital school. (n.d.). Retrieved January 2023, from Digital school technical design college: https://www.digitalschool.ca/the-evolution-of-cad-for-engineering-and-architectural-technicians/#:~:text=In%20the%201970's%2C%20early%20CAD,architectural%20and%20engineering%20firms%20everywhere

Drager, P., Letmathe, P., Reinhart, L., & Robineck, F. (2022). Measuring circularity: evaluation of the circularity of construction products using the ÖKOBAUDAT database. *Environmental sciences Europe, 34*(14). doi:https://doi.org/10.1186/s12302-022-00589-0

Duspot. (2023). *Duspot*. Retrieved February 2023, from https://www.duspot.nl/

Easen, N. (2017). *Construction: an industry ripe for tech disruption*. Retrieved January 2023, from Raconteur: https://www.raconteur.net/construction/construction-an-industry-ripe-for-tech-disruption/

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019). Potential of Circular Economy in Sustainable Buildings. *IOP Conference Series: Materials Science and Engineering, 471*(9). doi:10.1088/1757-899X/471/9/092051

Edirisinghe, R., London, K., Kalutara, A., & Aranda-mena, G. (2017). Building information modelling for facility management: are we there yet? *Engineering construction and architectural management, 24*(6), 1119-1154.

EIB & Metabolic. (2022). *Materiaalstromen in de bouw en infra.* EIB. Retrieved November 2022

Elghaish, F., Matarneh, S., Edwards, D., Rahimian, F. P., El-Gohary, H., & Ejohwomu, O. (2022). Applications of Industry 4.0 digital technologies towards a construction circular economy: gap analysis and conceptual framework. *industry 4.0 and digital technologies, 22*(3), 647-670.

EMF. (2015). *DELIVERING THE CIRCULAR ECONOMY - A TOOLKIT FOR POLICYMAKERS.* Ellen MacArthur Foundation. Retrieved from https://emf.thirdlight.com/file/24/neVTuDFno5ajUeneman5IbBE/Delivering%20the%20circular%20economy%3A%20a%20toolkit%20for%20policy makers.pdf

European Comission. (2014). *Report on critical raw materials for the EU: report of the ad hoc working group on defining critical raw materials.* Brussels: EU.

Florida department of transportation. (2000). *INFLUENCE OF HEAVY TRUCKS ON HIGHWAY BRIDGES.* Florida department of transportation.

Frangopol, D., & Liu, M. (2007). Maintenance and management of civil infrastructure based on condition, safety, optimization, and life-cycle cost. *Maintenance, Management, Life-Cycle Design and Performance, 3*(1), 29-41. doi:https://doi-org.tudelft.idm.oclc.org/10.1080/15732470500253164

Fu, F. (2018). *Design and Analysis of Tall and Complex Structures.*

Gassnes, A., Lederer, J., & Fellner, J. (2020). Material stock development of the transport sector in the city of Vienna. *Journal of industrial ecology, 24*(6), 1364-1378. doi:https://doi-org.tudelft.idm.oclc.org/10.1111/jiec.13024

Ghaffarianhoseini , A., Tookey, J., Ghaffarianhoseini, A., Naismith, N., Azhar, S., Efimova, O., & Raahemifar, K. (2017). Building Information Modelling (BIM) uptake: Clear benefits, understanding its implementation, risks and challenges. *75*, 1046-1053. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.rser.2016.11.083

Ghufran, M., Ahmad Khan , K., Ullah, F., Nasir, A., Al Alahmadi , A., Alzaed , A., & Alwetaishi , M. (2022). Circular Economy in the Construction Industry: A Step towards Sustainable Development. *Buildings, 12*(7).

Giel, B., & Issa, R. (2013). Return on Investment Analysis of Using Building Information Modeling in Construction. *Journal of Computing in Civil Engineering, 27*(5).

Goorhuis, P. (2020). *Value retention: preconditions for moving from demolition to deconstruction.* Enschede: University of Twente.

Grani, H. K. (2016). *Level of Development - LOD - as a Lifecycle BIM tool*. Retrieved from areo: https://blog.areo.io/level-of-development/

Greencirculedemolition. (2021). *THE DIFFERENCE BETWEEN DECONSTRUCTION AND DEMOLITION (AND HOW TO FIGURE OUT WHICH YOU NEED)*. Retrieved February 2023, from Greencircle: https://www.greencircledemolition.com/blog/the-difference-between-deconstruction-and-demolition

GSA. (n.d.). *Level of Detail*. Retrieved from GSA: https://www.gsa.gov/real-estate/design-and-construction/3d4d-building-information-modeling/bim-software-guidelines/document-guides/level-of-detail#:~:text=Level%20of%20Design%20%2F%20Development%20%2F%20Detail,data%20associated%20with%20the%20objects

Gu, B., Ergan, S., & Akinci, B. (2014). Generating As-is Building Information Models for Facility Management by Leveraging Heterogeneous Existing Information Sources: A Case Study. *Construction research congress 2014*, (pp. 1911-1920).

Guzzetti, F., Anyabolu, K., Biolo, F., & D'Ambrosio, L. (2021). BIM for Existing Construction: A Different Logic Scheme and an Alternative Semantic to Enhance the Interoperabilty. *Applied sciences, 11*(4). doi:https://doi.org/10.3390/app11041855

Haas, F., Krausmann, D., M. Weidenhoger, & Heinz, M. (2015). How circular is ghte global economy? An assessment of material flows, waste production and recycling in the EU and the world in 2005. *Journal of industrial ecology, 19*(5), 765-777.

Halfawy, M. (2008). Integration of municipal infrastructure asset management processes: challenges and solutions. *Journal of Computing in Civil Engineering, 22*(3), 216-229.

Harrewijn, T. (2019). *Reverse Engineering of existing reinforced concrete slab bridges.* Delft: TU Delft.

Hart, J., Adams, K., Giesekam, J., Tingley, D., & Pomponi, F. (2019). Barriers and drivers in a circular economy: the case of the built environment. *Procedia CIRP, 80*, 619-624.

Heinrich, M., & Lang, W. (2019). Capture and Control of Material Flows and Stocks in urban residential buildings. *IOP Conference Series: Earth and Environmental Science.* doi:doi:10.1088/1755-1315/225/1/012001

Heinrich, M., & Lang, W. (2019). *Materials Passports - Best Practice - Innovative Solutions for a Transition to a Circular Economy in the Built Environment.* Technische Universität München.

Heralova, R. (2017). Life Cycle Costing as an Important Contribution to Feasibility Study in Construction Projects. *Procedia engineering, 196*, 565-570.

Hevner, A., & March, S. (2004). Design Science in Information Systems Research. *Management information systems quarterly, 28*.

Hiete, M., Stengel, J., Ludwig, J., & Schultmann, F. (2011). Matching construction and demolition waste supply to recycling demand: a regional management chain model. *Building research & information, 39*(4), 333-351. doi:https://doi.org/10.1080/09613218.2011.576849

Hollings, N. (2019). *The Secrets of Digital Twins for the Cities of Tomorrow*. Retrieved from Equinix: https://blog.equinix.com/blog/2019/06/18/the-secrets-of-digital-twins-for-the-cities-of-tomorrow/

Honic, M., Ferschin, P., Breitfuss, D., Cencic, O., Gourlis, G., Kovacic, I., & De Wolf, C. (2023). Framework for the assessment of the existing building stock through BIM and GIS. *Developments in the Built Environment, 13*.

Honic, M., Kovacic, i., & Rechberger, H. (2019). Improving the recycling potential of buildings through Material Passports (MP): an Austrian case study. *Journal of clean production, 217*. doi:https://doi.org/10.1016/j.jclepro.2019.01.212.

Hossain, M., & Yeoh, J. (2018). BIM for Existing Buildings: Potential Opportunities and barriers. *IOP Conference Series: Materials Science and Engineering 371.*

Hossain, U., Ng, T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renewable and sustainable energy reviews*. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.rser.2020.109948

Huuhka, S., & Hakanen, J. (2015). POTENTIAL AND BARRIERS FOR REUSING LOAD-BEARING BUILDING COMPONENTS IN FINLAND. *Materials science*.

Hwang, B.-g., Ngo, J., & Teo, J. (2022). Challenges and Strategies for the Adoption of Smart Technologies in the Construction Industry: The Case of Singapore. *Journal of management & engineering, 38*(1), Special article. doi:https://doi.org/10.1061/(ASCE)ME.1943-5479.0000986

IAsset. (2022). *Hoe ga je kostenefficiënt met investeringen in de openbare ruimte om? Een duo-interview met de gemeente Boekel en iASSET.* Retrieved February 2023, from IAsset: https://iasset.nl/2022/01/26/hoe-ga-je-kostenefficient-met-investeringen-in-de-openbare-ruimte-om-een-duo-interview-met-de-gemeente-boekel-en-iasset/

IBM. (2022). *What is a digital twin*. Retrieved January 2023, from IBM: https://www.ibm.com/topics/what-is-a-digital-twin

Imran, M. (2020). *Material Stock Data Extraction using geographic imagery in material flow analysis for urban infrastructure.* l'UNIVERSITE DE TECHNOLOGIE DE TROYES.

International Organization for Standardization. (2011). *ISO 15686-1:2011(en) Buildings and constructed assets — Service life planning — Part 1: General principles and framework.* Retrieved March 2023, from https://www.iso.org/obp/ui/#iso:std:iso:15686:-1:ed-2:v1:en

IV Infra. (n.d.). *Oude bruggen moeten niet te snel worden afgeschreven*. Retrieved February 2023, from IV Infra: https://iv-groep.nl/nl/blog/overzicht/oude-bruggen-moeten-niet-te-snel-worden-afgeschrev

Jalinoos, F. (2015). *Reusing Bridge Foundations.* US Department of transportation. Retrieved from https://highways.dot.gov/public-roads/novemberdecember-2015/reusing-bridge-foundations

Janssen, M. (2022, December). Interview concerning structural recalculations. (C. Reit, Interviewer)

Jickling, R. (2020). *Advantages of 3D Terrestrial Laser Scanners*. Retrieved December 2022, from Hive: https://hivevp.com/advantages-of-3d-terrestrial-laser-scanners/

Kampinga, H. (2022). LinkedIn Post.

Kanters, M. (2022). *Explorative case study to gain insight on the consequences of circular infrastructural construction projects.* Delft: TU Delft.

Kharas, H. (2017). *THE UNPRECEDENTED EXPANSION.* Brookings institution. Retrieved 2022, from https://www.brookings.edu/wp-content/uploads/2017/02/global_20170228_global-middle-class.pdf

Khasreen, M., Banfill, P., & Menzies , G. (2009). Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability, 1* (3), 674-701. doi:https://doi.org/10.3390/su1030674

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit , E., Muller, J., Huibrechtse-Truijens, A., & Hekkert, M. (2018). Barriers to the Circular Economy: Evidence From the European Union (EU). *Ecological economics, 150*, 264-272. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.ecolecon.2018.04.028

Kishna, M., Rood, T., & Prins, A. (2019). *ACHTERGRONDRAPPORT BIJ CIRCULAIRE ECONOMIE IN KAART.* Den Haag: PBL.

Klatter, L. (2022). *Prognoserapport vervanging en renovatie.* Rijkswaterstaat.

Krause, K., & Haffner, A. (2019). Relevance of the information content in module D on circular economy of building materials. *Proceedings of the 6th international symposium on lifecucle civil engineering*, (pp. 1627-1633).

Krausmann, F., Lauk, C., Haas, W., & Weidenhofer, D. (2018). From resource extraction to outflows of wastes and emissions: the socioeconomic metabolism of the global economy 1900-2015. *Global environmental change, 52*, 131-140.

Kreike, B. (2022). *Circularity in infrastructure projects with early contractor involvement.* Delft: TU Delft.

Krigsvoll , G., Fumo, M., & Morbiducci , R. (2010). National and International Standardization (International Organization for Standardization and European Committee for Standardization) Relevant for Sustainability in Construction. *Sustainability, 2*(12), 3777-3791. doi:https://doi.org/10.3390/su2123777

Lai, R. (2023). Structural validation brige design tool. (C. Reit, Interviewer)

Lanau, M., & Liu , G. (2020). Developing an Urban Resource Cadaster for Circular Economy: A Case of Odense, Denmark. *Environmental science technology, 54*(7), 4675–4685.

Love, P., Jingyang, Z., Matthews, J., & Harbin, L. (2016). Systems information modelling: enabling digital asset management. *Advances in engineering software, 102*, 155-165.

Lunenborg, P. (2022, October). Interview with industry experts. (C. Reit, Interviewer)

MADASTER. (2023, march). *MADASTER*. Retrieved from MADASTER: https://madaster.nl

Markus, M., Majchrzak, A., & Gasser, L. (2002). Design theory for systems that support emergent knowledge processes. *MIS quarterly*, 179-212.

Mathijssen, J., Pedersen, A., Besseling, P., Rahman, A., & Don, H. (2008). *Dealing with Uncertainty in Policymaking.* The Hague: RIVM. Retrieved February 2023

Mekawy, M., & Petzold , F. (2018). BIM-Based Model Checking in the Early Design Phases of Precast Concrete Structures. *Conference of the Association for Computer-Aided Architectural Design Research in Asia.* doi:http://dx.doi.org/10.52842/conf.caadria.2018.2.071

Mohandes, S., Hamid, H., & Sadeghi, H. (2014). Exploiting Building Information Modelling throughout the whole lifecycle of construction projects. *Journal of basic applied science, 4*(9), 16-27.

Munaro, M., Fischer, A., Azevedo, N., & Tavares, S. (2019). Proposal of a building material passport and its application feasibility to the wood frame constructive system in Brazil. *IOP Conference Series Earth and Environmental Science, 225*(1). doi:10.1088/1755-1315/225/1/012018

NEBEST. (2021). *Closing the Loop.* NEBEST. Retrieved from NEBEST: https://www.nebest.nl/hoogwaardig-hergebruikte-viaducten-met-closing-the-loop/

NEN. (2022). *Industrieel Flexibel Demontabel.* NEN.

NIBE. (2019). *Potentie biobased material in de bouw.* Rijksoverheid.

Nicolai, R. (2019). *Analyse levensduur betonnen bruggen en viaducten.* HKV.

Oezdemir, O., Krause, K., & Hafner, A. (2017). Creating a Resource Cadaster—A Case Study of a District in the Rhine-Ruhr Metropolitan Area. *Buildings, 7*(2). doi:https://doi.org/10.3390/buildings7020045

Offenbeek, B. v. (2022). *Een tweede leven voor oude bruggen*. Retrieved February 2023 , from magazine rijkswaterstaat: https://www.magazinesrijkswaterstaat.nl/zakelijkeninnovatie/2020/02/hergebruik-bruggen

Okorie, O., Salonitis, K., Charnley, F., Moreno, M., Turner, C., & Tiwari, A. (2018). Digitisation and the Circular Economy: A Review of Current Research and Future Trends. *Energies, 11*(11). doi:https://doi.org/10.3390/en11113009

OneClickLCA. (n.d.). Retrieved February 2023, from oneclickLCA: https://www.oneclicklca.com/building-life-cycle-costing-in-construction/#:~:text=Life%20cycle%20cost%20analysis%20(LCCA,perspective%20to%20reduce%20overall%20costs

Orzeł, B., & Wolniak, R. (2022). Digitization in the Design and Construction Industry—Remote Work in the Context of Sustainability: A Study from Poland. *Sustainability, 14*(3). doi:https://doi.org/10.3390/su14031332

Oxand, E. T. (2022, December). Asset management. (C. Reit, Interviewer)

Papadopoulos, G., Gayialis, S., & Zamer, N. (2016). Supply Chain Improvement in Construction Industry. *Universal journal of management, 4*(20), 528-534. doi:http://dx.doi.org/10.13189/ujm.2016.041002

Pärn, E., Edwards, D., & Sing, M. (2017). The building information modelling trajectory in facilities management: a review. *Automation in construction, 75*, 45.

Platform CB’23. (2020). *Guide for measuring circularity.* Platform CB'23. Retrieved October 2022

Platform CB'23. (2020). *Guide for Passports for the Construction Sector version 2.0.* Platform CB'23.

PRINCE2. (n.d.). Prince2 project methodology. Prince2.

Probert, A., Miller, A., Ip, K., Beckett, K., & Schofield, R. (2010). Accounting for the life-cycle carbon emissions of new dwellings in the U.K. *12th International Conference on Non-conventional Materials and Technologies*, (pp. 1-13).

Quirk, V. (2012). Retrieved January 2023, from Archdaily: https://www.archdaily.com/302490/a-brief-history-of-bim

Rahimian, F., Goulding, J., Abrishami, S., Seyedzadeh, S., & Elghaish, F. (2021). *Industry 4.0 Solutions for Building Design and Construction: A Paradigm of New Opportunities.* Oxfordshire: Routledge.

Ramadoss, T., Alam, H., & Seeram, R. (2018). Artificial intelligence and internet of things enabled circular economy. *The international journal of engineering and science, 7*(9), 55-63.

Rampini, L., & Re Cecconi, F. (2022). ARTIFICIAL INTELLIGENCE IN CONSTRUCTION ASSET MANAGEMENT: A REVIEW OF PRESENT STATUS, CHALLENGES AND FUTURE OPPORTUNITIES. *Journal of Information Technology in Construction, 27*, 884-913.

Rashidi, M., Mohammadi, M., Kivi , S., Abdolvand , M., Truong-Hong, L., & Samali , B. (2020). A Decade of Modern Bridge Monitoring Using Terrestrial Laser Scanning: Review and Future Directions. *Remote sensing, 12*(22).

Riess, E. (2011). *The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses.* Crown Business.

Rijksoverheid. (2016). *Nederland circulair in 2050*. Retrieved October 2022, from Rijksoverheid: https://www.rijksoverheid.nl/onderwerpen/circulaire-economie/nederland-circulair-in-2050

Rijksoverheid. (2022, December 9). *Kabinet wil meer zekerheid over toevoer grondstoffen en halfproducten*. Retrieved January 2023, from Rijksoverheid: https://www.rijksoverheid.nl/actueel/nieuws/2022/12/09/kabinet-wil-meer-zekerheid-over-toevoer-grondstoffen-en-halfproducten

Rijksoverheid. (2023). *Coalitieakkoord 'Omzien naar elkaar, vooruitkijken naar de toekomst'*. Retrieved February 2023, from Rijksoverheid: https://www.rijksoverheid.nl/regering/coalitieakkoord-omzien-naar-elkaar-vooruitkijken-naar-de-toekomst/2.-duurzaam-land/klimaat-en-energie

Rijkswaterstaat. (2022). *Circulaire economie*. Retrieved November 2022, from Rijkswaterstaat: https://www.rijkswaterstaat.nl/leefomgeving/duurzaam-werken/circulaire-economie

Rivero, A.-J., & Garcia-Navarro, J. (2020). Management of end-of-life gypsum in a circular economy. *Advances in construction and demolition waste recycling*.

Roberts, C., Pärn, E., Edwards, J., & Aigbavboa, C. (2018). Digitalising asset management: concomitant benefits and persistent challenges. *International Journal of Building Pathology and Adaptation, 36*(2), 152-173. doi:DOI:10.1108/IJBPA-09-2017-0036

Romeijn, A. (n.d.). *evolutie van vaste bruggen vanaf 1940*. Retrieved December 2022, from bruggenstichting: https://bruggenstichting.nl/tijdschrift/ouder/48-bruggen-2002/588-evolutie-van-de-verschijningsvorm-van-vaste-bruggen-vanaf-1940

Royal Haskoning DHV. (2022). *Digital twins and asset management*. Retrieved January 2023, from Royal Haskoning: https://www.royalhaskoningdhv.com/en/newsroom/blogs/digital-twins-and-asset-management

Sauter, E., Lemmens, & Pauwels, P. (2020). *CEO & CAMO Ontologies: a circulation medium for materials in the.*

Schaafsma, D. (2022, December 13). *Flatten the curve*. Retrieved February 2023, from Cement online: https://www-cementonline-nl.tudelft.idm.oclc.org/flatten-the-curve

Schiller, G., Muller, F., & Ortlepp, R. (2017). Mapping the anthropogenic stock in Germany: Metabolic evidence for a circular economy. *Resources, Conservation and Recycling, 123*, 93-107. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.resconrec.2016.08.007

Sfakianaki, E. (2015). Resource-efficient construction: rethinking construction towards sustainability. *World Journal of Science, Technology and Sustainable Development, 12*(3), 233-242.

Shah, C. (2022). *Level Of Detail (LOD): Understand And Utilization*. Retrieved December 2022, from MarsBIM: https://www.marsbim.com/blog/level-of-detail-lod-understand-and-utilization/

Shen, L.-U., Lu, W.-S., Yao, H., & Wu, D.-h. (2005). A computer-based scoring method for measuring the environmental performance of construction activities. *Automation in construction, 14*(3), 297-309.

Shojaei, A., Ketabi, R., Razkenari, M., Hakim, H., & Wang, J. (2021). Enabling a circular economy in the built environment sector through blockchain technology. *Journal of Cleaner Production, 294*.

Shooshtarian, S., Reza Hosseini, M., Kocaturk, T., Arnel, T., & Garofano, N. (2022). Circular economy in the Australian AEC industry: investigation of barriers and enablers. *Building Research & Information , 51*(1), 56-68.

Siemens. (n.d.). *Building information modelling*. Retrieved March 2023, from Siemens: https://new.siemens.com/nl/nl/products/buildingtechnologies/digitalization/bim.html

Simon, H. (1996). *The Sciences of the Artificial.* London: MIT Press.

Sofistik. (n.d.). *Sofistik software*. Retrieved January 2023, from Sofistik: https://www.sofistik.de/loesungen/software-fuer-brueckenbau

Spring, M., & Araujo, l. (2017). Product biographies in servitization and the circular economy. *Industrial marketing management*, 126-137.

Stankevičius, M. (2018). *LITHUANIAN SOFTWARE DEVELOPMENT SECTOR: Upgrading through increases in innovation and scalability.* Aalborg university. doi:http://dx.doi.org/10.13140/RG.2.2.18178.79041

Stephan, A., & Athanassiadis, A. (2018). Towards a more circular construction sector: estimating and spatialising current andfuture non-structural material replacement flows to maintain urban building stocks. *Resources conservation and recycling, 129*, 248-262.

SWECO. (2022). *Revelop*. Retrieved February 2023, from SWECO: https://www.sweco.nl/actueel/verhalen/revelop-circulair-bouwmateriaal-op-een-plek/

Sykes, J. (2023, January). Reusability scanning. (C. Reit, Interviewer)

T3D. (2022, December). *Totaal Driedimensionaal*. Retrieved january 2023, from VNG: https://vng.nl/projecten/totaal-driedimensionaal

Teeuw, C., & Dijcker, R. (2017). *Duurzaamheidonderzoek hergebruik boogbrug Vianen.* Deventer: Witteveen+Bos.

Timmermans, M., van de Weijer, J., & Thijssen, I. (2021). *Beschikbaarheid en gebruik secundaire bouwmaterialen en producten.* Rijksoverheid.

Transitieteam Circulaire Bouweconomie. (2022). *Adviesroute naar een circulaire economie voor de bouw.* Retrieved November 2022

TU Delft. (2022). Engineering materials recycling cource. TU Delft.

Tyrrell, P. (2022, April). *Construction Asset Management Guide*. Retrieved from Fieldinsight: https://www.fieldinsight.com/blog/construction-asset-management/

Ubels, M. (2017). *Ongemak station Deventer, brug wordt gesloopt*. Retrieved December 2022, from DeStentor: https://www.destentor.nl/deventer/ongemak-station-deventer-brug-wordt-gesloopt~a436d86d/

Ullah, K., Lill, I., & Witt, E. (2019). An Overview of BIM Adoption in the Construction Industry: Benefits and Barriers. *2*(10), 297-303. doi:https://doi-org.tudelft.idm.oclc.org/10.1108/S2516-285320190000002052

UN. (2022). *Global issues: population*. Retrieved 10 2022, from United Nations: https://www.un.org/en/global-issues/population#:~:text=Our%20growing%20population&text=The%20world's%20population%20is%20expected,billion%20in%20the%20mid%2D2080s

University of Copenhagen. (n.d.). *Double diamond model*. Retrieved February 2023, from Innovation English: https://innovationenglish.sites.ku.dk/model/double-diamond-2/

Van den Berg, M. (2019). *Managing Circular Building Projects.* Enschede: University of Twente. doi:10.3990/1.9789036547703

Van Eldrik, M., Vahdatikhaki , F., Oliveira dos Santos, J., Visser, M., & Doree, A. (2020). BIM-based environmental impact assessment for infrastructure design projects. *Automation in construction, 120*.

van Offenbeek-Kuipers, B., Schous,, J., Luijten, C., de Vaal, W., & Valk, R. (2021). *Handreiking hergebruik bruggen.* Den Haag: AmRoR. Retrieved from https://www.nationalebruggenbank.nl/wp-content/uploads/2021/03/20607-RWS-AMROR-handleiding-bruggen-16PS.pdf

Vieiera, M., Pensioen, T., Goedkoop, M., & Huijbrechts, M. (2017). Surplus Ore Potential as a Scarcity Indicator for Resource Extraction. *Journal of industrial ecology, 21*(2), 381-390.

Visser, M. (2022). Outlook on digitization trends at public organisations. (C. Reit, Interviewer) Deventer.

Vree, J. d. (n.d.). *Voegovergang*. Retrieved December 2022, from Joostdevree: https://www.joostdevree.nl/shtmls/voegovergang.shtml

Wierzbicki, M., de Silva, C., & Krug, D. (2011). BIM – HISTORY and TRENDS. *CONVR2011, International Conference on Construction Applications of Virtual Reality.* UBC.

Wikipedia. (n.d.). *Material passport*. Retrieved from https://en.wikipedia.org/wiki/Material_passport

Wind, H. (2022, August). Retrieved March 2023, from GWW totaal: https://www.gwwtotaal.nl/2022/08/11/steeds-meer-bruggen-aangeboden-voor-hergebruik/

Winterstetter, A., Heuss-Assbichler, S., Stegeman, J., Kral, U., Wager, P., Osmani, M., & Rechberger, H. (2021). The role of anthropogenic resource classification in supporting the transition to a circular economy. *Journal of Cleaner Production, 297*. doi:https://doi-org.tudelft.idm.oclc.org/10.1016/j.jclepro.2021.126753

Wolbrink, S. (2023, January). Modelling costs from 2D data. (C. Reit, Interviewer)

Wouter Truffino. (2013). *Veiligheid en levensduur brug niet alleen afhankelijk van geld*. Retrieved January 2023, from Deopenbareruimte: https://deopenbareruimte.nu/veiligheid-en-levensduur-brug-niet-alleen-afhankelijk-van-geld/

Wuni, I. (2022). Mapping the barriers to circular economy adoption in the construction industry: A systematic review, Pareto analysis, and mitigation strategy map. *Building and Environment, 223*.

Yang. (2022). Concrete bridges course. *Concrete bridges*. Delft: TU Delft.

Yang, Z. (2015). *Developing and verifying a bottom-up methodology for bulk material flow analysis in China's urban infrastructure sectors.* Minnesota: University of Minnesota.

Yashavsi. (2022, February). *17 Different Types of Bridges Designs Around the World with Pros. & Cons.* Retrieved November 2022, from stylesatlife: https://stylesatlife.com/articles/types-of-bridge-structures-names-and-pics/

Zandee, D., Creed, A., Zutshi , A., & Nijhof, A. (2022). Aiming for bullseye: a novel gameplan for a circular economy in the construction industry. *Engineering, Construction and mangement*.

Zou, Z., & Ergan, S. (2019). *Leveraging Data Driven Approaches to Quantify the Impact of Construction Projects on Urban Quality of Life.* doi:https://doi.org/10.48550/arXiv.1901.09084

Zuidema, m., Saitua, R., & Smit, N. (2016). *Macro-economische verkenning betonakkoord.* EIB.

Appendix: A CE-transition obstacles & initiatives

1 PESTEL-analysis

1.1 Political

- Predominantly conservative coalitions, limiting the funding allocated to climate change & realising a CE and enforcing ambitious regulatory changes.
- There is still a lack of regulations that force projects to have a minimum secondary material input share or output, nor are there projections for the future. This leaves the ambitions to clients, where it is often the first ambition that falls as it is not regulated.
- Adams et al. (2017) have shown that there is a lack of known standard practices to implement circular economy concepts within the construction industry. These standards need to be implemented and enforced by the government.
- Funding is often allocated to projects that present short-term or certain benefits as this directly reflects back to the decision-maker. This political tendency hampers important innovations and investments that mainly show long-term benefits.
- Due to the decentralized management system in the Netherlands, organisations tend to develop their own transition roadmap, complicating it for the market.
- Human tendency to require results straight away, whereas in the circular economy the impact is mostly at the end of a structures' lifetime. Decision-makers are not in control anymore by then and would rather see profits short term that reflect on them.
- Regulations that are there (e.g., landfill ban), can be bypassed relatively easily.
- Risk-averseness of governments during projects where sustainability/circularity concepts are applied at the start and often suddenly 'left for the next project'. They represent the tax-payer's money and often see innovation despite their initial ambitions.

1.2 Economic

- Lack of funding available from the government to push the sector faster towards a circular economy: allow for higher quality tenders, subsidies, or innovation competitions.
- Lack of funding available at public organisations to facilitate the higher upfront investment costs to achieve circular results on the long term.
- Tendency of contractors to maximize profits, with already very small margins to work with, by finding cheap solutions that are often unsustainable and/or not circular.
- The transition requires companies invest into new technology/research/training, the impacts of COVID and global trends (recession, inflation, supply chain issues) limit this possibility.
- Attractiveness of raw material prices compared to secondary materials.
- Extra time is required to measure and validate environmental impact scores of designs.
- Uncertainty on the remaining value of reusable products, making it a risky endeavour for asset owners to harvest elements due to the extra costs involved for deconstruction for only little materials (Ali, 2019).
- Increased research costs for the integration of reused elements in the design.

1.3 Sociological

- Conservativeness in the construction sector, as traditionally innovation takes more time to be implemented (BIS , 2013) – resistance to change, especially by more senior workers who have spent their lives doing it the traditional way and feel like they lose importance due to this transition of the paradigm.

- Increasing population, middle class growth, and urbanisation trends demand more construction activities, requiring higher production. This is difficult to combine with a transition process where learning is centralised.
- Deeply rooted processes within the supply chain complicate radical changes as everything needs to be rethought, taking time to figure out.
- Lack of general awareness on the required changes for the circular construction economy transition and training in the market.
- Complexity of the supply chain and the short-term goals of most companies, not giving the needed attention for the end-of-life stage (Eberhardt, Birgisdottir, & Birkved, 2019).
- Companies and governments are not always familiar with working in multidisciplinary teams, as required for a circular approach.
- During a transition, companies will wait until technologies have diffused before making the investment, to avoid making unnecessary investments.
- Most of the stakeholders don't understand how CE concepts can be applied in a practical way for the Construction Industry (Adams, Osmani, Thorpe, & Thornback, 2017) (Eberhardt, Birgisdottir, & Birkved, 2019).
- Poor perception of quality of reused elements and insufficient understanding of the risks and benefits of circular materials and products.
- Contractors not being informed about circularity beyond what is described in the specifications results in missed circularity opportunities.

1.4 Technological

- Circularity potential for existing infrastructure is difficult to assess due to the lack of documentation on assets.
- The lack of material quantity information of the existing material stock limits the reliability of transition roadmaps that are based on material flow studies.
- The absence of physical data of elements complicates the design process with reused elements, as there is a lack of known supply. Thereby disincentivizing the exploration of reuse in the design phase.
- Lack of diffusion of reuse databases and measurement tools.
- Limited applications of harvested materials.
- Limited technology and frameworks to design for end-of-life of products.
- There is too much waste for the recycling companies to process. Expansion of existing companies and entry of new companies take time. Large projects have difficulty in offloading their construction waste (Ali, 2019).
- Recycling technologies cannot yet upcycle all the construction waste, therefore making the secondary material input in most infrastructures limited.
- The viability of renewable biobased materials is still at its infancy, making it impossible to have a large impact in phasing out raw materials in the foreseeable future.

1.5 Environmental

- Contrary to other materials, the recycling of construction materials is to be tackled at the local level because they have an economically and environmentally limited transport distance due to their comparatively low value and high mass (Hiete, Stengel, Ludwig, & Schultmann, 2011).
- Limited space on construction sites to separate and temporarily store construction materials, complicating the recycling supply chain.
- Biobased materials are also limited to earths planetary limitations.

- To become circular, first more raw materials need to be in circulation to develop a sustainable secondary materials market. The secondary material output is not enough to meet the construction material demand, even with 100% upcycling of all construction waste outputs (EIB & Metabolic, 2022).

1.6 Legal

- Tender specifications and awarding criteria are still often dominated by the costs aspect, disincentivizing sustainability and circularity influences in the bid.
- Traditional contract types are often unsuited for achieving circularity, new contract types are still in development and tested.
- Projects where reused elements are integrated need to adhere to norms for new structures, limiting the applicability of reused elements. New regulations need to be developed where this is taken into consideration (Kirchherr, et al., 2018).
- Companies do not want to share their sustainability/circularity data to keep a competitive advantage and use it for upcoming projects.
- New models are required for risk management and liability with reused elements (Ali, 2019).

2 CE-initiatives

2.1 Development of standards and information exchange platforms

With any transition, a shift is required for work-practices to generate the desired results. This often leads to industry players each finding their own way in a (still) underregulated environment, this generates a variety of methods applied on projects. As not every practice is as high-quality as another, projects suffer from the results, or parties bypass the rules which creates an uneven playing field. For this reason, standard practices are required to create an even playing field and create a unified approach towards projects. The standardized practices then ensure that industry players (can) have similar awareness and skills to execute projects and allows interoperability between parties. A lack of awareness or knowledge of a party within a project can create friction and resistance on the implementation. Before this is possible, a best practice must emerge. This requires knowledge sharing within the industry and diffusion of concepts. Generally, these exchange platforms are best managed by the government to ensure transparency and avoiding biases. Here, industry players can communicate their innovative methods, research findings, trends, technologies and learn from others, while the government can use this information for the development of standard practices. A centralised environment helps create more awareness and increases the knowledge base of the industry. Below, some concepts that need to be standardized are listed:

- Measuring circularity in designs.
- Lexicon for interpretation of terms.
- Material passport contents.
- Design methods to enable reusability in projects.
- Changing design standards to allow reuse while adhering to safety & functionality requirements.

2.2 Rules & regulations

The only method to enforce standard practices is through regulations. this is however a difficult tool to use in a transitioning environment as it is not always known how, when, and to what extent they need to be implemented considering the circumstances of the industry. Another downside of regulating is that it can hamper innovation, which is not desired. Below, some of the recurring regulations in literature and transition roadmaps are listed:

- Mandatory LCA, ECI & circularity studies on designs, to be used as sustainability and circularity indicators of projects, shared openly after projects.
- Material passports on all structures.
- Integration of circularity & sustainability in tender specifications & awarding criteria.
- Minimum recycled/reused input and/or output in projects.
- Registration of reusable materials on material databases.

2.3 Education & training

A key part in making a transition within an industry concerns the development of a workforce that is prepared to operate in a changed industry. Naturally, part of this workforce comes from academic graduates. By transforming the educational programmes to include CE-principles, the new workforce can be better prepared to create change within the industry by applying these concepts in day-to-day activities. Traditionally, older generations will be conservative in transitioning as their developed knowledge and skillset have proven to work during their careers. Trainings and workshops are required to also convince this part of the workforce towards prioritizing circularity in projects. Standards are essential content for this education & training effort and should be updated as time progresses.

2.4 BIM

One of the key enablers for the CE concerns Building Information Modelling (BIM). BIM is a product of the digitalization transition within the construction industry, where the entire project is centralised around the 3D model of the design. With this 3D model, all object information and communication can directly be attributed to the physical elements, thereby reducing ambiguity, and increasing work efficiency as all project information is documented in a single environment. Moreover, it allows seamless integration of designs from different disciplines for clash detection to minimize reworks. Overall, BIM reduces project costs over the entire project lifecycle, despite its higher upfront investment costs (Bryde, Broquetas, & Volm, 2013). Other benefits are shown in Figure 70. BIM produces a model that can be used in the operational phase and provides most of the information needed to generate material passports and reuse potential assessment and communication of individual elements (Ullah, Lill, & Witt, 2019).

Figure 70: BIM (Siemens, n.d.)

2.5 Material passports

A material passport (MP) is a document consisting of all the materials that are included in a product or construction. It consists of a set of data describing defined characteristics of materials in products, which give them value for recovery, recycling and re-use based on standardized (certification) methods

(Wikipedia, n.d.). Essentially all information relevant for the operational lifetime and EoL should be documented in this MP. Platform CB'23 established that a standardized passport for the construction sector would ensure that the right data was available in the correct manner. This creates awareness of the availability and quality of natural and technical objects for future generations. The primary goals of the use of a passport are ultimately upcycling materials, reducing the use of primary raw materials and the production of waste. It is precisely the ability to preserve and exchange object data in the construction sector that is essential for a circular construction world (Platform CB'23, 2020). According to (Spring & Araujo, 2017), product passports allow for (1) informed decisions about products' next reuse steps; (2) the creation of markets for reused or disassembled products; and (3) the generation of new service offerings around the product. Furthermore, BAMB (2020) poses that MP's create incentives for suppliers to produce healthy, sustainable, and circular materials/building products.

Material passports can be made on different scales (structure, element, product, or material), the element level is most important for reuse realisation while the asset MP is most important for asset management. Another important aspect of a MP is the date of generation, during design and construction, the data can nowadays easily be extracted using BIM, for existing structures this data is often lost or less accurate which impacts the use case of the MP. Figure 71 provides an impression of the type of data that should be stored in a MP. For more concrete items, CB'23 is developing a standardized list that is generated from a longer list of potential items as shown (Platform CB'23, 2020).

Product tracking code: **Product name:** **Manufacturer:** **Building Material Passport (BMP)** Last update: yyyy/mm/dd	**Sections description**
1 General data Product/commercial name; Use recommendation/restrictions Composition/materials; Performance characteristics Manufacturer/supplier; Technical data (strain/weight) Use period/time	Comprises the manufacturer/supplier data, the general description of the material/system, composition, recommendations and restrictions of use, performance requirements and criteria, intended use period.
2 Security measures (dafe data sheets) Security information (warnings/recommendations) Toxicological recommendations; Handling and storage instructions Risk identification/fire protection	Indicates safety information from material receipt to its disposal; warnings regarding the toxicological risks involved; first-aid and fire-fighting measures.
3 Sustainability Environmental declaration; LCA results and interpretacion Life cycle assessment (LCA) LCA boundaries and methodology	Involves LCA and environmental product declarations, the methodology used, the results and interpretation.
4 Use and operation Positioning and location in the building; Assembly instructions Connections details and requirements; Maintenance and cleaning	Indicates the positioning and location of the material in the building; assembly instructions; maintenance and cleaning; connections details and systems requirements.
5 Disassembly guide Disassembly instructions (removal/replacement of pieces) Transportation and storage instructions	Provides instructions for disassembly, removal, replacement of the pieces and components of the meterial/system. In addition, indicates best practices regarding transportation and storage.
6 Reuse potential End-of-life considerations (reuse/recycling/remodeling) Disposal options	Provides information regarding the reuse, refurbishment, recycling potential as well as disposal considerations at the end of life of the material.
7 History Use period; Latest uses/operations Verifications made during use; Updates during operations	Covers tests and verifications carried out during the material or system life, indicating its use period, past uses/operations, as well as its current state.
8 Other information References used/standards consulted Complementary material	Indicates sources, references and standards consulted, as well as details and descriptions of information used in the development of the passport.

Figure 71: Material passport functionalities (Munaro, Fischer, Azevedo, & Tavares, 2019)

2.6 Material databases for reuse

With the increasing use of MP's, a centralised database is required where these can be stored and managed. The existence of a consolidated database of material passports can help the evaluation and optimization of recycling potential and environment impacts (Honic, Kovacic, & Rechberger, 2019), even more so when the BIM models are linked to the MP so the market can be scanned for reusable elements in all the structures within the database. Initially, this centralized database will require a push from the government (e.g., by imposing obligation to create & upload MP's), but once there is a demand developed for the data, an economy with value creation (pull system) will emerge (Platform CB'23, 2020). Moreover, such a database can allow better large-scale studies for improved transition management. In the future, this database will serve as a material market, where one can buy materials/elements from owners of structures where it is known when the structure will be decommissioned. For this model to function, a centralized/decentralized hybrid model where centrally agreed standards and guidelines implemented at decentralized levels is essential for success (Platform CB'23, 2020). A software that is such a database is MADASTER, where MP's can be uploaded. However, to keep a regulated material market, it is essential that it should be controlled by the government. In doing so, the existing infrastructure/buildings become the new sources for materials instead of mines. Besides MADASTER, there are also more specific databases where elements can be offered for reuse purposes, for example (Duspot, 2023) and the (Bruggen bank, 2023) for bridges specifically.

2.7 10-R's framework

Next, a framework of strategies is developed that encapsulates the entire process of a construction project, shown in Figure 72. Starting at the top of the figure, the design phase, the most circularity can be captured by already reducing the need for products or material use before construction even started. The second section concerns strategies for already existing structures/products that try to maximize the remaining value of (half-) products. The remaining strategies concern materials that are not captured in the strategies above. Every project should have this framework centralized and integrated in their workflow, no matter the lifecycle stage of the product. At any time, the highest possible strategy should be explored and applied where possible, to ensure the highest level of circularity.

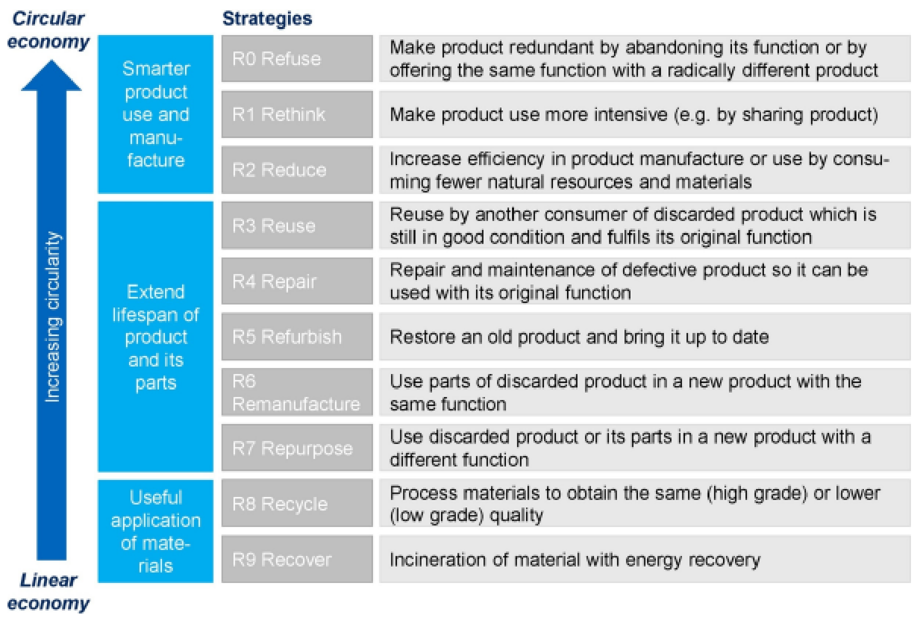


Figure 72: 10-R framework (Kirchherr, et al., 2018)

2.8 'Design for' – strategies and prefabrication

As already introduced in the previous initiative, changes should also be made to the front-end of the project, the design phase. Here, decisions can have the highest impact with respect to circularity. One strategy concerns 'Designing for Deconstruction/Disassembly' (DfD), where the design is developed with the idea that it should be deconstructed efficiently at the EoL. By considering deconstruction of the asset during the design phase, the designer can implement techniques to obtain higher material and/or element recovery rates. This could be by adding smart connections or modularization of the structure, as is incentivized with the Industrial, Flexible, and Demountable (IFD) framework for civil infrastructures. However, literature shows many more Design for X methods that can be considered. The benefits of including practices such as design for disassembly in the LCA, as it can reduce the value of embodied carbon and energy in buildings (Eberhardt, Birgisdottir, & Birkved, 2019) (Krause & Haffner, 2019). Besides designing for disassembly, practices such as designing for adaptability and change can increase the functional lifetime of the structure by already thinking about potential use-cases and implementing this in the design. This keeps materials/structures longer in their cycle and decreases the frequency of deconstructing, recycling, constructing and transportation, thereby saving resources and emissions.

Another trend that is increasingly being implemented in practice is prefabrication of construction elements. Instead of casting in-situ concrete on the construction site, complete elements are already casted off site and transported to the site when it is required. Modularization is a highly effective method that requires less energy, time, and space on site as elements fit like LEGO blocks due to the front-end engineering of the design, while not compromising the structural integrity.

2.9 New contracts & business models

A transformed industry also leads to the disruption of new business models to fit the changed environment, goals, boundary conditions, and regulations. Below a list is provided with some of the biggest changes with regard to business models in the construction industry.

- Contracts & collaboration.
    - Tenders involving circularity requirements and (a share of) award criteria are attributed to circularity and sustainability.
    - Total Cost of Ownership (TCO) models that shift the responsibility of the maintenance and potentially even EoL responsibility towards the contractor. Incentivizing them to think about these aspects in the design phase where it can be impacted and optimized.
        - Design-Build-Finance-Maintain (DBFM).
        - Infra-as-a-service.
    - Multidisciplinary project teams and Bouwteams to increase knowledge in the design phase on the rest of the lifecycles of the structure.
    - Partnerships between local governments and companies to realise local circular economies.
- Subsidies for the transitional period to push the market.
    - Small Business Innovation Research (SBIR), an innovation competition hosted by the government where companies’ costs are (partly) covered.
    - Pilots where a new technology/business model is being tested which has potential to become beneficial for the CE transition. Pilots are necessary to develop regulations in this new environment (Transitieteam Circulaire Bouweconomie, 2022).
- New services and technology arising from the CE.
    - Certification/measuring services for LCA & circularity assessments.
    - Recycling technologies – expansion of recycling industry and scaling up of technology.
    - EoL experts – more efficient demolition & deconstruction.
    - Material depots for storing & maintaining harvested elements.
    - Selling reusable elements.

2.10 Research & development

The last initiative is closely linked with all the previously mentioned initiatives. Research and Development (R&D) is necessary to make all the initiatives and concepts work in practice. Although R&D is very broad, the two main pillars with regards to the CE-transition are the recycling industry and renewable materials research. Academia play an important role here as this is government funded and non-profit oriented, allowing it to invest money into research. Secondly, companies play a role here as collectively there is a lot of capital to invest and a larger workforce to consult. Moreover, there is a need for them to develop themselves in order to maintain business. However, they are profit oriented and therefore more cautious in spending money with the uncertainty of success and future benefits of the investment. Pioneering/championing of these companies is essential in accelerating the circular economy transition, potentially even subsidized by the government.

As recycling is at the core of the circular construction economy, R&D should aim to further increase the recovery rates and waste separation practices on demolition sites, improve the efficiency of the recycling processes to minimize loss of materials in the chain, and improving technologies to upcycle materials. For some materials, recycling methods need to be developed from scratch. Research on biobased renewable materials is essential to make up for this (sometimes inevitable) loss in materials that occur in the recycling process, as well as replacing raw materials sooner rather than later. Of course, other R&D should also be explored, however this is outside of the scope of this research.

Appendix: B Material flow study: Dutch construction sector

To meet the future demand solely with secondary material input, the anthropogenic material stock needs to be large enough to supply such amounts of materials from decommissioned structures. A national material flow study predicts that there will be theoretical material deficiencies of 35%, 27% and 13%, in 2019, 2030 and 2050 respectively for the GWW-sector; assuming business as usual construction activities and 100% high grade recycling and reuse of construction materials (EIB & Metabolic, 2022). For the Building & Utility (B&U) sector the theoretical deficiencies are even larger: 78%, 75%, and 67% in 2019, 2030, and 2050 respectively. In 2019, the primary/secondary material input ratio of the GWW sector was 46%-54%; from this secondary material input, 88% concerns recycled granulates, 11% recycled concrete and industrial substances, and 0.6% is reused bricks. As recycling- and asphalt granulates are used in road/pavement construction, it means that the GWW-sector excluding road/pavement infrastructure had an 89%-11% primary to secondary material input share ratio in 2019, similar to the B&U sector. Moreover, in 2019, 79% of outgoing materials from decommissioned structures was recycled, 20% reused, and the remainder landfilled, left, or incinerated. As for the main component of civil artworks, concrete, most of the recycling results in granulates that go to road infrastructure or site elevation (97%), which is downcycling and not considered sustainable circularity, while only 3% ends up in new concrete (Zuidema, Saitua, & Smit, 2016). Figure 73 displays the ingoing and outgoing materials divided by asset type in the GWW-sector in 2019, Figure 74 shows the material origins of the ingoing material and material processing destination after EoL, also in 2019. This study indicates that the current built environment is not large enough to support a construction industry with consistent productivity levels. Even with 100% high value recycling and reuse of all outgoing materials, the material future demand cannot be met. Currently, although almost all outgoing materials are recycled or reused, only 10% of ingoing materials in civil structures (excluding roads & pavements) are secondary materials. This gap is to be filled by either primary or biobased materials, where biobased is expected to play a minor role due to ongoing R&D.

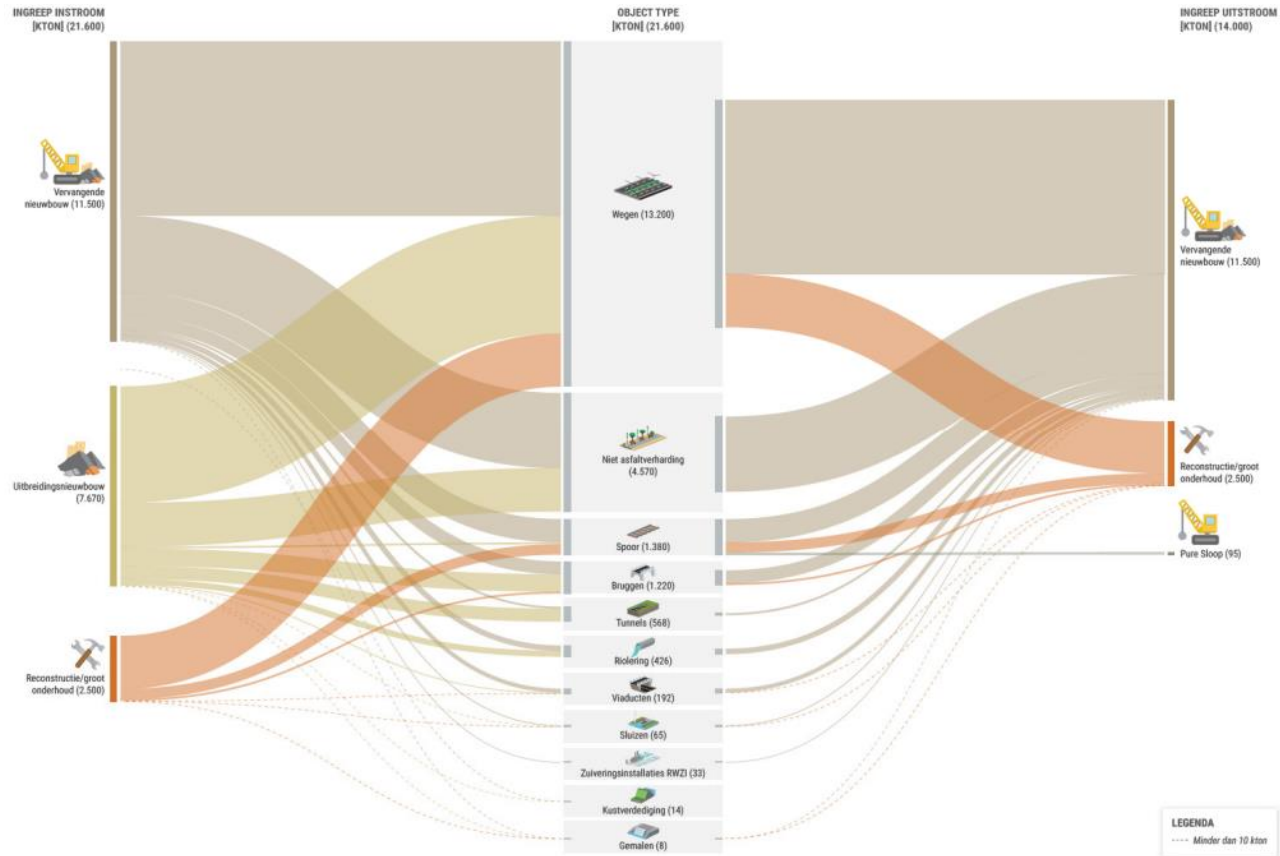


Figure 73: Construction activity material distribution per asset type

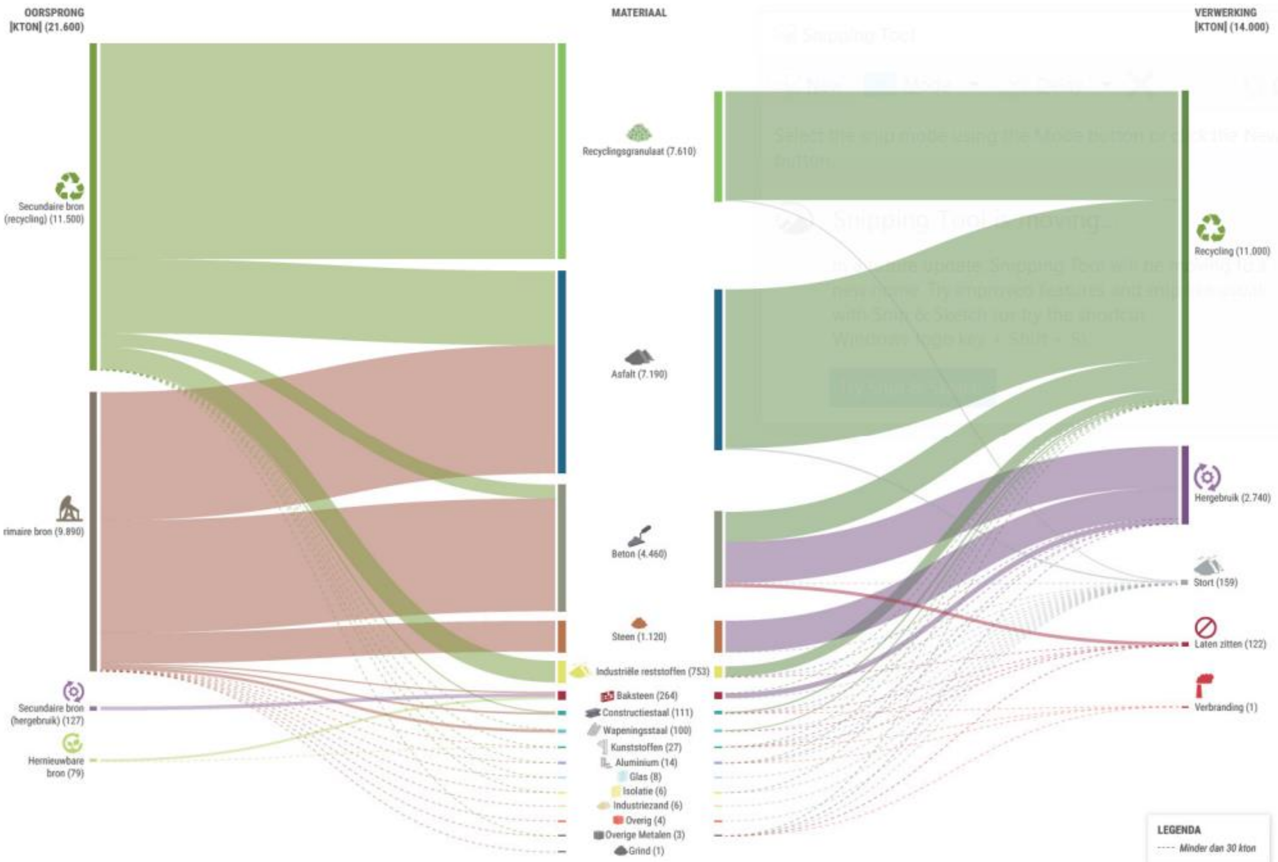


Figure 74: Material inflow and outflow

Appendix: C Reuse barriers in practice: an analysis

Lack of knowledge & incentives in practice

1. It is not yet a standardized part of the design methodology to consult material databases like Bruggenbank, DUSPOT, or MADASTER for finding and integrating reusable elements in the design (Wolbrink, 2023). The search for reusable elements quickly stops when the 'perfect' materials cannot be found; adjusting, reinforcing/enhancing, and/or maintaining the existing elements is not part of the solution space yet.
2. The iterative process in item 1 is more time consuming and costly compared to traditional design practices (Kanters, 2022). Due to the high upfront costs and generally tight budget, there is a lack of awareness on the potential benefits of realising reuse (Huuhka & Hakanen, 2015).
3. Even with structural data of elements, using second-hand elements is still perceived as risky, unsafe, and increases liability for contractors, steering them away from reuse (Huuhka & Hakanen, 2015).
4. Construction standards limit the use of reused materials due to the requirement of 100y design lifetime, which cannot be reached with reused elements, or requires significant over dimensioning of elements (Huuhka & Hakanen, 2015).
5. Existing structures were not constructed with deconstruction in mind (Huuhka & Hakanen, 2015), disincentivizing the reuse case as it complicates the harvesting process due to the increased probability of damages.
6. Transportation of large elements is not possible everywhere, requiring extensive studies and permits (Timmermans, van de Weijer, & Thijssen, 2021).
7. There are currently not enough storage depots for storing reusable construction elements to increase the probability of adoption in new projects (Timmermans, van de Weijer, & Thijssen, 2021).
8. Financial attractiveness of demolition and recycling over deconstruction and reuse (Huuhka & Hakanen, 2015). Moreover, deconstruction processes require longer due to the carefulness involved for demounting/splitting objects (Greencirculedemolition, 2021) (Copper8, 2022).
9. It is not yet standard practice to include circularity awarding criteria in the tender specifications or assigning them significant weight to outweigh the cost-criteria, thereby disincentivizing circular bids (Bakker, 2023).

Lack of data

1. Reuse databases currently do not have sufficient information on the reusable objects to effectively design with/around the elements. Information is often limited to a picture and basic (uncertain) data, that results in large uncertainty and risks (Bruggen bank, 2023). There is need for higher quality product information for current & future reusable elements (i.e.: geometry data on individual reusable elements, accompanied by attribute data) (Copper8, 2022).
2. There is a lack of data on the actual structural state of assets due to the increased traffic intensity and loading over time, compared to what the assets were designed for (Florida department of transportation, 2000). Consequently, either conservative assumptions must be made on the remaining lifetime & strength or recalculations initiated. This information is essential for managing the replacement & renovation activities timeline of the acreage. Moreover, this information is required for the contractor to manage the scheduling of the new project (with reused elements) (Huuhka & Hakanen, 2015).

3. There is often no maintenance record that dates back to the construction year (Lunenborg, 2022). Maintenance activities influence the degradation models and are essential in structural recalculations, both important methods for assessing the remaining lifetime of the asset.
4. Condition data is often documented in reports and its findings not actively monitored (Oxand, 2022). Condition data impacts the reusability of the element and whether repair is required.
5. There is uncertainty on the exact time-of-availability of elements, increasing risk for project developers. This data only becomes available closer to project execution (Copper8, 2022).

Unbalanced supply and demand

There is currently an unbalanced market for reused elements (Huuhka & Hakanen, 2015). The supply is highly unpredictable due to the dependency on data quality from the owners, whereas the demand is very low as it is not an integrated aspect of the design phase yet in addition to low data quality of the supply side making it unattractive due to the risk involved. Currently, the largest issue is the lack of supply of reusable elements (Wind, 2022). One of the reasons for this being that organisations tend to limit themselves to intraorganizational reuse via internal databases, limiting the applicability of the elements in a wider environment, and thereby supply (Copper8, 2022). As the supply and demand are not balanced, the economic side of reuse is not representable for what it could be, over-supply makes the elements very cheap and thus not attractive for the asset owner to put time and money into gathering the data, compared to demolition. Conversely, if demand is too high, the prices of reused elements skyrocket which makes reuse an unattractive solution considering the life-cycle-cost of the alternative. An efficient market prices the elements based on material availability, raw material prices and other market effects such as regulations/incentives. Currently, prices are very unpredictable due to a lack of pricing methods that reflect the market fairly.

Lack of applications

At the time of writing, most of the elements in bridge infrastructure can only be reused with the same function (high value reuse). When such an element is not demanded in the short period between the decommissioning announcement and deconstruction/demolition date, it needs to be either stored or demolished and recycled. When it has multiple applications, the scope for the demand is increased and the probability of reuse becomes larger. Currently, besides girders there are not many elements that provide this lower value reuse opportunity, thereby constraining the reuse economy (Huuhka & Hakanen, 2015). More research is required to analyse the lower value reuse application potential of more elements.

Appendix: D Nuances for CE transition steps in AM

Notes step 1:
A change is required for asset managers to adjust their perspective from short-term asset management to long-term. Currently, the activities mainly include routine inspections and maintenance activities as a result, the EoL is hardly taken into account or is starting to be included now with the R&R-task (Lunenborg, 2022). The proposed steps require significant effort that does not fit in the traditional budget for bridges. Traditionally, the asset data is only gathered when a recalculation is required, in which case the EoL is often near. Moreover, waiting until last-minute will result in unsurmountable costs peak in 10-15 years due to the construction boom and structures reaching a certain lifetime. The AM benefits will be limited when the data is gathered shortly before EoL. To make this investment worthwhile, the data gathering process should be brought forward. RWS is currently conducting efforts with tunnel infrastructure, where 'digital twins' are reconstructed from gathered asset data, despite not needing replacement for years to come. This study shows a predicted shortage of contractor availability to execute these activities on time, because of this, opportunities for improved portfolio management with respect to managing renovation and replacement activities can take place (in combination with data from step 2).

Notes step 2:
The output of this step should be a list of all the reusable elements within the acreage with their properties, estimated time-of-availability, and the remaining strength/lifetime, documented in a reuse database. With the centralized information on assets and elements with respect to their reusability and EoL, a higher remaining asset value can be realised by selling reusable elements. Moreover, the supply of reusable elements is increased due to the improvement of supply and communication to the market via the intermediary databases, which increases the attractiveness for adopting reuse methodologies in the design phase.

Notes step 3:
IFD and reuse are contradictory in nature as reused elements do not conform to the IFD standards due to their uniqueness and require to be 'designed around' instead of conforming to a standard. Both practices (reuse and IFD) are necessary to reach the circularity goals, where reuse is aimed at short-term circularity and IFD ensures future reusability. Incorporating reuse in the design also asks for a change in approach with respect to risk allocation and management due to uncertainties that come with using reused elements such as potential damages, reduced lifetime, element availability and material degradation. These risks cannot all be carried by the contracting party. Clear agreements need to be made on who carries what risks and who benefits from certain opportunities as this dynamic significantly changes when reused elements are involved. However, this goes beyond the scope of this research and is highly project specific.

Notes step 4:
There is a disparity between the interests of asset owner and project manager, as the asset owner's main concern is the minimization of unavailability of assets, while the project manager of the contracting side has to allocate equipment and manpower towards a certain timeframe. The asset owner will delay the deconstruction if the project construction is not ready, while this can be detrimental for the planning on the contractors side. contractual agreements can overcome this issue. Moreover, high data quality can reduce unexpected delays or damages in the deconstruction process through improved preparation.

Appendix: E Summary of the literature study

The literature study provides a knowledge base for the development phase as well as road map development in the recommendation in Chapter 6. The literature study started with the introduction of the CE in the context of the construction industry, fuelled by climate change that calls for a reduction in emissions and resource consumption. The industry needs to undergo a paradigm shift from a linear 'take-make-dispose' model towards a CE-model, in which reusing- and recycling materials are key. The traditionally conservative construction industry faces many transition barriers, that are to be overcome with initiatives set out in transition roadmaps. These roadmaps predominantly focus on realising a future built environment that allows a sustainable CE, while paying less attention to initiatives on leveraging short-term circularity using the existing built environment.

Looking at this existing built environment, there is large uncertainty on the material quantities and flow of materials over time. Considering the relationship between primary-, secondary-, and biobased materials in making up the material pool for construction activities, this information is invaluable. Currently, CE-transition roadmaps are based on material flow studies with highly uncertain data, especially in civil works, impacting its reliability. There is a lack of cost-efficient bottom-up material quantity modelling methods to create more reliable material flows on both local and global scales to better navigate the CE-transition. However, interventions like reducing the material demand, improving recycling & reuse technologies, and setting up international partnerships are required to help make the CE sustainable long-term.

The bridge R&R-task presents a great challenge from both AM and CE-transition perspectives, as it requires large investments and (capital) resources in a short period of time. Due to changes in functional requirements of bridges over time, opportunities present themselves for reusing bridge elements with remaining technical performance at time of decommissioning. However, due to the lack of high-quality asset data this opportunity is often not identified (timely). Based on a high-level analysis of bridge characteristics, concrete municipal vehicle bridges with beam- or slab structures were found to have the largest potential for realising reuse. The key barriers for realising reuse are identified as lack of knowledge and incentives on realising reuse in practice, lack of data, supply and demand imbalance and a lack of applications of reusable elements. Overcoming these barriers requires action from asset managers to inventory their acreage in terms of materials, geometry, and state, centrally documented such that it can be used for reusability assessments. Consequently, this information should be used in reuse databases and integrated in design practices to alleviate the financial and environmental impacts of the R&R-task.

The literature study proceeded with an analysis of the cause for this lack of asset data of existing infrastructure when the need is evident. The main contributors to this problem are the absence of technology at time of construction, loss of tacit knowledge through asset manager replacements over time, lack of client demand and need for information until now. In the unavoidable digitization transition, the first task for asset managers is to realise a complete 2D centralised AM system. In the future, a transition to 3D centralised AM to leverage BIM data is evident, requiring an upgrade of existing asset data to semi-accurate digital twins. The earlier such efforts are realised, the longer benefits for AM and the CE-transition can recoup the upfront investment. To conclude, the state-of-the-art literature was consulted to put the findings in perspective. This confirmed the urgent need for cost-efficient methods to obtain more complete-, higher quality, and geometric asset data of the existing built environment to accommodate the CE and digitization transitions.

Appendix: F Interview results

Interview topic \ Interviewee	Mun. Deventer	Mun. Almere	Prov. Overijssel	W+B experts	Conclusion
Current level of asset data quality & documentation	Observe environment for basic asset information (location, construction year, surface area, type, inspection report). Long-term maintenance contract for assets. GIS for locations, SharePoint for documents (unknown strategy). It is uncertain whether 2D drawings are retrievable for all assets.	GBI platform as 2D asset management system for internal operations like inspection reporting, maintenance operations, basic asset data, decompositions, linked to the individual asset. Currently working on digitizing 2D drawings and linking to GBI. Soil measurements are executed and visualised in a separate platform. IAsset for external communication.	IAsset environment for basic asset information (location, type, photo, constructon year, traffic class & inspection reports). Excel sheet for OTL including attributes, condition & maintenance management registration. Made interactive with PowerBI. It is uncertain whtehr 2D drawings are retrievable for all assets.	Constant referral process for trying to obtain drawings from organisations, no one knows where they are and if someone does it is an unorganised directory of drawings that takes time to organise. Generally inconsistent and incomplete data systems that take time to trace & communicate data.	In general, asset owners do not have a complete, centralised database for asset data. Platforms in use are 2D based, and currently still lack 2D drawings and specifications of existing assets, as these are not consistently documented over time.
Inspection & maintenance documentation	Only reports based on NEN standards, aiming to change to CUR117 to obtain element specific condition data that can be used for maintenance. An overview of maintenance activities is lacking.	Currently in reports that are analyzed after handover and resulting in maintenance activities. Not element specific. Information traceability is more difficult.	Standard reporting + object specific documentation in prescribed Excel format by Province.	Mainly NEN standard reporting, shifting to CUR117 for improved element specific information.	Inspection data is generally still documented in reports without any direct links to the individual elements. A transition is taking place from NEN to CUR standards to improve the condition documentation.
Current efforts to improve data quality & documentation	Aiming to centralize the basic asset data, maintenance activities and inspection findings in a manageable environment.	Digitizing drawings and working on completing a single centralized asset management environment. There is already a lot of data.	None, waiting on actual software functionality to replace Excel functionalities.	Slow realisation at public organisations that a change is required in their asset management quality.	The larger organisations are observed to be making the transition to complete their asset data documentation by centralising basic asset data around the 2D platform to optimize maintenance and inspection operations. This effort is just starting at smaller organisations and will require a lot of effort.
Representativeness of organisation	Very representative for small-medium sized municipalities (the majority of municipalities).	The organisation is on the larger side of the spectrum, there is more capacity/budget available per discipline which allows better management. The impact of poor management is more costly compared to small organisations which is a driver.	Not representative for other provinces w.r.t. documentation standards. Completely renovated the documentation strategy in recent years.	Observed correlation between documentation quality/completeness and increasing size of organisations. RWS and large municipalities have a lot of data that is relativel organised, small municipalities often don't.	The organisations represent the differences well, classifications can be made for small municipal organisations, larger municipal organisations and provinces. A general relation is found between size and data quality.
Cause for lack of complete data centralization	Change of management systems, lost knowledge due to changes in personnel and no standardized documentation strategy. Civil artworks were traditionally not paid much attention due to their low number and little maintenance requirements.	High costs and lack of urgency to focus on concrete bridges as priority was on other assets.	There is no suitable software that allows similar functionality, and the drawings & specifications were not documented with a consistent strategy, and hence lost.	Drawings were generally not used over the first half of the asset lifetime and therefore disregarded. The increase in traffic intensity and weight and CE-transition made the drawings important again. With time the knolwedge of where they are documented was replaced by new personnel.	The need for 2D data for asset management operations was low until recent times, due to increased traffic requirements and CE-transition there is a sudden need for them. Changes of management systems and personnel resulted in a loss of data, or uncertainty on their whereabouts, requiring a lot of effort to be retrieved. Bridges generally required little effort.
Circular economy efforts in organisation	Awareness is there, however this is far from practice. Timber bridge planks are occasionally reused. More information is required on the assets and processes need to be introduced. Currently, it does not look like a cost-efficient business case. There is a push for a reuse database.	Currently the demolition contractors are responsible for the disposal of materials or elements, this is out of the municipalities control. The municipality wants the conrol back to incentivize element harvesting and setting up material depots to realise more reuse. Current reuse concerns timber elements from bridges.	Reluctance w.r.t. the probability of finding a suitable second life location, reuse communication would improve by introducing a 3D visualisation.	There is ambition to work and design sustainably and circularly, often there is constraint from the client and costs remain dominant. Additionally, due to its newness the business case for integrating circular elements is often uncertain, requiring higher quality data on the supply side and reference projects.	Current efforts for a CE are limited to low value reuse of timber and occasional pilots. Ambitions are there to realise more, but the risks, uncertainty on the business case, and lack of data to link supply and demand make it difficult to realise on the short term. It is not part of the standard methodology at EoL.
Ambitions for upgrading to 3D asset management	Awareness on the R&R-task ahead increased, need for 3D visualisations especially for concrete vehicle bridges. Currently the focus is on achieving a complete 2D asset management system. There have been pilots for scanning the 'buitenruimte' in pointclouds. For civil structures, there is no budget.	There is ambition for the future, as digital twins are perceived as the future of asset management, however there is currently not a sensible business case due to the high upfront costs. The most interesting asset type would be concrete vehicle bridges.	Short term: small, no added benefit for managing the assets, as reuse is predicted to play a small part. Long term: digital twins of new infrastructure and visualisations of functionally replaced assets. There is also a lack in supporting software to manage this in, resulting in less incentive.	From the consultancy perspective there is a huge demand for the visualisation of existing infrastructure. For every renovation, the first task is to upgrade data to 3D. Secondly, designing with the 3D environment as reference improves the design quality and process. Thirdly, there is an urgent need for quality data on reusable elements that can be used in new projects, this is currently almost impossible.	The ambition to go to 3D asset management is widely shared and the benefits are clear, however the costs to do so make it an ambition for the future. There is uncertainty on how to manage this. The focus is on the first step: centralising the asset data in a 2D system. Digital twins are mainly pilots for new constructions. The most interesting asset would be concrete vehicle bridges due to their reusability value.
Implementation of tool in organisation	Tendered out. First a data mining process is required, most likely by using inspections to measure elements instead of gathering drawings. Currently there is no such capacity.	Tendering out the upgrade task for a large number of assets at once based on the organised 2D drawings. This is an effort for the future.	Currently, not in demand. Potential for future use by hiring engineering firm to execute this.	Tool would be deployed in projects where a 3D is required from 2D drawings to reduce manual modelling time.	In case of smaller organisations where 2D drawings and specifications are less probable, site measures will need to be performed. Across all organisations, the modelling effort would be outsourced to engineering consultants.

Figure 75: Interview Matri

Appendix: G Indirect costs and benefits 3D centralised AM

Indirect costs (not included in CBA):

1. Maintaining asset data throughout lifetime could require more time compared to current efforts. However, once a 2D system is realised, there will be similar efforts required, perhaps even more due to the inefficiency of some practices.
2. Research costs for exploring reuse in projects, these costs reflected in the bid process and are fuelled by an increase in supply of reusable elements in third-party databases/markets due to the 3D representations.
3. Extra time and costs for deconstruction w.r.t. demolition due to additional preparation, increasing steps to demount elements, carefulness of the operation to preserve the quality of the elements, and potential additional equipment usage.
    i. Insufficiently tested and measured in practice and highly differential per design. For bridges, the extra time could be somewhere between 25-50% on average as the structures are generally well understood and have limited elements and connections. However, this remains an assumption based on conversations with W+B colleagues.

Indirect benefits (not included in CBA)

1. Avoided costs for offloading construction waste, including crushing/separating transportation, and processing through the increased realisation of reuse.
2. Lower emissions through the increased realisation of reuse (in case of intra-organisational reuse), thereby contributing to the CE-goals (and potentially avoiding penalties for over-emitting in the future).
3. Decreased effort (costs) for project designers to try and integrate reuse in the design and the design as a whole within the surrounding environment, this cost reduction comes back to the asset manager in bid prices.
4. By postponing the recycling need of CDW through implementing reuse, the recycling industry can develop its recycling technology efficiencies in the meantime. When replacement comes around, the technology has advanced and higher-grade material can be obtained from the recovered CDW, thereby increasing its value compared to lower grade recycling.
5. Based on the individual material quantity data that can be synchronised with local/global data systems, the material flow models are improved. This can be beneficial for creating local circular economies and improving the Transition agenda goals.
6. With the more accurate material quantities and spatial insights, a better overview of the feasibility of the CE-goals per municipality can be obtained and a fairer penalty system can be implemented, as no municipality is the same and bound by certain historical constraints.
7. The Netherlands can become a pioneer in the circular economy and asset management, creating knowledge that can be exported to other countries that will face similar challenges in the future. Assuming the average cost saving through circular strategies is 5% - 15%, with every 1% of the road sector adopting the recommended strategy, the potential market we are dealing with is worth $15- 53 billion from 2016 to 2040 (Cao, 2022).
8. Increased reuse can lead to a more strengthened earnings capacity of the Netherlands as the dependency on raw materials decreases (Brouwer, 2022).

Appendix: H High-level bridge reuse analysis

1. Bridge types

Firstly, and most obviously, the type of bridge structure plays a role in determining the general reusability potential of bridges. Figure 76 displays the different types of known basic bridge structures. All bridges can be redirected to the design principles from these bridges. Due to the lack of studies on which structure types and elements are most suitable for reuse, a high-level analysis was conducted using Table 8. This framework has been inspired by (Brouwer, 2022) and was further improved for this study. No datasets were found on the distribution of bridge types in the context of the Netherlands. Based on expert knowledge at W+B, it was determined that beam- and slab bridges are most frequent, followed by arch bridges (especially found in the inner cities and foot- and cycling bridges). In this analysis, a division is made into two sections of bridge types based on their potential for reuse in practice. This does not exclude any bridge type from being reused, as it is a generalisation based on the characteristics. The results are displayed in Figure 78, where the bridges are ranked on their reusability and applicability and practice. This assessment is used to determine their potential impact on the CE-transition.

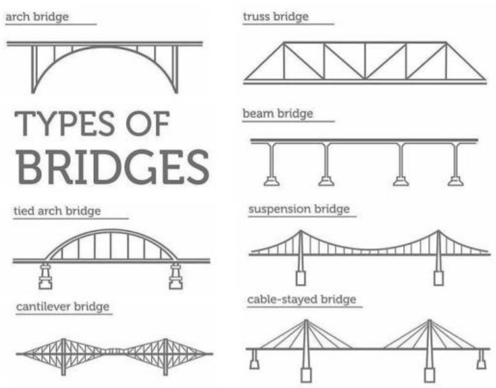


Figure 76: Structure types bridges (Yashavsi, 2022)

Figure 77: Arch bridge brick

Not practiceable for reuse: suspension, cable-stayed, cantilever, truss & brickwork arch bridges.
First and foremost, it can be concluded that suspension, cable-stayed, and cantilever bridge types are generally used for larger bridge spans and are highly specific for a certain location. Finding a suitable second life for these bridges is very difficult as large spans are not common, nor can the structures easily be deconstructed and transported. Truss bridges as shown in the top right are not that common in the Netherlands and are mainly used for larger, more rigid structures. Deconstructing these can be done if they are steel and have bolted connections. However, often they require laser-cutting, making reassembly more difficult. Lastly, traditional brickwork arch bridges (Figure 77), often found in city centres, are very difficult to reuse as they cannot effectively be deconstructed without the structure collapsing. This, and the dated construction method of these structures, makes reuse very difficult. loose bricks (if they can be recovered with sufficient quality) have potential for low-value reuse.

Potential for reuse: (tied) arch bridge & beam/slab bridges.
Arch bridge structures as shown in the top left of the figure do have reuse potential. These types of bridges mostly occur as foot- & cycling bridges with small spans and a smaller curve. Foot- and cycle bridges are only reusable in similar function on new locations when the remaining technical lifetime makes a sensible business case. The probability of this happening is unknown, but in general it can be assumed that technical replacement is more common than functional for financial reasons. In case of larger arch bridges of this type, transportation becomes more difficult as the bridge has limited base points which makes it fragile. Moreover, the arch and truss system connecting the arch to the deck are highly specific to the ground. For these reasons, it is assumed that only smaller arch bridges can be reused. Secondly, tied arch bridges. These bridge types are frequently transported by wated due to

their stability. Tied arch bridges tend to be used for larger spans, making them less likely to find a second life location. Most tied arch bridges are constructed with steel, making it more deconstructable with plasma cutting methods.

Lastly, the most promising bridge type for reuse: the beam/slab bridge. This bridge type can be constructed either with beams such as T-girders, inversed T-girders, box girders, infilled girders, and pre-flex girders, or by casting a concrete slab. Girders are often prefabricated and assembled on site, making them suitable for deconstruction (after removing the concrete compressive layer) (Brouwer, 2022). In case of concrete slabs, it is important to analyse how it is connected to the abutments and piers. When the entire structure is casted on site, detaching the elements might prove impossible without damaging the elements. In general, structures with 'dry' connections (i.e., via bearing systems) can be deconstructed and transported.

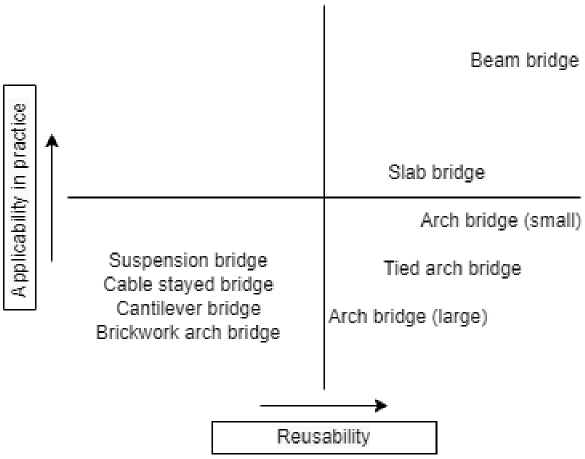


Figure 78: Reusability matrix for bridge structure types

2. Material type

Another aspect of bridge reuse concerns the construction material. The general options include (reinforced) concrete, steel, composite, timber, or brickwork. Composite being a combination of materials, generally steel and concrete in bridges. Table 7 displays an overview of some basic advantages and disadvantages of the different materials. From this overview, it can be concluded that concrete and steel bridges (and thereby also composite) are best suited for reuse. Considering the large share of concrete structures in the Netherlands (especially for spans <50m (Romeijn, n.d.) and the potential of emission-free steel production with hydrogen and renewable energy (in 10-15 years), concrete reuse will have the largest potential impact and should therefore be explored most promptly.

Table 7: Construction material reusability analysis

Material	Advantages	Disadvantages
Concrete	- Most bridges are concrete (>80%) - Largest overall value - Dry connections* - Prefab elements - Substructure reuse on same location*** - Low & high value reuse potential	- Wet connections** - Brittle - Not splitable (when reinforced) - Heavy for transport
Steel	- Very durable - Splitable (laser cutting) - Demountable (bolted connection) - Low value reuse potential (e.g., stiffeners/beams)	- Emission-free upcycling potential (high efficiency) in near future with hydrogen & renewables (TU Delft, 2022) (Bhaskar, Abhishek, Assadi, & Somehesaraei, 2022)

		- Adjustable
Composite	- Dry connections*	- Varying degradation profiles
Timber	- Low value reuse potential of planks and beams	- Short lifetime - Mainly used in foot/cycle bridges - Potential as fuel
Brick	-	- Not deconstructable, collapsing - Old structures, low quality bricks - Not used in new structures

*Dry connection: e.g., deck on bearing
**Wet connection: cast-in situ concrete merging as one element
*** Degrades less from increased loading compared to deck/girders due to the compressive quality of concrete & hardening over time

3. Loading profile

A distinction can be made regarding the type of road the bridge is located, as this already determines some key structural characteristics of the bridge. For simplicity, distinction is made between municipal, provincial, and national roadways. Each being designed to withstand specific traffic volumes and vehicle weights for a set design lifetime. National roads need to withstand the largest forces due to the large traffic intensities and freight transportation and are generally the strongest, followed by provincial and municipal roads. The increase in freight transport and their gross weight, axle weight and axle configuration over time accelerates the deterioration of the bridge due to fatigue damage and therefore reduces its service lifetime (Florida department of transportation, 2000). As freight transport is most intense on national roadways, technical replacements are more common for bridges located on them due to this phenomenon, followed by provincial and municipal roads. Technical replacements do not allow for reuse as the elements are not structurally reliable anymore, even for lower load cases. However, it could be that substructure elements are still structurally safe will the superstructure is not. Foot- & cycling bridges are excluded from this discussion as the loading profile has typically not increased.

4. Degree of volatility of the acreage

A second distinction is made in the degree of volatility of the acreage, meaning: how often are changes happening that require functional replacement or expansion of the asset. In general, the municipal acreages are the most dynamic due to changing land-use plans, visions of local environments, newly built neighbourhoods, etc. However, the RWS acreage has also had to deal with many bridge expansions (or replacements) due to increased traffic intensities. This volatility leads to more (unexpected) changes on the functionality requirements of bridges. An example of this phenomenon is a bridge in Deventer near the train station, which has been replaced, modified, and replaced again within a span of 10 years (Ubels, 2017). Practices like these are not desired and are inefficient use of resources, however, they do provide starting points for reuse realisation as there is much technical performance left in the bridge elements. Based on this characteristic, the municipal acreage is of highest interest for exploring reuse, however, other acreages should not be excluded.

5. Reuse value of elements

The reuse value score of an element is affected by three indicators: Structural, Economic and Environmental. The exact value differs per category. The structural value depends on the extent of over dimensioning of the element in the context of its new function, the economic value depends on cost differences with other alternatives, and the environmental value depends on the environmental emissions compared to other alternatives (Brouwer, 2022). Low-value reuse concerns reuse of an element that is in a different function than what it was designed for, whereas high value reuse is using the element in a similar purpose. An example is when a girder is reused as a girder, however, it becomes lower value reuse when it is far too over-dimensioned in its new function. Brouwer (2022) has conducted a study on reuse potential of RWS bridge girders, including low-value reuse applications, as discussed in Appendix: A. Other low-value reuse examples include the reuse of planks from footbridges for the construction of docks. Low-value reuse applications for bridge elements currently an underdeveloped field that reaches beyond the scope of this study.

To ensure the highest reuse value, RWS, provincial and municipal (vehicle) bridges have the highest potential as they can be reused in a similar purpose with lower loading profiles. However, RWS bridge elements have a limited pool of provincial bridges (2882) to reuse their elements in, which limits the high value reuse potential and quickly becomes lower value reuse due to over-dimensioning. Provincial bridges have the highest likeliness to find a high-value second life but are only limited in supply. Due to the versatility among municipal bridges in loading and the large number of bridges, municipal bridges can play the largest role from the reuse value perspective. Moreover, lower-value reuse applications have the least risk to be over-dimensioned.

Appendix: I Reuse of concrete bridges analysis

Before assessing the various bridge elements on reuse, the various circular indicators should be discussed. Brouwer (2022) has gathered multiple sources for terms that represent the characteristics of reusability, this served as inspiration for the terminology in this research, see Table 8.

Table 8: Reusability indicators

Indicator	Definition
Accessibility	Represents ow easy a certain element can be reached/accessed for inspection or deconstruction, without demolishing surrounding elements.
Adjustability	Represents the ease of adjusting a certain element such that it can fulfil a certain function with another shape compared to its original geometry.
Applicability	Determines to what extent an element can be used for purposes other than its current (intended) use, where many applications is better.
Availability	Describes the scarcity of similar elements with regards to how many become available within a certain period of time.
Deconstruct-ability	Determines how easily an element can be detached without damaging the surrounding elements, often by means of a connection. Also called demount-ability.
Durability	Represents the designed lifetime of a structure, in case of reuse it can also be described by how long an element can still serve in a certain functional location after deconstruction.
Modularity	Describes to what extent a structure or element can be divided into sub-elements (modules) that can be deconstructed with relative ease.
Recyclability	Describes to what extent the element can be recycled, where high-grade recycling (upcycling) is better than downcycling.
Reusability	Encapsulates the level of reuse that can be obtained with an element, where high-value reuse is fulfilling the same function as intended and low-value another application of the element as intended. This level is impacted by economic, environmental, and structural considerations, where over dimensioning (costs, strength, volume) negatively influences the value.
Split-ability	Determines how easily a certain element or part can be detached by force to subdivide one element into multiple, reinforcement negatively influences the score.
Transportability	Describes the ease of relocating an element by means of water or road, impacted by the size and weight of the element as well as available surrounding means (deep/wide enough waterway or obstacles on road).
Uniqueness	Represents the level of standardization of the element, where standardized elements require less research on reuse applications.

1 Superstructure

First a distinction is made between the various bridge types, before the different elements can be discussed. Suspension, cable-stayed, tied-arch and cantilever bridge types are generally used for larger bridges. Reuse in these bridge types is often more difficult as long spans are less common, in addition to that the functional performance must be lower in order to maintain safety and be cost efficient. These bridge types are outside of the scope of this research as they are few. The most common bridge type is the beam bridge. This bridge type can be constructed either with beams such as T-girders, inversed T-girders, box girders, infilled girders, and preflex girders, or by casting a concrete slab. Girders are often prefabricated and assembled on site, making them suitable for deconstruction. It is of key importance how the girders are connected to the rest of the structure, either via 'wet' or 'dry' connections. Wet connections are less suitable as concrete is casted on site to connect the beams to for example the compressive deck layer. Dry connections are for example bearing systems, which are better for disassembly.

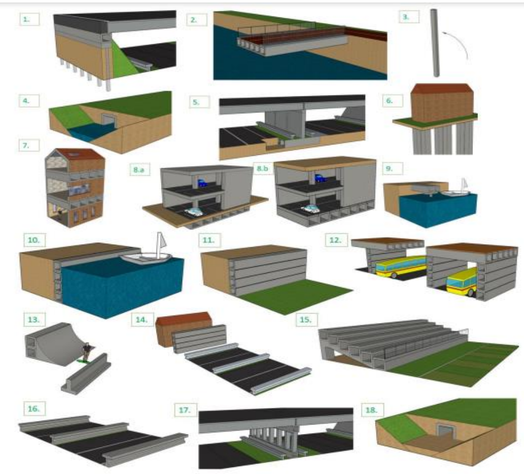
1.1 Girders

Brouwer (2022) has conducted a detailed study on the reusability of RWS viaduct girders. He collected data on 5 of the most common girders within the RWS database:

- HNP 75/98 (inverse T-girder)
- ZIP 700 (inverse T-girder)
- T-girder – not used anymore in new projects
- SDK 900 (box girder) – not used anymore in new projects
- SKK 1300 (box girder)

He further compared one case where Building As Usual (BUA) inversed T-girders with reused inversed T-girders for a 3 lane viaduct with 3 spans of ~20m (36x20m) based on the Structural, Environmental and Economic criteria for reuse value. This showed that for this project could save approximately 6000kg CO_2-eq and 147.360 Euros when reuse is applied, the structural aspect was also technically feasible, but depends on the type of girder and loading requirements and require analysis. It can therefore be concluded that high value reuse can certainly be attractive, however depends on many variables. Similar studies are currently conducted for other girder types as well (SDK900), which increases the robustness of reusing girders as a standard practice.

As for lower value reuse, an expert session was organized where the applications of girders were brainstormed (see Figure 79), from this session it was concluded that a culvert was considered the best application and a box girder the best fit due to its versatility. The main issue will be the structural assessment regarding adaptability and possible over dimensioning. It is however, still regarded as lower value reusing compared to same function application. In both cases, the dimensions and remaining strength are key in determining the optimal reuse value and application. In lower value reuse, the over-dimensioning aspect must be taken seriously, as too over-dimensioned might be a waste of resources. As the girders are often under 30m long, they are transportable. Due to the standardization, prefabrication, deconstructability, transportability and applicability aspect of girders, it makes them highly attractive to explore for reuse.



Design application	Design application
1. Abutment	10. Quay wall
2. Bicycle bridge	11. Retaining wall
3. Column	12. Roof/ Canopy
4. Culvert	13. Skate park
5. Foundation	14 Sound barrier
6. Foundation pile	15. Stand
7. (non-) residential	16. Traffic barrier
8. Parking garage a. Above ground b. below ground	17. Transverse girder
9. Pier	18. Wildlife tunnel

Figure 79: Low value reuse applications girder (Brouwer, 2022)

1.2 Cast in-situ slab deck

Cast in situ decks are generally very bridge specific, it is a civil structure after all. This characteristic makes it less 'readily' available for reuse as some adjustments are always needed. The most important aspect here is how it is connected to the girders, abutments, and pillars (if any). Wet connections making it increasingly more vulnerable when deconstructed. There is a distinction to be made for concrete slab bridges and compression decks used in combination with girders. The latter is not reusable as it needs to be demolished to reach the girder system, this layer is often 200-250mm thick [Brouwer, 2022]. The slab decks are generally thicker and have no girders supporting it. The slab decks have potential for high value reuse with decreased loading factors, however transportation is a limitation when the bridge deck increases in length. There are potential lower reuse value applications such as retaining walls or by splitting the deck up into concrete blocks used for a variety of applications in construction, both being difficult in practice due to the size and reinforcement and might not be the highest resource efficiency.

1.3 Arch & columns

Arches are highly specific constructions, designed for a certain location and height. The arch beam itself is therefore difficult to reuse with the same purpose. For larger arch bridges, the columns could be reused in lower value reuse applications. The issue here is that they are all different lengths, which makes its use limited in practice. Smaller arch bridges are often old and solid, this makes it impossible to disassemble, transport and reconstruct with the same structural integrity. It might be possible to reuse the pillar sections by trimming them and testing the remaining strength, however this needs to be explored further.

1.4 Trusses

Steel truss systems have good potential for reuse as the connections can be demounted relatively easy. As for concrete truss systems, the connections are wet connections, making them significantly more difficult to effectively disassemble. When splitted, they can serve other purposes, especially because they are of similar size throughout the structure. However, high value reuse is not possible, unless the truss system is transported for reuse, which has been done for steel structures in the past (concrete might prove a bigger challenge due to the weight).

1.4.1 Bearing & expansion joints

Bearings, as explained before, function as a connection between the sub- and superstructure and are located on top of abutments and pillars (if any). There are a variety of bearing systems, in practice it comes down to 3 types: hinged, roller-bearing, and clamped (Vree, n.d.). As for expansion joints, they are located between bridge decks, meant to connect bridge decks with each other or with the road. The most common expansion joint types in the Netherlands are nosing joints, mat joints, cantilever joints, flexible plug joints and the 'lamellenvoeg' (Vree, n.d.). Bearings and expansion joints are essential parts of a bridge as they to allow for minor movements and deformations between the sub- and superstructure, otherwise resulting in undesired effects such as cracking which impacts the structural integrity of the structure. These changes are caused by thermal expansion, loading, and soil settlement. Bearing systems and expansion are highly specific (though concepts are standardized) and generally have a lower lifetime than the rest of the structure, this makes them unsuitable for reuse (Brouwer, 2022).

1.5 Railing / barrier

The railing is probably the easiest element assess its reusability. This is mainly done by visual inspection as it is easily accessible, and deterioration can be spotted this way. Furthermore, its demount-ability is important, so, how it is connected to the bridge. A bolted connection is easily demountable, but when the pole is part of the concrete it becomes more difficult. Often, the railing is an important factor in the aesthetic of the bridge, making reuse less attractive as it should fit the bridge. When more railings become available due to the R&R task, more choice will indirectly result in more reused railings. Barriers are very standardized and therefore more suitable for reuse.

1.6 Curb stone/strip

Curb stones, in combination with railings, prevent derailing of vehicles from the road and bridge. These are highly standardized, modular, and prefabricated elements and can therefore be reused easily. Curb strips are wider variations of curb stones. The only issue is the potential interaction with the rails as this might be attached to the curb with bolt connections. It is possible that the curb is casted along with the bridge deck and that the railing is integrated, in this case the curb is not reusable and needs to be recycled.

1.7 Parapet

The parapet (or edge element) is not a structural element and is mostly implemented for aesthetical reasons, but also for safety. These elements are designed for a specific bridge, making them unsuitable for reuse. They are often prefabricated and can therefore also relatively easily be detached.

1.8 Rainwater discharge system (HWA)

This system provides potential for reuse, depending on the system that is used. The materials involved in this system are very small compared to the rest of the structure. Often, the system is integrated with the curb. The pipes can sometimes be demounted and reused if they are accessible. In general, the material amounts are so small, that is more practicable to recycle the materials unless the entire bridge deck is reused.

2 Substructure

The substructure transfers the load from the superstructure towards the load bearing soil. This implies that it is specifically designed for a certain physical location with soil measurements. Due to dynamic loading and environmental circumstances, the structure's foundation interacts with the soil causing settlement and displacements. The substructure is significantly more difficult to effectively reuse on other locations compared to the superstructure, this has multiple reasons. First and foremost, the substructure elements are less accessible since they are partly in the ground, which makes condition monitoring more difficult. Secondly, the exact geometry is often unknown, nor can the original position be inventoried without technical drawings (except pillars and part of the abutment). This limits the ability to accurately assess the integrity and capacity (structural and geotechnical) of existing foundations and the effects of their reuse when using current design codes. Moreover, if the geometry and structural strength are unknown, the elements can also not be communicated and linked to the demand side, making reuse impossible. Thirdly, the substructure elements are very unique and project specific, which makes it difficult to generalize and find a standardized set of applications for reuse (Brouwer, 2022). Next to that, the elements are generally too large for transportation, as they cannot be modularized. Lastly, the supports are in most cases constructed with in-situ concrete combined with a lot of steel and poured into the foundation, this makes it hard to demount and therefore reuse them (Brouwer, 2022). Due to these 'extra' challenges that come with reusing sub-structure elements on another location, it is often not considered. This is also reflected in the academic world, as substructure reuse has less of a prominent presence in current literature compared to superstructure reuse.

With that being said, it is not uncommon for bridge sub-structure elements to be reused in the same location. This is often a practicable solution as the last-mentioned problem from the previous section will be bypassed. However, the structure should be analysed based on settlement and strength to ensure that it can handle the future loads without causing problems. Reusing the substructure on the same location is often possible due to the fact that the superstructure suffers the most from the increase in traffic intensity and loading, causing higher moments in the spans. The substructure is mainly under compression, which is a strong characteristic of concrete. This has as a consequence that the substructure often has a higher remaining lifetime once decommissioned compared to the superstructure elements, leading to more favourable life-cycle-costs for alternatives with reused substructures. Ben Beerman, senior structural engineer with the FHWA Resource Center says that when compared to other alternatives, reusing the substructure can be an effective strategy to meet the objectives of accelerated construction in the areas of time savings, cost reductions, improved safety, and the need to minimize site impacts (Jalinoos, 2015).

Due to the increasing requirements for bridge design, it might be that the substructure is not suitable as is. In these cases, it does not have to mean the end for reuse, as there is the option to reuse the existing foundation by strengthening and enhancing its capacity through adding elements or improving the ground. An example is shown in Figure 80. Having insight in the current substructure might provide opportunities to keep it for the next bridge with minimal adjustments. This can be financially attractive, especially when the deck is replaced after 50 years when the foundation can go up to 100 years (Jalinoos, 2015). The potential time savings associated with foundation reuse can also reduce mobility impacts, a key goal of accelerated bridge construction (ABC) (Davis, Sanayei, Hoomaan, & Jalinoos, Journal of Bridge Engineering). However, there are certain risks involved due to the uncertainty of geometry, material properties and deterioration of the substructure. Determining the feasibility of foundation reuse requires multidisciplinary collaboration among staff with structural, hydraulic, geotechnical, and construction expertise (Jalinoos, 2015).

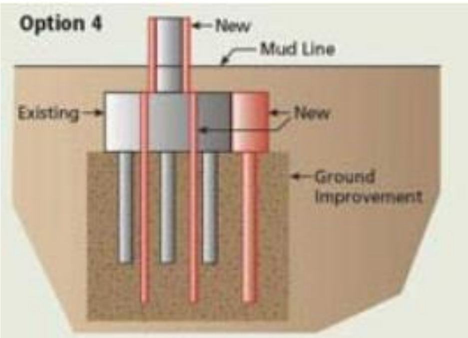


Figure 80: Foundation enhancement


Figure 81: Reusable column example

There are some elements that can be reused when the substructure is also replaced. When the pillar structure is constructed with column-type elements as depicted in Figure 81. Especially when there are many with similar geometry, making them applicable for other load-bearing structures besides bridges. The supporting beam can have similar structural applications or as lower value reuse such as a barrier. Furthermore, the embankment can be paved, in which case the bricks can be reused for similar purposes.

Appendix: J Concluding table beam/plate bridge reusability

Table 9: Element reusability analysis beam/slab bridges

Element	Common components	(Dis)advantages reusability
Foundation	I. Piles II. Pile cap	- Project specific design - Geometry irrecoverable after construction - Not designed for transport - Cast in-situ, hard to demount - Removing causes negative influence on soil + Reusable on same location + Suitable for reinforcement/enhancement
Abutment	I. Front wall II. Wing wall III. Transition slab	- Cast-in situ, too large for transport - Project specific design + Reusable on same location + Longer lifetime compared to deck
Embankment	I. Sand II. Cover tiles	+ Reusable tiles (high value) + Easily recoverable
Pillar support	I. Support/pillar/wall II. Column III. Support beam	- Generally unsuitable for transport due to size + Longer lifetime compared to deck + Potential for reusing columns/beams
Bearing	I. Hinged II. Roller bearing III. Clamped	- Project specific design + Standard concept - Low lifetime compared to structure - Not reusable (high nor low value)
Girder	I. Box girder II. T-girder III. Inverted T-girder IV. Preflex girder V. Infilled girder	+ Standardized types/models + Transportable + Prefabricated elements → demountable + Proven to be economic and environmentally beneficial to BAU + Many low-value reuse applications - Change of standards over the years - Uncertainty on state due to functional changes
Compressive layer	I. Compressive layer	- Cast in-situ - Needs to be demolished for girder reuse
Slab deck	I. Slab deck	- Cast in-situ (generally) - Not splitable - Difficult to transport with increasing size - Wet connection → not demountable + Dry connection plate bridges are reusable - Uncertainty on state due to functional changes
Expansion joint	I. Nosing joints II. Mat joints III. Cantilever joints IV. Flexible plug joints V. Lamellenvoeg	- Project specific design + Standard concept - Low lifetime compared to structure - Not reusable (high nor low value)
Curb	I. Curb stone II. Curb strip	+ Prefabricated elements → demountable - Interaction with railing mount + Standardized elements
Parapet	I. Parapet	- Connected to the slab/compressive layer, see slab deck

Edge element	I. Edge element	+ Prefabricated element - Not structural - Project specific design + Generally made from recyclable materials
Railing/Barrier	I. Safety railing II. Traffic barrier III. Guiderail	+ Demountable (when bolted connection) - Can be integrated in curb + Standardized designs - Many design variations (railings) + Widely applicable & large demand (railings) - Suited to bridge design
Rainwater discharge system	I. Pipes II. Gutter III. Drain	- Relatively low material mass - Not easily accessible - Integrated within other elements + Pipes are reusable

Appendix: K Breakdown structure bridge

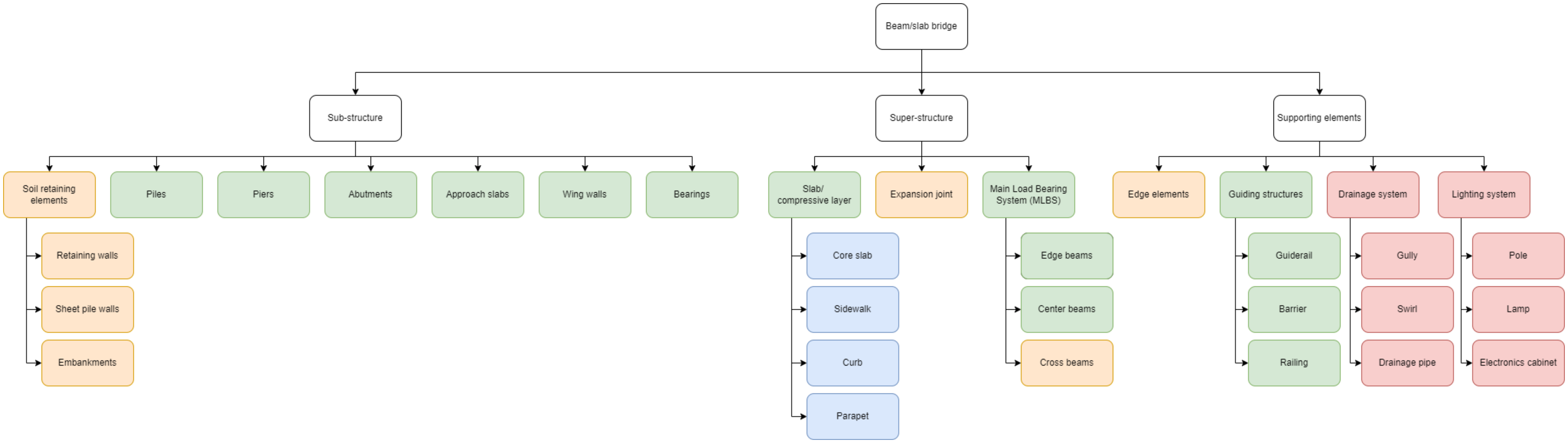


Figure 82: Bridge decomposition scope

Appendix: L Material passport input

General	Environmental	Abutments	Piers	Slab	Girders	Piles	Wing walls	Approach slabs	Bearings	Railings
Asset code	Primary material input (%)	Reinforcement (kg/m3)	Pier type	Traffic class	Model type	Reinforcement (kg/m3)	Reinforcement (kg/m3)	Slope	Bearing type	Type/model
Object name (NEN)	Renewable material from primary share (% of total we	Design load capacity	Reinforcement (kg/m3)	Design load capacity	Total length girder	Design load capacity	Design load capacity	Reinforcement (kg/m3)	Model	Chrome-6 layer inform
Object code	Sustainably produced from renewable share (% of tota	Concrete mix	Design load capacity	Continuous deck (y/n)	Design load capacity	Concrete mix	Concrete mix	Design load capacity	Design load capacity	Conservation type
Model uncertainty (score+reason)	Un-sustainably produced from renewable share (% of	Concrete strength	Span information	Length deck section	Pretensioning	Concrete strength	Concrete strength	Concrete mix		Steel strength
Construction year	Non-renewable material from primary share (% of tota	Finishing	Concrete mix	Span information	Reinforcement (kg/m3)	Bottom w.r.t. NAP	Finishing	Concrete strength		Impact class
Contractor	Secondary material input (%)	Bottom w.r.t. NAP	Concrete strength	Reinforcement (kg/m3)	Concrete mix					Finishing
Asset owner	Reusable output (%)		Finishing	Pretensioning	Concrete strength					
Manufacturer	Recyclable output (%)		Bottom w.r.t. NAP	Concrete mix	Slab connection type					
Material density	Incinerated output (%)			Concrete strength	Bottom w.r.t. NAP					
Volume	Landfilled output (%)			Finishing						
Last inspection date	Lost material (%)			Bottom w.r.t. NAP						
Upcoming inspection date	Harmful substances presence									
Last maintenance date	Reuse-scan: Material quality (incl. uncertainty)									
Upcoming maintenance date	Reuse-scan: Deconstructability (incl. uncertainty)									
Condition	Reuse-scan: Applicability (incl. uncertainty)									
Design lifetime (years)	Reuse-scan: Advice									
Decommissioning date (expected)	ECI-score (EUR)									
Comments										
Image										

Figure 83: Element parameters for tool

Appendix: M Handbook RE-design

Version 1
12-05-2023

Revit 2023
Dynamo core version: 2.13.1.3887
Dynamo Revit version: 2.13.1.3891

1 Tool description

After starting up the Dynamo script, the following screen should be displayed. Red text was added to help the user navigate the script more quickly. Each group of nodes (displayed in yellow blocks) represents a modelling feature, mostly for placing a type of element.

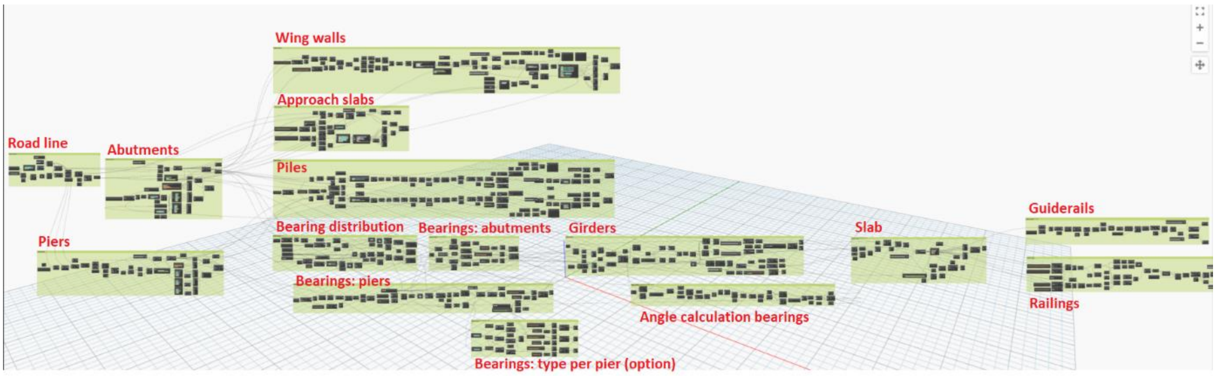
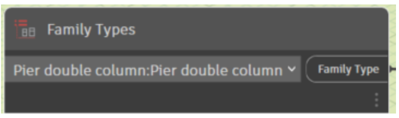


Figure 84: overview script

The model works as follows. The entire bridge is created using the bridge's road line (Dutch: 'weg-as'), and the relationships between individual bridge elements using their 'faces' and 'edges'. Each bridge element is a pre-modelled parametric family developed in Revit (either a Generic component model or an Adaptive component model if it concerns girders, railings, or guiderails). These elements are consisting of 'faces' that collectively make up the exterior of the element and are represented in a list when called for by the Element.Faces node. Every time a certain family instance is placed in the model, this list of faces will represent the same faces and are represented in the same order every time, no matter the individual (varying) parameter inputs of the family instances. Each face can be deconstructed into its perimeter curves (or lines), which can consequently be used to define new lines of points for the placement of other elements. Using these relations, a bridge can be constructed. As already indicated, each family instance (or: element) can be customized by defining its predefined parameters within the model. Moreover, some customization features have been built into account for the variation in bridge designs (e.g., beam bridge or slab bridge). Every time the model input is changed, all its dependencies will be updated automatically.

As part of the goal of this design tool aims to improve the asset management quality by increasing information documentation potential, an automated material passport is integrated within the workflow. In this material passport, important information can be stored directly at element level which is also beneficial for storing the reusability databases when this data concerns structural- and condition information. Considering that organisations might have different information needs for their assets and individual elements, customization is facilitated through an attribute database in Excel that allows both 'general' attributes that go to all elements as well as individual attributes that only go to one element category.

2 Design protocol

1. Open new architectural project template and save under new project name.
2. Set units of 'length' to meters with 3 decimals.
3. Import downloaded family database directory in project.
4. Go to manage->settings->shared parameters->create… and save new file under project name.
5. Adjust the 'Shared_parameter_file.xlsx' file based on the end-user's requirements and save file.
6. Open Dynamo player under manage-> visual programming, locate the folder where the 'Parametersetup.dyn' script is located, open the file, browse to the 'Shared_parameter_file.xlsx' file and run.
7. Open dynamo and open 'TheScript.dyn' file, make sure the run operator is on manual.
8. Assess drawings/measurements from site & project documentation for dimensions & materials.
9. Create the road line curve by points, or import from Revit (from e.g., Civil3D) using the Select.Element node. See next section for more details on how to do this.
10. Go to the handbook and select per element category the family variant applicable for the bridge based on the drawings and photo's. In the dynamo file, for each category select these variants by name and start filling in the parameters or copy them from the handbook.
    a. Selecting family node: 

    b. Relevant code blocks for parameter input are close by the node above, indicated by name.
11. Select the design options (see list below) applicable to the bridge.
12. Set run-operator to automatic, let it run once. When finished, move the abutment manually in Revit and let it recalibrate the model.
    a. Disconnect and connect the 'Element.Faces' node in the top right corner of the Piers placement group to recalibrate the bearings and piles if necessary.
13. Once satisfied with the output -> save dynamo file under new name for later changes.
14. Close dynamo, delete the unused girder in Revit and make manual adjustments to the model if required. Save project file.
15. Conduct multi-category material quantity take-off in Revit per material type and document this in the asset material passport in the Asset Management-tool.
16. Fill in element specific material passports, save file and link to AM DMS using 3rd party app.

3 Troubleshooting guidelines & tips

When working the script, the user is likely to encounter some issues. This chapter will provide some warnings that arose during the design phase of the tool.

- It is advised to keep the script on manual mode while changing elements as the script requires a lot of computing power, resulting in unnecessary waits. Only briefly set to automatic when running the model and re-running for calibration by moving the abutment manually.
- Be cautious with selecting groups (clicking anywhere in the green/yellow), as it will direct dynamo to collect all the elements in that group, which could take some time.
- If after the re-run, the bearings and/or piles for the piers are not adjusted based on the new parameters, disconnect the 'Elements.Faces' node and reconnect before running again.
- Ensure that the materials are already loaded in the project document in Revit to avoid errors.
- Only use letters and numbers in naming parameters (case sensitive), or it won't work in dynamo or with formulas.

4 Material passport customization

Starting with the material passport customizability for the users. This workflow is controlled by an Excel file (Shared_parameter_file.xlsx) in which the parameters are documented, categorization of Revit families, and Dynamo Player. Starting with the operator, Dynamo Player. Essentially, Dynamo player is simplified operator of dynamo scripts without requiring understanding the coding behind it. To run, the script could require predefined input variables and after running could provide output results. In this context, the script will require the input of an Excel file that is linked to the design tool setup. In this file, the attributes for elements can be specified, both for collective (all categories) and individual element categories. As different organisations will document different attributes based on their asset management strategy, this document can easily be adjusted based on the end-user's requirements. This can be done by going to the sheet in question (general, environmental, or any of the element specific), adding/removing rows and saving the file. It is paramount that only the rows with attributes are filled with text, otherwise the file will not run. The general sheet will look as follows when opened.

1	Shared Parameter Name	Shared Parameter Group	Parameter Type	Parameter Group	BIP Name (Automatic)	Instance	Category
2	Asset code	Asset management - General	Text	General	PG_GENERAL	Yes	All
3	Object name (NEN)	Asset management - General	Text	General	PG_GENERAL	Yes	All
4	Object code	Asset management - General	Text	General	PG_GENERAL	Yes	All
5	Model uncertainty (score+reason)	Asset management - General	Text	General	PG_GENERAL	Yes	All
6	Construction year	Asset management - General	Integer	General	PG_GENERAL	Yes	All
7	Contractor	Asset management - General	Text	General	PG_GENERAL	Yes	All
8	Asset owner	Asset management - General	Text	General	PG_GENERAL	Yes	All
9	Manufacturer	Asset management - General	Text	General	PG_GENERAL	Yes	All
10	Material density	Asset management - General	MassDensity	General	PG_GENERAL	Yes	All
11	Volume	Asset management - General	Volume	General	PG_GENERAL	Yes	All
12	Last inspection date	Asset management - General	Text	General	PG_GENERAL	Yes	All
13	Upcoming inspection date	Asset management - General	Text	General	PG_GENERAL	Yes	All
14	Last maintenance date	Asset management - General	Text	General	PG_GENERAL	Yes	All
15	Upcoming maintenance date	Asset management - General	Text	General	PG_GENERAL	Yes	All
16	Condition	Asset management - General	Text	General	PG_GENERAL	Yes	All
17	Design lifetime (years)	Asset management - General	Integer	General	PG_GENERAL	Yes	All
18	Decommissioning date (expected)	Asset management - General	Text	General	PG_GENERAL	Yes	All
19	Comments	Asset management - General	Text	General	PG_GENERAL	Yes	All
20	Image	Asset management - General	Image	General	PG_GENERAL	Yes	All

Figure 85: Example parameters

Due to dynamo back-end infrastructure limitations it is for now impossible to use columns C-G, this will be solved. For this reason, a temporary solution was implemented that bypasses this issue but automatically assigns all attributes (also the element-specific) as a text type in the 'general' parameter group in Revit. Within this general parameter group the attributes have the following order:

1. General attributes
2. Environmental attributes
3. Element specific attributes

5 Design options

Next, each of the design options integrated in version 1.0 of the tool are explained.

5.1 Road line input

The road line is the governing element that determines most of the model in terms of placement points. This requires a line or curve that starts and ends at the back edge of the abutment seats on either side (see family database for the placement point). This line is a projection of the actual road line in the negative Z-direction. The actual road line will be determined by bearing height, girder height (if applicable) and slab thickness. It is advised to let the curve start in the origin, for easy identification of pier locations, see point 4. It is paramount that the start point of the line has a lower x-coordinate than the endpoint to avoid issues with rotations.

The curve can be introduced in one of two ways, either by creating a NURBS-curve through control points based on x, y, z-coordinates given a certain degree, or by importing a line from a CAD file in Revit and selecting this element with the 'SelectModelElement' node. Which method is chosen is governed by the Boolean operator shown in the figure below. Default is false: creating a line in dynamo. The example shows NURBS curve through 4 control points with degree 3. Generally, the degree is set to integers 1, 2, 3 or 5, where 1 is straight lines from point to point (linear), 2= circular (quadratic) and 3 (cubic) and 5 (quintic) being curved lines of free form. It is advised to use 1 when the road line is a straight line, and 3.

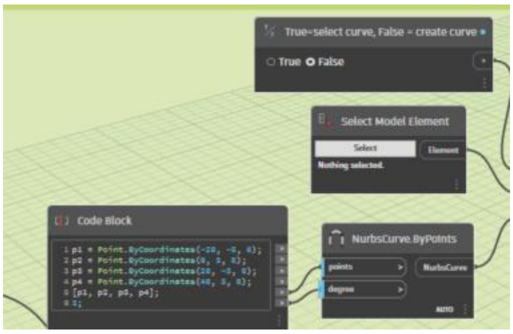


Figure 86: Road line input

5.2 Interchangeability of bridge elements with other variants

Second to the road line placement, the customizability of design variants (parametric families) is the most dominant aspect of the model as it governs the physical shapes of the individual bridge elements. As indicted in the previous section, for each group (with the exception of Road line, Bearing distribution, Bearings: type per pier, and Angle calculation bearings), the Family.Types node is present at least once. To find the right family type, consult the family database section int his handbook. Below each family type in the database, a piece of code can be found that can be copied in (each) code block connected to this family instance to obtain a valid model. These can later be adjusted for the actual values of the project. The parameter input code blocks have been standardized per element category (group) to ensure functionality across all variants in the database, however the input values should be adjusted to avoid unnecessary errors due to geometry constraints in the family. At any point, the family can be interchanged with another variant of the same category. Some groups (elements) require 2 family types to run the script, these are the wing walls (left +right sides), railings and guiderails (both for the post+railing and end post). For more information on how to develop design variants of specific categories, see section 6.

5.3 Beam bridge or slab bridge design

One of the key features of the tool concerns the ability to switch from a beam bridge to slab bridge instantly. This feature is implemented by means of a Boolean operator located in the 'Bearings: piers' group in the top-middle section. When set to 'true' a slab bridge is selected, while 'false' returns a beam bridge. The model is impacted by this decision as follows. Firstly, there will be only one row of bearings per pier for a slab bridge, while there are two for beam bridges (beam-end & beam-start). For slab bridges, the bearings are rotated in line with the pier rotation and placed in the middle (p=0.5) of the pier seat width, while for beam bridges the rotation is set such that the bearings of the beams face each other directly and located at p=0.25 and p=0.75 of the pier seat width. The slab is placed direction on the top side of the bearings while the compressive layer is placed on the highest point of the girders. The back wall height is automatically adjusted based on this decision too as it calculates the height of bearing+girder (beam bridge) or only the bearing (slab bridge). Figure 87 provides a side-by-side comparison of the different bridge types. Both pictures are made while dynamo was running, the blue lines will disappear when dynamo is closed.

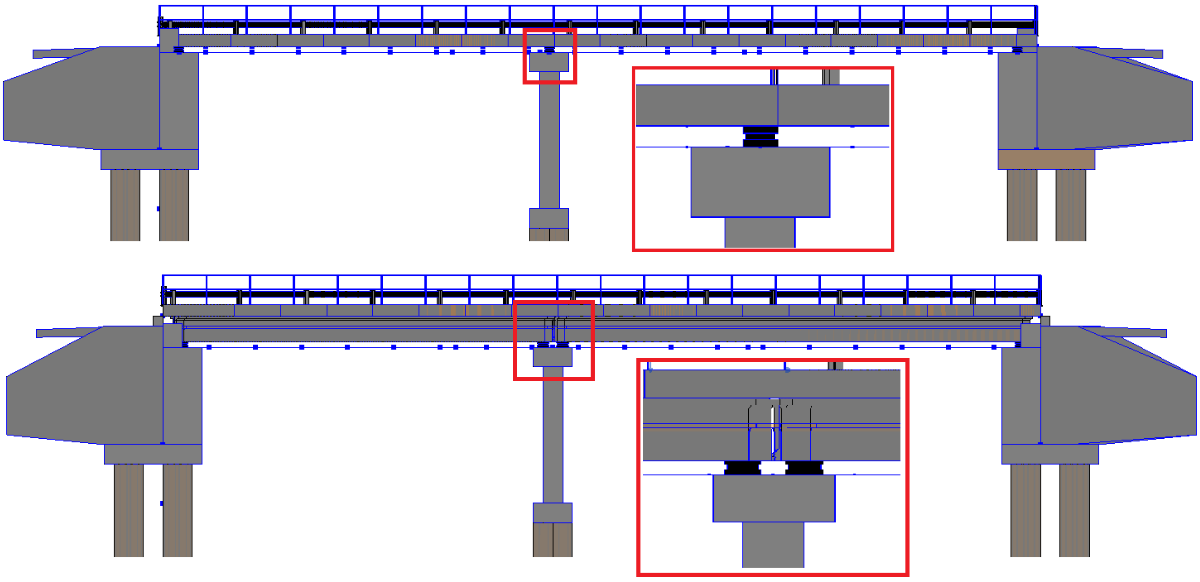


Figure 87: Beam or slab bridge differences

5.4 Abutment footing alignment

The footing of the abutment can occur in one of two ways, centred below the abutment or aligned with the front wall of the abutment, as represented in Figure 88. Considering the parametric characteristic of the element, most abutments can be modelled with this function alongside the other parameters of the abutment. However, there is space for making additions to an abutment family using the x1-x5 parameters built in the code block. The Boolean node can be found in the centre of the abutment group.

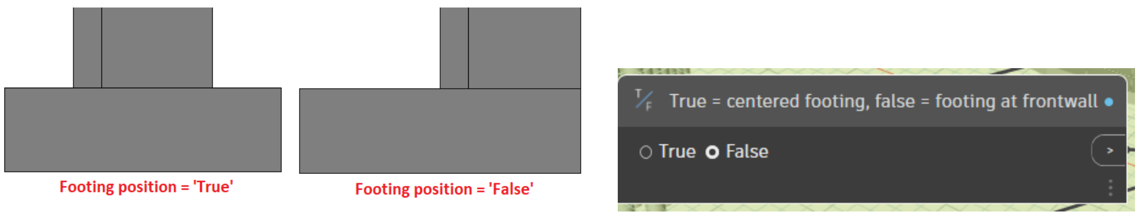


Figure 88: Abutment footing placement option

5.5 Setting the pier locations

The number of piers on a bridge and their locations can easily be changed based on the x-coordinate of the pier placement point (in the middle of the bearing seat face, see family database). Generally, the side view drawing of the bridge will expose the distance a certain pier is from the start of the bridge (abutment). When the road line is starting at the origin (advised), the user is only required to measure the distance **from the back edge of the abutment seat towards the centre of the pier(s) in x-direction**. These values can then be entered (or left empty in case there are none) in the list at the left-hand side of the pier-group.

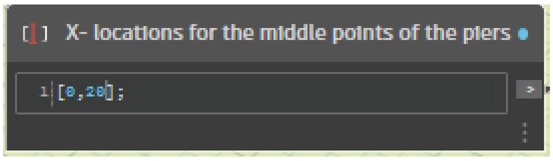


Figure 89: Node pier placement location

In case the bridge's road line is skewed/curved (i.e., the y-coordinate varies among the control points) and the drawings do not offer a side view in direction of the y-axis, an alternative method is offered: using the road line's segment length as placement point. Which method is more practical depends on the orientation of the drawings. Below, a visualisation of both methods is depicted with in two separate examples, one from the side view (left) and the other from the top view with a varying y-coordinate along the road line (right). The green line represents the x-direction method, and the blue line represents the segment length method. The values in the figure are imaginary.

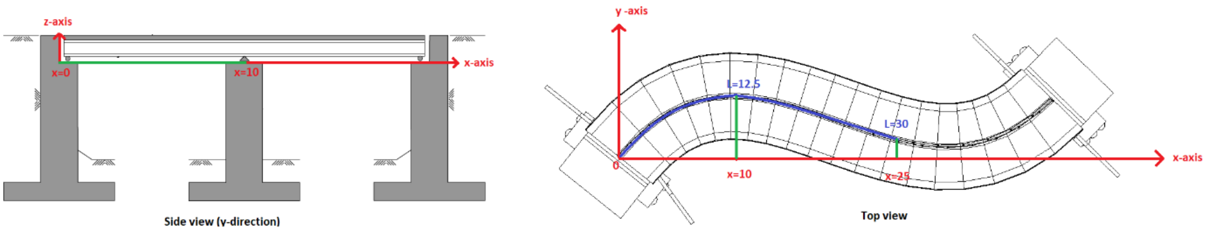


Figure 90: Pier placement options

5.6 Rotation for abutments & piers tangent to road line or set manually

The rotation angle for abutments and piers are automatically programmed to be in line (tangent) with their placement along the road line, as depicted in Figure 90 above. In practice this is not always the case, as displayed in Figure 91. The cause is often constraints from roads. For this reason, an option is built in where the abutments and/or piers are rotated in line with the y-axis. This is useful when the road line has varying y-coordinates. The nodes for this are located under the family type selectors and can be toggled by Boolean (true = in line with road line, false = y-axis).

Figure 91: Abutment angle options

5.7 Wing wall customization (rotation, placement, thickness & extrusion direction)

The wing walls have the most complex customizability interface across the elements in the model. This customizability can be found in the centre section of the group, while the object geometry parameters can be found on the right side (see point 2). Starting at the top, a Boolean operator can be found that determines whether the wing walls are 'inverted' to be part of the abutment (bool = false), see Figure 92 (left), or if it is extruded outwards where the placement point can be adjusted based on a parameter value using the front wall's width, see Figure 92 (right). The back wall's thickness is influenced by this Boolean operator when set to false. As the placement point parameter uses the front wall's width and rotates outwards, a standard operation is included to calculate the parameter value for when the wing wall is an extension of the front wall as a function of the selected wing wall thickness (code block below). To use this value (Max_p), connect line 10 to the ‘true’ input in the node directly to the right, when you want it customizable by using the slider, connect line 8. See Figure 92 (bottom) for a visualisation.

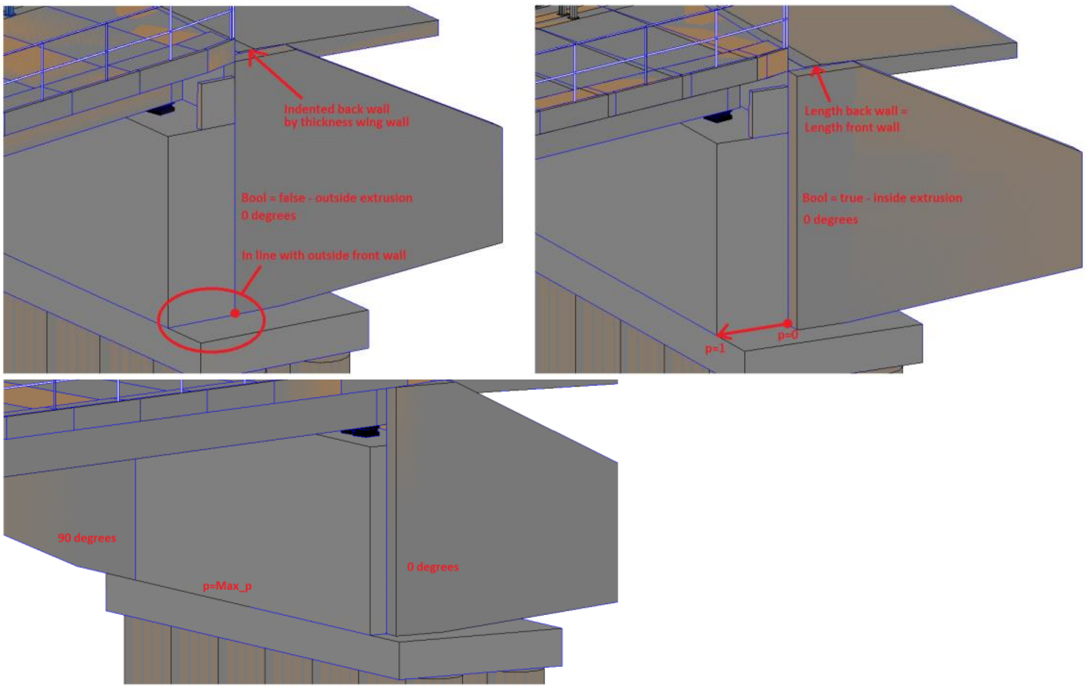


Figure 92: Wing wall placement

Lastly, the wing wall rotation. The rotation of the walls can be individually altered when the Boolean is set to true. These rotations are controlled by the sliders shown in Figure 93 (right), while the left side shows example configurations with 0 degrees (minimum), and 90 degrees angles. The coding ‘WW1’ stands for Wing Wall 1 which is always the right wing when facing the road, ‘A1’ stands for Abutment 1 which is always the abutment with the lowest x-coordinate.

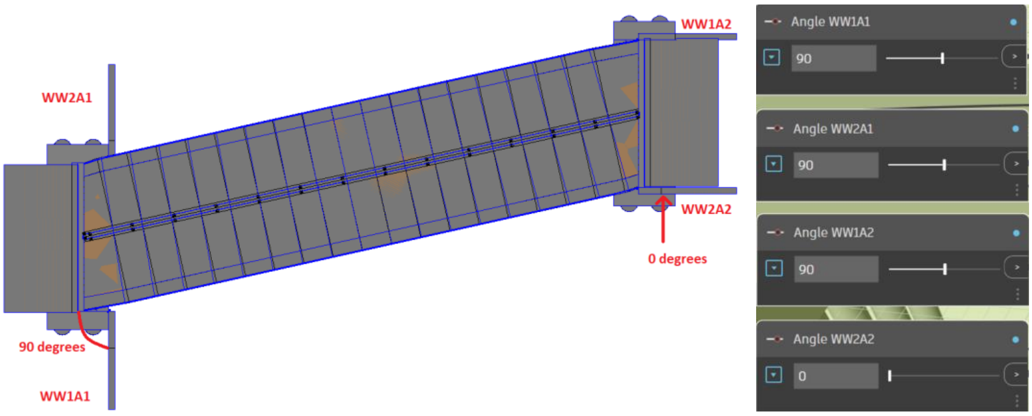


Figure 93: Wing wall customization

Lastly, the wing walls are set to the same height as the back wall, however this can be changed to the front wall height by connecting the ‘Front wall height’ node above the parameter input code block on the right-hand side of the group to the input parameter ‘H’. For manual input, replace ‘H’ in the code block for values for the individual wing walls.

5.8 Pile configuration per footing

The piles can be configurated per footing by first setting the number of rows (lines over the length/long side of the footing). To do this, the nodes in Figure 94 can be used. Each number in the list represents the nr of rows, where the first index always refers to the pier/abutment with the lowest x-coordinate and the last index with the highest x-coordinate. As there are always two abutments, the list length is always two. For piers, the list length must be the same length as the nr of piers in question (more is possible but they will not have a function). The figure below has two abutments with two rows each, and three piers also with two rows each. In the tool, up to 4 rows are built in with standard parameter values, as displayed in Figure 94. These rows are visualised using a sample footing geometry in Figure 94, however any geometry is possible as long as it has straight lines on the long edges (see right side for more examples). The user can also edit these parameters to their liking using list ‘x’, where the first element represents 1 row, etc.

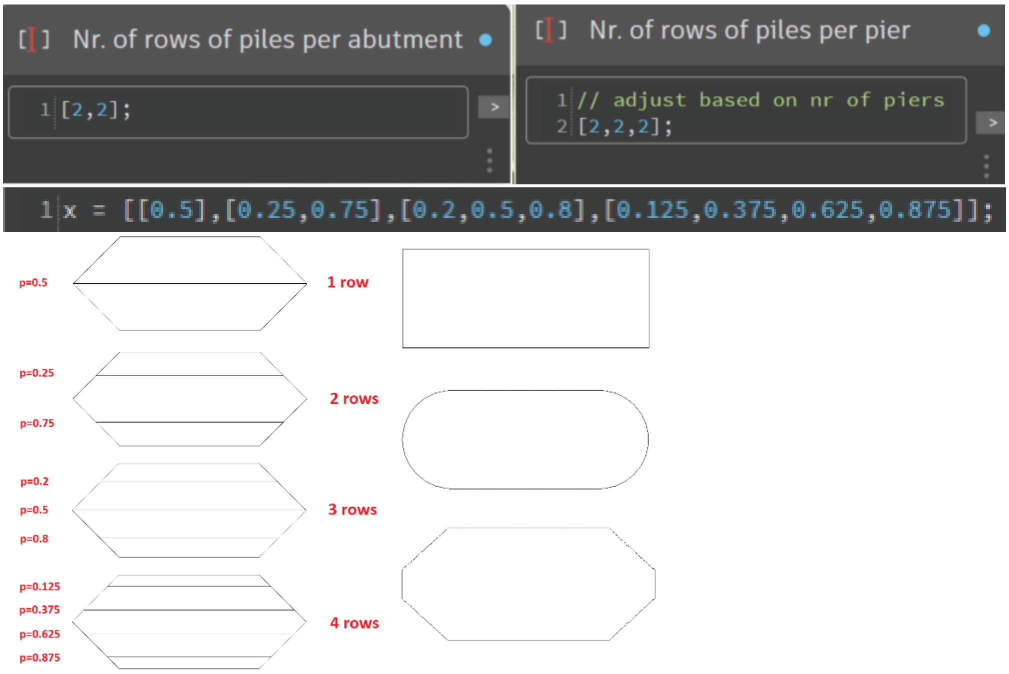


Figure 94: Pile footing configuration

As for the number of piles on each row, this can be determined using the nodes in the figure below. By default, the script will use the ‘Curve.PointsAtSegmentLengthFromPoint’ node. This takes the line (row), selects a starting point on that line by parameter (default=0.5, or middlepoint), and starts to place points on that line with distance ‘x’ (code block line 2) in both directions from the starting point until the line ends. Using p=0.5 as starting point ensures that for all rows the piles are placed symmetrically. In the yellow outlined code block, the distance between points can be set. The second option is to connect the ‘Curve.PointsAtEqualSegmentLength’ node to the code block input ‘x’ by connecting the blue line(s). This method divides the line into equal segments (line for in yellow outlined code block), thereby also ensuring a standard distance between piles. In case the edge piles are partly outside of the footing, the red line(s) can be connected to remove them, or the piles can be manually deleted after dynamo is closed.

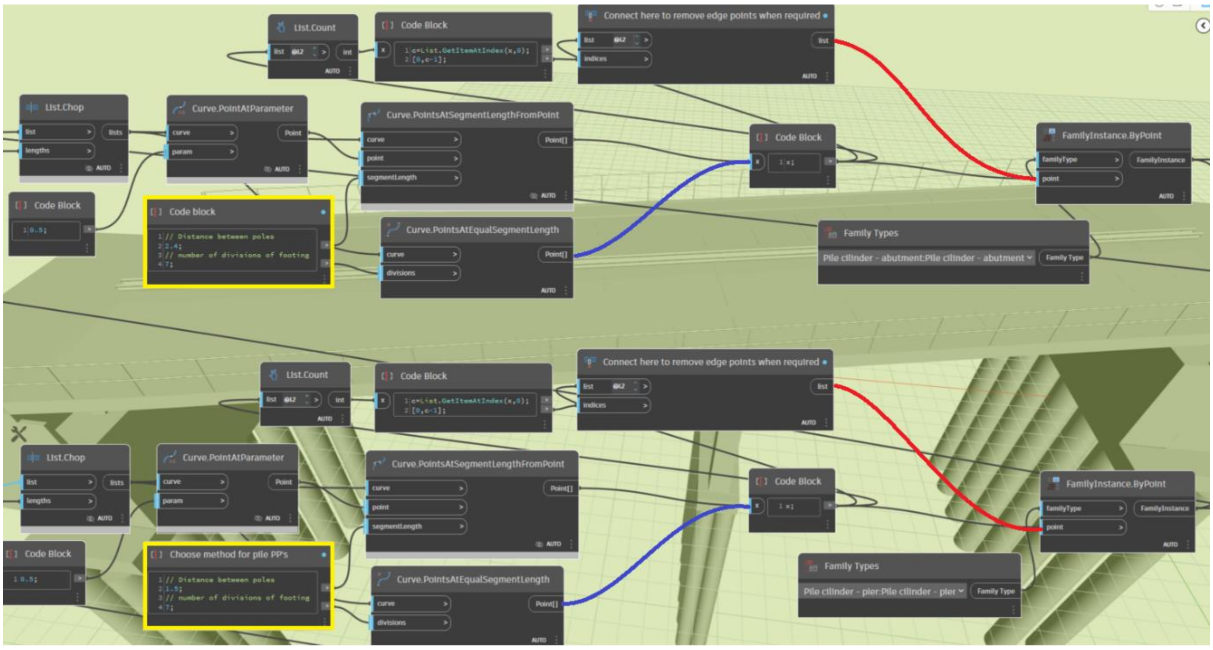


Figure 95: Script pile configuration

Lastly, the pile length is automatically calculated for a given Z-coordinate. This value is displayed using a watch node at the top- and bottom right side of the group for abutments and piers respectively. These value(s) can be used for setting the input parameter 'Length pile'.

5.9 Bearing configuration & edge beam option

Bearings can be configured by three parameters: the number of bearings in a row, the distance from the front edge of the abutment's bearing seat, and the distance between bearing placement points (for slab bridges). In case of a beam bridge, the bearing distances are predefined by the selected girder's width parameter. These parameters are all found on the left side of 'Bearing distribution' group as sliders. Here, also the option to select edge beams or not can be found, as this defines the outer bearing placement points. The edge beams are further defined in the 'girder' group. Below, a situation where edge beams are enabled (hence the short distance between outside bearings) is displayed. dA is the distance from the front edge of the abutment seat, while dB displays the distance between two bearings (only effective when slab bridge is activated).

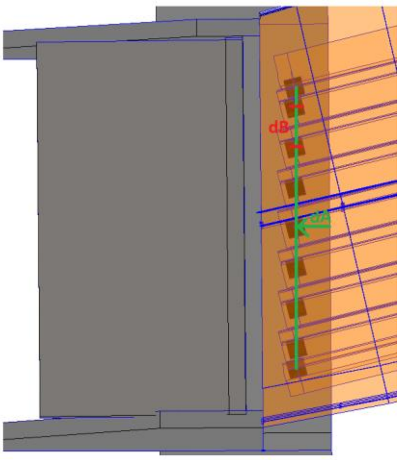


Figure 96: Bearing parameters

5.10 Option for different bearing types per pier

In practice, not all piers will have the same types of bearings. This design option is facilitated by the group ‘Bearings type per pier’. In the bottom right section of the ‘Bearings: piers’ group, a Boolean operator can be found that enables this function. The Boolean is set to ‘true’ by default (identical bearings for all piers). Once the Boolean is set to false, the group becomes active and bearing families can be selected per pier along with their parameters. For full functionality, after switching the Boolean operator, reconnect the bearing placement points and rotations nodes.

5.11 Railings at curb or side of curb/edge element & distance between poles

Lastly, there is an option to change the railing placement point from the top of the curb towards the side edge of the slab, as well as the distance from the outer top corner of the curb. This distance is in negative Z-direction when the side-connection is active, and inwards to the bridge when the top-curb connection is active. This is displayed in the figures below, where the left-hand side shows a side-connection and the right-hand side a top connection. The offset values are operated by a number slider found in the middle of the group. Besides this option, there is also the possibility to determine the distance between poles by means of a number slider found just right of the offset slider. This is similar for the guiderails group, only here the offset distance concerns the distance to each side of the road measured from the road line.

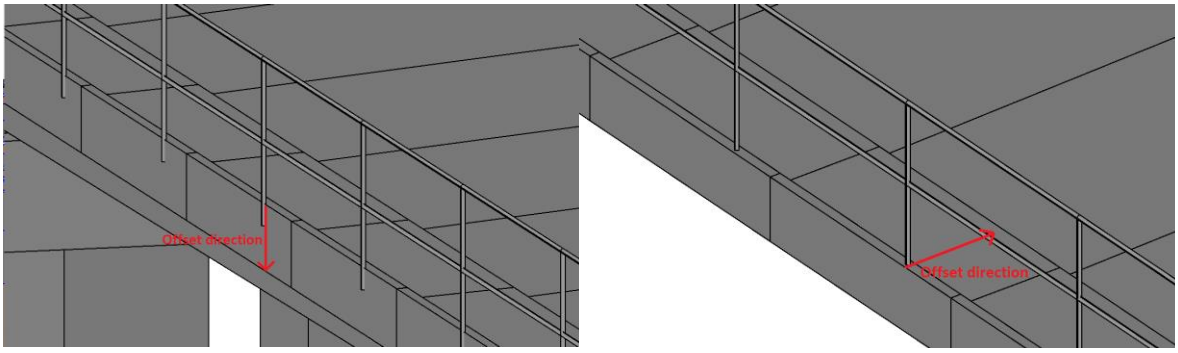


Figure 97: Railing placement directions

6 Design rules: family database

The family database is at the centre of the design tool, as it determines the robustness of the model output. To achieve a working script for any design variant that is used, some design rules need to be followed. These design rules are described in this chapter and are categorized by element type.

6.1 General

- Placement points in dynamo refer to the origin of the model, that being the crossing of the centre lines at the reference level for generic model components, or the adaptive points for adaptive components. For reference, see the red dots figures in the family database for each element type.
- A script is available where a given family can be tested on what index of the '' Element.Faces' node is a certain face and what edge from 'Surface.PerimeterCurves' relates to the correct edge. These indices can then be put as parameters under the model properties parameter group, using integers as type.
- All parameters used must be 'instance parameters'.
- Use the parameter names as provided in the script for each element type to avoid errors or add new names in both the script and families in the database of that particular element.
- In general, it is advised to start naming the parameters from the bottom up for a more logical sequence.
- Assign the family to the correct category type as indicated in brackets.
- Parametrize the material of the element(s) in the family.
- When opening a new family (both generic and adaptive), start with setting units to meters to as dynamo will work in meters too.

6.2 Generic models

6.2.1 Abutment (Abutments - Abutment Foundations)

- The placement point should be on the back edge of the seat (when facing the bridge).
- The abutment must face the eastward direction when on the Re. Level view.
- When making design variants, it is advised to use the existing model as a base and expanding on it using the x1-x5 parameter slots already built in the script.
- Check if the indices of the faces and edges are still correct.
- Footing/pile cap should be included in the family.

6.2.2 Pier (Piers)

- Placement point must be located on the centre point of the bearing seat.
- Footing/pile cap should be included in the family.
- Bearing seat & bottom of footing face indices, with both long edges perpendicular to the road of both faces added as parameters.

6.2.3 Bearing (Bearings)

- Placement point at the centre of the bottom of the bearing plate.
- Add parameter function to family that calculates the total height of the bearing: 'Total height' using the formula section.

6.2.4 Wing wall (Abutments – Abutment Walls)

- Placement point in the bottom corner of the wing wall.
- Model in 'Left' view in the top right quadrant.

- Select the element and parametrize the 'extrusion start' and 'extrusion end' in the properties window under the constraints group. The name does not matter at this point.
- Load the family into a new generic model family and place it in the top right quadrant on the reference level view for the 'right side wing'. Select the solid and go to the property window to save all parameters under the same names. Test out which of the extrusion parameters extrudes the form northward (in reference level view) with **a positive value**. Name this parameter 'Positive extrusion thickness' and the other 'Negative extrusion thickness' and set this one to zero.
- Create another generic model family and load the wing wall family and on the top left quadrant for the left side wing. Follow the same steps as for the right wing, only now look for the extrusion parameter that makes the extrusion go northward in the reference level view with **a negative value**. Name this parameter 'Positive extrusion thickness' and the other 'Negative extrusion thickness' and set this one to zero.

6.2.5 Approach slab (Abutments – Approach slabs)

- Placement point in the bottom middle edge of the placement side.
- Model in 'Front' view in the top right quadrant (going into bottom right quadrant to obtain height difference between left side and right side).

6.2.6 Piles (Structural Foundations)

- Placement point in middle of the pile top.

6.3 Adaptive components

Adaptive components require a different approach compared to generic models. First the general workflow is explained, after which some specific steps are discussed for the individual elements.

- Open a new generic adaptive component file, set units to meters and open the reference level view.
- Step 1: create profile
    - Use model lines and reference lines (instead of references planes, as this can create an undesired offset) to create a profile for (part of) the element.
    - Save family.
- Step 2: create face
    - Load the adaptive profile family into a new adaptive component family and place it on the reference level, the centre point will be the placement point for placing the family in another family.
    - Select the model line and 'create form'. If possible, select the 'surface' option directly. If not right click somewhere in the window and left click outside of the pop-up window once, then press spacebar switch between surface and solid.
    - When selecting the newly created surface, in the properties window parametrize all the profile's parameters again in the new adaptive family.
    - Save family.
- Step 3: setting up adaptive component
    - Open a new adaptive family file.
    - Place two model points anywhere in the window, select them and 'make adaptive'. When selecting the adaptive components, under the properties window, set 'orient to' to 'global (z), then Host (xy)'.

6.3.1 Slab/compressive layer (Bridge Decks)

- Set work plane on the adaptive point's (1) z=0 plane and place a reference point on the adaptive point. In the properties window of the reference point, parametrize the 'Rotation Angle' and name this 'ROT_A'.
- Repeat for the other adaptive point (2) but name this parameter 'ROT_B'.
- Hide the adaptive points from view.
- Load slab family surface created in step 2 in the family, set workplane to the reference point's x=0 plane and place the surface such that the bottom edge's middle point coincides with the reference point. Use the 'Place on Work Plane' if necessary to align. Move the surface manually if this still doesn't work.
- Repeat this task for the other reference point.
- For both surfaces, re-parametrize all parameters in the new adaptive family file.
- Hoover over surface A and press tab until in the bottom left it shows 'Name_surface_family: Face' and left click. Now hoover over the other surface and press tab until it says the same and ctrl+left click. Now select 'create form'.
- Select the form and parametrize the material.
- Test element with the 'Looking up faces & edges.dyn' file and add the faces & edges for railing and/or guiderail placement as parameters.

6.3.2 Girder/edge beam (Bridge framings - Girders)

- Create reference line, turn on 3D snapping, and place a line between both adaptive points.
- Load the girder surface family and place the surface on both planes resulting from the reference line (directly opposite of each other).
- For centre beams:
  - Make sure that the girder's bottom edge's centre coincides with the adaptive point.
- For edge beams:
  - Bottom most right/left (depending on which is modelled) of the beam must coincide with the adaptive point. See examples in family database.
- For both surfaces, re-parametrize all parameters in the new adaptive family file.
- Hoover over surface A and press tab until in the bottom left it shows 'Name_surface_family: Face' and left click. Now hoover over the other surface and press tab until it says the same and ctrl+left click. Now select 'create form'.
- Hoover over surface A again until it shows 'Name_surface_family: Face' and left click, create form again. Select the form and parametrize the positive offset and negative offset parameters. Name the one that extends the beam 'Offset over bearing', set the other one to zero.
- Repeat for surface B.
- Select the forms and parametrize the material.
- After saving the file (using naming for left side or right side), mirror the beam w.r.t. the reference line and save again using the other side's name.
- For centre beam:
  - Create a parameter that calculates the 'Total height' (highest point of the girder) based on the other parameters.
  - Create a parameter that calculates the 'Formwork height' (edge just below top height) based on the other parameters, used for aligning the edge beam.
- For edge beam:
  - Include variable 'Total height' in the mode, which will be determined in the script to align edge beam height with centre beam height.

6.3.3 Railing (Railings)

- TBD, improvements will be made in this workflow.

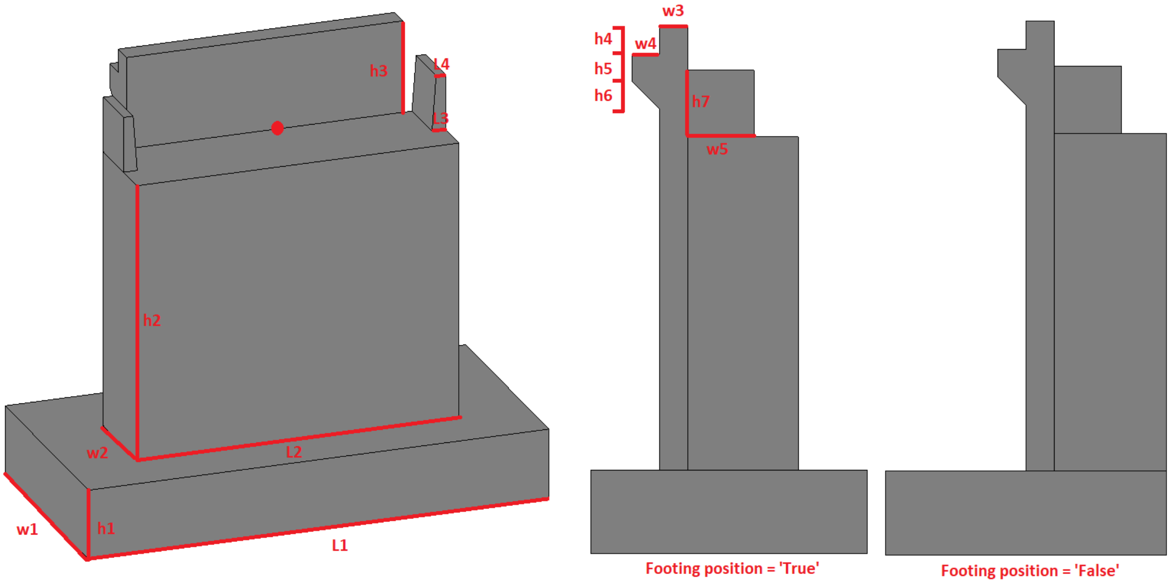
6.3.4 Guiderail (Signage)

- TBD, improvements will be made in this workflow.

7 Design variants database

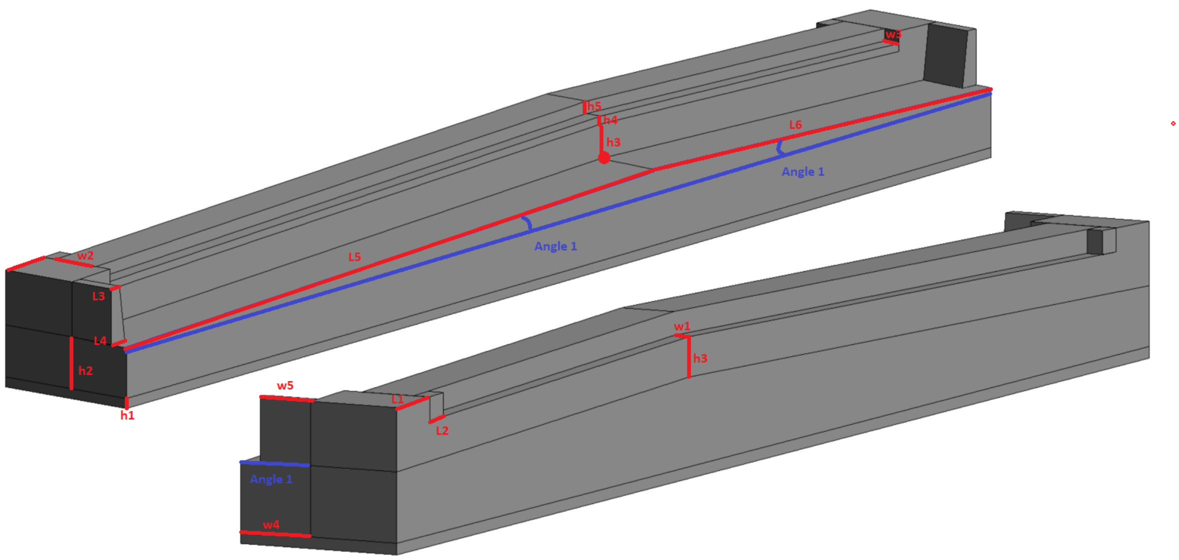
7.1 Abutments

7.1.1 Abutment A



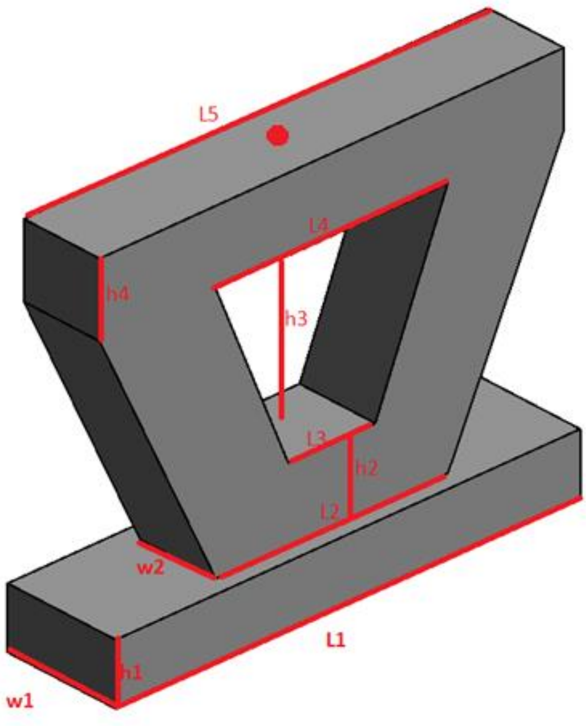
* Set 'w5' to zero when there are no safety walls! Only after completing the model.
** Back wall in figure is displayed for when there are wing walls on the side of the abutment.

7.1.2 Abutment B

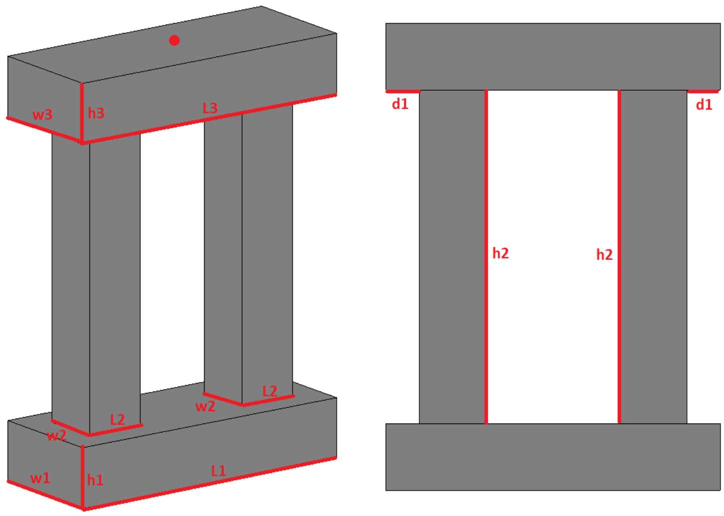


7.2 Piers

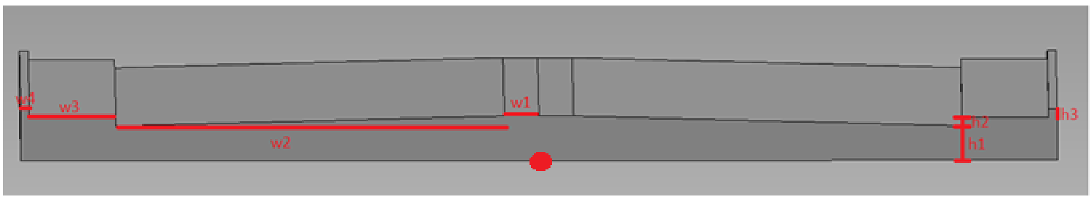
7.2.1 Pier triangle



7.2.2 Pier double column

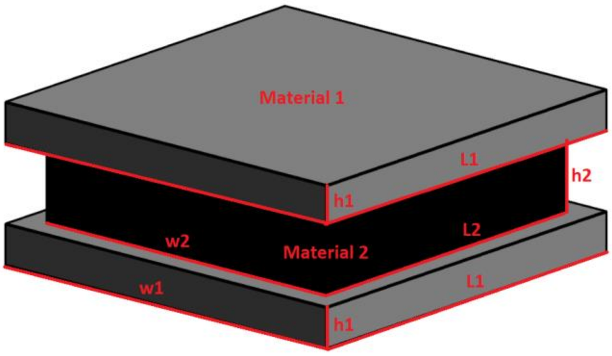


7.3 Slabs

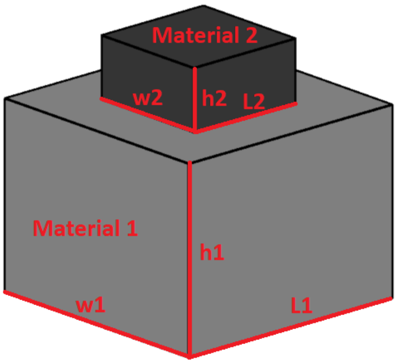


7.4 Bearings

7.4.1 Pot bearing A

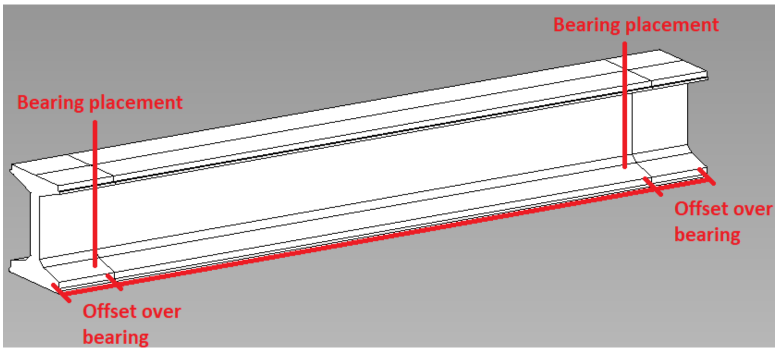


7.4.2 Pot bearing B

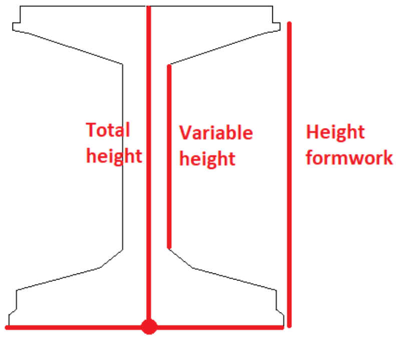


7.5 Girders

For all girders:

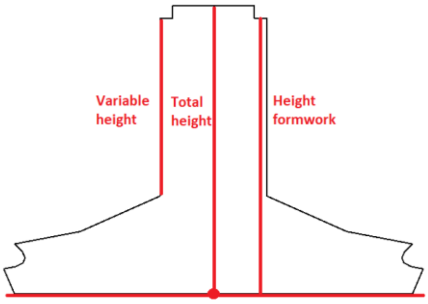


7.5.1 HIP – compressive layer



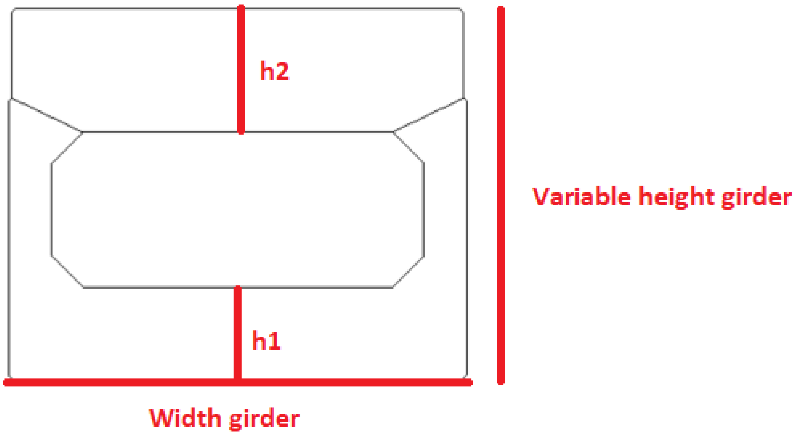
Set 'Total height' and 'Height formwork' as extra paramters.

7.5.2 ZIP 500-900



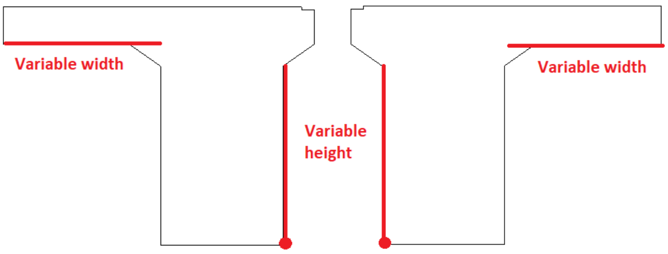
Set 'Total height' and 'Height formwork' as extra paramters.

7.5.3 HKP



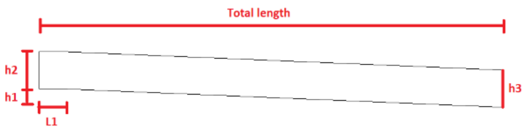
7.6 Edge beams

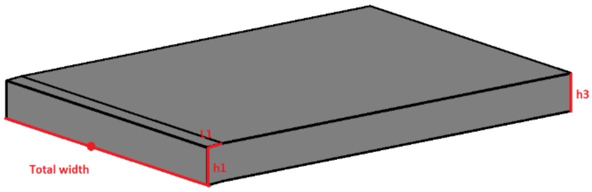
7.6.1 TNR edge beams



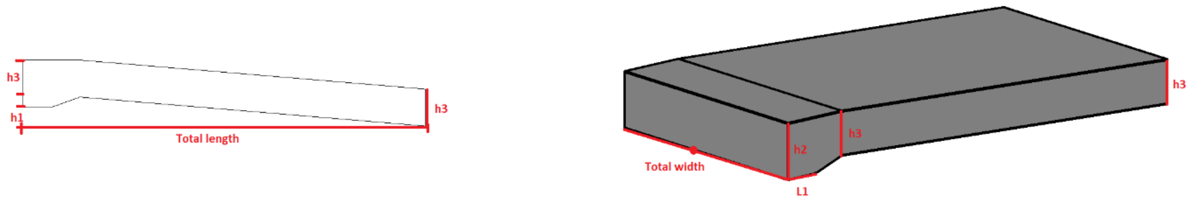
7.7 Approach slabs

7.7.1 Approach slab type A

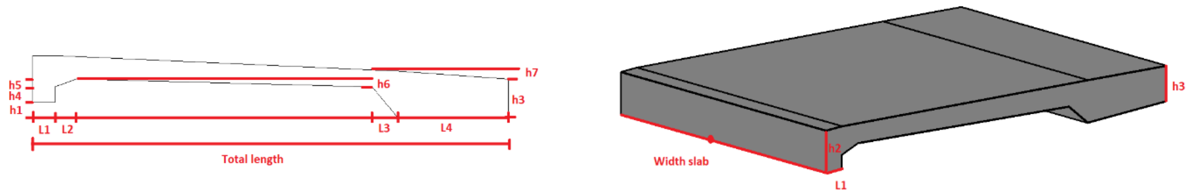




7.7.2 Approach slab type B

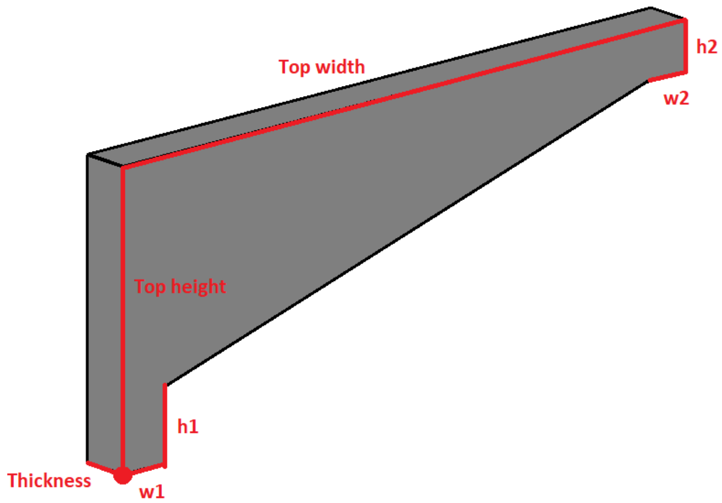


7.7.3 Approach slab type C

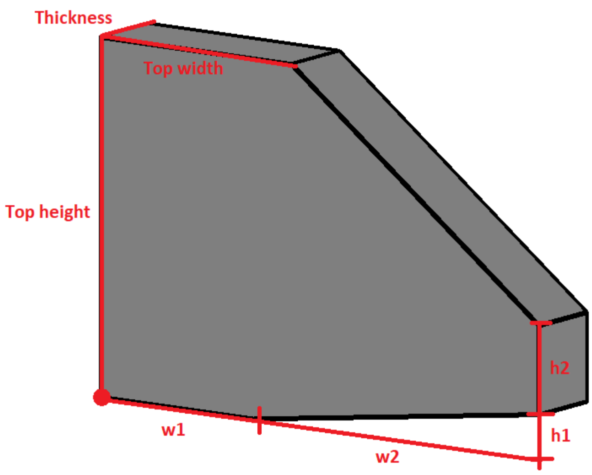


7.8 Wing walls

7.8.1 Wing wall type A

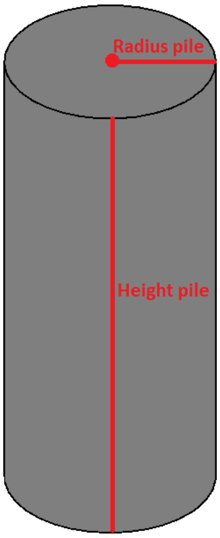


7.8.2 Wing wall type B



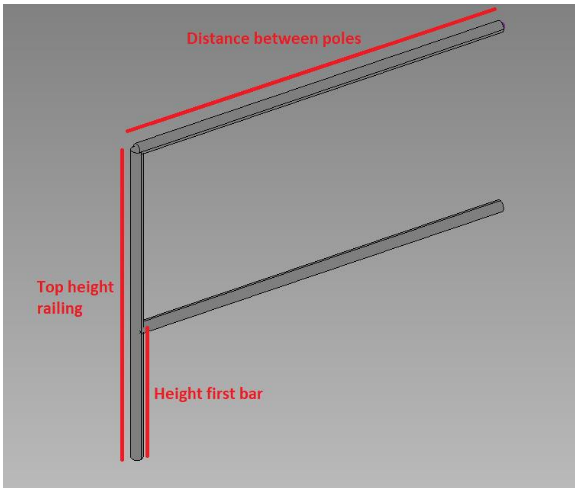
7.9 Piles

7.9.1 Type A



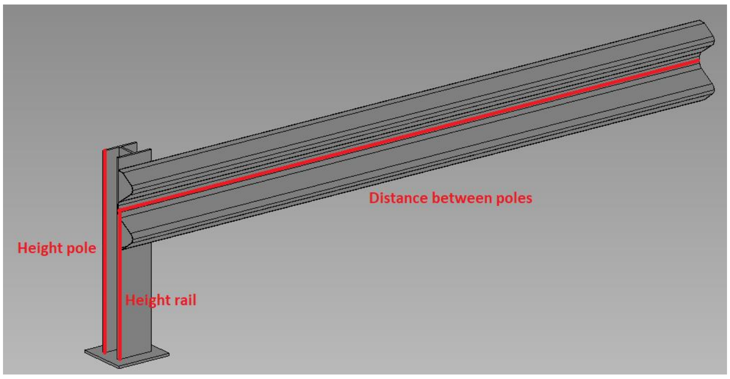
7.10 Railings

7.10.1 Type A



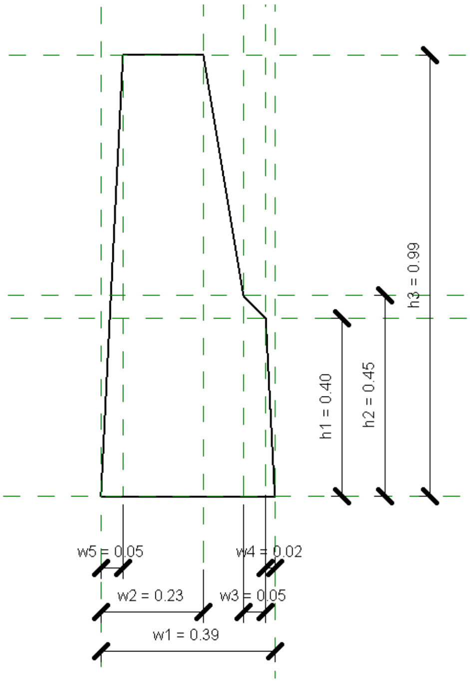
7.11 Guiderails

7.11.1 Type A



7.12 Barriers

7.12.1 Type A



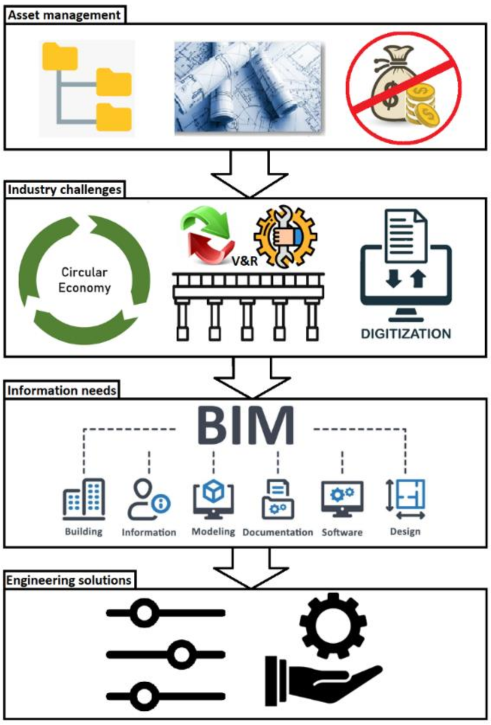
Appendix: N White paper for policymakers

Circularity starts with quality asset management: a reverse engineering effort for bridge infrastructure.

Problem description

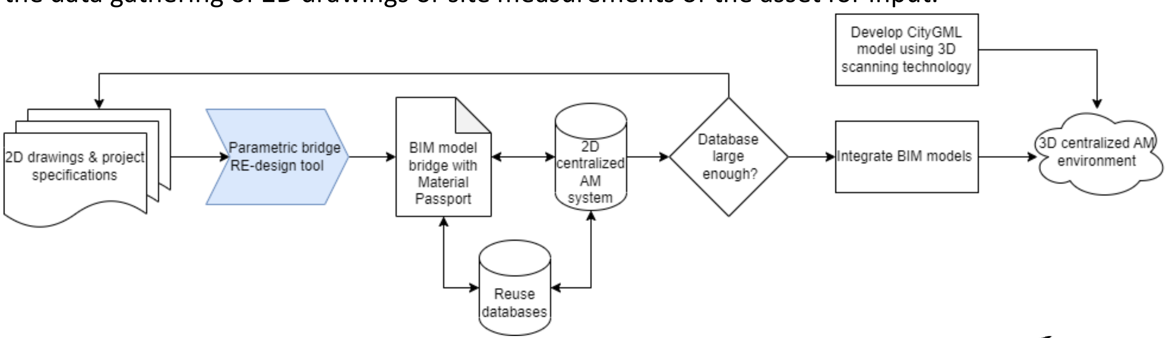
Asset managers are now dependent on the data quality resulting from the past decades where little priority was given to civil artworks, to achieve outcomes that call for current-day information standards (BIM). The challenges they face include the Circular Economy Transition and Replacement & Renovation Task, additionally there are demands for an increasingly digitized strategy. The issues are summarized in the following three points:

1. Lack of quality asset/element data to pursue inter-organisational reuse due to high uncertainty and large upfront research costs for demand parties currently, complicating the CE-goals.
2. Insufficient data on actual structural state of bridges due to functional changes over time, making the management of the activity timeline (maintaining/renovating/replacing) for the acreage difficult to flatten the expected decommissioning peak.
3. Increasing gap between existing- (2D drawings, often 'lost') and new infrastructure (BIM) asset data quality and management strategies, large upfront investment to upgrade the existing acreage to 3D BIM to create centralised high-quality AM.



Solution

The solution to these problems is captured in the following flowchart. Central in this approach is the specifically developed parametric RE-design tool for bridge infrastructure that allows cost-efficient generation of bridge 3D BIM, tailored to AM needs described above. A prerequisite for this process is the data gathering of 2D drawings or site measurements of the asset for input.



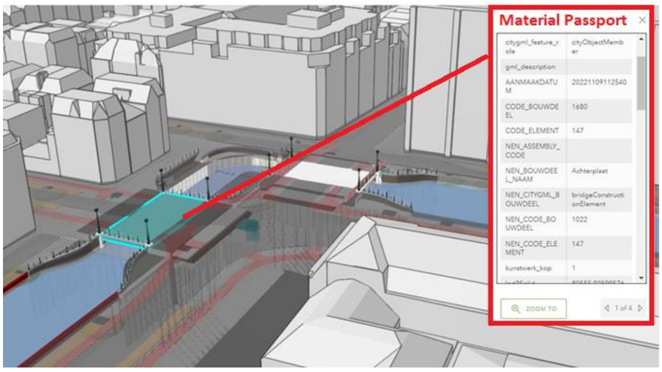
Benefits

1. Save up to 80% of traditional modelling costs per bridge (fixed beam/slab).
2. Accelerate digitization & digitalisation transition within your organisation to enjoy longer benefits of the investment.
3. Improve information management, traceability & communication, condition monitoring, through high quality centralized documentation of assets.
4. Easily accessibile element specific attribute data.
5. Increase quality supply of reusable elements in reuse databases for higher probabilities of reuse realisation, thereby increasing probability value of acreage by improved reuse realisation potential.
6. Enhanced maintenance & decommissioning efficiency through visualisation of the asset.
7. Reduced reusability scanning & structural recalculation efforts.
8. Obtain material quantities of assets for setting up local CE-models and improving more accurate data input for material flow models used for developing transition roadmaps.
9. Enhanced spatial planning decision making and visualisation.

2D to 3D centralised AM

2D

3D



Appendix: O Condition & maintenance register

ID	Description	Condition score	Issuer + Date	Asset type + ID	Object type + ID	Link to model	Inspection report	Inspection date
0	Starting corrosion	5	REIC6 1-1-2023	Bridge 0013	Barrier A12	Link	Download Link	22-11-2019
1	Replacement advised	1	REIC6 1-1-2023	Culvert 0213	Pipe 1	Link	Download Link	10-5-2020
2	Cracks found	3	REIC6 1-1-2023	Bridge 0163	Deck 1	Link	Download Link	22-11-2019
3	Broken streetlamp	0	REIC6 1-1-2023	Viaduct 0015	Lamp post A123	Link	Download Link	18-9-2018
...								

Continued ...

Priority	Severity	Status	Activity	Activity window	Activity owner	Maintenance report	Closure date	Last update + name	Comments
Low	Medium	Open	Protection layer	2023-2024	TBD		Download Link	REIC6 1-1-2023	
Urgent	High	Closed	Replacement	okt-20	BAM	1-11-2020	Download Link	REIC6 1-1-2023	
High	Critical	WIP	Active monitoring	2019-2022	Mun. Deventer		Download Link	REIC6 1-1-2023	
Medium	Low	On hold					Download Link	REIC6 1-1-2023	Might be replaced in new project

Figure 98: Enlarged inspection & maintenance registers