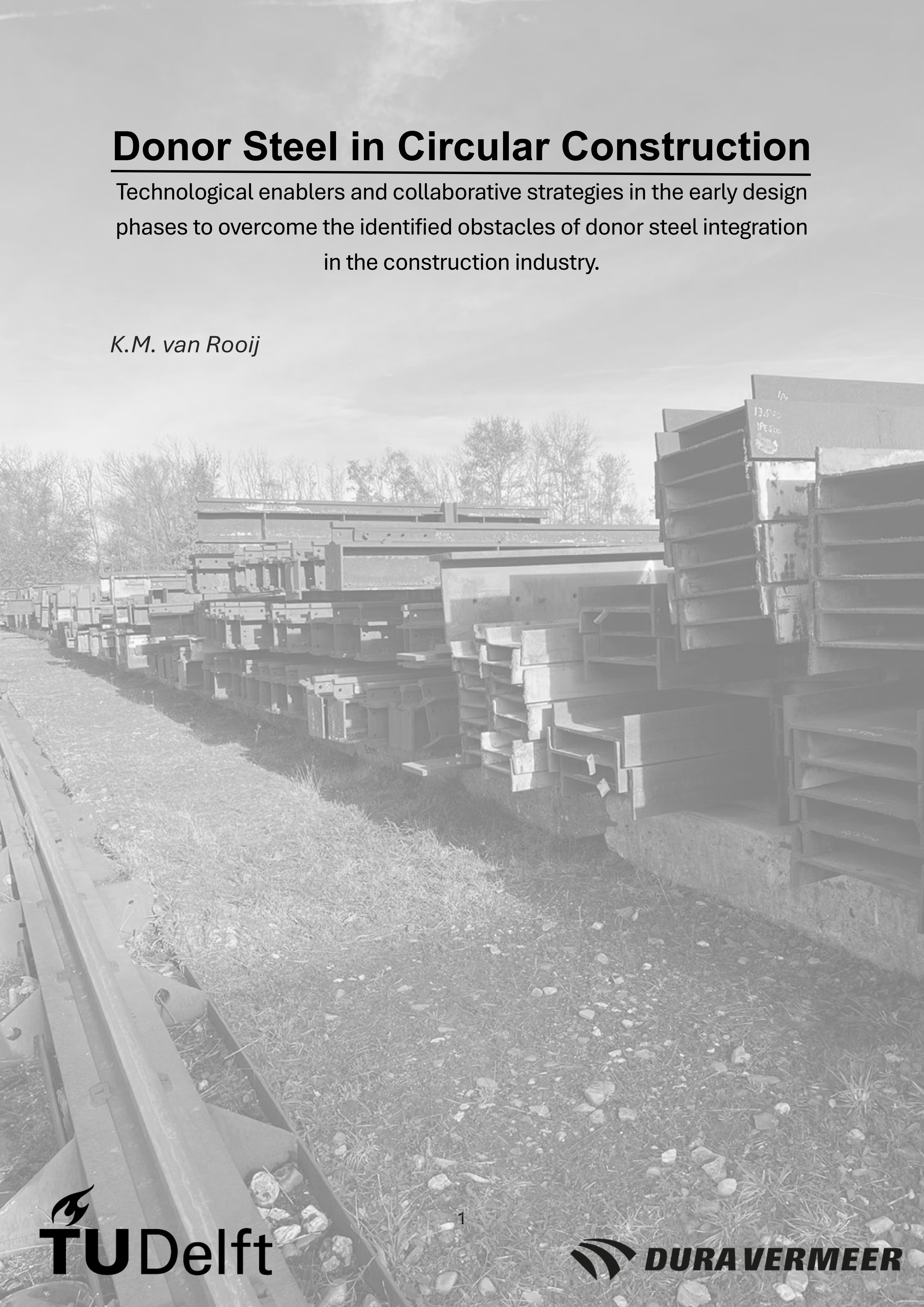
Donor Steel in Circular Construction

Technological enablers and collaborative strategies in the early design phases to overcome the identified obstacles of donor steel integration in the construction industry.

K.M. van Rooij



Integrating Donor Steel in Circular Construction:

Technological enablers and collaborative strategies in the early design phases to overcome the identified obstacles of donor steel integration in the construction industry.

By

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Coorperation with Dura Vermeer

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Preface

This thesis is the final step towards obtaining my Master’s degree in Construction, Management and Engineering (CME), which is part of my double degree together with my Master's degree in Architecture, Urbanism and Building Sciences. The outcome of the CME master's thesis will serve as the basis for the master's thesis in Architecture, but both will be separate studies with distinct graduation processes.

Furthermore, this thesis marks the finalisation of my study period at the TU Delft, during which I gained a great deal of academic knowledge and formed valuable memories. Over the last half year, I had the opportunity to investigate steel reuse in infrastructure and built environment projects. The graduation thesis has not only deepened my knowledge of the subject but also strengthened my personal research skills and professional independence.

Throughout this thesis, I received valuable feedback and support. I would like to thank Dura Vermeer for allowing me to conduct my graduation thesis and for providing their facilities, knowledge, and network. In particular, I would like to thank Lisanne Timmerman (supervisor Dura Vermeer) for her valuable insights, detailed feedback, and general support throughout the whole process. I would also like to thank Marleen Verstegen (team manager) for her continuous enthusiasm for the subject and for broadening my personal network in the sector. Moreover, I would like to thank my other colleagues at Dura Vermeer for their genuine interest in the topic, pleasant and motivating working atmosphere, and other assistance.

Additionally, I want to thank my supervisors from the TU Delft. Daan Schraven for his detailed feedback on academic structures and overall constructive feedback with helpful suggestions. Karel van den Berghe for broadening my engineering perspective and for helping me better understand the historical dimension of my work. Mohammad Hamida for his valuable academic insights, references, and overall supervision during the whole process. Moreover, I want to thank all interviewees for their time and valuable discussion during the interviews. Lastly, I would like to thank my boyfriend, family, and friends for their support and encouragement during the process.

Executive summary

The construction sector needs to reduce its material use and environmental impact, due to its significant CO_2 emissions and energy consumption. Structural steel plays a significant role in this challenge while preserving a high carbon content. Moreover, many buildings and structures contain steel components that still possess substantial value. Steel reuse, also known as donor steel, involves harvesting steel elements from existing structures and using them in new projects, offering clear circular potential. However, despite the availability of innovations and technologies and increasing sustainability ambitions in the sector, donor steel is still not widely applied in practice.

This thesis researched how early-stage decision-making can support the integration of donor steel in circular construction projects. Therefore, the main research question states:
"How can applications of digital solutions and conditions for collaboration in the early design stages help to address the identified key obstacles to integrate donor steel in circular construction projects?"

To answer this question, a twofold approach was adopted: an exploratory approach and a case study approach. Data from exploratory interviews with construction stakeholders and multiple case studies were compared with the literature review, which identified five obstacles to donor steel. The following five obstacles were identified: supply and demand mismatch, certification and design standardization, the absence of legal frameworks, cost and economic uncertainty, and a lack of collaboration and transparency. The obstacles encompass technical, financial, regulatory, and organizational domains, indicating that technical obstacles alone do not hinder the widespread adoption of donor steel.

The exploratory interviews with stakeholders across the construction supply chain provided insights into how these obstacles manifest in practice. The interview data confirmed that 'cost uncertainty', 'certification & design standardization', and 'supply & demand mismatches' were the most significant obstacles in practice. The regulatory obstacle appeared less decisive than the literature review suggested, while several additional obstacles emerged, particularly related to client decision-making and timing. Additionally, 'lack of collaboration and transparency' was perceived as an obstacle in the interviews, but as an enabler in the case study research, showing the importance of strong collaborative structures in reuse projects. Moreover, the case study research provided further insights into how donor steel application is approached in real projects. The data showed that the key enablers were: early integration of digital and sustainability tools, strong collaborative structure with stakeholder engagement, and client sustainability ambitions. Showing the importance of digital solutions applications, such as BIM, MP's, and material testing, supporting donor steel integration.

Overall, this thesis shows that the integration of donor steel is primarily constrained by early-stage organizational and economic conditions, rather than by technical constraints or the lack of digital solutions. The application of these digital tools is practical when embedded within the collaborative procurement process, early stakeholder engagement, and clear client commitment to circularity.

Finally, longitudinal, process-oriented research is recommended to generate more generalisable findings and to develop a coherent framework that provides actionable guidelines for future donor steel applications. Furthermore, practitioners should explicitly consider donor steel in the early design and procurement phases, support early stakeholder engagement, and integrate digital and sustainability tools early in a project to reduce uncertainty and prevent late-stage rejection. Additionally, policymakers must offer clarity and consistency in certification procedures and documentation requirements to reduce the perceived certification and regulatory risks.

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Nomenclature

Abbreviations	Definition
APIs	Application Programming Interfaces
BIM	Building Information Modeling
BOF	Basic Oxygen Furnace
CE	Circular economy
CEV	Carbon Equivalent Value
CO2	Carbon dioxide
CoBie	Construction Operations Building Information Exchange
DBFM	Design, Build, Finance, Maintain
DBM	Design, Build, Maintain
DfD	Design for Deconstruction
DT	Digital Twin
EAF	Electiric Arc Furnance
ECI	Environmental Cost Indicator, Dutch 'Milieu Kosten Indicator' (MKI)
EU	European Union
EoL	End of Life
IPE	I-Profile Européen
IFC	Industry Foundation Classes
IoT	Internet of Things
LCA	Life Cycle Assessment
LiDAR	Light Detection and Ranging
MP	Material Passport
MPG	Milieu Prestatie Gebouwen
MVD	Model View Definitions
MT	Magnetic particle testing
NDT	Non-Destructive Testing
NTA 8713	Nederlandse Techniche Afspraak 8713
OES	Optical emission spectroscopy
RAW	Regeling Administratieve Voorwaarden
RDF	Resouce Description Framework
RT	Radiographic or X-ray testing
S235/S355	Structural steel grades according to EN 10025
UT	Ultrasonic testing
XRF	X-ray fluorescence

1. Introduction

1.1 Research context

The construction industry plays a central role in the transition towards Net Zero Emissions, as it is responsible for approximately 11% of global CO2 emissions and 36% of the European Union's (EU) energy consumption (Karakosta, C. et al., 2025). Building materials are one of the most significant contributors to this global carbon footprint. Industry actors must be committed to achieving these ambitions to become climate-neutral by 2050 (European Commission, 2024). Steel is one of the most widely used building materials in the sector; around 50% of global steel production is used in construction (World Steel Association, 2024). The production of steel is not circular at the moment and needs to decarbonize to achieve the climate-neutral by 2050 regulations (European Commission, 2024).

To stimulate this transition in the Netherlands, the Bouwakkoord Staal (2022) was signed, setting binding ambitions for the Dutch steel and construction industry. The Bouwakkoord Staal (2022) is a collaborative initiative developed by many players in the steel industry (e.g., designers, contractors, manufacturers). The agreement sets a target of at least a 60% reduction in CO2 emissions by 2030 compared to 1990. Transitioning from a linear economy to a circular economy is essential to achieving the target (van Buren et al., 2016). Therefore, it states that circular strategies, such as reuse and recycling (Figure 1.1), must be integrated in design, production, and construction lifecycles (Bouwstaal akkoord, 2022).

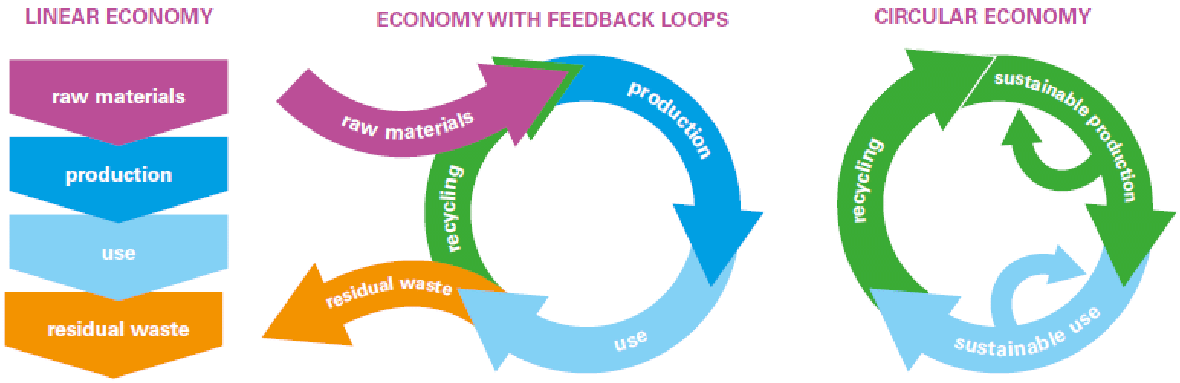
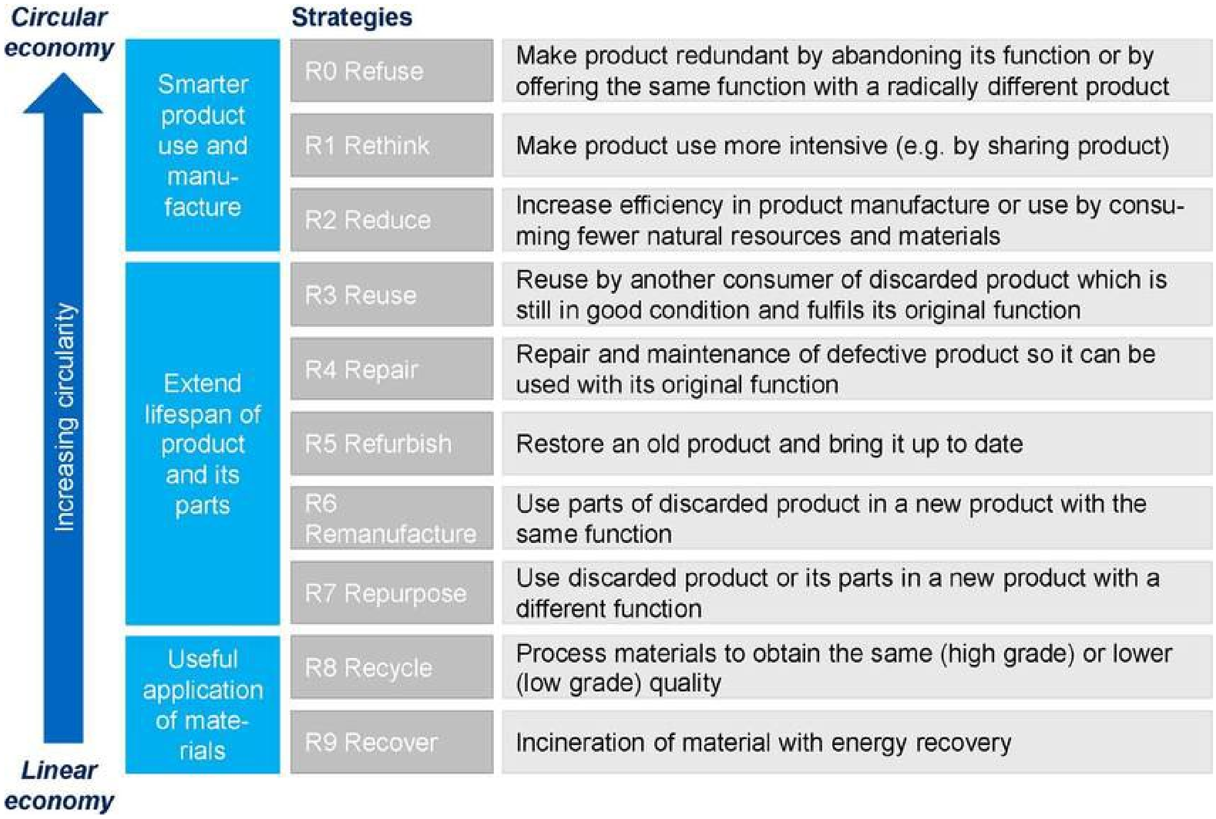


Figure 1.1: 'Linear economy', 'Economy with feedback loops' and 'Circular economy' (van Buren et al, 2016)

The circular economy framework (CE) aims to maximize the value of materials and products and minimize waste streams throughout their life cycle. These circular design strategies serve as a guide towards achieving Net Zero Ambitions; the 10R framework provides a structured hierarchy of these strategies, including recycling and reuse (Kirchherr et al., 2017).

Examining the CE strategies (Figure 1.2), reuse is one of the most impactful approaches, following the manufacturing strategies. Furthermore, it is positioned higher than strategy recycling because it preserves both the functional and material integrity of elements (Kirchherr et al., 2017). Recycling materials often involves significant energy use and carbon emissions; by reusing materials, the embedded carbon and energy are preserved for a more extended period (Yeung et al., 2017).



	Strategies	
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

Figure 1.2: The circular economy framework, with the 10Rs (Kirchherr, J. et al, 2017).

Steel is traditionally recycled at the end of life (EoL) and melted into new products (Figure 1.3). This process effectively recovers resources, but it remains energy-intensive and carbon-intensive (Yeung et al., 2017). In contrast, the reuse of steel retains the embedded carbon, avoids the environmental burden of remelting, and reduces the raw material demand (Kirchherr et al., 2017). Reused steel elements, which are dismantled from an existing building and then reused in new construction (Figure 1.3), are referred to as donor steel (Byers et al., 2023).

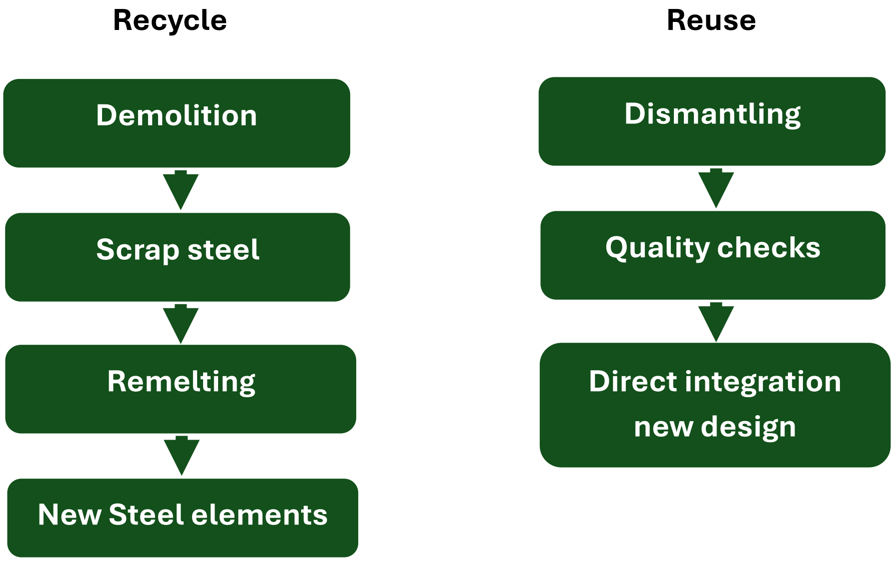


Figure 1.3: Simplified diagram of the different steps in both strategies: recycle and reuse (based on Dunant et al, 2017)

Moreover, buildings typically have a lifespan of 60-80 years; the technical lifespan of constructional steel elements can exceed 100 years (Jones & Kobb, 2021; World Steel Association, 2024). This created an opportunity to extend the life of structural steel elements. Donor steel may seem like an innovation in circular construction, but steel reuse has always been a historical present. During WWII, steel reuse reached its peak due to material scarcity and economic necessity (Addis, B., 2006). Suggesting that reuse is not a technical novelty, but becomes feasible under specific governance and economic conditions. Currently, the challenges are therefore less about technical capacity and more about realigning processes and responsibilities to enable reuse at scale.

History suggests that reuse depends more on organizational than on technical obstacles, indicating that the success of donor steel applications depends on early decision-making, collaborative structures, and procurement processes. During the early design stages, structural configurations, contractual commitments, and material specifications are still adaptable (Dunant et al., 2017). During later project stages, the design is inflexible due to contractual lock-ins, significantly reducing the feasibility of donor steel integration (de Ridder H.A.J, 2009). Digital solutions can support early-stage decision-making by providing traceable, reliable information on the geometry and material properties of donor steel components, thereby bridging the information gap between existing buildings and new design processes (Kovacic & Honic, 2021). However, digital tools alone are insufficient; strong collaborative structures are equally important for enabling donor steel integration (Innovations Origins, 2024).

1.2 Research problem

Despite the significant environmental potential and technical feasibility, donor steel integration remains limited in practice. Even though the steel components can be identified in a building, checked, modified, and reused in other buildings (Meng et al, 2023). The application of donor steel is still not widely adopted. The bottleneck of transitioning to a circular building industry lies not in the technology but in the absence of integrated collaboration strategies (Schraven et al., 2024).

Previous studies have identified multiple obstacles, including technical, regulatory, and social obstacles, leading to insufficient integration into early design decisions (Innovation Origins, 2024). Empirical understanding of how these obstacles manifest, interrelate, and can be jointly addressed in practice is limited.

Digital tools and collaborative procurement models are frequently proposed as enablers of reuse, but their combined role in addressing these barriers has not yet been systematically explored. Therefore, this research first seeks to clarify the key obstacles to donor steel reuse with literature and validation by experienced stakeholders, and subsequently investigates the integration of digital solutions and collaborative conditions in practice.

1.3 Aim, objective, and scope

This research aims to identify, validate, and structure the key obstacles to donor steel reuse in the Dutch construction industry and explore ways to increase its use. Steel reuse, defined as donor steel, is the use of construction steel components as a whole at the product end of life

(EoL). Additionally, the study aims to examine how digital solutions and collaborative conditions can help address these obstacles in early-stage decision-making and manifest in practice.

This research seeks to generate empirically grounded insights into the interactions among obstacles, technologies, and collaborations for steel reuse, and thereby inform future design, policy, and procurement strategies. The thesis will focus on steel reuse in 'Infrastructure projects' and 'Built environment projects'. Doing so, this thesis contributes to the ambitions of the Bouwakkoord Staal (2022) and supports the broader Net Zero Ambition of the Dutch construction sector (European Union, 2024).

1.4 Research questions

The main research question of this thesis will be the following:

"How can applications of digital solutions and conditions for collaboration in the early design stages help to address the identified key obstacles to integrating donor steel in circular construction projects?"

To answer this main question, the following sub-questions will be investigated:

1. *'What key obstacles hinder the integration of donor steel in construction projects?'*
2. *'How do applications of digital solutions influence the identification and mitigation of these donor steel obstacles in early project stages?'*
3. *'What conditions for collaboration in contract and procurement phases enable or constrain donor steel integration?'*
4. *'How can insights from the previous research questions be synthesized into general findings that support early decision-making on donor steel projects?'*

Insights from sub-questions 1-3 were synthesized to answer sub-question 4, generating practice-based insights that extend beyond the existing literature.

1.5 Dura Vermeer context

Dura Vermeer is the supervising partner of this research. The company has several specialized divisions, including built environment and infrastructure, each with its own unique expertise. These experts provide valuable in-depth feedback for the research. As one of the leading contractors in the Dutch construction sector, Dura Vermeer ensures the study remains closely aligned with real-world industry practices and conditions.

The company already has extensive knowledge and experience with the reuse of structural steel. Several past projects have applied donor steel, and current projects continue to explore its potential. These cases provide a valuable foundation for the thesis. Moreover, the company has signed the 'Staalbouw akkoord 2022', which shows its ambitions towards a circular steel industry. Therefore, the research question addressed in this thesis is directly relevant to Dura Vermeer's sustainability ambitions. The company has committed itself to the transition of the construction industry, with one of its transition pathways focusing on the sustainable use and reuse of steel.

1.6 Double degree explanation

This thesis will be the first part of a graduation period as part of a Double Degree program, in which MSc Architecture, Urbanism and Building Sciences and MSc Construction Management and Engineering are combined. This thesis will fulfill the graduation requirements for the MSc in Construction Management and Engineering. In addition, it will serve as a foundation for the MSc Architecture, Urbanism, and Building Sciences thesis.

1.7 Thesis structure

This section outlines the thesis, connecting all the chapters and research questions. Figure 1.4 illustrates the chapters of this thesis and their connections to the sub-questions.

Chapter 1 introduces the master's thesis, explaining the background, problem statement, scope definition, and research questions.
Building on the introduction, **Chapter 2** presents a literature review of the circular economy concept and its design strategies. Here, the obstacles to adopting steel reuse identified in the existing literature are presented. Moreover, the innovations and technologies available to overcome these obstacles are elaborated. Additionally, the different Dutch procurement and contracting strategies are presented, and their roles in shaping the conditions for collaboration and stakeholder engagement.
Building on the literature review and the identified research gap, **Chapter 3** presents the methodology, which uses a twofold approach to address the main research question.
Furthermore, **Chapter 4** presents the results of the twofold approach, the exploratory research and case study research. The data from the exploratory interview are presented on the obstacles identified by various stakeholders in the construction sector, followed by data from the multiple-case study research on various domains, and then a cross-case analysis.
The results of the empirical research are then analysed alongside the literature review in **Chapter 5**, which elaborates on how the research findings fit within the existing literature and explains the research's limitations.
Lastly, **Chapter 6** presents the conclusions of this thesis, answering the sub-question and the main research questions, and offering recommendations for future work.

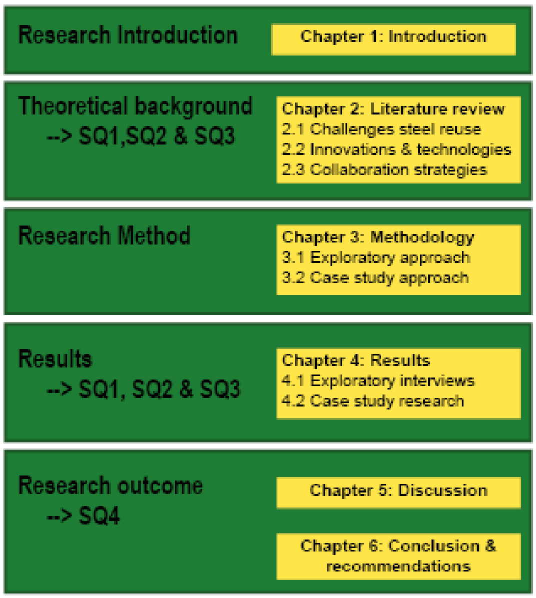


Figure 1.4: Thesis outline.

2. Literature review

The literature review elaborates on the relevance of steel reuse practices, the obstacles associated with them, and presents applications of digital solutions to overcome these obstacles. Furthermore, early collaboration and stakeholder engagement are essential for donor steel integration. Therefore, the most common Dutch procurement procedures will be discussed from a collaborative and stakeholder engagement perspective.

Diving deeper into the R-strategies, studies show that reusing steel can reduce CO2 emissions by up to 87% compared to producing virgin steel. In contrast, recycling steel reduces CO2 emissions by only 50-60% compared to virgin steel (Hart et al., 2019).

Table 2.1: CO2 emissions of recycled steel and reused steel (based on Commissie Verduurzaming Bouwketen Staal, 2025).

Production route	**CO_2 -emission per ton of steel**
Steel scrap in an electrical oven (EAF) with grey electricity	500-750 kg CO_2/ton steel
Steel scrap in an electrical oven (EAF) with green electricity	350-400 kg CO_2/ton steel
Reused steel; donor steel	100 kg CO_2/ton steel

There are multiple scenarios for the reuse of structural steel, depending on the scale and degree of the intervention (PROGRESS project, 2021). The different scenarios and interventions, along with their descriptions, are listed below (Figure 2.1).

D_0: Reuse of the entire steelwork or its part (e.g., several bays) in situ without disassembly
D_1: Reuse of the whole disassembled steelwork (may include the envelope)
D_2: Reuse of the fabricated components (e.g., sandwich panels, columns)
D_3: Reuse of the constituent products (e.g., sections, plates)

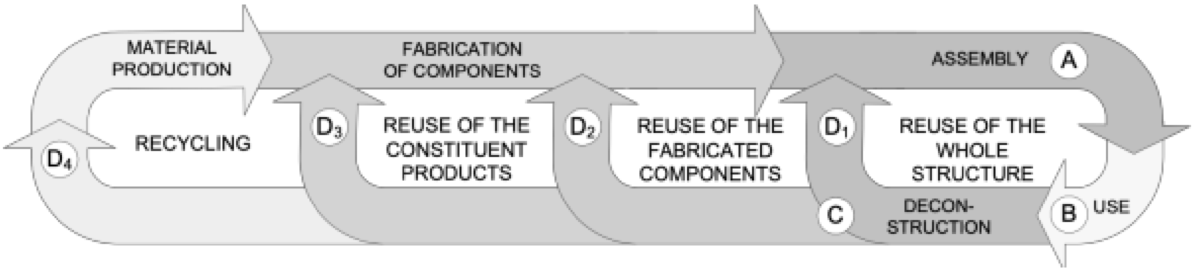


Figure 2.1: Different scenarios for the reuse of structural steel (PROGRESS project, 2021).

The focus of this thesis primarily lies on scenarios D_1 and D_2. This method represents the most feasible approach for donor steel projects. Additionally, this method aligns with Dura Vermeer's ambitions and the national goals for circular construction (Bouwakkoord staal, 2022).

To conclude, the reuse of steel offers greater environmental benefits than recycling. Among the different methods, the reuse of individual structural elements (component level) is the most relevant for the Dutch construction industry, so-called donor steel elements. However, this method presents significant technological and organizational challenges. These aspects will be discussed in the following subsections.

2.1 Obstacles to steel reuse

The obstacles associated with the large-scale application of donor steel are the following, which have been distinguished from the literature review:

- Supply and demand
- Certification and design standardization
- Absence of legal frameworks
- Costs and economic uncertainty
- Collaboration and transparency

The obstacles are interconnected, encompassing economic, institutional, and technical aspects, and must be addressed to scale up the use of donor steel in the construction industry. In addition, the obstacles are treated as equally important, since the literature review does not indicate their relative severity or rank.

2.1.1 Supply and demand

The current availability of donor steel is insufficient despite the market demand. Factors such as timing, size, quantity, and grade make design integration more complex (Dunant et al., 2018). Supply and demand pose distinct obstacles and logistical puzzles in scaling up the use of donor steel. In addition, timing is often the most problematic aspect, as demolition and deconstruction occur at different times, and storing the steel for a period is necessary, resulting in extra costs, as elaborated in § 2.2.4 (Tingley et al., 2017).

First, the supply of donor steel involves identifying steel that will no longer serve its current purpose. Two cases that could occur are: the site of a building is repurposed (e.g., an office or school is demolished), or the structure no longer fulfills its intended purpose (e.g., an outdated bridge that is no longer in use). In these cases, the steel's current condition needs to be known or tested. Assessing the material properties of steel is often uncertain, which is a significant obstacle to its reuse (Tingley et al., 2017). The material properties are not always properly documented at the beginning of a steel component’s lifecycle; if this is not the case, testing is needed to determine the residual strength of the element. Information management from the beginning of a component's lifecycle is essential.

Figure 2.2 illustrates the various information and material flows between stakeholders to ensure effective information management. Most of the time, information flows from the fabricator to the supplier between components (“elements”). They are responsible for the data of the steel components during the early lifecycle stages (Dunant et al., 2017). These two stakeholders play a crucial role in ensuring the vertical integration of information within the supply chain. This reduces the uncertainty regarding the quality of the steel components. To elaborate, vertical integration is the arrangement of the supply chain in which stakeholders pass their knowledge across the various stages of the process.

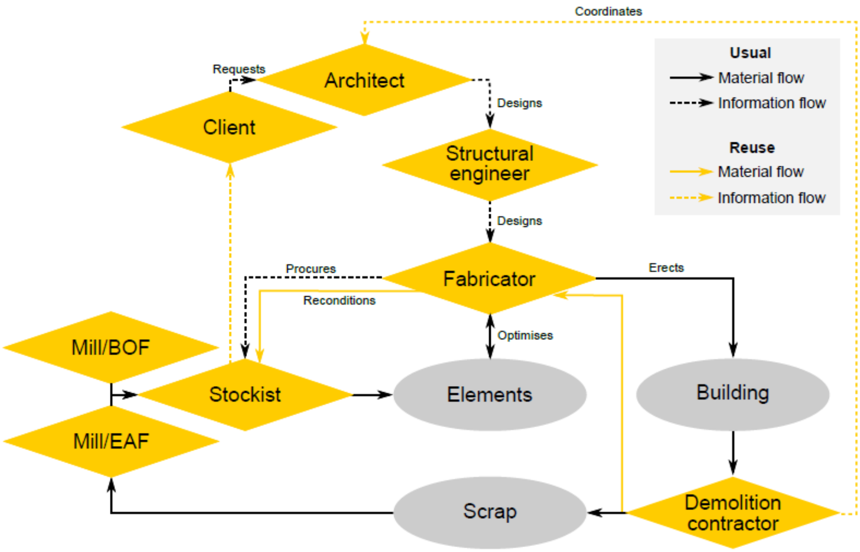


Figure 2.2: The information and material flows of steel in the construction value chain between different stakeholders. (Mill/BOF and Mill/EAF are steel fabricators) (Dunant et al., 2017).

Second, the demand for donor steel is not continuous, which presents additional obstacles. When donor steel is harvested, and the material properties of the components are established, a suitable location for the reused components must be identified. The location and properties of the donor steel are interconnected; specific properties may be suitable for one location but not for another. The intended application site and current condition of the donor steel are therefore interconnected. The challenge is finding a new application at the right place and time (Kanyilmaz et al., 2023). In addition, if the right steel is not available at the right place, for example, across the country, transportation costs and emissions lower the value of donor steel (Tingley et al., 2017). The supply and demand of donor steel must align, and eliminating supply uncertainty for stakeholders is essential to a successful process.

When direct application of donor steel is not possible, the steel components need to be stored and mapped. Currently, there is a lack of centralized stockyards. Additionally, the existing stockyards lack transparent databases, which limits predictability and makes it difficult for architects to work with donor steel (Kanyilmaz et al., 2023).

The supply-and-demand imbalance for donor steel creates uncertainty in the procurement process, eroding confidence in donor steel as a reliable option.

2.1.2 Certification and design standardization

The second obstacle is the certification and design rules for reused steel components. Currently, numerous NEN standards are available for designing with ‘new steel’. These specifications outline the design requirements and are referred to as Eurocodes (CEN members, 2002). The Eurocodes ensure safe designs for load-bearing structures in projects. Together with the Duch Building Decree, they form a safe foundation for design practices in the Netherlands (Eikelboom et al., 2001). As mentioned before, these standards apply to new designs; therefore, they do not apply to reused steel.

The absence of these standards for donor steel creates uncertainty regarding the testing of the mechanical performance and safety. Recently, a national initiative, NTA 8713 (2023), has been developed, providing a guideline (not a standard) for the design of buildings using reused steel components (Bouwen met Staal, 2024). Moreover, the Platform CB'23 also provides first steps towards reuse protocols, although these are not yet widely adopted (Platform CB'23, 2021). These initiatives and platforms represent the first step in establishing guidelines for constructive donor steel. For other types of steel, such as sheet piles or steel secured from infrastructure projects, there are currently no guidelines in place. As a result, not all types of steel can be assessed for safe reuse, and limited knowledge of how to test them hinders reuse (Kanyilmaz et al., 2023). The absence of NEN standards presents a challenge for engineers, hindering the implementation of donor steel.

The question is, why are these standards not being developed? Unfortunately, this is a very complex process, and these adaptations present high costs. Writing new Eurocodes requires collaboration among hundreds of experts and involves collaboration among national standardization bodies, industry experts, and technical experts (Denton et al., 2012). This is a highly time-consuming and intensive process involving numerous stakeholders. This process ensures donor steel is available for fast and smooth implementation. Although the standards need to be addressed and developed, the first steps towards donor steel need to be taken outside the existing codes, using NTA 8713 and Platform CB'23.

2.1.3 Absence of legal frameworks

The legal and regulatory environment for steel reuse is underdeveloped (§2.1.2). The absence of standards for donor steel makes CE marking and liability rules even more challenging, as they are also designed for new products (Kanyilmaz et al., 2023). Products need to be approved and regulated at the European level (Halonen et al., 2024). All construction products are marked with a CE marking, which signifies compliance with relevant EU legislation (Condotta & Zatta, 2021). Construction products can only be sold if they have this mark and approval. The standard marketing conditions of these products are set by the Construction Products Regulation (CPR) within the European Economic Area (EEA) (Parliament, 2011). These conditions form the 'technical language' for evaluating construction products based on their performance and for creating a universal approach across the EU (Condotta & Zatta, 2021).

This process is illustrated in Figure 4.2. The products receive a CE marking once all the required checks have been completed. The CE marking assesses the performance of an individual component, taking into account its specific application. The CE marking, also known as the Declaration of Performance (DoP), is required for all construction products to verify their suitability for application (Halonen et al., 2024).

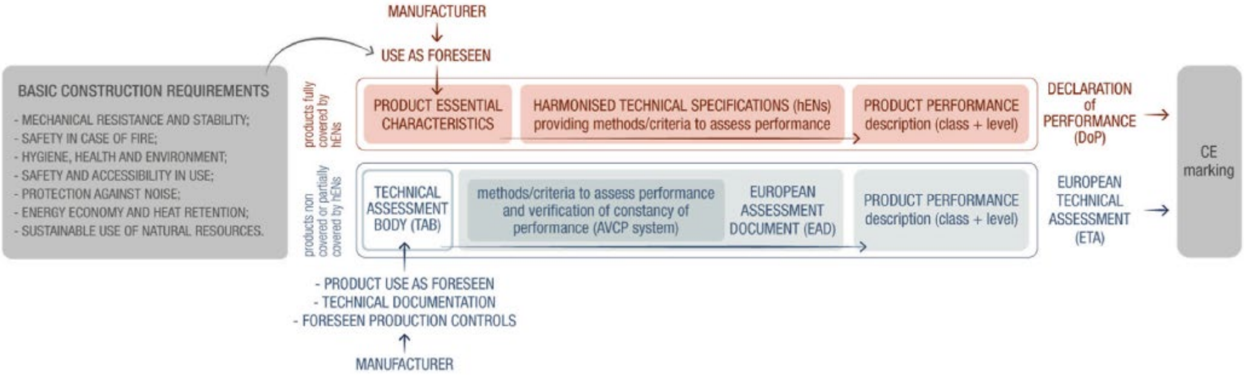


Figure 2.3: Standards for construction products in the EU leading to the CE marking (Condotta et al, 2021).

For reused products, such as donor steel, two challenges arise when obtaining the CE marking. First, the donor steel is already on the market, and the process shown in Figure 2.3 to obtain a CE marking is only for new products (Halonen et al., 2024). Currently, there is no opportunity for donor steel to obtain a CE marking.
Second, even if it were possible, the existing process and standards do not apply to testing donor steel performance. These standards are only designed for the performance testing of new components. The gaps in processes like these are referred to as 'legal vacuums' and present a critical obstacle to implementing donor steel (Condotta & Zatta, 2021). These gaps need to be filled; an example of the potential flow of reused elements, as required by EU laws, is illustrated in Figure 2.4. This figure illustrates a method for reusing elements to obtain a CE marking, thereby positively impacting the market for reused projects.

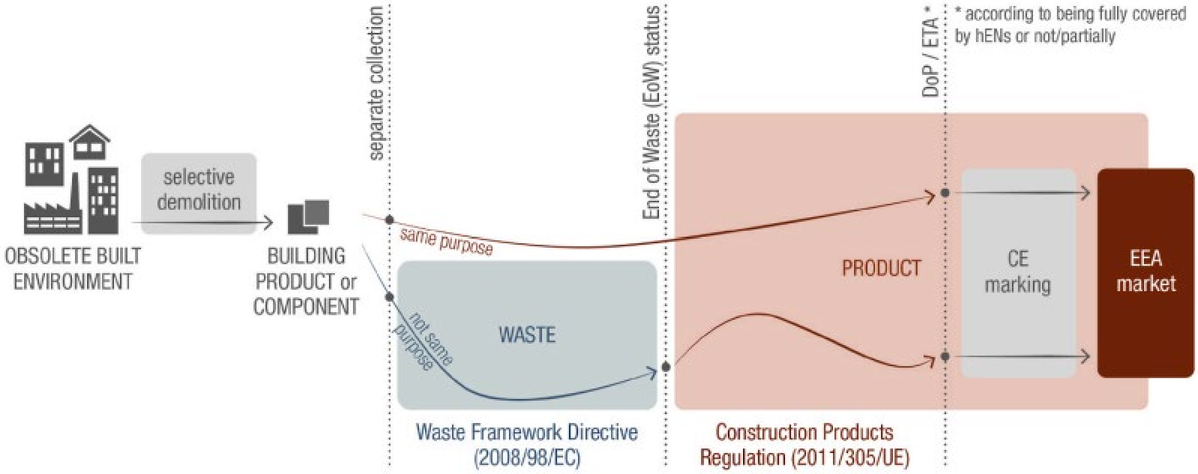


Figure 2.4: Potential flow for reused construction products in the EU leading to the CE marking (Condotta & Zatta, 2021).

2.1.4 Costs and economic uncertainty

Currently, donor steel is, in most cases, more expensive than using new steel components (Dunant et al., 2018). The main cost drivers are selective deconstruction, storage, cleaning, testing, and certification (Tingley et al.,2017). However, donor steel can be more profitable under the right circumstances. When the dismantling location is close to the reuse site, and the components require no additional testing, donor steel can be more cost-effective than new steel components (Dunant et al., 2018). Under the wrong circumstances, reuse can increase costs and thereby hinder the adoption of donor steel.

Measuring the exact cost difference is complicated and uncertain, while the cost of producing a new component is unclear (Cheng et al., 2024). This process consists of multiple stages, from design to erection, and involves numerous stakeholders. Additionally, reusing steel involves multiple stages, including careful deconstruction and, in some cases, storage costs. Storage costs can vary significantly by location. Figure 2.5 illustrates this comparison in terms of cost and process. In short, determining the profit or loss per stakeholder is very challenging; as a result, it often remains uncertain, which hinders the adoption of donor steel.

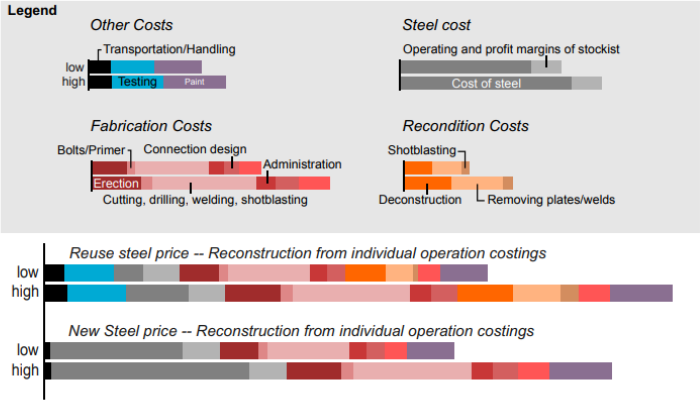


Figure 2.5: Comparison between reused and new steel prices (Dunant et al., 2018).

Although cost plays a crucial role in the successful adoption of donor steel, the carbon savings are not rewarded in this process. Currently, carbon reductions are not systematically integrated in tendering or procurement models (Kanyilmaz et al., 2023). In some cases, the client emphasized the 'Environmental Cost Indicator' (ECI), which measures the shadow costs of environmental impacts (Yeung et al., 2017). Shadow costs are the hidden costs of environmental impacts, expressed in monetary terms, that are not directly included in the price of a product or service. The ECI is specifically for infrastructure, built environment uses the Milieu Prestatie Gebouwen (MPG), both use the same calculation method; the Life Cylce Analysis (LCA). The lack of integration of environmental impact indicators results in weak economic incentives, making donor steel applications almost possible only under client-driven sustainability ambitions or in projects with clear carbon-reduction goals.

2.1.5 Collaboration and transparency

Finally, to scale up the application of donor steel systematic collaboration across the supply chain is crucial. The obstacles mentioned earlier are closely related to the level of trust or distrust among all stakeholders in the supply chain. The construction industry is currently highly fragmented, characterized by limited data sharing and divided responsibilities (Tingley et al., 2017). Transparent information on material flows is essential to designers; otherwise, they cannot anticipate reuse possibilities, and demolition contractors do not prioritize deconstruction over scrap sales. Initiatives such as the Dutch 'Bouwakkoord Staal' (2022) and its Roadmap 2023 highlight the need for sector-wide change, cooperation, transparency, and the use of material passports (BAS, 2022).

In contrast, the nature of the construction industry is not particularly open to innovation and tends to adopt a resistant attitude (Hart et al., 2019). Large organizations are reluctant to change their way of working because the linear approach is deeply ingrained in their culture. The shift towards reuse requires greater flexibility from designers, as they must work with limited steel components. The circular approach is often perceived as a restriction of design freedom, and innovative engineering solutions are therefore necessary.

Lastly, trust in reused components is crucial, including for the structure's users. The lack of confidence in reused components and uncertainties in quality and design standards can lead to distrust among users. This obstacle is linked to design standards to ensure safe design. However, the consensus on the environmental benefits of reuse is clear and will positively contribute to acceptance (Tingley & Davison, 2011).

2.1.6 Summary of the obstacles

The literature review revealed five obstacles to the adoption of donor steel. The obstacles cover various disciplines.

1. **Supply and Demand**: Material properties are sometimes uncertain. If the properties are known, the right project must be identified. One component may be suitable for one location but not for another. The donor steel must be available at the right place and time, which requires aligning supply and demand.
    - Material properties (Technical)
    - Availability (Technical/Organizational)
2. **Certification and design standards**: The existing NEN standards are only applicable to new designs. The NTA 8713 provides guidelines for the reuse of steel from buildings; however, a gap remains for steel profiles from infrastructure projects.
    - Assessing structural safety (Technical)
3. **Absence of legal frameworks:** In the EU, components can be qualified with a CE mark, but this is not possible for reused materials.
    - EU regulations (Regulatory)
4. **Cost and economic uncertainty:** The cost for donor steel is higher compared to new steel components, and is not evenly distributed in the construction industry. Costs are important to companies and contribute to the successful adoption of donor steel.
    - Cost (Economic)
5. **Collaboration and transparency:** The entire construction industry needs to be engaged and trust in the supply chain must be built. The resistant attitude needs to change towards a more open-minded approach.
    - Attitudes and perceptions (Behavioural/Organizational)

Table 2.2: Summary of the identified obstacles in the existing literature.

Obstacles	Explanation	Category
Supply and demand	- Material properties - Availability	➔ *Technical* ➔ *Organizational*
Certification and design standards	- Assessing structural safety	➔ *Technical*
Absence of legal frameworks	- EU regulations	➔ *Regulatory*
Cost and economic uncertainty	- Cost	➔ *Economic*
Collaboration and transparency	- Attitudes and perceptions	➔ *Behavioral/Organizational*

2.2 Digital solutions for steel reuse

The applications for the following digital solutions, to speed up the donor steel process and to overcome the identified obstacles, are:

- Material testing
- Material passports
- Reality capture methods
- BIM model
- Digital twins

The different applications of these technologies can help facilitate the integration of donor steel projects.

2.2.1 Material testing

The foundation for donor steel is material testing, which ensures the structural safety, durability, and compliance with certification requirements of the reclaimed steel components. Many existing steel members lack traceable documentation and CE marking; testing the material establishes the chemical, mechanical, and geometrical properties before reuse (Brown et al., 2019). Material tests also support the re-certification process under NTA 8713 (2023) and BS EN 1090, ensuring that the donor steel meets the Eurocode design standards. When no or insufficient information is available about the steel, the material must be tested at multiple levels to ensure its quality. The different tests can be categorized into three themes, elaborated below.

Dimensional and visual inspection
Each component of a batch must be inspected for straightness, geometric tolerances, and corrosion, in accordance with BS EN 1090-2 and EN 10034/10056. Components with deformations over 5% of the section thickness are considered critical and must be corrected or excluded from reuse. Additionally, visual examination reveals corrosion, plastic deformation, and fire damage, all of which can affect residual strength (Brown et al., 2019).

The geometric data for each component must be recorded in a database, along with additional test information. Later, the data can be transferred into a BIM model or material passport; the value of these technologies will be discussed in §2.2.2 and §2.2.4.

Mechanical and non-destructive testing
The application of donor steel requires the knowledge of the component's ultimate strength, elongation, ductility, and internal integrity. According to SCI P427 (Brown et al., 2019), all reclaimed components must undergo non-destructive testing (NDT) before use. Additionally, selective destructive tests should be conducted on representative samples from each batch of similar components. This batch-based approach minimizes the testing costs while ensuring reliable results.

The different non-destructive tests are:

- **Ultrasonic testing (UT):** This test detects internal cracks, laminations, and weld discontinuities by transmitting high-frequency sound waves through the component.

- **Magnetic particle testing (MT):** This test detects surface and near-surface flaws using magnetic fields and iron oxide particles.
- **Radiographic or X-ray testing (RT):** This test is particularly used for thick-welded components. The X-rays expose internal flaws, weld defects, and corrosion pockets (Applied Technical Services, 2015).
- **Hardness testing:** This test allows an indirect measurement of the steel components' strength (SCI P427, App. C).
- **Optical emission spectroscopy (OES):** This semi-non-destructive test determines the chemical composition of the steel, including alloying elements and contaminants (Brown et al., 2019 - SCI P427, App. E).

In addition to the NDT, destructive mechanical testing is performed on one or more components of the batch. These tests provide yield and ultimate strength, elongation, strain behavior, and determine toughness at various temperatures (Brown et al., 2019). Brütting et al. (2019) explained that such mechanical verification enables the reuse of steel components across projects with minimal safety risks. This confirms that donor steel retains its structural performance after decades of use.

Chemical composition and weldability
Following NDT testing, chemical testing is necessary to verify that the reclaimed steel components meet current weldability and durability requirements. The two tests to determine the elemental composition: 'non-destructive optical emission spectroscopy (OES)' and 'destructive chemical analysis', both on drillings or swarf (Brown et al., 2019 - SCI P427, App. E). The test results are then used to calculate the Carbon Equivalent Value (CEV), which indicates the weldability of the steel components.
For example, donor steel components with S235 or S355 (steel strength) typically have a CEV ≤ 0.45%, which is permitted for standard welding procedures. High CEV results in preheating or modified welding parameters. The maximum measured CEV in a batch is used in all cases to ensure conservative design assumptions (Brown et al., 2019).

Moreover, chemical testing helps identify toxic coatings, such as chromium VI ("chroom 6"), which are typically present in older protective paints or galvanization layers. Before the steel components are re-coated or fabricated, these layers must be tested and removed if necessary. Laboratories use surface spectroscopy, X-ray fluorescence (XRF), or chemical spot tests to test these layers; all the tests follow the Dutch ARBO safety guidelines (Brütting et al., 2019). Especially, the "chroom 6" detection is essential for safety and environmental compliance before cutting, blasting, or welding donor steel components. Once coatings are removed under controlled conditions (chemical stripping or grit blasting) and modern corrosion-resistant systems are applied, the components meet the ISO 12944 standard (Brown et al., 2019).

2.2.2 Material passports

The implementation of reliable donor steel relies on the digital documentation and traceability of test results and component data from material testing and verification procedures (§ 2.2.1). Material passports (MPs) are defined as digital interfaces that provide a certified identity of a single, identifiable component, built upon its life-cycle registrations (van Capelleveen et al., 2023). The MPs connect physical components into digital information flows, enabling understanding of their reuse potential, circular value, and sustainability performance. They unlock the intrinsic value of components by making their properties and history visible and accessible (Luscuere L.M., 2016).

This concept, the material passport, is operationalized by Platform CB'23 (2023) for the Dutch construction context and defined as *"a digital dataset that documents what an object consists of (qualitatively and quantitatively), how it is built, where it is located, and who owns it"* (Platform CB'23, 2023). The data structure enables stakeholders, including contractors, designers, asset owners, and recyclers, to utilize the same component identifiers and attribute lists, thereby providing interoperability throughout the entire construction chain.

Three main data categories can be integrated into MPs: **Material composition, Lifecycle data,** and **Circular performance indicators.** The material composition data include the chemical and mechanical properties extracted from testing (§ 2.2.1). The lifecycle data consists of usages history, manufacturing date, and prior applications. The circular performance indicators for a component are environmental impact (MKI/LCA), disassembly potential, and residual value indicators.

The Platform CB'23 (2023) makes frameworks for MPs for various levels, ranging from individual steel components to building elements and full structures. This approach ensures that the MP of a donor component reused in a new project remains linked to both the source and the new structure. Madaster (2022) and Metabolic's Circular Economy platform (2021) are international online platforms that demonstrate how MPs can be clustered into interoperable databases. Madaster (2022) forms a *"material bank"*, while Metabolic (2021) shows the potential for MPs in *"visible, valuable, and active assets within a circular economy"*.

Platform CB'23 'Leidraad'(2023) constructed a standardized framework for using open data formats (e.g., RDF/linked data) and hierarchical levels based on the NEN 2550-2 and EN 15804. This structure enables MP data to be accessible across decades and software systems, which is necessary for long-life infrastructure assets. The data will remain with its source (e.g., demolition contractor or steel supplier) while being connected via standard component identifiers, ensuring privacy and accessibility, forming a hybrid governance model (Platform CB'23, 2023).

MPs have clear benefits, but also several challenges will remain: **data interoperability, data quality**, and **adoption incentives.** The data interoperability integrates passport initiatives and the taxonomies and units between different software systems, which remain complicated. Moreover, ensuring accurate data quality and verified entries from testing laboratories and suppliers remains challenging. Additionally, adoption incentives remain complex, making it difficult to align data registration costs with the long-term value of recycling and ownership.

However, Rijkswaterstaat recently conducted pilot projects with the GWW-passport at the Rabobank UC18 renovation, demonstrating that MP can successfully integrate as-built data, testing results, and ownership structures into a single coherent record (Platform CB'23, 2023).

MPs, in combination with material testing (§ 2.2.1), create a traceable digital identity for every donor steel component. This digital identity enables certified reuse, supports LCA assessments, and facilitates integration into BIM and future digital twin environments (see § 2.2.4 and § 2.2.5), thereby closing the feedback loop between circular data management and physical assets.

2.2.3 Reality capture methods

Reality capture technologies can serve as bridge between physical donor steel components and their digital representation. The digital representation can aid in material testing and be linked to the MPs. Reality capture methods are: ‘laser scanning (LiDAR)’, ‘photogrammetry’, and ‘3D scanning’. These methods enable precise documentation of as-built conditions and support the integration of donor steel data into BIM environments. This process can serve as the technical foundation for the Scan-to-BIM workflow, in which existing components are transformed from physical structures into digital, reusable assets (Kovacic & Honic, 2021). In § 2.2.4, BIM models, their possibilities, and integration will be further elaborated.

3D scanning utilizes active or passive sensors to collect millions of spatial data points, which together form a detailed “point cloud” of the donor steel component. The most accurate method for donor steel components is laser-based scanning, with point precision within 2-5mm under optimal conditions (Li et al., 2024).

For donor steel components, 3D scanning offers a non-destructive and data-rich alternative to traditional manual surveying. This new approach enables precise measurements of geometry, corrosion damage, alignment, and deformation, enabling engineers to more accurately evaluate whether a steel component can be dismantled and reused (Nagy et al., 2022).

Most structural components in demolition projects lack documentation or show deviations due to deformation or fire exposure (van Hooff, 2021). In these cases, scanning can provide objective data on the component's current state, even before material testing and dismantling, saving time and costs. This enables decisions on Value Retention Processes (VPRs), such as refurbishment or repair, which highly depend on accurate dimensional and geometric information.

3D scanning is an essential enabler for urban mining and BIM-based resource assessment (Kovacic & Honic, 2021). Kovacic and Honic (2021) developed an Integrated Data Assessment and Modeling (IDAM) framework that couples laser scanning with ground-penetrating radar (GPR) to capture both geometric and subsurface information. The integration enables the creation of detailed as-built BIM models that include material compositions and structural geometry. This is a necessity for generating MPs and realizing material stocks.

The compatibility between 3D scanning, material passports (MPs), and BIM models is essential for scaling up donor steel implementations. Data collected from 3D scanning, such as deformation, geometric profiles, component identifiers, and corrosion levels, can be linked to the passport entries using open data schemas (e.g., IFC, RDF). The research by Kovacic & Honic (2021) demonstrates that point cloud data can be effectively integrated with material and test data. These combined data sets can then generate BIM-supported material passports that form the foundation for digital secondary material cadastres.

Moreover, the 3D scanning can be part of a digital information ecosystem that fills the ‘information gap’ between disassembly and new design stages (Byers et al., 2024). Scanned geometries enable automatic component classification for reuse, facilitating the connection between supply-side data (donor buildings) and demand-side design models. Creating a continuous data loop from scan to MP to BIM model, where each donor component has its own digital identity and can evolve through multiple reuse cycles.

2.2.4 BIM models

Building Information Modeling (BIM) is a digital representation of a project that integrates data for analysis, design, and decision-making through standardized formats such as Industry Foundation Classes (IFC). Model View Definitions (MVDs) are implemented in the BIM and specify the information exchange between subsets for specific workflows. This mechanism ensures the connectivity between different software disciplines (Sanchez et al., 2024). This central digital environment connects fragmented BIM datasets into a comprehensive digital ecosystem that supports decision-making for reuse, construction, and circular design. The BIM serves as a data archive and a platform for scenario simulation, bridging the gap between existing and future building lifecycles (Koutamanis et al., 2023).

BIM is a combination of processes, technologies, and policies that help to manage building information throughout its lifecycle (Succar et al., 2012). Traditional modeling tools do not go as far as BIM, which goes beyond geometric information. BIM also incorporates semantic, temporal, and environmental data, forming a multidimensional framework for project planning. This enables the integration of Design for Deconstruction (DfD) and Material Passports (MPs), 3D scanning, and material testing data, turning static digital models into dynamic, data-driven material banks (Mercado S., 2020).

The integrated approach of BIM allows donor steel components to be easily identified, assessed, and reused, with traceable information on their mechanical properties, disassembly characteristics, and environmental impact. 3D scanning (§ 2.2.3) provides high-quality geometric data, in combination with the registration of MPs (§2.2.2), the BIM functions as a data convergence layer. BIM links the geometric, material, and environmental attributes using standardized data schemas (e.g., IFC, RDF, CoBie), enabling a data archive across design, construction, and facility management platforms (Huang et al., 2023).

The BIM workflow, reuse-oriented, builds on three sequential stages.
First, **Software implementation and model enrichment.** The BIM can combine datasets from testing, MPs, and scanning with the rest of the design into one model. Open data structures (e.g., IFC/RDF) provide cross-system connections, enabling each donor steel component to maintain its own identity and history (Huang et al., 2023). Moreover, the Scan-to-BIM process delivers as-built geometries of all the building components, which can be connected to material and testing data, serving as a 'digital twin' (§ 2.2.5) later in the process (Esnaashary Esfahani et al., 2019).
Second: **Disassembly analysis.** The framework of Mercado Siles (2020) showed that BIM can calculate the Deconstructability Score, which evaluates the level of disassembly and reuse possibilities. Parameters such as accessibility, connection type, and contamination risk are also included in the BIM object properties. With these parameters, the model can simulate 4D and 5D disassembly sequences to optimize logistics, costs, and safety. These mechanisms for real-time updates form the basis for the Digital Twin framework (§2.2.5).

Third, **Reuse and scenario modelling.** The validated donor components can be digitally transferred into new BIM models, with links to their MPs and LCA values. This 6D BIM-LCA coupling model calculates embodied carbon reductions and energy savings, enabling early-stage comparisons of reused and new materials (Gao et al., 2024). In addition, this stage ensures that donor steel components retain their data identity when used in a new project, enabling traceability in future reuse cycles (Koutamanis et al., 2023).

Sanchez et al. (2024) combined all steps to form a standardized MVD system, integrating disassembly planning into the BIM model (see Figure 2.6).

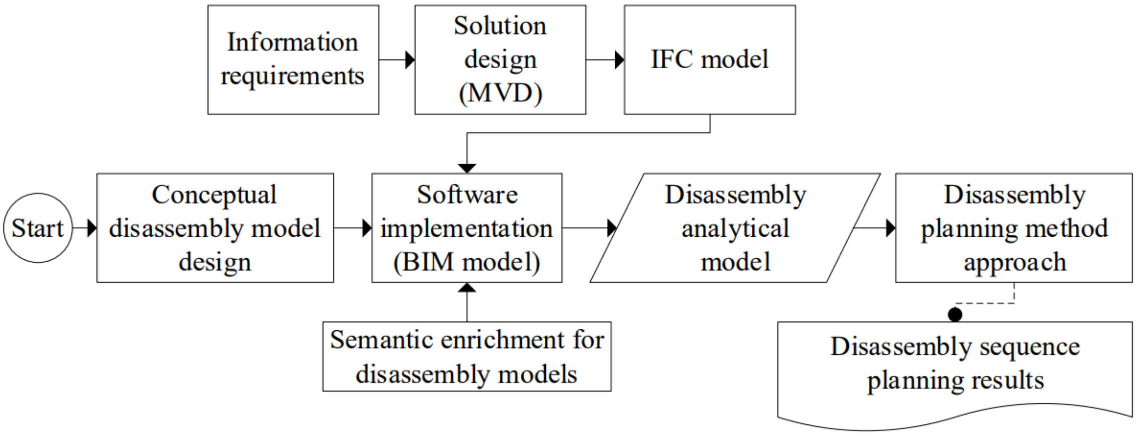


Figure 2.6: Workflow for the implementation of a disassembly planning MVD for BIM models (Sanchez et al., 2024).

Despite these benefits, the BIM's full potential for donor steel is hindered by several technical and institutional challenges: **Interoperability and data integration, Information completeness,** and **Organizational resistance.** The Integration of the different data sets from testing, 3D scanning, MPs, and LCA requires standardized schemas and robust Application Programming Interfaces (APIs) across the sector (Huang et al., 2023). Moreover, information or models from the donor structure often lack the detailed information needed for accurate reuse planning (Esnaashary Esfahani et al., 2019). Additionally, the industry needs to shift from project-based to life-cycle-based data management, which requires new contractual frameworks and collaborative structures between stakeholders (Mercado Siles, 2020).

These challenges need to be addressed to develop the open BIM system for circularity (CB'23, 2023) and to link it to sensor-based platforms for real-time monitoring, which serve as a connection to Digital Twin environments, as elaborated in § 2.2.5 Digital Twin.

2.2.5 Digital Twins

Digital Twins (DTs) established through BIM (§ 2.2.4) represent the next evolutionary step in digital construction technologies. BIM models provide comprehensive, static digital models, whereas Digital Twins incorporate real-time data, enabling two-way interaction between the digital model and its physical asset. The DT creates a continuously updated information environment that shows the current condition and predicts the performance of each component, thereby completing the feedback loop among design, operation, and future reuse (Meng et al., 2023).

The DT can evolve from the BIM; the BIM delivers structured, object-based information, while the DT adds sensing, simulation, and synchronization. Transforming the BIM form "as-designed" to "as-lived" DT model, where real-time data from inspection devices, sensors, and IoT systems (Internet of Things) continuously update the DT (Meng et al., 2023).

The Digital Twin environment combines three technologies to ensure a living representation that can monitor degradation, predict maintenance needs, and inform the next reuse cycle (Liu et al., 2023). These three technologies are: **IoT and data transmission networks, 3D model-based simulations,** and **Machine learning analytics.** First, the Internet of Things (IoT) consists of a network of physical objects that connect to the internet and gather real-time data. Second, 3D model-based simulations, such as BIM models, are used to create a 3D representation of the physical objects in a system, containing data and properties for every object. Third, machine learning is a form of artificial intelligence that trains the DT to improve itself by collecting and analysing data. This way, DTs are trained to make real-time adjustments based on data collected from the physical asset, helping decision-making in a project.

The DT has been recognized as a key enabler of sustainable material management within the circular economy (Meng et al., 2023). DTs enable construction actors to quantify, visualize, and optimize circular material flows, connecting demolition, reuse, and new design more easily. In the realization of projects, DTs enable: **Dynamic monitoring of reused elements, Traceable lifecycle monitoring,** and **Predictive planning.**
Where dynamic motoring of reused components ensures that donor steel components meet the safety and performance expectations of the new design. IoT sensors provide real-time data on donor steel components, such as vibrations, corrosion, and strain (Meyendorf et al., 2023). With traceable lifecycle monitoring, the MPs of donor steel components can be enhanced with new data after each reuse cycle. Moreover, predictive analytics can be used in a DT to estimate the Remaining Useful Life (RUL) of structural components, enabling engineers to identify when donor steel components need to be inspected, repaired, or replaced (Liu et al., 2023). Additionally, predictive planning helps determine dismantling or maintenance timing, which can be assessed based on real performance trends. Additionally, DTs can simulate future disassembly and reuse scenarios, enabling designers to plan and design with donor steel components (Meng et al., 2023).

The dynamic nature of the DT makes it a "circular enabler" that can manage data from multiple sources, including real-time asset data, BIM databases, and MPs, all in a single system. The real-time integration provides data confidence and decision transparency for reuse strategies, making the reuse process more organized (Boje et al., 2020).

Despite these benefits, the DT's full potential for donor steel is hindered by several challenges limiting large-scale implementation: **Model integration, Data volume and complexity,** and **Standardization and governance.** The model integration remains a technical bottleneck, due to the integration of data from multiple sources: MPs, BIM, and sensors (Boje et al., 2020). Moreover, the data volume and complexity indicate that the real-time sensor networks need advanced cloud storage and processing capabilities; not every project has access to or funding for these resources. Additionally, the standardization and governance mechanisms currently hinder consistent circular applications, while there is no open standard for Digital Twin data exchange (Meng et al., 2023).

However, integrating DTs with circular economy principles provides long-term benefits, such as reduced waste, increased material recovery rates, and improved salvage value throughout the lifecycle of construction assets (Meng et al., 2023).

2.2.6 Summary opportunities innovations and technologies

In summary, innovations and technologies can help overcome the obstacles mentioned in § 2.1. Figure 2.2 summarizes the added value of each technology for each obstacle mentioned in §2.1; see Appendix G for the detailed version.

Table 2.3: Summary of the added value for each technology for each obstacle in § 2.1.

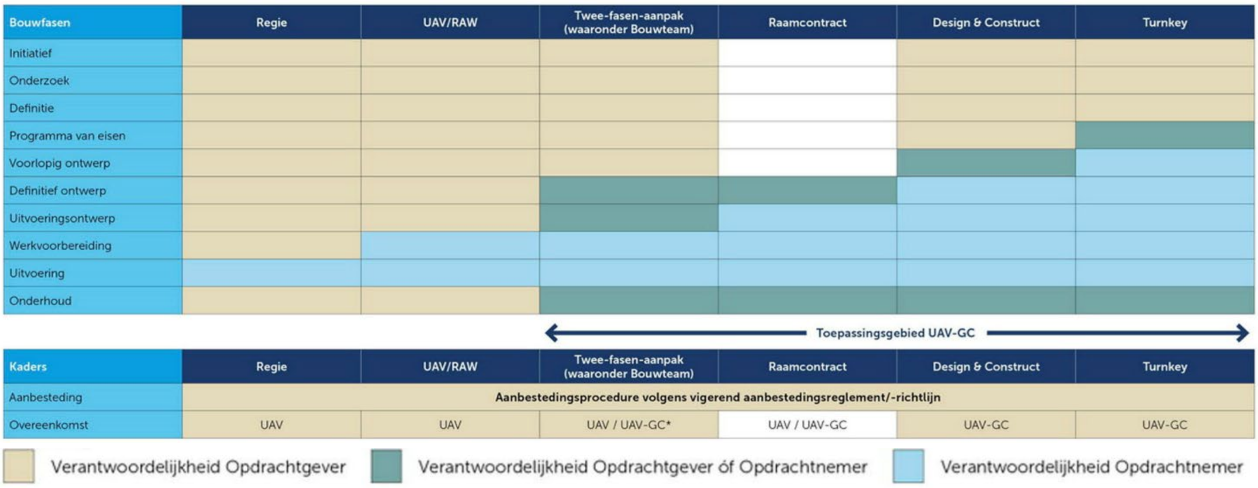
Obstacle (§ 2.1)	**Added value of:**			
	MP's	***3D scanning***	***BIM model***	***Digital Twins***
Supply & Demand	- Overview of supply - Support digital environment	-Accurate geometrical documentation	-Integrates inventories -Provides early reuse matching	-Continuous tracking with IoT & sensors -Dynamic inventory
Certification & Design standardization	-Link test & CE data to component (according to NEN/NTA)	-Detailed dimensional data -Supports safety assessments	-All data in one model (MP, testing, 3D, ECI) -Ensuring traceable quality control	-Real-time monitoring for recertification standards
Absence of legal frameworks	-Shared data governance -Standardized platform (CB'23)	-Measurable records -Legal documents for certification	-Open data standards -Providing transparent governance data	-Transparent, traceable digital thread -Linking physical to digital
Costs & Economic uncertainty	-Document environmental values (e.g., ECI, CO_2) -Strengthening CE business	-Reducing redesign & surveying costs	-Real-time lifecycle & cost simulations (5D BIM/ LCA) -visualizing financial & environmental benefits	-Reducing replacement cost by predictive forecasting
Collaboration & transparency	-Creates digital language -Allowing cross-case reuse & lifecycle management	-Facilitating data exchange (Scan-to-BIM model) -Improving workflow coordination	-Shared visual data platform for actors -Improving coordination & decision-making	-Shared accessibility to live data -Providing trust and coordinated decision-making

2.3 Collaborative conditions

To integrate donor steel into the early design stages, a project needs intensive collaboration, shared risk management, and early stakeholder engagement. Procurement and contracting strategies play a decisive role in shaping these collaboration conditions and stakeholder engagement, and in determining when stakeholders are involved, how responsibilities are allocated, and whether incentives for transparency and joint problem-solving exist (de Ridder H.A.J., 2009). The six most common Dutch procurement procedures will be discussed from the perspective of collaboration and stakeholder engagement, which are:

- **Coordination of management** (Regie)
- **Bid-Build** (RAW-Bestek)
- **Design team, Alliance & Partnering, two-phase contracts** (Collaborative models)
- **Framework agreement** (Raamcontract)
- **Design-Construct & Engineering-Construct** (D&C, E&C)
- **Design, Build, Finance, Maintain** (DBFM)

These procedures are presented in Figure 2.7, providing an overview of the tender and procurement processes and their associated risk distributions (Dura Vermeer, 2024). The procedures are positioned from traditional models to Integrated Project Delivery (IPD).



Bouwfasen	Regie	UAV/RAW	Twee-fasen-aanpak (waaronder Bouwteam)	Raamcontract	Design & Construct	Turnkey
Initiatief	🟨	🟨	🟨	⬜	🟨	🟨
Onderzoek	🟨	🟨	🟨	⬜	🟨	🟨
Definitie	🟨	🟨	🟨	⬜	🟨	🟨
Programma van eisen	🟨	🟨	🟨	⬜	🟨	🟩
Voorlopig ontwerp	🟨	🟨	🟨	⬜	🟩	🟦
Definitief ontwerp	🟨	🟨	🟩	🟩	🟦	🟦
Uitvoeringsontwerp	🟨	🟨	🟩	🟦	🟦	🟦
Werkvoorbereiding	🟨	🟦	🟦	🟦	🟦	🟦
Uitvoering	🟦	🟦	🟦	🟦	🟦	🟦
Onderhoud	🟨	🟨	🟩	🟩	🟩	🟩

← Toepassingsgebied UAV-GC →

Kaders	Regie	UAV/RAW	Twee-fasen-aanpak (waaronder Bouwteam)	Raamcontract	Design & Construct	Turnkey
Aanbesteding	Aanbestedingsprocedure volgens vigerend aanbestedingsreglement/-richtlijn					
Overeenkomst	UAV	UAV	UAV / UAV-GC*	UAV / UAV-GC	UAV-GC	UAV-GC

🟨 Verantwoordelijkheid Opdrachtgever 🟩 Verantwoordelijkheid Opdrachtgever óf Opdrachtnemer 🟦 Verantwoordelijkheid Opdrachtnemer

Figure 2.7: Typical Dutch construction tender and procurement processes (CROW, 2025).

2.3.1 Traditional model

Traditional procurement models, such as 'Coordination of management (Regie)' and 'Bid-Build (RAW-Bestek)', are characterised by:

- Sequential project phases.
- Strong separation of roles and responsibilities, with a low degree of collaboration.
- Limited incentives for early collaboration, transparency, and joint problem-solving.
- Rist allocation is primarily based on legal boundaries rather than joint optimisation.

Traditional procurement models do not facilitate strong collaboration and constrain early or general stakeholder engagement, making it challenging to address uncertainties associated with circular strategies, such as steel reuse (de Ridder H.A.J., 2009).

Coordination of management (Regie)
This traditional contract is a cost-reimbursable procurement method in which the contractor executes the project directly under the client's control. The client keeps the responsibility for the project's design, coordination, and decision-making (ActiZ, 2024). The risks and decisions remain centralised, providing minimal support for stakeholder engagement, agreement, transparency, and joint problem-solving. Making this form of procurement poorly suited for circular ambitions, such as the application of donor steel.

Bid-Build (RAW-Bestek)
The Bid-Build contract follows a standard, traditional procurement approach, with a strict separation between the design and execution phases (de Ridder H.A.J., 2009). There is limited interaction and collaboration among designers, contractors, and suppliers during the early project phases. The risks and decisions are legally bound in the contract (UAV/FIDIC), providing minimal support for transparency, information sharing, and joint problem-solving. Making this form of procurement poorly suited for circular ambitions, such as the application of donor steel.

2.3.2 Integrated Project Delivery model (IPD)

Integrated Project Delivery models, such as ‘Collaborative contracts’ (Design teams, Alliances, Two-Phase contracts, framework agreement) and ‘integrated contracts’(D&C, E&C, DBFM), are characterised by:

- Early stakeholders engagement in the project lifecycle.
- Shared incentives through shared risks, goals, and transparency.
- Facilitating joint decision-making in the design and engineering phases.
- Enabling adaptive solutions under uncertainty.

IPD models facilitate strong collaboration strategies and early stakeholder engagement, addressing uncertainties in circular strategies, such as steel reuse (de Ridder H.A.J., 2009).

Design team (Bouwteam) - *Collaborative contract*
This collaborative contract, the Design team, introduces structural early collaboration by facilitating early stakeholder engagement during the design phase. The client involves the main contractor early in the design and engineering phase. The exchange of informal knowledge is supported while maintaining individual contractual responsibilities (de Ridder H.A.J., 2009). The execution risks remain largely the same as in a traditional model. The Design Team facilitated early stakeholder engagement, transparency, and joint problem-solving. Making this form of procurement suited for circular ambitions, such as the application of donor steel.

Alliance and Partnering - *Collaborative contract*
The Alliance and Partnering contracts present the highest level of collaboration within the Dutch procurement models. This model enables collaboration among stakeholders with different individual interests to work toward a common goal. The risks and rewards are shared in this form of procurement, enabling joint decision-making, long-term cooperation, and high transparency through open-book financing (de Ridder H.A.J., 2009). Making this form of procurement best suited for circular ambitions, such as the application of donor steel.

Two-phase contracts - *Collaborative contract*

The Two-phase contract is a model in which the procurement procedure is split into two phases:

- Phase 1: Collaborative design and engineering, where the contractor advises on buildability, costs, and logistics.
- Phase 2: If the agreement on risk allocation and price is reached, the same contractor receives the execution contract.

This way, the contract combines early collaboration with later contractual certainty, whereas phase 1 enables early stakeholder alignment and risk allocation, and the technical and economic uncertainties can be jointly assessed (de Ridder H.A.J., 2009). Although phase 2, the execution phase, often reverts to UAV or UAV-GC conditions, this model still effectively connects the traditional model with the IPD model, making them valuable for projects with circular ambitions (Staatscommissie Bouwregelgeving, 1989/2012) (CROW, 2000/2005/2025).

Framework agreement (Raamovereenkomst) - *Collaboration contract*

The Framework agreement establishes long-term contractual relationships between clients and one or more contractors. The model facilitates continual cooperation across multiple projects, reducing transaction costs and the need for repeated negotiations and providing opportunities for learning, trust-building, and innovation (PIANOo, n.d.). Although the individual call-off contracts may still be traditional models, the long-term nature of the Framework agreement created early stakeholder engagement and shared learning, which are essential for circular strategies and donor steel applications.

Design & Construct / Engineer & Construct - *Integrated contract*

The D&C and E&C contracts integrate the design/engineering and execution responsibilities under a single contractor, per the UAV-GC conditions (CROW, 2005). The model facilitates early contractor involvement and risk allocation with more transparency. The way the design and execution decisions are aligned within a single contract. Although this form of procurement has traditional features, such as traditional stakeholder engagement (client-contractor), this contract facilitates more intensive early collaboration, making it valuable for projects with circular ambitions (de Ridder H.A.J., 2009).

Design, Build, Finance, Maintain (DBFM) - *Integrated contract*

The DBFM contracts facilitate integration across the full lifecycle of a project by assigning long-term responsibilities to a private consortium comprising multiple contractors. This consortium is responsible for maintaining long-term alignment of design, construction, and maintenance interests. This contract incentivises optimising the project's lifecycle performance rather than short-term costs. Although DBFM contracts are competitive and complex, they foster strong internal collaboration within consortia, encouraging long-term thinking that can support circular strategies, such as steel reuse (de Ridder H.A.J., 2009).

To summarize, collaborative and integrated procurement strategies are essential to enable stakeholder agreement and early decision-making under uncertainty. Traditional models constrain collaboration through fragmented risk allocation and incentives. IPD models provide institutional conditions for trust, transparency, and joint problem-solving, which are key to donor steel integration in the early design stages.

2.3.3 Comparison between the different contracting models

Both contracting and procurement models have distinct features and can be compared based on the following collaborative conditions and responsibilities, as shown in Table 2.4. These collaborative conditions all have an important role in enabling donor steel integration.

Table 2.4: Comparison between the different contracting models and donor steel enablers (Based on CROW, 2000/2005/2025; de Ridder H.A.J., 2009)

Collaborative conditions:	**Traditional model**	**IPD model**
	Regie & RAW-Bestel	Collaborative & Integrated
Intensive collaboration	X	V
Shared risk allocation	X	V
Early stakeholder engagement	Possible	V
Transparency	Minimal	High
Joint problem-solving	X	Possible
Long-term coorperation	X	Possible
Responsibilities:		
Design	Client	Contractor/ Together
Realisation	Contractor	Contractor
Maintenance period	Client	Contractor/Client

From Table 2.4, it can be concluded that IPD models have more features that align with collaboration conditions that enable donor steel integration (de Ridder H.A.J., 2009). In addition, there are exceptions within the various models, as indicated per the contact form in § 2.3.1 and § 2.3.2.

3. Methodology

The literature review identified the following research gaps: the ranking of obstacles in their relative severity and the ways in which obstacles, digital solutions, and collaborative conditions are experienced in practice.

Therefore, the methodology of this thesis is a twofold approach: an exploratory approach (study 1) and a case study approach (study 2). Both methods are combined in this thesis to examine the weight of the obstacles perceived in practice and how technologies and collaborative strategies influence the early-stage integration of donor steel in construction projects. In the construction industry, having diverse insights and experts is crucial for providing a deeper understanding of the problem. At the same time, the practices vary widely between projects and are shaped by both tangible (technologies and data) and intangible (culture and governance) factors.

First, **Study 1: exploratory interviews** were conducted to identify which perceived obstacles to donor steel reuse are experienced across the construction supply chain. The exploratory interviews validate, rank, and expand upon the obstacles identified in the literature review (§ 2.1) and reveal additional obstacles that are less visible in academic studies.
Second, **Study 2: the case study research** will employ a multiple-case study approach to examine how the obstacles identified in the literature review materialize in real-world projects, and how digital solutions and collaboration arrangements influence the early-stage decision-making in practice. Therefore, the case study research does not introduce new obstacle categories, but tests, contextualizes, and deepens the insights obtained from the literature review.

The two studies were conducted separately; therefore, the results and insights from each study are presented separately in Chapter 4: Results and compared separately to the literature review in the discussion. Additionally, the key findings from each study are later combined to answer the sub-questions and main research question. Table 3.1 shows what both studies aim to investigate.

Table 3.1: Methodology structure including Study 1 and 2 and their investigation aim.

Study 1: Exploratory approach	**Study 2: Case study approach**
• Validating the identified obstacles in the literature review • Ranking the obstacles in their relative severity • Explore/Identify additional obstacles	• Test the identified obstacles in practice • Test the influence of the digital solutions in practice • Test the influence of collaborative conditions in practice
↓	↓
○ Identify all obstacles & occurrences	○ Conclusion/summary per case
↓	↓
○ Categorisation into 5 obstacles of the literature review and rank them.	○ Cross-case analysis: - key enablers (collaboration) - key obstacles - influence digital solutions

3.1 **Study 1:** Exploratory approach

The exploratory research approach includes exploratory interviews with professionals in the Dutch construction sector. The civil construction industry comprises various companies and institutions, each with distinct roles and corresponding interests. The exploratory interviews provided an understanding of which party held which functions and stakes, as presented in Table 3.1. The objective of the exploratory interviews is to verify and expand upon the theoretical findings from the literature review and develop strategies that may stimulate the adoption of steel reuse across the entire supply chain. Therefore, the categorisation of the identified obstacles in the literature review was decisive in the results.

First, human participation was initiated by ethical approval from the TU Delft Human Research Ethics Committee (HREC). After approval, potential stakeholders were contacted for interviews, which were then initiated.

3.1.1 Selection criteria for interview participants

Selecting appropriate participants for the exploratory interviews is essential to ensure that the data gathered is relevant and representative of the sector. Participants are selected through purposive sampling, targeting those with significant experience or expertise in steel reuse, circular construction, or digital technologies (Patton M. Q., 2015). The following criteria led to the selection of the participants:

- **Type of organization:** The participants need to represent key stakeholders in the building sector, and are essential to the steel supply chain. The following stakeholders were identified: clients, contractors, demolition contractors, engineering consultancy firm, architects, and steel manufacturers. The goal is to interview at least three participants per stakeholder group to obtain a balanced and broad perspective.
- **Role and expertise:** Within these organizations, key stakeholders hold various positions such as project engineers, circularity managers, sustainability advisors, or structural engineers. The different perspectives contribute to a comprehensive understanding of the technological and organizational aspects of donor steel implementation in the construction sector.
- **Professional experience:** Every participant must have at least three years of experience in the construction supply chain and have direct or indirect involvement in projects that are related to circular design or material reuse, preferably steel reuse. This criterion will be confirmed both before the interview and during the introductory part, in which participants explain their roles, backgrounds, and specific experiences with steel reuse.

The initial list of participants will be compiled in collaboration with Dura Vermeer experts to ensure access to relevant stakeholders and ongoing projects. The interview invitations were sent via email, which included an explanation of the research objectives, the consent procedure, and the estimated interview duration.

3.1.2 Conducting the interviews

The exploratory interview format was selected to ensure consistency across the interviews, while allowing flexibility to explore emerging topics in greater detail (Braun & Clarke, 2006). The interview protocol was prepared in advance (see Appendix A), which includes a set of open-ended guiding questions divided into three thematic sections. This format allows participants to elaborate on the topics, and the follow-up questions depend on their responses. The interviews were conducted in person whenever possible; when scheduling or location constraints prevented in-person meetings, they were conducted via an online meeting. Moreover, the duration of the interviews differed from 45 minutes to an hour.

The interviews always start with an opening statement outlining the study's purpose, the confidentiality agreements for participants, and their data rights. The participants were asked to sign an informed consent form (Appendix B). In addition to this consent form, the interview was audio-recorded for transcription analysis.

The interview protocol in Appendix A consists of three parts:

1. **Introductory questions:** These questions establish the context and verify the participant's background and familiarity with steel structures and the circular construction.
2. **Exploratory questions:** This part consists of two interconnected themes: the 'obstacles to steel reuse' and 'innovations and technologies for reuse'. The participants were first asked to express and elaborate on their own views and perspectives on the obstacles to steel reuse. Afterward, the identified obstacles, innovations, and technologies in the literature review are presented and discussed with the participant. The participants were also asked to propose strategies to overcome these obstacles.
3. **Concluding questions:** Lastly, the participants are encouraged to reflect on the future of the circular construction sector and donor steel. Additionally, participants were allowed to share any further thoughts or recommendations for the study.

Frequently, follow-up questions were asked to clarify statements and examples of the topics. This approach ensures that abstract statements are supported by practical experience, thereby increasing the depth and validity of the data obtained.

3.1.3 Sufficiency and amount of practical data

The goal was to interview at least three participants per actor category, as described in § 3.1.1. The data sufficiency was determined by thematic saturation: 'the point at which there were no new insights that emerged from additional interviews' (Braun & Clarke, 2006). When interviews later revealed no new perspectives, the data set was deemed sufficient for the analysis. In contrast, divergent or contradictory perspectives and opinions across interviews were considered as valuable findings, as they reflect the complexity and lack of consensus surrounding donor steel applications.

Moreover, the order in which the interviews were conducted may influence the data collection process. While the researcher's understanding can evolve, the follow-up questions mentioned in § 3.1.2 can become more targeted . This can potentially lead to minor variations in depth across interviews (Braun & Clarke, 2006). Furthermore, donor steel is a dynamic and rapidly evolving field, and legal, technological, or policy updates that occurred during the interview period may have influenced participants' perspectives. These contextual dynamics were documented and considered in the analysis and discussion chapters to ensure transparency in interpretation.

3.1.4 Conducted exploratory interviews

An overview of the exploratory interviews is presented in Table 3.2, which lists the actors, their roles in the supply chain, and the number of interviews conducted. In total, 28 participants were interviewed; the interview data are presented in Chapter 4, Results.

Table 3.2: Stakeholders and their roles in the construction sector, with the conducted Interviews.

Actor	*Role in the supply chain*	*Number of interviews*	*Interviewee*
Client (project owner)	Defining the project requirements, securing funding, and overseeing the project.	**4**	1-4
Steel Manufacturer	Manufactures and processes steel components based on design specifications and ensures quality control.	**5**	5-9
Contractor	Responsible for the execution of the construction projects and ensuring structural integrity.	**7**	10-16
Engineering Consultancy firm	Providing civil engineering expertise regarding analysis and design in compliance with the Dutch and EU standards.	**5**	17-21
Architect	Responsible for designing the project and preparing drawings, in compliance with requirements and regulatory standards.	**4**	22-25
Demolition Contractor	Responsible for dismantling existing structures and recovering reusable components.	**3**	26-28

3.2 **Study 2**: Case study research

Creswell (2013) argued that case study research is a qualitative design used to explore a bounded system (the case) through detailed, in-depth data collection from multiple sources. The approach is mainly used when the aim is to understand the 'how' and 'why' a phenomenon occurs. The approach described by Creswell (2013) aligns with Yin's (2018) recommendation that case studies are an appropriate means of investigating contemporary issues within their natural context, but in contrast, Yin's (2018) research should be guided by theoretical positions. The approach used in this thesis aligns more closely with Creswell's (2013) three defining topics, including a 'bounded system'. This thesis defines the 'bounded system' as construction projects in which donor steel is identified, assessed, and reused or evaluated through technological and collaborative means.

3.2.1 Rationale and approach

Aspects of the frameworks by Creswell (2013) and Yin (2018) are used to guide the case study research as a linear yet iterative process encompassing design, planning, preparation, collection, analysis, and reporting. In this study, the cases are steel projects that have adopted reuse-oriented scenarios or overlooked this possibility, even though it would be technically possible. This approach of this study is in line with Creswell's three defining topics of qualitative case studies:

1. Focusing on a '**bounded system**' (specific projects where donor steel is applied, evaluated, or overlooked)
2. Providing an '**in-depth, contextual description'**.
3. Using '**multiple sources of evidence**' (documents, interviews, and artifacts)

The multiple-case design is employed, whereas a single-case design does not permit both literal replication (identifying consistent patterns) and theoretical replication (contrasting different outcomes) across cases. Every case presents a distinct real-life context in which steel reuse is applied, evaluated, or overlooked, and different technologies are used, evaluated, or overlooked. The cases collectively offer a broader insight into the enabling and constraining factors for the circular construction sector in the Netherlands.

3.2.2 Case selection criteria

Creswell's (2013) principle of 'purposeful selection' and Yin's (2018) principle of 'replication logic' are used to choose the cases and ensure the relevance and variation of the different case studies. Each selected project has the potential to apply donor steel or comparable reuse strategies. The selection criteria for the case studies were:

- **Application of donor steel components:** The project involves donor steel components.
- **Integration of technological tools**: The application of the technological tools identified in the literature review needs to be made possible. Moreover, at least one of the six identified technological tools (material testing, material passports, real capture methods, BIM model, or digital twin) must be integrated into the project to support assessment and traceability.
- **Inclusion of circularity assessment**: The case needs to incorporate the circularity measurement instruments, such as Life Cycle Assessment (LCA) or the Environmental Cost Indicator (ECI).
- **Multiple stakeholder engagement:** The project needs to involve cooperation between at least two key stakeholders (e.g., engineer, contractor, client, architect, steel manufacturer, or engineering consultancy firm), to enable the analysis of governance and organizational dynamics.
- **Access to evidence:** The project documentation, design data, and contact with relevant stakeholders need to be available to ensure data triangulation. All projects will be from Dura Vermeer to ensure this.

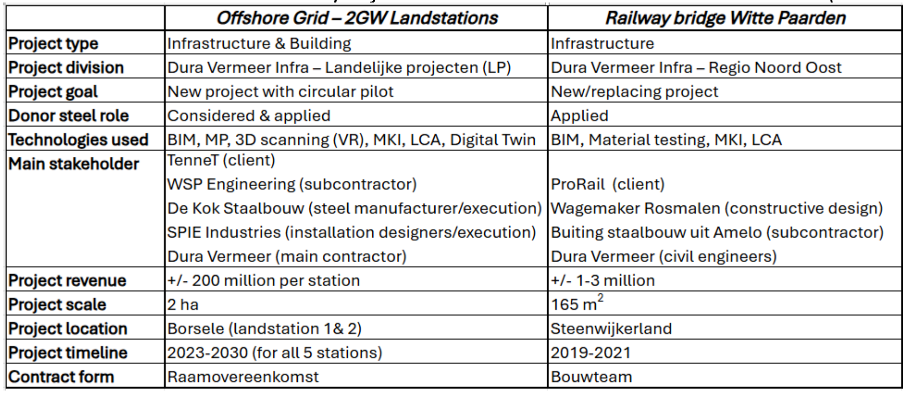
This purposive, criterion-based sampling yields information-rich cases that can reveal how technologies and governance frameworks shape the application of donor steel (Creswell, 2013; Yin, R.K., 2018).

3.2.3 Selected case study's

The case study research will consist of four different projects, two 'infrastructure projects' and two 'build and environmental projects', that will be compared for their application, consideration, or overlooking of donor steel. The chosen projects are:

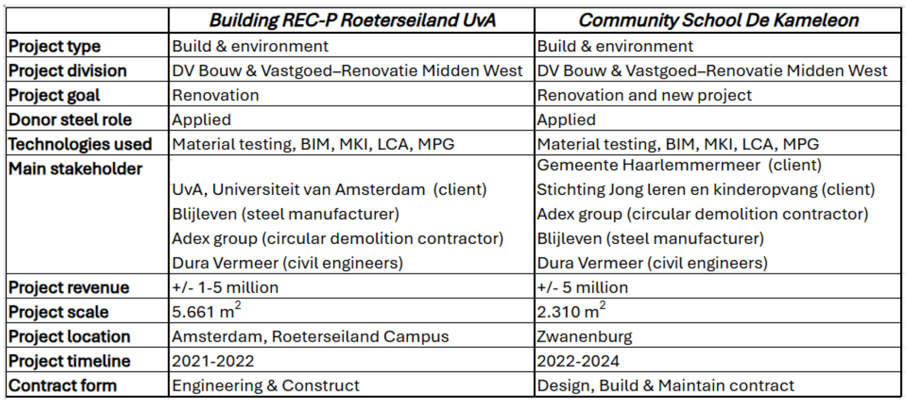
1. **Offshore Grid - 2GW Landstations** ~TenneT, Borselle *(infrastructure)*
2. **Railway bridge Witte paarden** ~ProRail, Steenwijkerland *(infrastructure)*
3. **Building REC-P Roeterseilandcampus** ~UvA, Amsterdam *(Build & environment)*
4. **Community School De Kameleon** ~private sector, Zwanenburg *(Build & environment)*

Table 3.3: Overview of all the project information for all four case studies (Based on Dura Vermeer, 2024).



	Offshore Grid – 2GW Landstations	***Railway bridge Witte Paarden***
Project type	Infrastructure & Building	Infrastructure
Project division	Dura Vermeer Infra – Landelijke projecten (LP)	Dura Vermeer Infra – Regio Noord Oost
Project goal	New project with circular pilot	New/replacing project
Donor steel role	Considered & applied	Applied
Technologies used	BIM, MP, 3D scanning (VR), MKI, LCA, Digital Twin	BIM, Material testing, MKI, LCA
Main stakeholder	TenneT (client) WSP Engineering (subcontractor) De Kok Staalbouw (steel manufacturer/execution) SPIE Industries (installation designers/execution) Dura Vermeer (main contractor)	ProRail (client) Wagemaker Rosmalen (constructive design) Buiting staalbouw uit Amelo (subcontractor) Dura Vermeer (civil engineers)
Project revenue	+/- 200 million per station	+/- 1-3 million
Project scale	2 ha	165 m^2
Project location	Borsele (landstation 1& 2)	Steenwijkerland
Project timeline	2023-2030 (for all 5 stations)	2019-2021
Contract form	Raamovereenkomst	Bouwteam

Infrastructure



	Building REC-P Roeterseiland UvA	***Community School De Kameleon***
Project type	Build & environment	Build & environment
Project division	DV Bouw & Vastgoed–Renovatie Midden West	DV Bouw & Vastgoed–Renovatie Midden West
Project goal	Renovation	Renovation and new project
Donor steel role	Applied	Applied
Technologies used	Material testing, BIM, MKI, LCA, MPG	Material testing, BIM, MKI, LCA, MPG
Main stakeholder	UvA, Universiteit van Amsterdam (client) Blijleven (steel manufacturer) Adex group (circular demolition contractor) Dura Vermeer (civil engineers)	Gemeente Haarlemmermeer (client) Stichting Jong leren en kinderopvang (client) Adex group (circular demolition contractor) Blijleven (steel manufacturer) Dura Vermeer (civil engineers)
Project revenue	+/- 1-5 million	+/- 5 million
Project scale	5.661 m^2	2.310 m^2
Project location	Amsterdam, Roeterseiland Campus	Zwanenburg
Project timeline	2021-2022	2022-2024
Contract form	Engineering & Construct	Design, Build & Maintain contract

Built environment

Each case study met the selection criteria described in § 3.2.2. The comparative framework will focus on the ‘replication logic’ described by Yin (2018) and the ‘cross-case analytical process’ outlined by Creswell (2013). The comparison framework for the case study research consists of five analytical dimensions and a conclusion, C1-C6, elaborated in Appendix C. The analytical dimensions used in the case study analysis were derived from the literature findings, as elaborated below:

C.1: Technological integration

- Referring to the integration of digital solutions in § 2.2.

C.2: Design and planning process

- Referring to the stage and design strategy of the donor steel integration.
- Referring to the ‘supply and demand’ obstacle in § 2.1.1.

C.3: Collaboration and governance

- Referring to the collaborative conditions in § 2.3.
- Referring to the ‘collaboration and transparency’ obstacle in § 2.1.5.

C.4: Economic and logistical feasibility

- Referring to the ‘certification and design standardization’ obstacle in § 2.1.2.
- Referring to the ‘costs and economic uncertainty’ obstacle in § 2.1.4.

C.5: Regulatory and certification constraints

- Referring to the ‘certification and design standardization’ obstacle in § 2.1.2.
- Referring to the ‘absence of legal frameworks’ obstacle in § 2.1.3.

C.6: Outcome and lessons learned

- Summarizing the key enablers and key obstacles of the project.

These combined insights formed the selection of consistent analytical lenses across all cases, ensuring comparability and analytical coherence. Each case study will be introduced with background information.

1. **Offshore Grid - 2GW Landstations** ~TenneT, Borselle *(infrastructure)*

The three-year framework agreement (‘Raamovereenkomst’ in Dutch) for the Offshore Grid 2GW Landstations from TenneT officially commenced in 2023. ‘Landstations’ are onshore converter stations; five ‘landstations’ will be built. The first will be built for the IJmuiden Ver Alpha project in Borssele, the other four locations are: ‘Nederwiek 1’, ‘Nederwiek 3’, ‘Doordewind 1’, and ‘Doordewind 2’. TenneT required a roadmap to learn from each station and make them more sustainable. These onshore stations function as converters between the offshore wind farms, in accordance with the new, innovative 2GW standard. Dura Vermeer will carry out the civil works, buildings, and building-related installations for the five onshore converter stations (Dura Vermeer, 2024).

2. **Railway bridge Witte paarden** ~ProRail, Steenwijkerland *(infrastructure)*

Dura Vermeer regio Noord Oost replaced a 100-year-old railway bridge in collaboration with ProRail. The bridge is located in Witte Paarden, which is part of the municipality of Steenwijkerland. The 1868 Witte Paarden traffic bridge is of great importance to the local agricultural traffic and needs to be replaced due to corrosion damage and load restrictions. The new bridge had to be built on short notice because the existing bridge was no longer considered safe (Dura Vermeer, 2024). The new bridge needed to meet several additional requirements, including allowing future track expansion (from 4.0 to 4.5 meters) and increasing the free space profile (PVR) (Dura Vermeer, 2024).

3. **Gebouw REC-P Roeterseilandcampus** ~UvA, Amsterdam *(Built environment)*

The building P at the Roeterseiland Campus (REC-P) of the University of Amsterdam was renovated by Dura Vermeer Renovation Midden West. Sustainability was the University of Amsterdam's top priority, as discussed later (Dura Vermeer, 2023). The building was initially built in the early 1960s and designed by architect Kees van der Wilk from the Department of Public Works. The building currently comprises lecture halls, study areas, offices, and other learning facilities. The 2021 renovation included the efficient integration of large ducts and a new, well-organized spatial layout within the building (Gemeente Amsterdam, n.d.).

4. **Community School De Kameleon** ~Municipallity, Zwanenburg *(Built environment)*

The primary school De Kameleon was renovated and expanded by Dura Vermeer Renovatie Midden West. The school, located in Zwanenburg, has been transformed into a modern and sustainable community school (Dura Vermeer, 2022). The original building, built in 1971, is 950 m^2 and will be renovated and expanded by 1,357 m^2, bringing the school to a total of 2,307 m^2.

The school accommodates around 310 students and also serves as a neighbourhood meeting place (Gemeente Haarlemmermeer, 2022). The project had a high sustainability goal and wanted to use as many reused materials as possible (Dura Vermeer, 2022).

3.2.4 Data collection procedures

Data collection will be conducted in accordance with the principles of triangulation and the chain of evidence (Yin, R.K., 2018). Each case study will incorporate the three complementary data sources from Creswell (2013) to ensure diverse and converging lines of inquiry:

- **Archival and project documentation:** Documents such as design reports, BIM models, environmental assessments, and technical data related to donor steel will be assessed.
- **Supplementary visual and digital materials**: This source includes 3D scans, photographic records, BIM models, project websites, and real-time planning if they are available.
- **Qualitative interviews (if needed):** Only used if the questions from Appendix C could not be answered with the two data sources mentioned above. During a brief interview with the case's project staff, the questions in Appendix C were asked. These interviews are separate from those in Study 1, but the same consent form was used (Appendix B).

Every data source contributed to a complete understanding of the project. Data collection is followed by a case study protocol, developed prior to the fieldwork, to maintain consistency and reliability across the different case studies (Yin, R.K., 2018).

3.3 Summary of the research approaches

The twofold approach combines exploratory interviews with multiple case studies to provide a broad identification of barriers with in-depth contextual understanding. The exploratory interviews were used to validate and refine the obstacles identified in the literature, while the case study research examined how these barriers materialize in concrete project settings (see Figure 3.1). The research applies an analytical structure from the literature review across the case study approach to enable systematic comparison while allowing for contextual nuance to emerge.

The results of the approaches will be used to generate empirically grounded insights into the interactions among obstacles, technologies, and collaborations for steel reuse, thereby contributing to the broader context of steel reuse strategies.

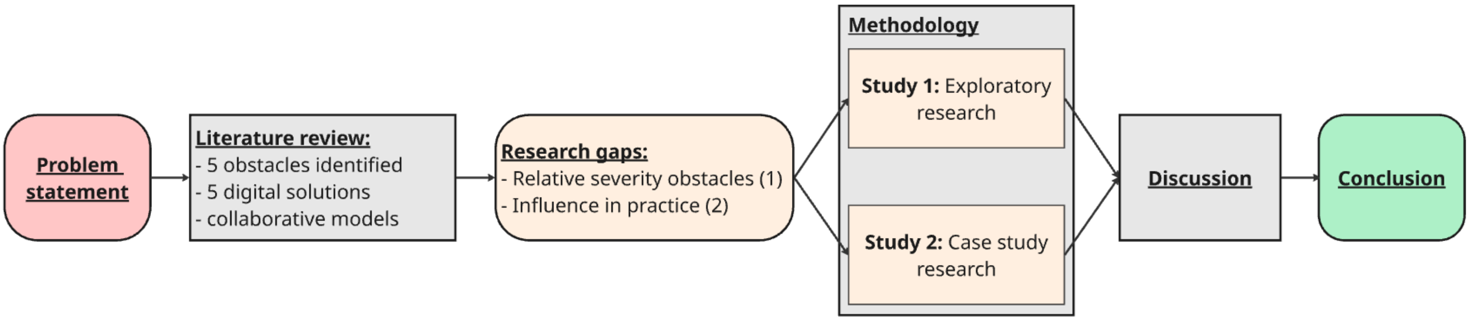


Figure 3.1: Overview of the methodology structure and identified research gaps.

4. Results

This chapter presents the results of the exploratory interviews and case study research. The research will help to identify the main obstacles and enablers to donor steel application. The interview protocol is in Appendix A, and the comparison framework for the case study research is elaborated in Appendix C.

4.1 Exploratory interviews

The exploratory interviews provided empirical insights from professionals in the Dutch construction sector. During the interviews, stakeholders are asked about the obstacles they encounter in reusing steel components. The collected topics are listed in § 3.1.2. The overview of this data is presented in Table 3.1. The blue numbers in brackets [X_1, X_2] (X_1 = obstacle number, X_2 = specific citation number) are used later in the analysis and results to refer to specific citations in the interview data.

4.1.1 Description of obstacles from the interview data

During the exploratory phase of the interviews, the interviewees mentioned 12 obstacles to the application of donor steel. The obstacles emerged from the exploratory questions in the interview protocol and are elaborated below in an integrated overview. The most relevant citations and supporting information for each obstacle are provided, including references to the corresponding interview transcripts via file markers.

1. Availability of donor steel
One of the most frequently mentioned obstacles by all the interviewees is the availability of donor steel components. This obstacle forms a problem for new, renovation, and infrastructure projects. A key challenge is that choosing donor steel limits your options; you can only work with the available profiles – *Interviewee 6 (steel manufacturer)* [1.1]. Furthermore, the donor steel components need to be released at the right time, at the correct location, and in the right amount or size – *Interviewee 14 (contractor)* [1.2]. Moreover, for infrastructure objects, the availability of the most common profiles is even more limited; for example, significant works of art (bridges, viaducts, etc.) are less common and have a long lifespan – *Interviewee 1 (client)* [1.3].

In addition, the available supply must be listed somewhere so parties know what is available and in what quantities. The supply of donor steel for building and environmental projects is often fragmented across dozens of demolition sites and suppliers, making it difficult to compile an inventory – *Interviewee 16 (contractor)* [1.4]. Moreover, even if donor steel components are available today, their availability in 6-7 years remains uncertain, making it difficult for significant, long-term projects to use donor steel elements – *Interviewee 20 (engineering consultancy firm)* [1.5]. Furthermore, demolition contractors often choose to sell the steel to the scrap market, which generates immediate income with minimal risk – *Interviewee 6 (contractor) and Interviewee 26 (demolition contractor)* [1.6].

2. Steel harvesting, storage, and logistics
The storage of the donor steel supply is possible in itself, but the combination of storage, transport, inspection, and temporary processing constitutes a clear obstacle. The storage of

donor steel requires money, space, and planning – *Interviewee 9 (steel supplier) and Interviewee 28 (demolition contractor)* [2.1]. Specifically, transporting the donor steel components is an additional cost and logistical task for projects – *Interviewee 16 (contractor)* [2.2].

In addition, time is a constraint in real estate projects; buildings must be demolished quickly, leaving little time to harvest and dismantle steel components – *Interviewee 18 (engineering consultancy firm) and Interviewee 27 (demolition contractor)* [2.3]. Moreover, most of the time, clients do not choose the sustainable demolition option, which allows more time to harvest and dismantle materials, but instead choose the traditional option – *Interviewee 26 (demolition contractor)* [2.4]. Moreover, harvesting and dismantling materials are only helpful if the material properties are known; otherwise, the harvested materials are not valuable – *Interviewee 18 (engineering consultancy firm)* [2.5].

3. Project suitability and scalability
Not all project types are suitable for donor steel applications. Unique or heavily loaded structures, such as bridges, are complex to reuse – *Interviewee 14 (contractor)* [3.1]. For example, a bridge or viaduct has such specific dimensions and support points that do not match every situation – *Interviewee 2 (client) and Interviewee 15 (contractor)* [3.2].

In addition, the scalability of donor applications is currently very complex, as the current stock is not sufficient for large projects requiring large quantities of steel – *Interviewee 5 (steel supplier)* [3.3]. Risk is acceptable only for temporary buildings; the negative properties of donor steel are mitigated by its temporary use – *Interviewee 5 (steel supplier)*.

4. Testing, certification, and quality assurance
Testing and certification of the donor steel components were also often mentioned in the interviews. Some interviewees found testing and certification of donor steel components to be a real obstacle in the process. The material properties and history of most donor steel components are unknown, and complete documentation is missing – *Interviewee 15 (contractor), Interviewee 12 (contractor), and Interviewee 1 (client)* [4.1]. Furthermore, tests to determine material properties, such as destructive testing, batch testing, and metal testing, are expensive and are not included as standard in the project cost analysis – *Interviewee 6 (Steel supplier)* [4.2]. Moreover, the certification process to obtain a CE-marking for the donor steel components does not exist entirely; guidelines and standards do not exist or are well known – *Interviewee 2 (client)* [4.3].

In some cases, the requirements and quality assurance clients request are so stringent that testing or certification alone is not enough to convince them – *Interviewee 6 (steel supplier) and Interviewee 11 (contractor)* [4.4].

Additionally, fatigue is a difficult material property to test, posing an important obstacle to infrastructure, as mentioned by multiple interviewees. The only way to test this material property is to break the donor steel component, making the component unusable – *Interviewee 14 (contractor), Interviewee 1 (client), and Interviewee 20 (engineering consultancy firm)* [4.5].

In contrast, some interviewees view testing, certification, and quality assurance as technical steps that need to be resolved. In their opinion, this is just a step in the process, just like calculating the construction – *Interviewee 18 (engineering consultancy firm), Interviewee 19 (engineering consultancy firm), and Interviewee 22 (architect)* [4.6].

5. Design standardization and technical integration

The interviewees with a design background indicate that donor steel elements do not fit standard new designs. Currently, there are no uniform design standards for donor steel profiles – *Interviewee 18 (engineering consultancy firm)* [5.1]. Furthermore, donor steel components are most often processed and adapted to fit new designs, and redesigning does cost a lot of time and money – *Interviewee 18 (engineering consultancy firm) and Interviewee 23 (architect)* [5.2]. The implementation of donor steel requires the constructors to account for uncertainties and additional design work – *Interviewee 16 (contractor)* [5.3].

The construction industry needs to change to become a circular sector, design regulations for grid structures and demountability are the most important to reach this goal – *Interviewee 9 (steel supplier) and Interviewee 15 (contractor)* [5.4].

6. Technical limitations

Technical limitations include fatigue, corrosion, and unknown load history. Fatigue behaviour of the donor steel components is difficult to determine, especially in bridges, where monitoring is important to enable reuse of elements – *Interviewee 14 (contractor) and Interviewee 17 (engineering consultancy firm)* [6.1]. Moreover, corrosion and preservation should be reassessed when donor steel components are applied – *Interviewee 12 (contractor)* [6.2].

7. Absence or inadequacy of legal frameworks and regulations

Despite the publication of the NTA 8713 in 2023, some interviewees still cite the absence of legal frameworks and regulations as an obstacle to implementing donor steel. The NTA 8713 is still very new and not yet widely known, especially among municipalities and specific clients – *Interviewee 12 (contractor) and Interviewee 24 (architect)* [7.1]. Moreover, the absence or inadequacy of legal frameworks and regulations makes clients afraid of liability – *Interviewee 21 (engineering consultancy firm)* [7.2]. Additionally, the CE marking does not apply to reused materials; the European Union is lagging behind – *Interviewee 9 (steel supplier*) [7.3].

8. Future expectations depend on regulations and digitalization

While not a direct obstacle, many interviewees stated that the future of donor language will only become truly feasible when: digital libraries/marketplaces emerge, regulations are harmonized across Europe, and materials are better labeled and tracked in material passports – *Interviewee 9 (steel supplier) and Interviewee 14 (contractor)* [8.1].

9. Costs and economic feasibility

Almost all of the interviewees mention the cost and economic feasibility. Harvesting and dismantling materials for reuse takes more time than standard demolition work, making it more expensive – *Interviewee 27 (demolition contractor)* [9.1]. Additionally, the price of scrap steel is currently very high, so demolition contractors are more likely to choose this option – *Interviewee 27 (demolition contractor)* [9.2]. Moreover, the storage and transportation of the donor steel components make it a more expensive option than new steel – *Interviewee 28 (demolition contractor)* [9.3]. The tests necessary to obtain the material properties of the donor steel components are expensive – *Interviewee 8 (steel supplier)* [9.4].

Furthermore, the uncertainty about the suitability and the risks of double costs in the event of unfavourable test results is high – *Interviewee 20 (engineering consultancy firm)* [9.5]. Cost and risks are interrelated in the construction sector – *Interviewee 21 (engineering consultancy firm)* [9.6]. Moreover, contractors often choose new materials when sustainability is not rewarded in tenders, because the cost of new steel is lower than that of donor steel components – *Interviewee 10 (contractor)* [9.7].

In contrast, a single interviewee stated that, in his project, the cost of donor steel could fit within the planned project budget, but noted that this is rare – *Interviewee 14 (contractor)* [9.8]. Moreover, another interviewee stated that testing and modifying the donor steel elements is often more expensive than new steel. However, when you broaden the cost picture to include installation, the percentage difference is no longer significant – *Interviewee 13 (contractor)* [9.9].

10. Risks and liability

Another frequently mentioned obstacle for all the interviewees is risk and liability. As mentioned before, the costs and risks are interrelated, making clients and contractors reluctant – *Interviewee 21 (engineering consultancy firm)* [10.1]. Additionally, the risk of double cost in the event of unfavourable test results is high – *Interviewee 20 (engineering consultancy firm) and Interviewee 12 (contractor)* [10.2].

Furthermore, the discussion of who will bear the risks and liabilities in cases of double costs, delays, or errors in a project due to the use of donor steel remains open – *Interviewee 1 (client) and Interviewee 20 (engineering consultancy firm)* [10.3]. Moreover, the infrastructure projects in which donor steel has been used are challenging to insure, as insurers signal high risks – *Interviewee 2 (client)* [10.4].

Additionally, in some cases, the consequences of project failure are so severe that the client does not want or dare to use reused materials – *Interviewee 10 (contractor)* [10.5]. In these cases, the requirements for the steel components are so stringent and detailed that the contractor is reluctant to take the risk – *Interviewee 5 (steel supplier)* [10.6].

11. Unfamiliarity, perception, and culture

Although the reuse of materials is not new, it remains unknown to many stakeholders in the supply chain and sector. For some municipalities and specific clients, the application of donor steel is very new and unfamiliar, which makes them wary and suspicious – *Interviewee 12 (contractor) and Interviewee 25 (architect)* [11.1]. Furthermore, reuse or secondhand steel is associated with lower quality and more liability than new steel – *Interviewee 10 (contractor)* [11.2]. Several interviewers mentioned the lack of trust.

Additionally, contractors and designers do not want to use donor steel due to a lack of experience and a lack of trust – *Interviewee 24 (architect)* [11.3]. Gaining this knowledge can be a time-consuming and challenging process; the materials need to be found, tested, and processed, but with whom? – *Interviewee 8 (steel supplier)* [11.4].

Furthermore, conservatism and a fear of dimensional deviations are significant problems within the building sector – *Interviewee 21 (engineering consultancy firm)* [11.5]. Contractors and designers need to be open to this change and work together to achieve the goals of a circular sector – Interviewee 23 (architect) [11.6].

12. Collaboration, chain transparency, and data sharing

The construction sector has a fragmented supply chain, hindering reuse opportunities. Stakeholders in this supply chain often keep data on material properties to themselves – *Interviewee 21 (engineering consultancy firm)* [12.1]. Furthermore, the unfamiliarity of steel reuse creates distrust among clients; second-hand is seen as riskier – *Interviewee 10 (contractor)* [12.2].

Moreover, the application of donor steel is hindered through the entire civil ecosystem that must follow, but responsibility is diffuse – *Interviewee 9 (steel supplier) and Interviewee 19 (engineering consultancy firm)* [12.3].

4.1.2 Overview of the ‘obstacles’ mentioned in the interviews

The obstacles mentioned in the interviews, elaborated in §4.1.1, are presented in Table 4.1. The table provides an overview of the 12 obstacles mentioned during the interviews, categorized into the 5 themes/obstacles from the literature review. Based on this data, the frequency of each obstacle type is determined and presented in Table 4.2, which will be used to analyze the interview data in the discussion (§ 5.1.1).

Table 4.1: Overview of all obstacles mentioned in interviews by different stakeholders.

Obstacle (literature)	**Obstacle** (interviews)	**Client**	**Steel Supplier**	**Contractor**
		Interviewee	**Interviewee**	**Interviewee**
Supply and Demand	1. Availability of donor steel	**1_2**	**5_7_9**	**10_11_12_14_16**
	2. Steel harvesting, storage, and logistics	**1**	**5_9**	**10_11_16**
	3. Project suitability and scalability	**1**	**5_7**	**10_11_14**
Certification & design standardization	4. Testing, certification, and quality assurance	**1_2**	**5_9**	**10_11_12**
	5. Design standardization and technical integration	**1_2**	**5_9**	**10_11_12**
	6. Technical limitations	**1_2**	**7_9**	**10_11_12**
Absence of legal frameworks	7. Absence or inadequacy of legal frameworks and regulations	**1_2**	**7_9**	**10_ 11_12**
	8. Future expectations depend on regulations and digitalization	**1**	**5_7_9**	**10_11_16**
Cost & economic uncertainty	9. Costs and economic feasibility	**1_2**	**5_7_9**	**10_11_12_15_16**
	10. Risks and liability	**1_2_3**	**5_9**	**10_11_13_14_15**
Lack of collaboration & transparency	11. Unfamiliarity, perception, and culture	**1_4**	**5_7_9**	**10_11_12_14_15_16**
	12. Collaboration, chain transparency, and data sharing	**1_2**	**9**	**10_11_12**

Obstacle (literature)	**Obstacle** (interviews)	**Engineering Consultancy firm**	**Architect**	**Demoliton Contractor**
		Interviewee	**Interviewee**	**Interviewee**
Supply and Demand	1. Availability of donor steel	**17_18_21**	**22_23**	**26_27_28**
	2. Steel harvesting, storage, and logistics	**17_18**	**22**	**26_27**
	3. Project suitability and scalability	**17_18_21**	**22_23**	**26_28**
Certification & design standardization	4. Testing, certification, and quality assurance	**17_18_21**	**22_24**	**26_27**
	5. Design standardization and technical integration	**17_18_21**	**22_23_24**	**26_27**
	6. Technical limitations	**17_18_21**	**22**	**26_27**
Absence of legal frameworks	7. Absence or inadequacy of legal frameworks and regulations	**17_18_21**	**22**	**26**
	8. Future expectations depend on regulations and digitalization	**17_19_21**	**22**	**26_27_28**
Cost & economic uncertainty	9. Costs and economic feasibility	**17_18_20_21**	**22_23_25**	**26_27_28**
	10. Risks and liability	**20_21**	**22**	**26_27**
Lack of collaboration & transparency	11. Unfamiliarity, perception, and culture	**17_19_21**	**22_23_25**	**26_28**
	12. Collaboration, chain transparency, and data sharing	**17_18_21**	**22_25**	**26**

Table 4.2: Obstacles and their occurrence.

Obstacle (literature)	**Obstacle** (interviews)	**Occurrance**
Supply and Demand	1. Availability of donor steel	18
	2. Steel harvesting, storage, and logistics	11
	3. Project suitability and scalability	13
Certification & design standardization	4. Testing, certification, and quality assurance	14
	5. Design standardization and technical integration	13
	6. Technical limitations	13
Absence of legal frameworks	7. Absence or inadequacy of legal frameworks and regulations	12
	8. Future expectations depend on regulations and digitalization	13
Cost & economic uncertainty	9. Costs and economic feasibility	20
	10. Risks and liability	15
Lack of collaboration & transparency	11. Unfamiliarity, perception, and culture	19
	12. Collaboration, chain transparency, and data sharing	12

Legenda occurrance:

High low

4.1.3 Analysis of interview data regarding 'obstacles.'

The interview data revealed 12 obstacles to the implementation of donor steel components. Table 4.2 shows the occurrence of these twelve obstacles, with three that were mentioned significantly more often than the others. These three obstacles were:

1. 'Costs and economic feasibility' *(interviews)* → '**Cost & economic uncertainty**' *(literature)*
2. 'Unfamiliarity, perception, and culture' *(interviews)* → '**Lack of collaboration & transparency**' *(literature)*
3. 'Availability of donor steel' *(interviews)* → '**Supply and Demand**' *(literature)*

These three obstacles were mentioned across all stakeholder groups and are therefore conceptually grouped under the term 'overhead obstacles', referring to the five obstacles identified in the literature review. The analysis further suggests that these overhead obstacles are closely related to several other obstacles mentioned by interviewees. These additional obstacles are referred to as 'underlying obstacles' to structure the interview analysis. Each overhead obstacle will be elaborated, and the perceived relationships with the underlying obstacles will be described using illustrative citations from the interview data presented earlier (referenced as [X_1, X_2]).

Overhead obstacle 1: 'Costs and economic uncertainty.'

The first identified overhead obstacle in this study is 'Costs and economic uncertainty'. The interviewees across all the stakeholder groups emphasized that in the current market context, reused steel is often more expensive and more uncertain than new steel. The testing, logistics, and design modifications need to be taken into account, which will create additional costs and risks [9.3] & [9.4].

Furthermore, the overhead obstacle 'costs and economic uncertainty' can be linked to several underlying obstacles:

- **Steel harvesting, storage, and logistics**
  Demolition contractors and steel suppliers emphasised that the storage and transportation of the donor steel component would entail additional costs and logistical tasks for the project [2.1] & [2.2]. Moreover, the harvest and dismantling of the steel components also give additional costs, due to the additional needed time [2.3] & [2.4].
- **Testing, certification, and quality assurance**
  The risk of double cost mentioned in the 'cost and economic feasibility' obstacle [9.5] is caused by the necessary tests and certifications for donor steel elements, where the history of the component is unknown [4.1]. Moreover, these tests are expensive and not included in the standard cost analysis of a project [4.2].
- **Design standardization and technical integration**
  The interviewees with a design background indicated that donor steel components often do not fit standard new designs, necessitating redesign, which takes more time and therefore costs more [5.1] & [5.2].
- **Risks and liability**
  The costs and risks are interrelated in the construction sector [10.1]. As mentioned

before, the risk of double cost in the event of unfavourable test results is high [10.2]. Furthermore, the discussion of who will bear the risks and liabilities is important in the context of costs; to bear higher risks, a contractor also wants to incur higher costs [10.3].

These underlying obstacles suggest that the overhead obstacle 'costs and economic uncertainty' is not an isolated issue, but emerges from obstacles 2, 4, 5, 9 and 10.

Overhead obstacle 2: 'Lack of collaboration & transparency'

The second identified overhead obstacle in this study is 'lack of collaboration & transparency'. The interviewees mentioned that although reuse of materials is not new, it remains unknown to many stakeholders in the supply chain and sector [11.1]. Furthermore, reused or secondhand steel is associated with lower quality and more liability than new steel [11.2]. Several interviewees mentioned a lack of trust, which remains a severe issue in the sector [11.3].

Furthermore, the overhead obstacle 'lack of collaboration & transparency' can be linked to several underlying obstacles:

- **Absence or inadequacy of legal frameworks and regulations**
  Despite the publication of NTA 8713 in 2023, interviewees still report that stakeholders remain unfamiliar with steel reuse or with NTA 8713 [7.1]. Moreover, gaps in the legal framework and regulations make clients afraid and perceive donor steel as unsafe [7.2].
- **Future expectations depend on regulations and digitalization**
  While not a direct obstacle, some interviewees still state that the future of donor language (e.g., emerging digital libraries/marketplaces) is not yet defined, which makes stakeholders conservative and raises fears of cultural change [8.1].
- **Collaboration, chain transparency, and data sharing**
  The construction sector consists of a fragmented chain of suppliers and stakeholders. These stakeholders in this supply chain often keep data on material properties to themselves, hindering reuse possibilities [12.1]. Furthermore, this secrecy of data keeping creates distrust and unfamiliarity with the possibilities of reuse [12.2].

These underlying obstacles suggest that the overhead obstacle 'lack of collaboration & transparency' is not an isolated issue, but emerges from obstacles 7, 8, 11 and 12.

Overhead obstacle 3: 'Supply and Demand.'

The third identified overhead obstacle in this study is 'supply and demand'. All the interviewees, especially the contractors, mentioned that the availability of donor steel components was a significant obstacle. The supply of donor steel components in the Netherlands is limited, which, in turn, limits design options [1.1]. Furthermore, the supply of donor steel components is often fragmented across dozens of demolition sites and suppliers, hindering the creation of an inventory [1.4]. Moreover, the donor steel components need to be available at the right time, location, amount, and size [1.2].

Furthermore, the overhead obstacle 'supply and demand' can be linked to several underlying obstacles:

- **Steel harvesting, storage, and logistics**
  The steel harvest hinders the availability of donor steel, while buildings must be

demolished quickly, leaving little time for harvesting and dismantling steel components [2.3]. Moreover, during storage, steel components can be affected, and their quality can decrease if they are not stored appropriately [2.1].

- **Project suitability and scalability**
  Some interviewees mentioned that not all project types are suitable for donor steel applications, due to their unique, heavily loaded structures [3.1]. The current donor steel supply does not meet the specific dimensions and support points required for infrastructure projects, such as bridges and viaducts [3.2]. Additionally, the scalability of donor applications is currently very complex, as the current stock is not sufficient for large projects requiring large quantities of steel [3.3].
- **Testing, certification, and quality assurance**
  The history or material properties of the harvested donor steel components are often unknown, making testing and recertification needed before they can be sold to the next project [4.1]. Furthermore, fatigue is a difficult material property to test, posing an important obstacle to infrastructure, as multiple interviewees noted. The only way to test this material property is to break the donor steel component, making it unusable and decreasing the supply [4.5].
- **Design standardization and technical integration**
  Interviewees with a design background stated that donor steel components often do not fit standard new designs, meaning that the current supply cannot be integrated directly [5.1]. To implement the currently available supply of donor steel components, the design regulations for grid structures and demountability need to change [5.4].
- **Technical limitations**
  The available donor steel components often have technical limitations, such as fatigue, corrosion, and unknown load history [6.1].

These underlying obstacles suggest that the overhead obstacle ‘supply and demand’ is not an isolated issue, but emerges from obstacles 1,2, 3, 4, 5, and 6.

Figure 4.1 presents an overview of the identified underlying obstacles and their associated overhead obstacles.

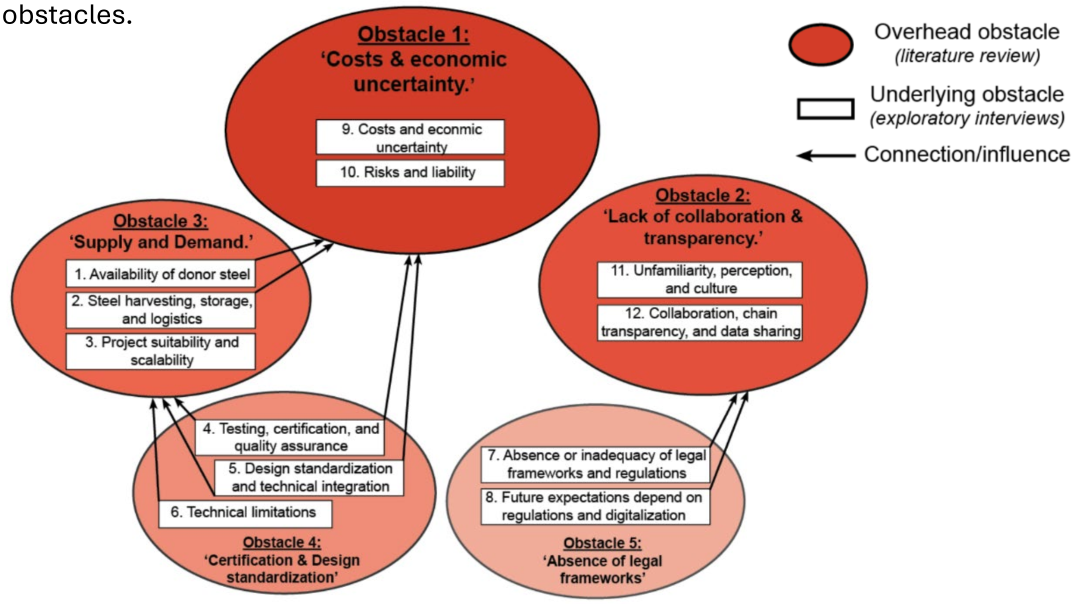


Figure 4.1: Overview of the overhead obstacles (oval) and their ‘underlying obstacles’ (rectangular).

4.2. Case study research

The case study research will consist of four different projects, two ‘infrastructure projects’ and two ‘build and environmental projects’, that will be compared on the analytical dimensions C1-C6 (see Appendix C). As mentioned in § 3.2.3, the chosen projects are:

1. **Offshore Grid - 2GW Landstations** ~TenneT, Borselle *(infrastructure)*
2. **Replacement spoorburg Witte paarden** ~ProRail, Steenwijkerland *(infrastructure)*
3. **Building REC-P Roeterseilandcampus** ~UvA, Amsterdam *(Built environment)*
4. **Community School De Kameleon** ~private sector, Zwanenburg *(Built environment)*

4.2.1 Offshore Grid -2GW Landstations *~Infrastructure*

C1: Technological integration

The ambition of Dura Vermeer and De Kok Staalbouw is to use constructional donor steel at every station; if this is not possible, low-emission steel (approximately 50% less CO2 than the traditional process) will be used for every steel component. The contract states the ambition to continuously improve in sustainability, ECI, and circularity at each station (Dura Vermeer PEP, 2022). The implementation of donor steel suits this ambition and was therefore presented to TenneT in the early design phase. This also fits with Dura Vermeer's own sustainability vision and transition paths (Dura Vermeer PEP, 2022).

The client, TenneT, and the project itself, the wind energy converter, also have high sustainability expectations and goals. Hence, the integration of donor steel aligns with the client and the project (Dura Vermeer PEP, 2022). Figure 4.2 presents a visualization of the first design by Arcadis for a ‘Landstation’ and the materialization of its different building parts (van Haasteren, T., 2022).

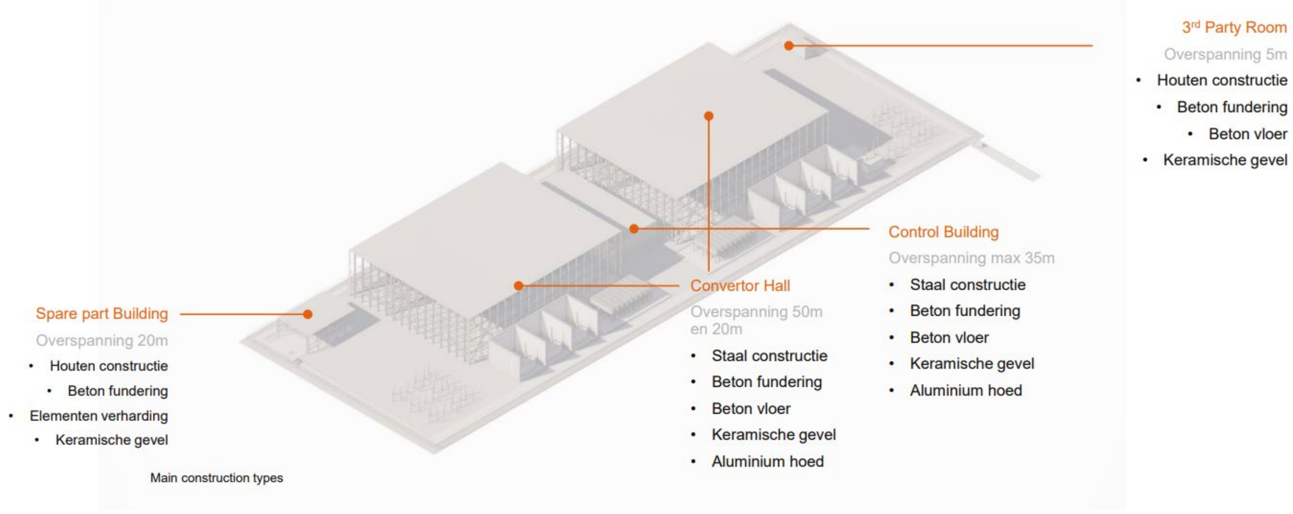


Figure 4.2: The first design from Arcadis and the materialisation of a ‘Landstation’ for TenneT (van Haasteren T., 2022).

Dura Vermeer and its steel supplier, De Kok Staalbouw, have high ambitions for donor steel applications. The roadmap for these ambitions of the steel manufacturer and supplier 'De Kok Staalbouw' (2023) for the steel components of all the stations is presented in Figure 4.3.

Figure 4.3: Roadmap for the donor steel application ambition for all five onshore stations (De Kok Staalbouw, 2023).

Furthermore, each onshore station has its own project goals and ambitions for the application of donor steel components, as listed in Table 4.3.

Table 4.3: Project goals and ambitions for all five onshore stations (De Kok Staalbouw, 2023).

	IJmuiden van Alpha (1)	*Nederwiek 1 (2)*	*Nederwiek 2 (3)*	*Doordewind 1 (4)*	*Doordewind 2 (5)*
Current project phase	Realisation	Design	Start Design	-	-
Low CO_2 profile steel	Application (10 ton minimum)	Application (10 ton minimum)	Application (10 ton minimum)	Application (10 ton minimum)	Application (10 ton minimum)
CO_2-neutral steel hollow sections	-	Application (10 ton minimum)	Application (10 ton minimum)	Application (10 ton minimum)	Application (10 ton minimum)
CO_2-neutral steel sheet and strip material	-	-	Test application	Test application	Application (10 ton minimum)
Donor steel tests	GGI package, façade, outbuildings	GGI package, façade, outbuildings	GGI package, façade, outbuildings	GGI package, façade, outbuildings	-
Donor steel application ambition	10 – 20 ton steel (if possible)	Minimum 20 tons of steel	Minimum 50 tons of steel	25% of the total construction steel	As much as possible
Donor steel application	0 ton steel	-	-	-	-

Table 4.3 presents the design and realization process of the five onshore stations, where Station 1, IJmuiden van Alpha, is used to test and experiment with donor steel applications, and the use of CO_2-neutral steel is limited to profile steel components. In Station 5: Doordewind 2, donor steel will be applied wherever possible, and the test results from the previous stations will be applied. This shows the goal of learning and becoming more sustainable at every station (Dura Vermeer PEP, 2022).

De Kok Staalbouw uses demountable steel profiles from a construction site in northern France. Figure 4.4 presents the profiles, each consisting of a material passport detailing the technical and material properties of its component. Material testing was conducted by EMR beforehand, so additional testing is not needed in this case (De Kok Staalbouw, 2023). An example of a material passport for a steel profile is provided in Appendix D. All available steel components, along with their corresponding material passports, are compiled in a harvest list.

In addition, a BIM model is constructed for the first 'landstation', IJmuiden van Alpha, with a clear structure as agreed in the Raamovereenkomst (Dura Vermeer BEP, 2022). The BIM model will be constructed in 4D and 5D, enabling the project to be realized on time and within budget. The project location is captured and measured with 3D scanning. This as-built scanning, combined with the BIM model, also enables 'Virtual Reality' (VR) of the model, allowing for a 100% realistic experience of the design on-site before the 'landstation' is even built. The VR simulation also provides virtual safety walks to identify all risks and prevent project delays (Dura Vermeer BEP, 2022).

Te verwachten voorraad Q1 2025:

Profiel	Lengte	Tonnage
HEA180	8000-8300	11
HEA220	7200-7650	7
IPE160	7150-8600	1
IPE180	9900-10100	3
IPE330	6500	40
IPE450	8000-14500	29
IPE550	7600-8000	2
		94

Route:
Constructie gedemonteerd in Noord Frankrijk (Lille)
Gekeurd en bewerkt bij EMR (Coventry)

Figure 4.4: Construction stock demounted in northern France, tested and adapted by EMR (De Kok Staalbouw, 2023).

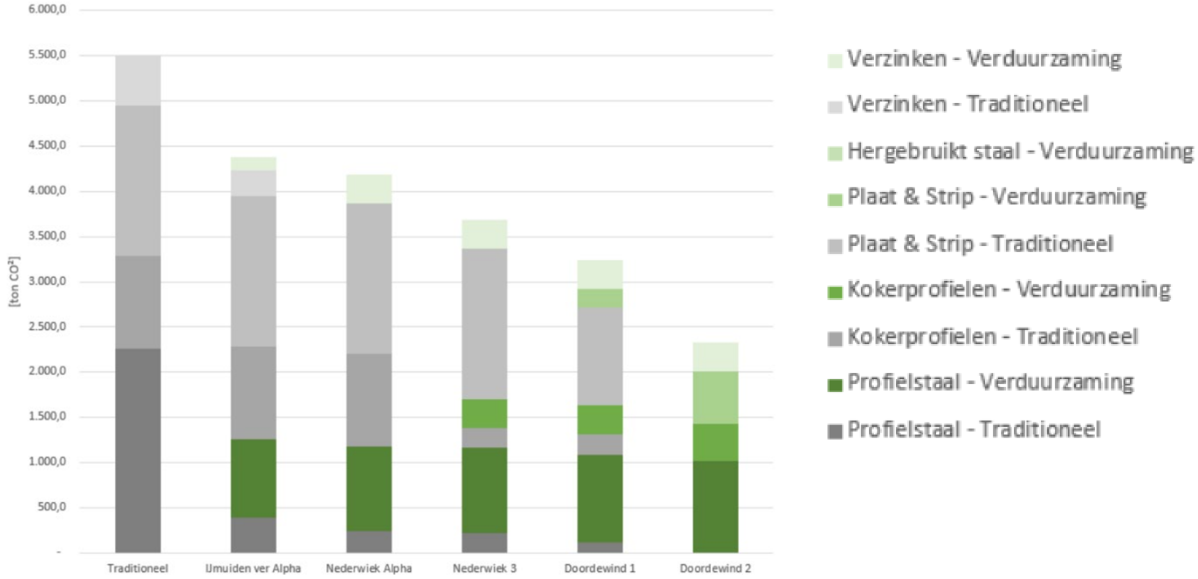
Furthermore, De Kok Staalbouw also investigated the environmental impact of donor steel compared to Salcos steel, a green-produced steel with low CO_2 emissions (Bouwakkoord staal, 2024). Using data from the material passports, the Global Warming Potential (GWP) was calculated, as presented in Table 4.4 (De Kok Staalbouw, 2023).

Table 4.4: Environmental comparison between virgin, Salcos, and donor steel (based on De Kok Staalbouw, 2023).

	GWP	**CO_2 reduction of traditional rolled steel**	**Reduction kg CO_2 per 1.000 kg steel**
Traditionally rolled steel	688 kg CO_2	-	-
Salcos steel (green steel)	366 kg CO_2	47%	322 kg CO_2
Donor steel	15 kg CO_2	98%	673 kg CO_2

In addition, the ECI, LCA, and CO_2 emissions were calculated in the tender phase and are monitored in the design and realisation phases. The expected CO_2 emissions calculation for all stations is presented in Table 4.5. These are expected calculations and may differ from the final results upon realization. CO_2 reduction and sustainability goals at each station are clearly indicated in the sustainability percentages, which increase exponentially.

Table 4.5: Steel timeline with CO_2 emissions and sustainability goal for every station (Dura Vermeer, 2022).



C2: Design and planning process

Reuse was already introduced in the framework agreement for the Offshore Grid 2GW Landstations. In this agreement, Dura Vermeer and De Kok Staalbouw proposed to build the construction of the 'Convector hall' and 'Controle building' (Figure 4.2) partly from donor steel components (Dura Vermeer PEP, 2022). The introduction of steel reuse aligns with the sustainability theme from the client, TenneT, which encompasses climate, circularity, nature, climate adaptation, and human rights (van Haasteren, T., 2022). The introduction of reuse was implemented most straightforwardly, facilitating the integration of donor steel into the project process.

The early introduction of reuse was made possible by research conducted by Dura Vermeer and De Kok Staalbouw beforehand (De Kok Staalbouw, 2023). As mentioned earlier, the availability and certification of the donor steel components were not an issue in this case, as the research conducted beforehand ensured this. While Arcadis has already developed the station's construction design, the strategy for the structural design with reuse applications is the '*Design and search strategy'*. The structural design is created first, and then the necessary donor steel components are implemented (Dura Vermeer PEP, 2022). This strategy is applied to all stations to incorporate more donor steel components into the realization of every station.

Moreover, although the availability and certifications were not an issue in this case, implementing reuse still might affect project planning or the timeline (De Kok Staalbouw, 2023). Currently, the realization phase of Station 1, IJmuiden van Alpha, has begun; however, donor steel components have not yet been implemented in this station (Dura Vermeer, 2024). This aligns with the ambitions outlined in Table 4.3, which also includes the goal of implementing at least 20 tons of donor steel components at the second station. This station is currently in the VO phase ('voorlopige ontwerp'), and the implementation of donor steel has not yet been determined (Interviewee 2, 2GW Landstations).

C3: Collaboration and governance

The 2GW Landstations from Tennet are covered under a three-year framework agreement. The main stakeholders: Tennet, Arcadis, Dura Vermeer, De Kok Staalbouw, SPIE Industries, and WSP

Engineering, in this framework agreement, were due to this contract form early aligned in the process. As mentioned earlier, Arcadis prepared the preliminary design for the Landstations in advance, and the sustainability goals were described in the contract (Dura Vermeer PEP, 2022). In the Dura Vermeer PEP (2022), the start of the partnership and design collaborations in the DO-advice phase are described and listed. The document outlines the factors necessary for a successful collaboration. The following factors are listed:

SF1: Starting and investing in a coorperation from the very beginning.
SF2: Controlling the chain by working with fixed partners across the whole framework agreement.
SF3: Standardising processes within the portfolio together with the connected Station contractor.
SF4: Continuously improving as one portfolio instead of separate projects.
SF5: Openly sharing all the knowledge and innovations on sustainability and safety.
SF6: Regularly monitoring the progress and making adjustments together, where necessary.
SF7: Transparency over the efficiency and costs.
SF8: Using digital construction expertise to support ongoing improvements.

After the contract is awarded on 17 February 2023, the project team will begin the DO-advise phase. The focus in the early project phases was on SF1 and SF3. The stakeholders will begin building a long-term collaboration with all the involved stakeholders, providing high-quality advice on the design development by TenneT and Arcadis. In addition, Dura Vermeer will prepare the management system to achieve the highest possible level of process maturity. The stakeholders together drafted the ‘Project Management Plan’(PMP) for the first project, which is in line with the maturity level agreed with TenneT. These actions show that all stakeholders were aligned early on and worked as a team from the beginning of the project (Dura Vermeer PEP, 2022).

Moreover, trust and communication influence the decision-making in the project. In the PMP, a detailed description is given of how reliable communication, collaboration, and mutual understanding form the basis of successful decision-making. The Dura Vermeer PEP (2022) document emphasises several success factors, underscoring the importance of trust and communication. SF1 emphasizes the importance of investment in cooperation from the beginning and maintaining this investment throughout the whole project (Dura Vermeer PEP, 2022).

Furthermore, SF5 emphasizes openness and reciprocity; stakeholders should share their knowledge and innovations to ensure the project's success (Dura Vermeer PEP, 2022). This indicator reflects a high level of trust and transparency, which supports the donor steel application process. Together with regular monitoring, SF6, the donor steel application process, and CO_2 emissions are clearly organized.

The three-year framework agreement, together with the open way of working and collaboration structure, indicates that a collaborative approach supports the decision-making in this project. This collaborative approach is closer to an Integrated Project Delivery (IPD) than a traditional contract. The Dura Vermeer PEP (2022) document shows that the project is based on long-term partnerships, with shared responsibilities and joint processes, rather than linear coordination and separated roles. To elaborate, section C1 and C2 describe that the design and realisation teams include all stakeholders from TenneT, Dura Vermeer, and subcontractors. The teams are led by a Realisation Manager and an Integral Design Leader, who are responsible for content alignment and managing internal project interfaces (Interviewee 1, 2GW Landstations). This structure shows all stakeholders collaborating as a team rather than following a traditional contractor-client separation.

C4: Economic and logistical feasibility

Besides being a cost-efficient way to reduce CO_2 emissions, donor steel can also be cost-efficient in general (De Kok Staalbouw, 2023). De Kok Staalbouw (2023) conducted a cost analysis of CO_2-neutral steel versus donor steel components; the results are presented in Table 4.5. The cost of Salcos' CO_2-neutral steel is calculated based on the Q1 2025 situation. The calculation of the donor steel components is based on an estimate from the steel supplier in the North of France, as mentioned before. The actual cost may differ from these calculations due to market fluctuations and differences in suppliers.

Table 4.5: Cost-efficiency analysis of CO_2-neutral steel and donor steel per 1.000kg CO2-reduction (based on De Kok Staalbouw, 2023).

	Cost-efficiency (€) per 1.000 kg CO_2-reduction
Salcos steel (green steel)	€282,28
Donor steel	€460,62

Table 4.5 shows that donor steel is a better option in terms of environmental costs and economic efficiency (De Kok Staalbouw, 2023). Donor steel can reduce the CO_2 emissions and be cost-efficient in this specific case. The MPs are essential for these calculations, enabling detailed data on the technical and material properties of components and ensuring the project's quality, safety, and environmental impact (De Kok Staalbouw, 2023). Testing of the donor steel components was therefore not applicable.

In contrast, De Kok Staalbouw (2023) writes that the financial calculations are based on current market costs and availability. In addition, they write that the components in traditional applications in the production process have not yet been tested. The weldability and galvanization process still needs to be tested for the 2GW program. Research into these topics will be conducted during the project, as noted in Table 4.3, and optimization will be considered for applicability in each project.

Although TenneT has ambitious sustainability goals, as described by van Haasteren (2022), the implementation of donor steel components for Stations 2, 3, 4, and 5 is still under discussion. Therefore, answering the question about ‘the client's willingness to pay for the sustainable benefits of donor steel application’ is not possible.

C5: Regulatory and certification constraints

The NTA 8713 will be used to assess donor steel applications and to optimize and test the geometric and material properties of donor steel components. The guidelines of NTA 8713 ensure that the technical and safety regulations outlined in NEN-EN 1993 for steel constructions are followed (De Kok Staalbouw, 2023).

The donor steel components also have some practical criteria, which are the following (De Kok Staalbouw, 2023):

- The steel must come from a building built in the Netherlands after 1955.
- Steel from specific structures cannot be used (e.g., heavily loaded structures, steel with fire damage).
- Steel demounted from buildings can be used, if the geometric and material properties are fixed in a material passport.
- If the steel structure is not dismantled, but remains in the original building where its lifespan is extended, then the NEN 8700 needs to be followed.
- Steel types, such as weathering steel, stainless steel, and cast steel, are not applicable for donor steel applications.

De Kok Staalbouw (2023) utilizes a donor construction dossier (‘donorbouwwerkdossier’) as the initial step in determining whether an existing structure can be reused. The goal of the dossier is to gather as much original documentation of the structure as possible, including building drawings, calculations, and documents detailing the properties of the steel components used. The most important documents are:

- **Construction drawings and calculations:** Providing insights into the steel profiles and steel types used. This way, the technical properties of the steel components can be declared.
- **Declaration of Performances (DoP):** These documents provide the material properties of the steel components.

Additionally, the NTA distinguishes between the reliability of the various documents, assigning each a ranking that reflects its reliability (De Kok Staalbouw, 2023). The most reliable documents have ranking one and so forth, realizing the following ranking of documents:

1. DoP, inspection documents, or CE-marking documents.
2. Manufacturing drawings or documents.
3. Implementation-ready design drawings.
4. Specification drawings and calculations.
5. Design drawings and calculations.

Suppose none of the documents above are available. In that case, the technical and material properties of the steel components must be tested to determine if they can be used as donor steel components. Moreover, the 2GW projects have ‘Gevolgklasse 3’, which means that if construction fails, the impact will be significant, necessitating highly detailed and accurate testing of material properties.

The structural safety of TenneT is assured using NTA 8713, the structure described above, and the available MPs for the donor steel components.

C6: Outcome and lessons learned

The main insights from the technological, organizational, economic, and regulatory analyses of the 2GW Landstation case will be elaborated here in the lessons learned. The lessons learned will highlight the enablers and obstacles for the donor steel integration in the project and outline the implications for future donor steel projects.

First, the key obstacles of the 2GW Landstations can be summarized in the following themes:

1.) **Certification and design standardization.**
The station's steel construction falls under ‘Gevolgklasse 3’, requiring strict reliability and detailed documentation (De Kok Staalbouw, 2023). While material passports are available for French donor steel components, future reuse depends heavily on the reliability of the documents under NTA 8713.
Moreover, the client, TenneT, has its own high-quality assurance requirements, in addition to the NTA 8713 requirements, to prevent project defects. These requirements are so stringent because the consequences of defects during the operational phase are enormous for TenneT (Interviewee 1, 2GW Landstations).
2.) **Cost & economic uncertainty.**
The integration of donor steel components results in a 98% reduction in CO2 emissions. However, the cost-efficiency (€ per avoided CO_2) is heavily dependent on the following aspects: ‘market availability’, ‘logistic costs’, and ‘processing requirements’. These aspects create difficulties in developing a clear business case, especially for a conservative, cost-driven client. The client, TenneT, currently has a strict project schedule because it needs the projects completed at a specific time. Additionally, as mentioned before, TenneT still had not yet committed financially to the application of donor steel for later stations (Interviewees 1 & 2, 2GW Landstations).
Moreover, despite TenneT's strong sustainable ambitions, discussions on time and cost among TenneT, Dura Vermeer, and De Kok Staalbouw are still ongoing (Interviewee 1, 2GW Landstations). The client, TenneT, still had not yet committed financially to the application of donor steel for later stations.

Second, the key enablers of the 2GW Landstation case can be summarized in the following four themes:

1.) **Early integration of reuse in the contract and design.**
The donor's steel ambitions were already embedded in the framework agreement. The ambitions of Dura Vermeer, in collaboration with De Kok Staalbouw, to apply donor steel were already set out in the early stages of the framework agreement in 2023, in the detailed roadmap for its application across all five onshore stations. The ambitions align with TenneT's sustainability ambitions (van Haasteren, T., 2022).
Furthermore, a clear digital strategy (4D/5D BIM, 3D scanning, VR) was established in the tender phase, enabling early planning and risk identification (Dura Vermeer BEP, 2022).
2.) **Availability of high-quality donor steel with material passports.**
De Kok Staalbouw previously sourced demountable steel profiles from France, each with a validated material passport, eliminating the need for material testing to determine material properties. Additionally, the steel profile harvest list from France provided a transparent overview of available components (De Kok Staalbouw, 2023). Ensuring the *‘Design and search strategy’* and donor steel integration are possible at every stage for every station.

3.) **Strong collaboration structure.**
The Framework agreement consists of a strong collaboration structure that ensures early alignment among all stakeholders: TenneT, Dura Vermeer, WSP, SPIE, and De Kok Staalbouw (Dura Vermeer, BEP, 2022). The project team was obliged to follow the explicit collaboration success factors, SF1-SF8, which emphasize transparency, trust, digital construction expertise, and continuous improvement, making donor steel application possible for future stations (Dura Vermeer BEP, 2022).

4.) **Client sustainability ambition supports reuse.**
The client, TenneT, sustainability strategy focuses on climate, circularity, nature, and adaptation, creating a strong mandate for reuse and CO2-neutral steel solutions (van Haasteren, T., 2022). In contrast, if donor steel is applied at stations 2 and 3, it is still under discussion with TenneT due to time and cost constraints in the project (Interviewee 1, 2GW Landstations).

To summarize the 2GW Landstations case, the following Table 4.6 is presented, in which the conclusions of C1-C5 can be found, and a summary of the key obstacles and enablers. The lessons learned from this case study are presented in the discussion chapter.

Table 4.6: Summary of the 2GW Landstation case for all five analytical dimensions and conclusions.

	Offshore Grid – 2GW Landstations
Donor steel role	Considered / Piloted / Full application
Availability of donor steel	Harvest list, MPs available, suitable demountable profiles
Client sustainability ambitions	High: sustainability strategy focuses on climate, circularity, nature, and adaptation.
C1: Key technologies used	BIM 4D/5D, Mp's, Digital Twin, 3D scans, VR
C2: Reuse integration phase	Early (contract phase)
Reuse strategy	'*Design & Search strategy.*'
C3: Governance/ collaboration model	Framework agreement; SF1-SF8 Similar IPD (integrated project delivery model)
Stakeholder alignment	Early alignment through a framework agreement
Trust & communication indicators	High transparency and shared learning
C4: Economic feasibility	Donor steel cost-efficient; saving 98% CO2 emissions
Logistical feasibility	No testing required for material properties, but weldability tests are pending.
C5: Certification constraints	'Gevolgklasse 3', NTA 8713 requirements, plus TenneT's own quality assurance requirements
C6: Conclusion	
Key obstacles	1. Certification and design standardization 2. Cost uncertainty and client willingness to pay.
Key enablers	1. Early integration of reuse in the contract and design. 2. Availability of high-quality donor steel with MPs. 3. Strong collaboration structure. 4. Client sustainability ambition supports reuse.

4.2.2 Replacement Railway Bridge Witte Paarden *~Infrastructure*

C1: Technological integration
The ambition to utilize the constructive donor steel at the project Witte Paarden was initiated by Dura Vermeer. The sustainability proposal and the presentation to the client, ProRail, proposed using donor steel from the OpenIJ consortium project, comprising BAM and Volker Wessels (Dura Vermeer, 2024). The Witte Paarden project had a strict schedule, whereas the bridge no longer met the requirements and had an axle-load restriction (ProRail, 2021). Still, donor steel was available, while steel support beams from another project were available during that period (Dura Vermeer, 2024).

These steel support beams came from the project Sea Lock in IJmuiden. The beams could be easily reused, while they had previously been used as temporary support structures during the construction of the locks. The beams were bought initially new for the Sea lock project and were still in excellent condition for reuse in the replacement railway bridge, Witte Paarden. The beams were temporary steel structures installed in the headbulkheads and remained in place for 2 years (Dura Vermeer, 2024). The temporary construction was statically loaded only, with no dynamic or fatigue loading. In addition, the bridge deck is made of composite, an innovative plastic material with minimal weight, reducing the amount of material used and lowering CO_2 emissions. The minimal weight and certified steel beams enabled the use of donor steel (Dura Vermeer, 2020).

The proposal was approved by the client, ProRail, during the early stages of contract finalisation. The proposal aligned with ProRail's sustainability ambitions, stating that ProRail aims to be CO_2-neutral in 2030 (ProRail, 2020). In addition, ProRail aims to build a circular economy, meaning that materials must be used in a circular manner and waste materials or components must be reused (ProRail, 2020). These ambitions are directly in line with the sustainability proposal, including the application of donor steel.

From the Sea Lock IJmuiden project, five HEB900 beams of 16,7 m were bought and made into 4 HEB900 beams of 19,1 m for the Witte Paarden project. While the beams were already certified and had the proper certificates, all the needed material properties were known. Based on the beam data, a BIM model was constructed for both the new and traditional designs of the railway bridge (Dura Vermeer, 2020). Figures 4.6 and 4.7 show the traditional design with concrete beams and the new sustainable design with the reused beams.

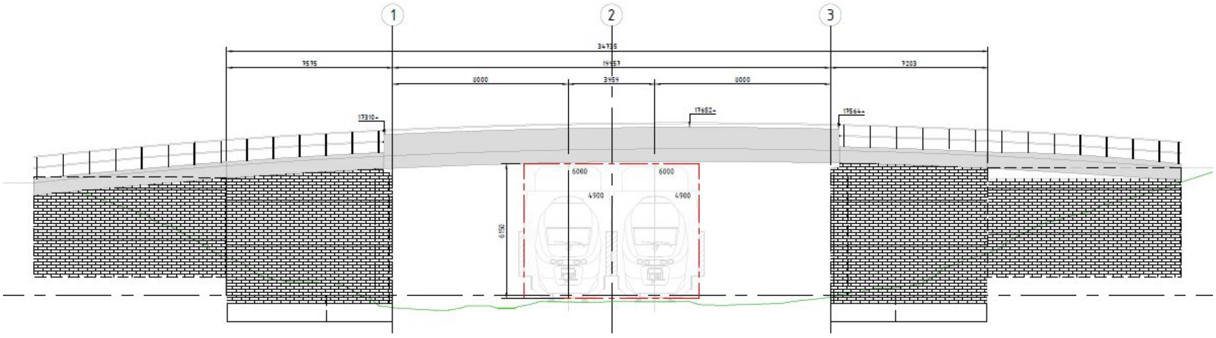


Figure 4.6: Traditional design to replace the viaduct with a concrete construction (Ingenieursbureau Boorsma, 2019).

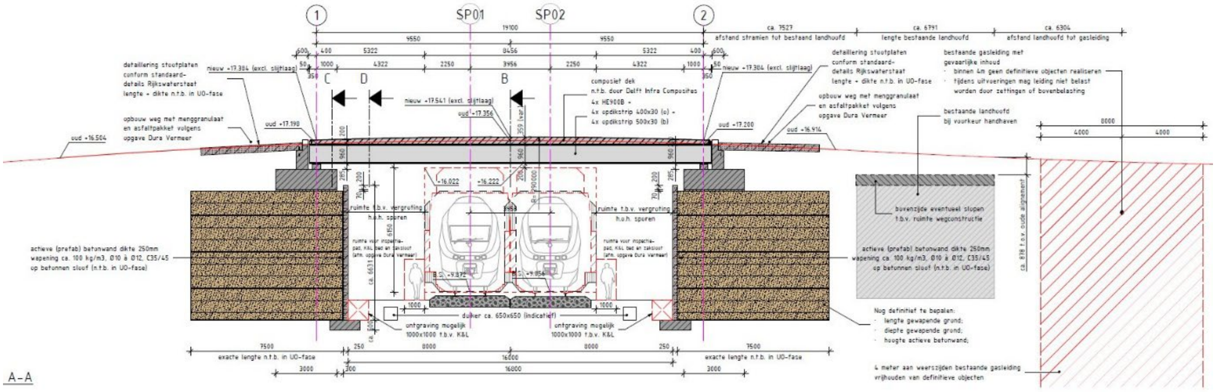
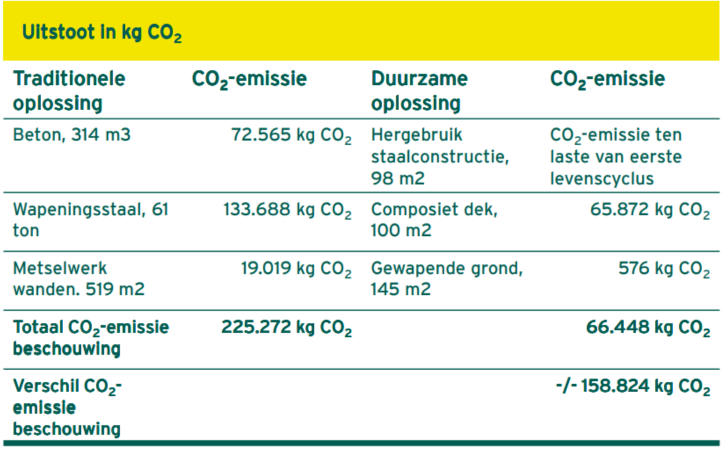


Figure 4.7: Final sustainable design railway viaduct Witte Paarden, section AA' (Dura Vermeer, 2020).

Both designs were compared on economic and sustainability grounds through a cost, ECI, and CO_2 emission comparison. Table 4.7 presents the difference in CO_2 emissions between the traditional and sustainable designs. This table shows that the donor steel application, together with the composite roof and reinforcement, reduced CO_2 emissions by 158.824 kg compared to the traditional design (Dura Vermeer, 2020).

Table 4.7: CO2 emission comparison between the traditional design and sustainable design of the railway viaduct Witte Paarden (Dura Vermeer, 2020).



Uitstoot in kg CO_2

Traditionele oplossing	**CO_2-emissie**	**Duurzame oplossing**	**CO_2-emissie**
Beton, 314 m3	72.565 kg CO_2	Hergebruik staalconstructie, 98 m2	CO_2-emissie ten laste van eerste levenscyclus
Wapeningsstaal, 61 ton	133.688 kg CO_2	Composiet dek, 100 m2	65.872 kg CO_2
Metselwerk wanden. 519 m2	19.019 kg CO_2	Gewapende grond, 145 m2	576 kg CO_2
Totaal CO_2-emissie beschouwing	**225.272 kg CO_2**		**66.448 kg CO_2**
Verschil CO_2-emissie beschouwing			**-/- 158.824 kg CO_2**

C2: Design and planning process

As mentioned in C1, Dura Vermeer introduced reuse during the finalisation of the contract. They provided the client, ProRail, with a traditional design and a sustainable design option and demonstrated the differences in environmental factors, such as reductions in ECI and CO_2 (Dura Vermeer, 2020).

The strategy that was used for the structural design with reuse applications was the *'Design for reuse strategy'*. The donor steel components were identified first: the temporary beams for the Sea Lock IJmuiden project. A design was created using the available components. From the Sea Lock IJmuiden project, five HEB900 beams of 16,7 m were bought and made into 4 HEB900 beams of 19,1 m. The donor beams have been modified and welded to achieve the necessary length for the new project Witte Paarden's overstrain (Dura Vermeer, 2020). Figure 4.8 shows the constructive design with the implemented donor steel components. In Figure 4.8, the grey steel beams are the donor steel components. The green and red horizontal steel braces are made of 97% HEB1000 recycled steel (Dura Vermeer, 2020).

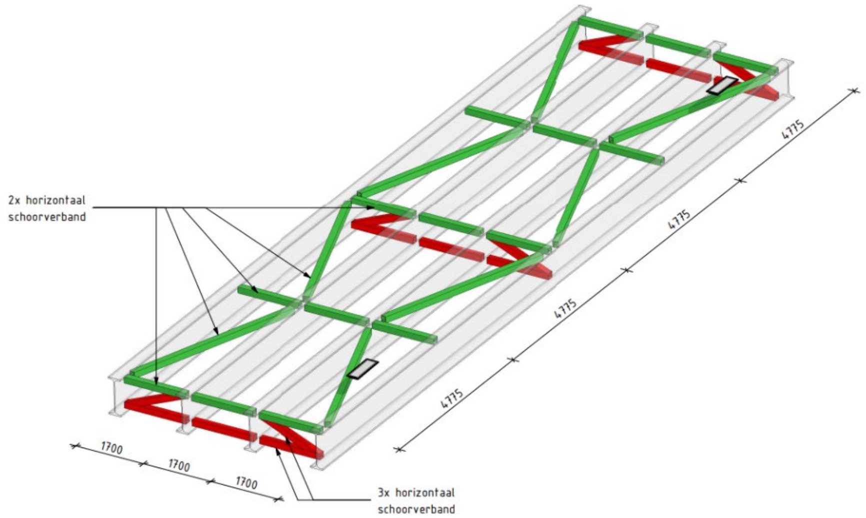


Figure 4.8: 3D buttress bond detail of the new sustainable design for the railway viaduct Witte Paarden (Dura Vermeer, 2020).

The availability of donor steel did not influence the structural design, as the donor steel components had already been identified and could be directly implemented, given their certification and information about their past life (Dura Vermeer, 2024). In addition, the modifications to the donor steel beams made direct implementation possible in the design without redesigning the construction. Moreover, the timing of both projects made the donor steel application possible; the reuse application did not affect the feasibility or project planning of either project (Interviewee 1, Witte Paarden).

C3: Collaboration and governance

The project Witte Paarden involved multiple stakeholders: the client, ProRail; the contractor, Dura Vermeer, Wagenmaker Rosmalen, and Buiting Staalbouw uit Amelo; and subcontractors. While the bridge was deemed unsafe at the time, the Witte Paarden project had to be carried out immediately (ProRail, 2021). Dura Vermeer was then chosen to construct, design, and realise this project. Therefore, the stakeholders were aligned early in the process, and they chose to apply donor steel in the early design phases (Dura Vermeer, 2020).

The trust and communication between the stakeholders went well, while the client, ProRail, spoke only with Dura Vermeer to ensure clear, structured information (Nationale Staalprijs, 2022). Dura Vermeer then hired two subcontractors to make the constructive design and process the new and donor steel components (Dura Vermeer, 2020). The tasks and responsibilities were very clearly written in the contract, resulting in clear, structured information (Interviewee 1, Witte Paarden).

The project was realised in the form of a ‘Bouwteam’, meaning that the client, main contractor, and subcontractors work closely together and share risks and responsibility towards the project (Nationale Staalprijs, 2022). This open way of working and collaborative structure indicate that a collaborative approach supports decision-making in this project. This collaborative approach is closer to an Integrated Project Delivery (IPD) than a traditional contract.

C4: Economic and logistical feasibility

No cost comparison was available between the new and donor steel components. The economic feasibility cannot, therefore, be determined and is not applicable in this case. Initially, ProRail suggested a traditional design, but, given Dura Vermeer's sustainable design, it chose the sustainability benefits of donor steel application (Dura Vermeer, 2020). Sustainable design with donor steel elements was also feasible within the available budget (Nationale Staalprijs, 2022).

Storage did not pose any challenges to the application of the donor steel components, because the timeline of the Sea Lock IJmuiden harvest project aligned with the realisation of the Witte Paarden project. The donor steel beams could be directly harvested and transported to the subcontractor, Buiting Staalbouw uit Almelo, for testing and modifications (Nationale Staalprijs, 2022).

As mentioned before, the donor steel components had original material certificates, and their past life was known (Dura Vermeer, 2024). Still, the beams were tested to meet ProRail's safety standards (Nationale Staalprijs, 2022). The modifications, consisting of welding the five shorter beams into four longer beams, were carried out in accordance with NEN-EN 1993-1-9 and subsequently ultrasonically tested to ensure they were defect-free (Nationale Staalbouwprijs, 2022). Although multiple tests were needed, they did not affect the project's budget or logistical feasibility (Dura Vermeer, 2020).

C5: Regulatory and certification constraints

The NTA 8713 was not applicable, as it was published only on June 1, 2023, after the project was realized in 2021 (Bouwen met Staal, 2024). The Eurocodes set the guidelines for modifying the donor steel HEB900 beams. The HEB900 beams sourced from the temporary structure at the IJmuiden Sea Lock project were visually inspected before purchase for the Witte Paarden project. After purchase, the beams were tested, and small microcracks were found at the attachment points of the temporary chain welds. The cracks were removed, the steel was preheated, rewelded, ground smooth, and retested with penetrant testing (Nationale Staalprijs, 2022).

The original material certificates, CE marking, and verified heat number could not be matched to the beams after these tests, so additional laboratory testing was required in agreement with ProRail (Nationale Staalprijs, 2022). The donor steel beams were tested for fracture strength, chemical composition, and yield strength. The results met the current ProRail standards, including Rijkswaterstaat ROK 1.4 (Nationale Staalprijs, 2022).

After the tests, the donor steel beams were cleaned and modified; the five original beams were turned into four longer beams, as mentioned before. The weldings were assessed for fatigue according to NEN-EN 1993-1-9, and, in addition, production requirements from a higher detail category (112) were applied. The welds were tested with ultrasonic testing to ensure their quality (Nationale Staalprijs, 2022).

In contrast, ProRail sets regulations that prohibit butt welds in the web and flanges within the same cross-section (regulation OVS0030-6; Nationale Staalprijs, 2022). Dura Vermeer met this requirement by proving and testing the beam to ensure it has sufficient capacity without relying on the flanges at the weld location (Dura Vermeer, 2024).

The test was conducted in accordance with detailed category 63 (Table 8.3 of NEN-EN 1993-1-9) and detailed category 112, ensuring that the structural safety of the client and donor steel components could be assessed (Nationale Staalprijs, 2022).

C6: Outcome and lessons learned

The main insights from the technological, organizational, economic, and regulatory analyses of the Witte Paarden case will be elaborated here in the lessons learned. The lessons learned will highlight the enablers and obstacles for the donor steel integration in the project and outline the implications for future donor steel projects.

First, the key obstacles of the Witte Paarden case can be summarized in the following three themes:

1.) **Certification and (lack of) design standardization.**
Although the donor beams from the IJmuiden Sea Lock project were certified, welding marks from temporary chain connections had caused microcracks in the donor steel beams. Resulting in the required extensive laboratory testing, removal, preheating, repair welding, grinding, and retesting of the donor steel beams, according to the NEN-EN 1993-1-9 (Nationale Staalprijs, 2022).
Moreover, the railway infrastructure projects of ProRail require fatigue analysis, fracture toughness testing, and stringent compliance with ProRail standards (Nationale Staalprijs, 2022). ProRail's OVS0030-6 strictly prohibits butt welds in webs and flanges within the same cross-section. Dura Vermeer had to prove that the sustainable design provided sufficient capacity without relying on these zones.
Additionally, the railway bridge complies with higher detail categories (63 and 112), and ultrasonic testing for welds created additional work and tests. Still, the application of donor steel was feasible within the project timeline. These requirements and stringent compliance with ProRail standards complicate the use of modified donor steel beams, resulting in additional testing.

Second, the key enablers of the Witte Paarden case can be summarized in the following four themes:

1.) **Availability of high-quality donor steel with MPs (certifications).**
The steel beams from the temporary construction of the IJmuiden Sea Lock project served as donor steel for the Witte Paarden project and aligned perfectly with the project's timing (Dura Vermeer, 2024). The Sea Lock project concluded at precisely the right moment, making the donor steel components available without the need for storage. The alignment of donor steel availability with project timing connected perfectly.
Moreover, the donor steel beams from the IJmuiden Sea Lock project were already certified, material properties and history were known, and they were structurally suitable for the Witte Paarden project (Dura Vermeer, 2024). This eliminated uncertainty regarding material origin, which is typically a barrier in donor steel projects.

2.) **Client sustainability ambition supports reuse.**
The client, ProRail, has its own sustainable ambitions to be a CO_2-neutral operation by 2030 and to promote the circular use of materials (ProRail, 2020). These ambitions align with the implementation of donor steel components, facilitating the approval of sustainable alternatives.

3.) **Early integration of digital and sustainability tools.**
The project integrated and applied BIM, LCA, and ECI during the early tender phase. During this phase, the traditional concrete-beam reference design was compared to the

donor-steel solution. This comparison in the BIM model, with integrated LCA and ECI, demonstrated clear environmental benefits and ensured technical feasibility (Dura Vermeer, 2024).
Moreover, the existing railway bridge was deemed unsafe by ProRail and required immediate replacement, leaving little time for redesign and risking unforeseen delays (ProRail, 2021). Still, the use of digital and sustainable tools enabled the implementation of donor steel.

4.) **Strong collaboration structure.**
The Bouwteam structure fostered early stakeholder alignment, shared risk, and transparent communication, similar to those in Integrated Project Delivery (IPD) (Nationale Staalprijs, 2022). This form of contracting supports rapid decision-making despite the project's emergency timeframe, enabling donor steel integration through strong collaboration.

To summarize the Witte Paarden case, the following Table 4.8 is presented, in which the conclusions of C1-C5 can be found, and a summary of the key obstacles and enablers. The lessons learned from this case study are presented in the discussion chapter.

Table 4.8: Summary of the Witte Paarden case for all five analytical dimensions and conclusions.

	Replacement railway bridge Witte Paarden
Donor steel role	Applied
Availability of donor steel	Harvest list, CE certification available, suitable demountable profiles
Client sustainability ambitions	High, CO_2-neutral by 2023
C1: Key technologies used	BIM, Material testing, LCA, MKI
C2: Reuse integration phase	Early (contract phase)
Reuse strategy	*‘Design for reuse strategy’.*
C3: Governance/ collaboration model	Bouwteam Similar IPD (integrated project delivery model)
Stakeholder alignment	Early alignment through a Bouwteam
Trust & communication indicators	High transparency and shared learning
C4: Economic feasibility	Donor steel cost-efficient; saving 72.565 kg CO_2 emissions
Logistical feasibility	Extensive testing required (microcracks, welding, ultrasonic testing)
C5: Certification constraints	High regulatory requirements, detail categories 63 and 112 to NEN-EN 1993-1-9.
C6: Conclusion	
Key obstacles	1. Certification and (lack of) design standardization
Key enablers	1. Availability of high-quality donor steel with MPs. 2. Client sustainability ambition supports reuse. 3. Early integration of digital and sustainability tools. 4. Strong collaborative structure.

4.2.3 Building REC-P Roeterseilandcampus UvA *~Built environment*

C1: Technological integration

Dura Vermeer Renovatie Midden West aims to apply circularity as much as possible in the renovation project, as in the renovation of the building REC-P. Dura Vermeer mapped all available building materials for reuse with the demolition contractor and the client, using a material flow inventory (Dura Vermeer, 2022). Multiple elements were identified for reuse in the building, including steel staircases and aluminium window frames. The reuse and circularity ambitions of Dura Vermeer and the client, UvA, were high in this project.

The renovation of REC-P also included a roof garden, resulting in necessary reinforcements to the roof. The steel structure needed for roof reinforcement was provided by donor steel elements (Dura Vermeer, 2024). Figure 4.9 shows the steel reinforcement structure, consisting primarily of HEA160, HEB180-280, and IPE180-360 profiles (Blijleven, 2022). Around 30% of the steel structure consists of donor steel elements (Interviewee 3, REC-P).

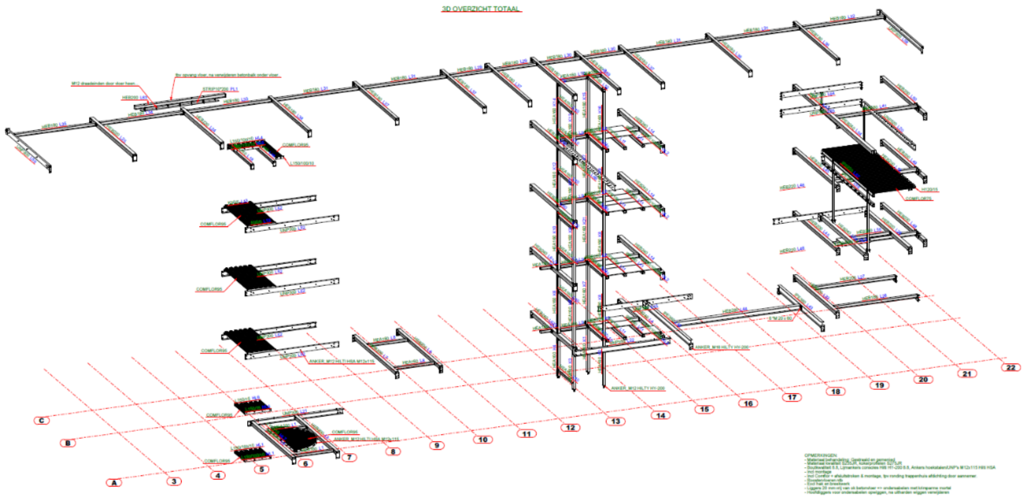


Figure 4.9: 3D overview of the reinforced steel structure in the building REC-P (Blijleven, 2022).

The steel reinforcement structure was originally designed using S355 steel profiles, but not enough were available. This resulted in redesigning the construction with S355 and S235 profiles, while the S235 could be more easily sourced (Blijleven, 2022). The final steel grades used for the steel construction of REC-P are S235 and S355, in accordance with NEN-EN 10025-2 (Blijleven, 2022). The beams and columns for the new part of the steel structure consist primarily of HEB180-280 profiles and IPE360 profiles (Blijleven, 2022). The donor steel components that were considered for reuse were the following profiles: HEB180 (S355), HEB200 (S235), HEB240 (S355), HEB280 (S355), and IPE360 (S235) (Blijleven, 2022).

The material properties of these different profiles were verified through testing. A part of the beam material testing report is available in Appendix E (Blijleven, 2022). The test report shows that multiple tests were performed, such as tensile strength, yield strength, elongation, and material type tests (Blijleven, 2022). All the components “satisfy the requirements” per NEN-EN 10025-2 and have been certified (Blijleven, 2022). After the tests, the donor steel components are shot-blasted and primered, thermally galvanized, and power-coated (Blijleven, 2022). Material passports were not available for these components.

The initial idea to apply donor steel elements came from the sustainability advisor, who was involved in the project (Interviewee 1, REC-P). The sustainability advisor stated:
"The client already had ambitious goals for circularity and had mapped out the materials they wanted to see returned in the building, and the request was basically: contractor, explain how you are going to reuse those products, and where you see additional circular opportunities?" (Dura Vermeer, 2023).
This shows that the client, UvA, had high sustainability and circularity ambitions, and that the application of donor steel aligned with those ambitions. Moreover, Figure X presents the Material flow inventory and how this was implemented together with the client, UvA, and contractor, Dura Vermeer, showing the high circular ambitions (The decision to use donor steel elements was made during the project's design phase, with the help of the demolition contractor, Adex, and the steel manufacturer, Blijleven (Interviewees 1 & 2, REC-P).

Furthermore, a BIM model was made for the steel construction design. Later, the available and suitable donor steel components were implemented in the original BIM model (Interviewee 1, REC-P). The material properties of the donor steel components were verified through material testing conducted and certified by Blijleven (Blijleven, 2022).

The division 'Build and Environment' uses different circularity measurement tools than the division 'Infrastructure' (Interviewee 1 & 2, REC-P). The 'Build and Environment' uses, besides the LCA, CO_2, and ECI, also the 'Milieu Prestatie Gebouwen' (MPG). During the tender phase, CO_2, LCA, ECI, and MPG calculations are performed for each project. These calculations do not differ, most of the time, from the realisation calculations (Interviewee 1, REC-P). For building REC-P, these calculations were performed, but the initial documents could not be used, so detailed information was unavailable.

C2: Design and planning process
Reuse of various elements was introduced during the concept and tender phases, but reuse of steel was explicitly introduced during the detailed design phase. Blijleven designed the reinforced steel structure, and the sustainability advisor from Dura Vermeer searched for donor steel components suitable for the construction design (Interviewee 1, REC-P). The strategy *'Design and search'* was used in this project to integrate the donor steel components in the structural design. The structural design was first developed for the building REC-P. Later, the donor steel components were identified.

The availability of donor steel influenced the structural design and the number of donor steel elements implemented immensely (Interviewee 2, REC-P). The sustainability advisor for Dura Vermeer stated that more than 12 donor steel merchants were contacted to identify suitable donor steel components in the required quantities. In the end, with the help of demolition contractor Adex and steel manufacturer Blijleven, the donor steel components were found and tested (Interviewee 2, REC-P). Moreover, the donor steel components did not affect the feasibility or project planning, whereas Blijleven tested and modified them on time in line with the project planning.

C3: Collaboration and governance
The main stakeholders, UvA (client) and Dura Vermeer (contractor), were early aligned in the process due to the overarching sustainability ambitions. On the project page of Dura Vermeer

(2023), it states: *“This project stands out because of the high circularity ambitions set by the client. Our task was not only to achieve these goals, but also to take additional steps towards more circular opportunities wherever possible.”* showcasing this alignment.

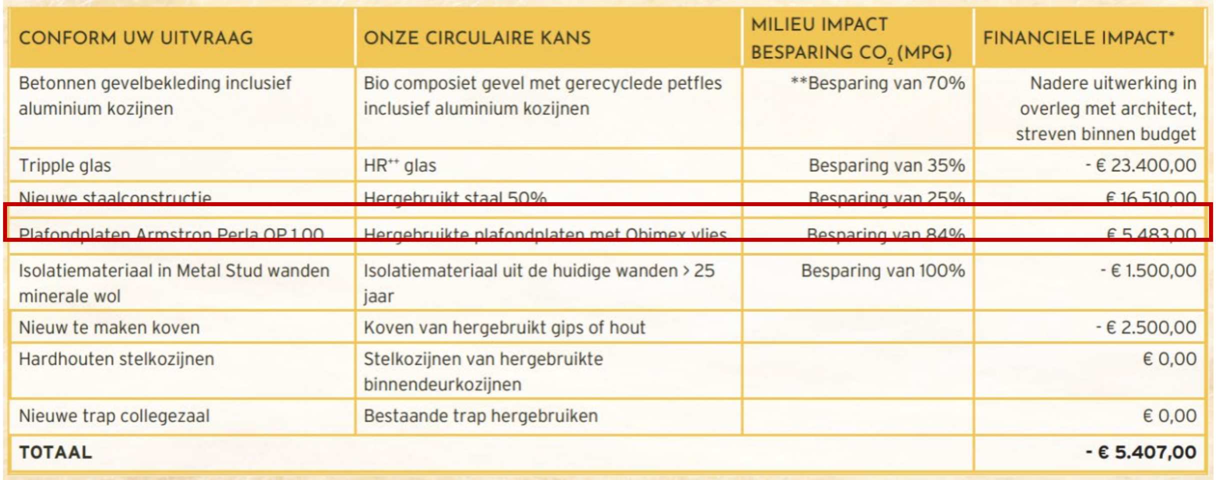
In addition, the collaboration with the demolition contractor Adex resulted in a detailed inventory of the building's materials using a material flow map (Dura Vermeer, 2023). Dura Vermeer (2023) stated that Adex helped them reuse existing materials and give them new life within the project. Moreover, strong collaboration with Blijleven made the application of donor steel possible (Interviewee 2, REC-P). This shows that all stakeholders were aligned from the outset and throughout the process to enable reuse.

In contrast, the project was initiated as a traditional contract, but the cooperation and collaboration among the different stakeholders demonstrate decision-making characteristics of integrated project delivery. The sustainability advisor at Dura Vermeer stated that the sustainability ambitions were only realised through this collaborative approach (Interviewee 1 & 2, REC-P).

C4: Economic and logistical feasibility

The sustainability advisor at Dura Vermeer conducted a cost analysis comparing donor steel components and new steel components (Interviewee 1, REC-P). In the end, the donor steel costs were higher than the new steel elements. The cost difference was not significant due to the war between Russia and Ukraine, which increased the price of new steel (Interviewee 2, REC-P). Table 4.9 presents a cost-efficiency comparison of all circular opportunities for REC-P; not all of these opportunities were wholly or partly realised (Dura Vermeer Renovatie Midden-West, 3.1, 2023). The application of 50% donor steel resulted in a 25% MPG reduction and costed €16.510 (Dura Vermeer Renovatie Midden-West, 3.1, 2023).

Table 4.9: *Circularity opportunities for the project REC-P, with calculated MPG reduction and cost (Dura Vermeer Renovatie Midden-West, 3.1, 2023).*



CONFORM UW UITVRAAG	ONZE CIRCULAIRE KANS	MILIEU IMPACT BESPARING CO_2 (MPG)	FINANCIELE IMPACT*
Betonnen gevelbekleding inclusief aluminium kozijnen	Bio composiet gevel met gerecyclede petfles inclusief aluminium kozijnen	**Besparing van 70%	Nadere uitwerking in overleg met architect, streven binnen budget
Tripple glas	HR^{++} glas	Besparing van 35%	- € 23.400,00
Nieuwe staalconstructie	Hergebruikt staal 50%	Besparing van 25%	€ 16.510,00
Plafondplaten Armstron Perla OP 1.00	Hergebruikte plafondplaten met Ohimex vlies	Besparing van 84%	€ 5.483,00
Isolatiemateriaal in Metal Stud wanden minerale wol	Isolatiemateriaal uit de huidige wanden > 25 jaar	Besparing van 100%	- € 1.500,00
Nieuw te maken koven	Koven van hergebruikt gips of hout		- € 2.500,00
Hardhouten stelkozijnen	Stelkozijnen van hergebruikte binnendeurkozijnen		€ 0,00
Nieuwe trap collegezaal	Bestaande trap hergebruiken		€ 0,00
TOTAAL			**- € 5.407,00**

Eventually, the cost of donor steel was higher, and the difference in the cost of donor steel components was 46,8% higher than that of new steel, amounting to €6.649,15. The total cost comparison can be found in Appendix F (Blijleven, 2022). The client, UvA, did pay for the sustainable benefits of the donor steel applications, given the relatively low costs relative to the significant sustainable impact (Interviewee 2, REC-P).

Testing and transportation of the donor steel elements posed no challenges, while Blijleven was responsible for testing the beams and certifying them.

C5: Regulatory and certification constraints

The NTA 8713 was not applicable, as it was published only on June 1, 2023, after the project was realized in 2022 (Bouwen met Staal, 2024). The Eurocodes provide guidelines for S235 donor steel components. The steel tests and weldings complied with the NEN-EN10025-2, NEN-EN 10210-1, and NEN-EN 10219-1 (Blijleven, 2022). The tests validated the safety and strength required for the donor steel components. As part of the test, the donor steel beams were certified and issued new CE markings (Blijleven, 2022).

The client, UvA, was assured of the structural safety of the donor steel beams due to the tests and new certifications they ultimately received (Interviewee 1 & 2, REC-P).

C6: Outcome and lessons learned

The main insights from the technological, organizational, economic, and regulatory analyses of the building REC-P case will be elaborated here in the lessons learned. The lessons learned will highlight the enablers and obstacles for the donor steel integration in the project and outline the implications for future donor steel projects.

First, the key obstacles of the building REC-P case can be summarized in the following two themes:

1.) **Supply and demand mismatch.**
The sustainability advisor for Dura Vermeer mentioned in an interview that over 12 donor steel suppliers were contacted before the required profiles could be sourced. The availability directly influenced the amount of donor steel that could be applied. Moreover, the structural design was changed to use S235 donor steel components rather than the original S235, which was even harder to find (Blijleven, 2022).
Moreover, the history and certification of the sourced donor steel components were unavailable, necessitating required testing and new CE markings (Dura Vermeer, 2023). The implementation was still feasible, but the testing added time and internal coordination. Moreover, the implementation of the donor steel elements was only possible due to the steel manufacturer Blijleven's positive attitude, which was responsible for the tests, certifications, modifications, and the redesign of the structure (Interviewee 1 & 2, REC-P).

2.) **Absence of legal frameworks.**
During the project's realisation phase (2021-2022), the NTA 8713 had not yet been published, meaning that no official Dutch testing protocol for donor steel in buildings existed (Blijleven, 2022). The test and welding had to comply with the NEN-EN10025-2, NEN-EN 10210-1, and NEN-EN 10219-1, creating uncertainties in the approval process (Blijleven, 2022).

3.) **Certification and design standardization**
While the NTA 8713 had not yet been published, the test and welding had to comply with the NEN-EN10025-2, NEN-EN 10210-1, and NEN-EN 10219-1, creating uncertainties in the approval process (Blijleven, 2022).

Second, the key enablers of the building REC-P case can be summarized in the following four themes:

1.) **Client sustainability ambition supports reuse.**
    The circular ambitions of the client, University of Amsterdam (UvA), and contractor, Dura Vermeer, were aligned from the start of the project. The UvA explicitly required the contractor to demonstrate how materials from the original building could be reused and present additional circular opportunities (Dura Vermeer, 2022). These ambitions provide a strong foundation for implementing donor steel components.
2.) **Strong collaboration structure.**
    Strong collaboration structures were created among the different stakeholders: contractor (Dura Vermeer), demolition contractor (Adex Group), and steel manufacturer (Blijleven) (Dura Vermeer, 2022). The demolition contractor, Adex Group, created a material flow inventory of the existing building, revealing which components could be directly reused and where donor steel could substitute new material in the roof reinforcement (Dura Vermeer, 2022).
    Moreover, the steel manufacturer, Blijleven, was responsible for the testing, certification, redesigning, and modification of the donor steel components (Blijleven, 2022). Their role and positive attitude towards the implementation of donor steel were critical to making reuse technically feasible and in compliance with the client's structural requirements, UvA (Interviewee 1, Kameleon).
3.) **Early integration of digital and sustainability tools.**
    The reinforced steel roof structure was modelled in a BIM. Later, the available donor steel components were added to the model. This way of working enabled transparency around the structure's geometry, fit, and structural behaviour (Blijleven, 2022).
4.) **Client willingness to pay for the circular solutions.**
    The client, UvA, not only had high circular ambitions, but was also willing to pay more for the implementation of donor steel. The UvA accepted the slight cost difference in implementing donor steel elements, recognizing the significant sustainable benefits, which align with their institutional ambitions.

To summarize the building REC-P case, the following Table 4.10 is presented, in which the conclusions of C1-C5 can be found, and a summary of the key obstacles and enablers. The lessons learned from this case study are presented in the discussion chapter.

Table 4.10: Summary of the building REC-P case for all five analytical dimensions and conclusions.

	Building REC-P Roeterseiland UvA
Donor steel role	Applied
Availability of donor steel	Difficult, limited availability, sourced through >12 suppliers
Client sustainability ambitions	High sustainability and circularity ambitions
C1: Key technologies used	Material testing, BIM, MKI, LCA, MPG
C2: Reuse integration phase	Detailed design phase
Reuse strategy	*"Design and search strategy'.*
C3: Governance/ collaboration model	Engineering & Construct Traditional contract with a strong collaborative structure.
Stakeholder alignment	Early alignment
Trust & communication indicators	High transparency and shared learning
C4: Economic feasibility	Donor steel is cost-efficient; specific savings not conducted
Logistical feasibility	Extensive testing required (yield, tensile, elongation, chemical properties)
C5: Certification constraints	Eurocode testing requirements (NEN-EN10025-2, NEN-EN 10210-1, and NEN-EN 10219-1)
C6: Conclusion	
Key obstacles	1. Supply and demand mismatch. 2. Absence of legal frameworks. 3. Certification and design standardization
Key enablers	1. Client sustainability ambition supports reuse. 2. Strong collaboration structure. 3. Early integration of digital and sustainability tools. 4. Client willingness to pay for the circular solutions.

4.2.4 Community School De Kameleon *~Built environment*

C1: Technological integration

Dura Vermeer Renovatie Midden West aims to apply circularity as much as possible in the renovation project, as in the renovation of the primary school De Kameloen. Dura Vermeer mapped all available building materials for reuse with the demolition contractor and the client, using a material flow inventory (Dura Vermeer, 2022). Multiple elements were identified for reuse in the building, including aluminium and wooden window frames, laminated timber beams, and parts of the old steel structure. The reuse and circularity ambitions of Dura Vermeer and the client, Gemeente Haarlemmermeer, were high in this project (Dura Vermeer, 2022).

Part of the school's old steel structure was reused and left untouched. The school's expansions consist of 85% new steel structure and 15% donor steel components, see Figure 4.10 (Dura Vermeer, vlog 1, 2025). The steel grades used for the steel construction of De Kameleon are S23, in accordance with NEN-EN 10025-2 (Blijleven, 2023). The beams and columns for the new part of the steel structure consist primarily of HEA120-260 profiles and HEB180, HEB200, and HEB260 profiles (Blijleven, 2023). The new steel structure is designed with bolts for demountability to accommodate future reuse (Dura Vermeer, vlog 1, 2025). The donor steel components that were considered for reuse were the following profiles: HEA160-220 and 260 (S235), HEB180 and 260 (S235), HEM180 (S235), and IPE270 (S235) (Dura Vermeer, 2024).

The donor steel components were sourced from the demolished town hall in Haarlemmermeer (P. Bekkering, 2024). The material properties of these different profiles were verified through testing (Blijleven, 2023). Afterwards, the donor steel components are shot-blasted and primered, thermally galvanized, and power-coated (Blijleven, 2022). Material passports were not available for these components.

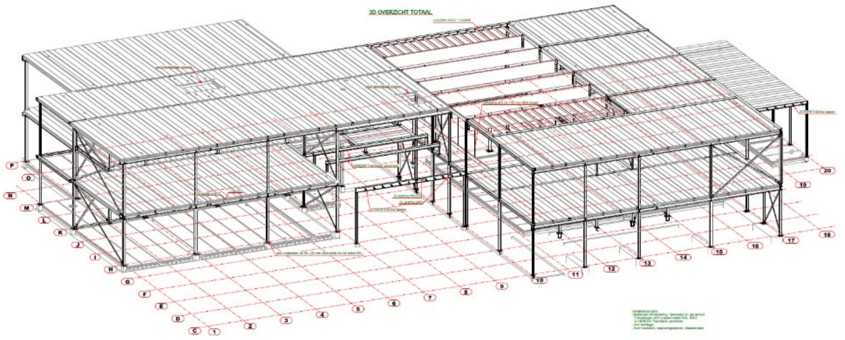


Figure 4.10: 3D overview of the new steel structure, with 15% donor steel components in De Kameleon (Blijleven, 2023).

The choice to implement donor steel elements was made during the early design and planning phase of the project. The high ambitions of Dura Vermeer Renovatie Midden West and the client, Gemeente Haarlemmermeer, aligned early in the process, and reuse became a prominent theme throughout the whole project (Interviewees 1 & 2, Kameleon). That reuse and circularity were also requirements in the client's official tender and rating plan; therefore, the application of donor steel was in line with the client's sustainability requirements (P. Bekkering, 2024).

The Tekla Structures steel construction in the Blijven (2023) steel montaging report is generated from a BIM model. The steel construction model was made first, and the available donor steel components were matched to the original design (Interviewee 3, Kameleon).

The division ‘Build and Environment’ uses different circularity measurement tools than the division ‘Infrastructure’ (Interviewees 1 & 2, Kameleon). The ‘Build and Environment’ uses, besides the LCA, include CO_2, ECI, and MPG. During the tender phase, CO_2, LCA, ECI, and MPG calculations are performed for each project. These calculations do not differ, most of the time, from the realisation calculations (Interviewees 1 & 2, Kameleon). The MPG, CO_2, LCA, and ECI calculations were performed for the project De Kameleon, but not all of the initial documents could be used.

Due to the absence of the initial documents, the following information was available from another project, which demonstrates the reduction of CO_2 in LCA modules A-C for donor steel:

Table 4.11: Circularity scenarios relevant to steel reuse (based on B. van Vliet).

Product Type	**CO_2 emissions A-C (kg)**	**Reduction vs. new**
New heavy steel	337,282 kg	-
Circular steel (XCarb)	174,955 kg	48% reduction
Reused steel	93,437 kg	72% reduction

In addition, some information on the CO_2 calculations was available for the project. In CO_2 calculations, applying 15% donor steel components to the steel structure reduced CO_2 emissions by 6,600 kg (Dura Vermeer, vlog 1, 2025). A detailed CO_2-report was made for the project De Kameleon, which included the donor steel and new steel elements in the category 2 or 3 for heavy construction steel, and data was used from the ‘National Milieu Database’ (NMD) (Dura Vermeer, 2024). The calculations were only made for the LCA modules A-C for the entire life cycle, except for module D (Dura Vermeer, 2024).

C2: Design and planning process

Reuse was introduced overall in the project during the tender phase, as the client's official tender and rating plan (P. Bekkering, 2024). Steel reuse was introduced in the early design and planning phase of the project, as mentioned before. Still, the strategy used for the structural design with reuse applications was ‘*Design and search’* (Interviewees 1 & 2, Kameleon).

Blijleven first prepared the structural design, and the beams used in the design were identified. The availability of donor steel posed a significant challenge, according to the sustainability advisor at Dura Vermeer (Interviewee 2, Kameleon). The steel strength required for the initial structural design was S355, which had to be sourced (Interviewee 3, Kameleon). Eventually, the design was modified to use the available S355 donor steel beams and other available S235 donor steel beams (Interviewee 3, Kameleon). The availability of donor steel influences the eventual structural design of De Kameleon.

The sustainability advisor for Dura Vermeer mentioned that, even though the client's ambitions were high, costs and time remained problems and were discussed in the project for the reused steel elements (Interviewee 1, Kameleon). More information about the feasibility and project planning was not available.

C3: Collaboration and governance
The main stakeholders, Gemeente Haarlemmermeer (client) and Dura Vermeer (contractor), were aligned early due to the procurement method (P. Bekkering, 2024). The procurement method used for the project was a 'Design, Build and Maintain' (DBM) contract, which involves early collaboration. The DBM contract integrates design, construction, and 20 years of maintenance, requiring early alignment among designers, engineers, and contractors. The Gemeente Haarlemmermeer initiated this contract form to combine the two typically separate financial streams: building costs and the 20-year maintenance budget. Forcing the parties to consider long-term performance together, from the start of the project (P. Bekkering, 2024).

The tender included a 'Total Cost of Ownership' (TCO) model, which requires the stakeholders to develop integral long-term solutions. The different stakeholders, Dura Vermeer and the two architect firms, had to communicate to fulfill the requirement early. In addition, C-Creators were brought in early by the Gemeente Haarlemmermeer to set the sustainable and circular requirements and make them measurable and verifiable in the tender phase. This positioned the sustainability advisors in the early design phases of the project (Gemeente Haarlemmermeer, 2022).

Moreover, the integrated financial structure meant that all stakeholders had shared incentives and long-term responsibility for the project. The financial structure reduced the risk aversion and increased openness to circular options (Gemeente Haarlemmermeer, 2022).

The DMP contract is an integrated project delivery model: design, construction, and long-term maintenance are combined into a single contract. Therefore, decision-making in the project is supported by an integrated delivery model rather than a traditional contracting form (P. Bekkering, 2024).

C4: Economic and logistical feasibility
No cost comparison was available between the new and donor steel components. The economic feasibility cannot, therefore, be determined and is not applicable in this case.

The testing did not pose any challenges for the application of the donor steel elements (Interviewee 3, Kameleon). Blijleven did the transport and storage; therefore, it is not the responsibility of Dura Vermeer. The tests and modifications to the donor steel beams required time and needed to be accounted for in the project's planning (Interviewee 3, Kameleon).

As mentioned before, the sustainability advisor for Dura Vermeer mentioned that, even though the client's ambitions were high, costs and time remained problems and were discussed in the project for the reused steel elements (Interviewee 1, Kameleon). In contrast, the Gemeente Haarlemmermeer received a national subsidy for 'Aardgasvrije en Frisse Scholen' (P. Bekkering, 2024). Moreover, De Kameleon was a pilot for the Gemeente Haarlemmermeer, indicating that the Gemeente Haarlemmermeer intentionally sought to explore the boundaries of its sustainable and circular goals (P. Bekkering, 2024).

The cost of donor steel components was €0,80 per kg more expensive than new steel, resulting in a cost difference of €12.400 (Blijleven, 2024).

C5: Regulatory and certification constraints
The NTA 8713 was applicable because it was published only on June 1, 2023 (Bouwen met Staal,

2024). The NTA 8713 provides guidelines for testing and the requirements for donor steel components (Blijleven, 2023). The tests validated the safety and strength required for the donor steel components. As part of the test, the donor steel beams were certified and issued new CE markings (Blijleven, 2023).

The client, Gemeente Haarlemmermeer, was assured of the structural safety of the tested donor steel beams based on the tests and the new certifications they ultimately received (Interviewee 3, Kameleon).

C6: Outcome and lessons learned

The main insights from the technological, organizational, economic, and regulatory analyses of the community school De Kameleon case will be elaborated here in the lessons learned. The lessons learned will highlight the enablers and obstacles for the donor steel integration in the project and outline the implications for future donor steel projects.

First, the key obstacles of the Kameleon case can be summarized in the following two themes:

1.) **Supply and demand mismatch.**
    The structural design initially required S355 steel. Sourcing sufficient S355 donor beams proved challenging, necessitating design adaptations to combine them with S235 donor beams (Blijleven, 2023). The availability of suitable donor steel components directly influenced the final structural solution.
2.) **Cost and economic uncertainty.**
    Even though the client had strong, sustainable, and circular ambitions, the sustainability advisor noted that costs and planning for the donor steel components were continuously discussed (Interviewee 1, Kameleon). The necessary material testing, transport, and modifications of the donor steel components required additional time, which had to be integrated into the project planning.

Second, the key enablers of the Kameleon case can be summarized in the following four themes:

1.) **Client sustainability ambition supports reuse.**
    The client, Gemeente Haarlemmermeer and Stichting Jong Leren, had explicit circular requirements in the tender and rating plan. Reuse and circularity were central in the selection criteria and evaluation framework (P. Bekkering, 2024). Moreover, Dura Vermeer Renovatie Midden West shared these ambitions, making circularity a central theme in this project from the start (Dura Vermeer, 2022).
2.) **Strong collaboration structure.**
    The integrated Design, Build & Maintain (DBM) contract combines the design, construction, and 20 years of maintenance of the project into a single financial and contractual structure (P. Bekkering, 2024). Additionally, this Total Cost of Ownership (TCO) focus encouraged stakeholders to consider long-term performance, material durability, and lifecycle costs rather than short-term CAPEX alone, thereby supporting the business case for circular and reusable components (P. Bekkering, 2024).
    Moreover, the demolition contractor, Adex Group, together with the contractor, Dura Vermeer, mapped the reusable materials in the existing community school, including

parts of the old steel structure (Dura Vermeer, 2022). This method created a broad reuse palette and made reuse a visible and tangible part of the project. Moreover, the 15% donor steel components in the construction design originally came from the old community school and the demolished town hall in Haarlemmermeer, both owned by the client. Making the harvest of the donor steel components possible (P. Bekkering, 2024). Additionally, the new and donor steel structure is designed with bolted connections, enabling future demountability and reuse possibilities (Dura Vermeer, 2022).

3.) Early integration of digital and sustainability tools.
The steel structure for the new community school was designed in a Tekla/BIM model, making the integration of donor steel components easier. The integration of digital tools enabled matching donor steel components to the structural design (Blijleven, 2023). Moreover, LCA, CO_2, ECI, and MPG calculations were used to evaluate the sustainable performance of the donor steel and other reused components (Interviewee 1, Kameleon). The application of 15% donor steel in the construction design reduced CO_2 emissions by approximately 6,600 kg (Dura Vermeer, vlog 1, 2025).

To summarize the Kameleon case, the following Table 4.12 is presented, in which the conclusions of C1-C5 can be found, and a summary of the key obstacles and enablers. The lessons learned from this case study are presented in the discussion chapter.

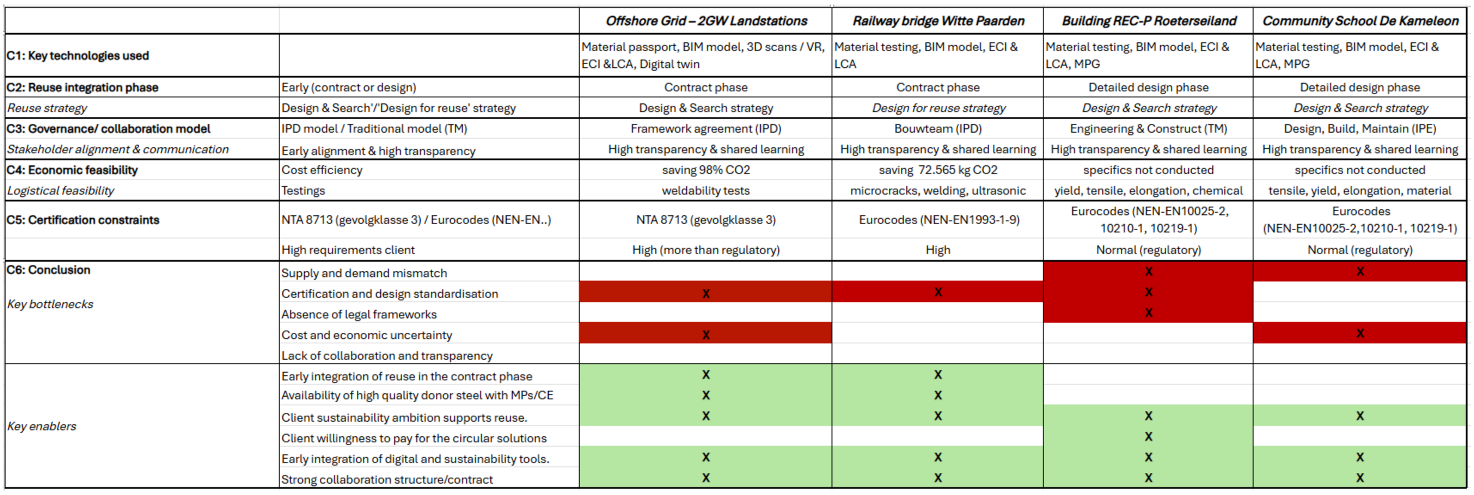
Table 4.12: Summary of the Kameleon case for all five analytical dimensions and conclusions.

	Community School De Kameleon
Donor steel role	Applied
Availability of donor steel	Difficult, limited availability and quality
Client sustainability ambitions	High sustainability and circularity ambitions
C1: Key technologies used	Material testing, BIM (Tekla), ECI, LCA, MPG
C2: Reuse integration phase	Detailed design phase
Reuse strategy	*“Design and search strategy’.*
C3: Governance/ collaboration model	Design, Build, Maintain (DBM) Similar IPD (integrated project delivery model)
Stakeholder alignment	Early alignment
Trust & communication indicators	High transparency and shared learning
C4: Economic feasibility	Donor steel cost-efficient; specific savings not conducted
Logistical feasibility	Extensive testing required (tensile strength, yield strength, elongation, material type) and surface treatments (shot blasting, priming, galvanization, and coating)
C5: Certification constraints	Eurocode testing requirements (NEN-EN10025-2, NEN-EN 10210-1, and NEN-EN 10219-1)
C6: Conclusion	
Key obstacles	1. Supply and demand mismatch 2. Cost and economic uncertainty.
Key enablers	1. Client sustainability ambition supports reuse. 2. Strong collaboration structure. 3. Early integration of digital and sustainability tools.

4.2.5 Cross-case analysis

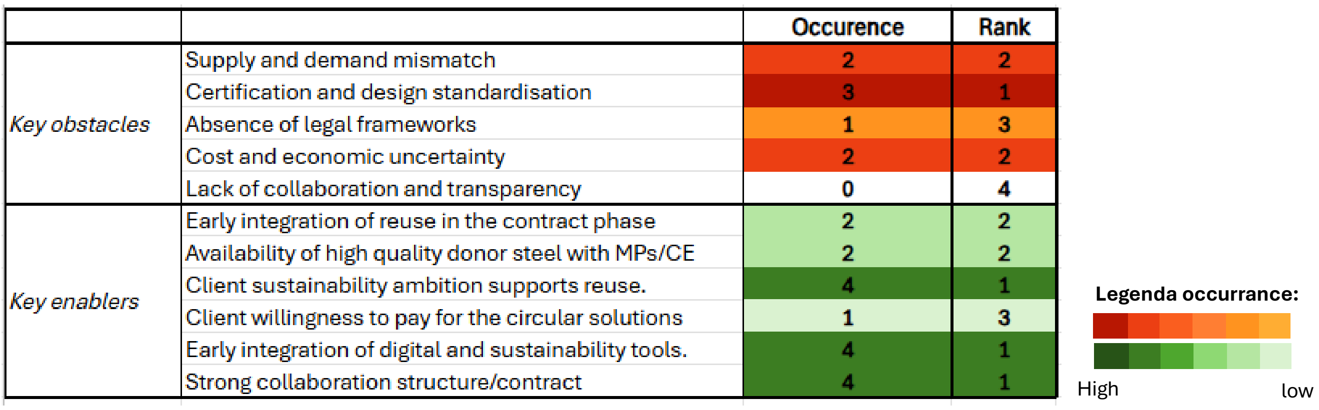
The cross-case analysis of the data from the four cases is presented in Table 4.13, see Appendix H.2. The table provides an overview of the conclusions of the researched themes, C1-C6, for the four cases. The obstacles are presented in red and the enablers in green. Based on this data, the frequencies of the bottlenecks and enablers in C6 are determined and presented in Table 4.14. Table 4.14 will be used to compare the literature review and case study data in § 5.2.

Table 4.13: Cross-case analysis of C1-C6 for the four case studies, with red key obstacles and green key enablers.



		Offshore Grid – 2GW Landstations	***Railway bridge Witte Paarden***	***Building REC-P Roeterseiland***	***Community School De Kameleon***
C1: Key technologies used		Material passport, BIM model, 3D scans / VR, ECI &LCA, Digital twin	Material testing, BIM model, ECI & LCA	Material testing, BIM model, ECI & LCA, MPG	Material testing, BIM model, ECI & LCA, MPG
C2: Reuse integration phase	Early (contract or design)	Contract phase	Contract phase	Detailed design phase	Detailed design phase
Reuse strategy	Design & Search'/'Design for reuse' strategy	Design & Search strategy	*Design for reuse strategy*	*Design & Search strategy*	*Design & Search strategy*
C3: Governance/ collaboration model	IPD model / Traditional model (TM)	Framework agreement (IPD)	Bouwteam (IPD)	Engineering & Construct (TM)	Design, Build, Maintain (IPE)
Stakeholder alignment & communication	Early alignment & high transparency	High transparency & shared learning	High transparency & shared learning	High transparency & shared learning	High transparency & shared learning
C4: Economic feasibility	Cost efficiency	saving 98% CO2	saving 72.565 kg CO2	specifics not conducted	specifics not conducted
Logistical feasibility	Testings	weldability tests	microcracks, welding, ultrasonic	yield, tensile, elongation, chemical	tensile, yield, elongation, material
C5: Certification constraints	NTA 8713 (gevolgklasse 3) / Eurocodes (NEN-EN..)	NTA 8713 (gevolgklasse 3)	Eurocodes (NEN-EN1993-1-9)	Eurocodes (NEN-EN10025-2, 10210-1, 10219-1)	Eurocodes (NEN-EN10025-2,10210-1, 10219-1)
	High requirements client	High (more than regulatory)	High	Normal (regulatory)	Normal (regulatory)
C6: Conclusion *Key bottlenecks*	Supply and demand mismatch			X	X
	Certification and design standardisation	X	X	X	
	Absence of legal frameworks			X	
	Cost and economic uncertainty	X			X
	Lack of collaboration and transparency				
Key enablers	Early integration of reuse in the contract phase	X	X		
	Availability of high quality donor steel with MPs/CE	X	X		
	Client sustainability ambition supports reuse.	X	X	X	X
	Client willingness to pay for the circular solutions			X	
	Early integration of digital and sustainability tools.	X	X	X	X
	Strong collaboration structure/contract	X	X	X	X

Table 4.14: Key bottlenecks in red and key enablers in green and their occurrence with ranking.



		Occurence	Rank
Key obstacles	Supply and demand mismatch	2	2
	Certification and design standardisation	3	1
	Absence of legal frameworks	1	3
	Cost and economic uncertainty	2	2
	Lack of collaboration and transparency	0	4
Key enablers	Early integration of reuse in the contract phase	2	2
	Availability of high quality donor steel with MPs/CE	2	2
	Client sustainability ambition supports reuse.	4	1
	Client willingness to pay for the circular solutions	1	3
	Early integration of digital and sustainability tools.	4	1
	Strong collaboration structure/contract	4	1

Legenda occurrance:

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High low

Table 4.14 shows that the following three key obstacles occur most frequently:

1. **Certification and design standardization**
2. **Supply and demand mismatch / Cost and economic uncertainty**

Certification-related obstacles were identified in both infrastructure and building projects and were mainly related to verification requirements, uncertainties around testing procedures, and liability allocation. Moreover, cost uncertainty was present in multiple cases and is linked to the certification obstacle, due to additional testing, logistics, and the risks of double costs. In contrast, supply-and-demand mismatches occurred only in the built environment cases. The alignment between the available components, the donor steel's dimensions and strength, and the architectural design proved challenging.

Remarkably, lack of collaboration and transparency was not identified as an obstacle in any of the cases. All cases applied donor steel, characterized by strong collaborative structures and contractual agreements, such as IPD models. These models facilitate early stakeholder engagement, shared responsibility, and transparency, thereby reducing uncertainty (§ 2.3).

Furthermore, Figure 4.14 also identifies three key enablers for donor steel applications:

- **Client sustainability ambition supports reuse.**
- **Early integration of digital and sustainability tools.**
- **Strong collaboration structure/contract.**

Collaboration and transparency are, in the case study analysis, not an obstacle but an enabler across all cases, helping address challenges related to certification, costs, and availability. The case study analysis shows that strong collaboration structures are essential, while donor steel integration involves economic, technical, and organisational uncertainties. These uncertainties cannot be managed by one stakeholder, making shared incentives, transparent decision-making, and early stakeholder alignment essential to jointly address these risks.

Finally, the cross-case analysis shows that digital solutions reduce early-stage uncertainty by enabling early assessment of the environmental impact and design compatibility. Tools such as BIM models and materials testing facilitate these assessments. Making it possible to lessen the impact of the obstacles 'Certification and design standardisation' and 'Cost and economic uncertainty', by reducing the risks of double costs and providing insights into the ECI. The ECI is often also a scoring category in tenders for this type of project, which makes calculating the ECI, and by extension, digital solutions, even more important.

5. Discussion

This chapter discusses the key findings of the exploratory research and case study research. Additionally, reflects on the implications and contributions to the existing literature and presents the study's limitations.

5.1 Key findings

The findings from the exploratory interviews and case study research are presented and compared with the literature review to provide new insights into this field of research. These new insights form the basis for the emerging findings in § 5.1.3.

5.1.1 Comparison of literature and interview data

The literature review did not provide a ranking of the severity of the obstacles. Therefore, based on the exploratory interview data presented in Table 4.2, the overhead obstacles identified in the literature review are ranked by frequency in Table 5.1, indicating their relative severity. Additionally, Table 5.1 presents the number of interviewees who mentioned the obstacles themselves during the conversation or agreed with them. See Appendix H.2 for detailed information on which interviewees mentioned every obstacle.

Table 5.1: Ranking and occurrences of the overhead obstacles from the literature review during the interviews.

Ranking: Obstacle from literature	Occurrance			Ranking
	mentioning themselves	confirmation asking	**Total**	
Costs and economic uncertainty	**15**	5	**20**	**1**
Lack of collaboration and transparency	**14**	5	**19**	**2**
Supply and demand mismatch	**14**	4	**18**	**3**
Certification and (lack of) design standardization	**10**	4	**14**	**4**
Absence of legal frameworks	**6**	7	**13**	**5**

Legenda occurrance:
🟥🟥🟥🟧🟧🟧🟨
High low

Table 5.1 shows similarities between the obstacles identified in the literature and those in the interview data. The most frequently mentioned obstacles in the interviews were:

1. ‘**Costs and economic uncertainty**’: 71% (20 out of 28)
2. ‘**Lack of collaboration and transparency**’: 68% (19 out of 28)
3. ‘**Supply & demand mismatch**’: 64% (18 out of 28)

First, the obstacle ‘Cost and economic uncertainty’ is presented in the literature as the ‘uncertainty in the cost’ (Dunant et al., 2018) or the ‘complexity and uncertainty of the cost difference’ (Cheng et al., 2024). Additionally, the underlying obstacle 10 ‘Risk and liability’ is also included in this overhead obstacle, while risk and liabilities are always presented and evaluated in cost, which was not mentioned in the literature review.
Second, ‘Lack of collaboration and transparency’ is also identified in the literature review, referred to as ‘the resistant attitude to innovations’ (Hart et al., 2019) and ‘limited data sharing and transparency’(Tingley et al., 2017).
Third, the obstacle ‘Supply and demand mismatch’ is also identified in the literature as ‘sourcing of the steel’ (Kanyilmaz et al., 2023).

However, there is some variation between the literature and the interview data regarding two of the five obstacles identified in the literature review. The obstacle ‘Certification and design standardization', elaborated in § 2.1.2 as the 're-certification of design standards' (Kanyilmaz et al., 2023), is only mentioned by 50% of the interviewees (14 out of 28). The obstacles were mentioned only a few times by interviewees and confirmed by even fewer, resulting in disagreement in half of the interviews. Therefore, it can be concluded that there is no alignment between the theory and practice regarding this obstacle.

Additionally, the obstacle 'Absence of legal frameworks', elaborated in § 2.1.3, as 'lack of legal frameworks' (Condotta & Zatta, 2021; Halonen et al., 2024), is only mentioned and confirmed by 46% of the interviewees (13 out of 28). 15 interviewees denied the obstacle, indicating a difference between theory and practice regarding it.
Lastly, the five overhead obstacles from the literature review correspond to the 12 underlying obstacles identified during the interviews (§ 4.1.1). During the analysis of the identified obstacles in the exploratory research in Figure 4.1 (§ 4.1.3), the relationships among the overhead obstacles emerged. Figure 5.1 shows the interactions between obstacles 1-3 and obstacles 4 and 5 (see ranking Table 5.1).

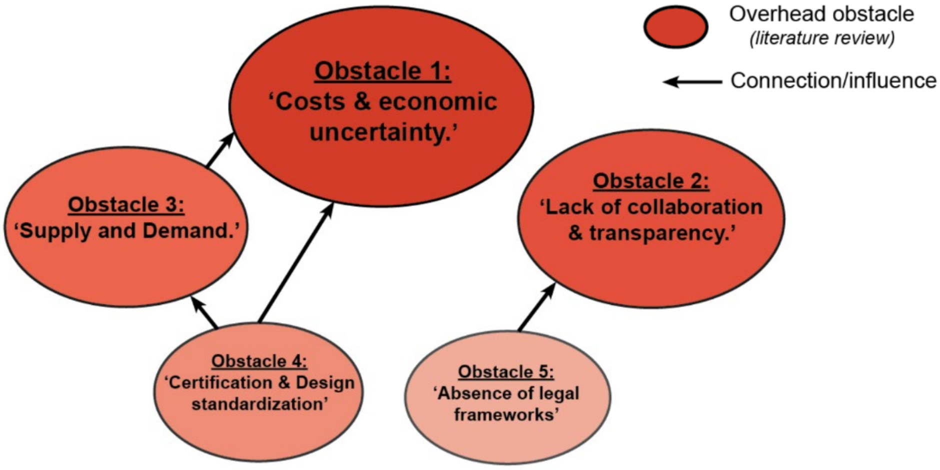


Figure 5.1: Overview of the overhead obstacles (oval) and their 'underlying obstacles' (rectangular).

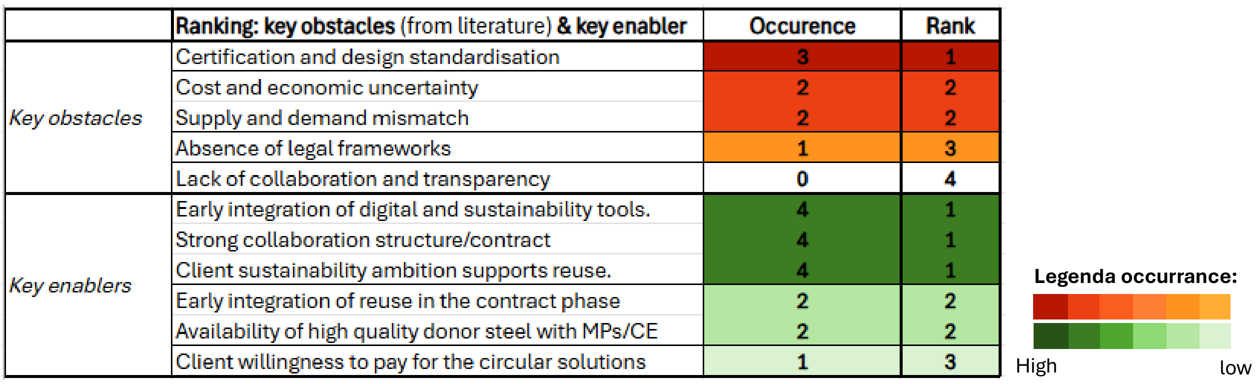
Findings exploratory interviews
The following findings may provide new insights within this field of research:

- The three obstacles: 'Cost and economic uncertainty', 'Lack of collaboration and transparency', and 'Supply and demand mismatch', are recognized in both theory and practice. These overhead obstacles, presented in § 4.1.3, are therefore relevant when exploring strategies to stimulate adoption among different stakeholders.
- The obstacle 'Certification and design standardization' partially recognizes the difference between the theory and practice. This may suggest that this obstacle is partly acknowledged in the literature, but may be interpreted differently in practice. Moreover, the lack of familiarity among the interviewed stakeholders may also play a role.
- The obstacle 'Absence of legal frameworks' appears to be in a disalignment between theory and practice. This may indicate that the obstacle is only partially recognized by the interviewed stakeholders, or that they consider it potentially irrelevant.

5.1.2 Comparison of literature and case study data

The cross-case analysis identified key obstacles and enablers across all cases, which are ranked by occurrence in Table 5.3.

Table 5.2: Ranking and occurrences of the key obstacles and enablers from the case study data.



	Ranking: key obstacles (from literature) **& key enabler**	**Occurence**	**Rank**
Key obstacles	Certification and design standardisation	3	1
	Cost and economic uncertainty	2	2
	Supply and demand mismatch	2	2
	Absence of legal frameworks	1	3
	Lack of collaboration and transparency	0	4
Key enablers	Early integration of digital and sustainability tools.	4	1
	Strong collaboration structure/contract	4	1
	Client sustainability ambition supports reuse.	4	1
	Early integration of reuse in the contract phase	2	2
	Availability of high quality donor steel with MPs/CE	2	2
	Client willingness to pay for the circular solutions	1	3

The obstacles that occurred the most in the case study data were:

1. ‘**Certification and (lack of) design standardization.**’
2. ‘**Costs and economic uncertainty**’ / ‘**Supply and demand mismatch.**’

First, ‘Certification and (lack of) design standardization’, presented in the literature review, highlights the lack of standardized design rules and the time-consuming testing required to assess the mechanical performance and safety of donor steel components (Kanyilmaz et al., 2023). Second, ‘Cost and economic uncertainty’, presented in the literature review, emphasizes the uncertainty regarding testing costs, re-certification, logistics, and timing in the case study projects (Dunant et al., 2018; Cheng et al., 2024).
Third, ‘Supply and demand mismatch’, presented in the literature review, also occurred twice, but only in the built environment projects. While both projects were originally designed with S355 steel, which had to be changed to the available S235 donor steel, corresponding with the ‘availability dependence’ in the literature review (Dunant et al., 2018). In contrast, both infrastructure projects presented key enabler 2: ‘availability of donor steel with MP’s/CE’, which enabled the use of donor steel and obviated the need to assess material properties (Tingley et al., 2017). The obstacle is perceived differently across the two construction fields; practice offers a more nuanced and detailed perspective of the obstacle.

Moreover, the obstacle ‘Absence of legal frameworks’, as presented in the literature review, was mentioned by only one project, indicating a gap between theory and practice (Condotta & Zatta, 2021; Halonen et al., 2024).

Lastly, the obstacle ‘Lack of collaboration and transparency’ was not identified in any of the cases, but is represented in as key enabler 1: ‘Strong collaboration structure/contract’, since all cases applied donor steel and had strong collaborative structures and contractual agreements. The literature review confirms this enabler by emphasizing the need for collaboration, trust, and transparency as critical conditions for donor steel applications (Tingley et al., 2017). Moreover, all cases presented the following enabler: ‘Client sustainability ambition supports reuse’, which showcases the client's ambition and willingness to collaborate.

Furthermore, the enabler: ‘Early integration of digital and sustainability tools’ occurred in every case. Digital solutions reduce early-stage uncertainty by enabling early assessment of environmental impact and design compatibility (Koutamanis et al., 2023). Additionally, MP’s and material testing data turn the static digital models of the projects into dynamic, data-driven material banks (Mercado S., 2020).

Findings case study data

The following findings may provide new insights within this field of research:

- The three obstacles: “Certification and design standardization’, ‘Cost and economic uncertainty’, and ‘Supply and demand mismatch’, are recognized in both theory and practice. All occurred in two or more of the cases and are therefore relevant when exploring strategies to stimulate adoption among different stakeholders.
- The obstacle ‘Absence of legal frameworks’ appears to be in a disalignment between theory and practice. This may indicate that the obstacle is only partially recognized in the case studies, or that it was not relevant to these projects.
- The obstacle ‘Lack of collaboration and transparency’ was not identified in any of the cases, but presented as a key enabler, showcasing the importance of this obstacle in both theory and practice.
- The key enabler: ‘Early integration of digital and sustainability tools’ occurred in every case, showcasing the importance of this enabler in both theory and practice.

5.1.3 Emerging findings

The key findings from the exploratory research and case study research can be integrated and related to the obstacles identified in the literature review. Combining the perceived obstacles (interviews) with observed project-level dynamics (case studies) provides a more nuanced understanding of how and why donor steel applications succeed or fail in practice.

The exploratory interviews have confirmed and ranked the five obstacles identified in the literature review, shown in Table 5.1. Particularly, ‘Cost and economic uncertainty’, ‘Lack of collaboration and transparency’, and ‘Supply and demand mismatch’ were frequently mentioned by the stakeholders during the interviews. The exploratory interviews revealed that these obstacles are not isolated but are interrelated with the other two (Figure 5.1). In addition, these obstacles were originally framed as general or anticipated risks rather than as emerging from interactions among technical requirements, timing constraints, organisational arrangements, and stakeholder expectations (Kanyilmaz et al., 2023; Cheng et al., 2024).

The case study research demonstrated how these obstacles manifested and emerged in practice and under which conditions they became critical, refining this earlier perception. For instance, the obstacle ‘Cost and economic uncertainty’ was associated with uncertainty about testing and logistics among the interviewees, while the case studies showed that economic uncertainty is strongly linked to early decision-making and timing (Dunant et al., 2018; Cheng et al., 2024). For example, the Witte Paarden case (§ 4.2.2) better controlled costs due to early integration of donor steel, whereas late-stage consideration increases economic risk. Additionally, the interviewees described the obstacle ‘Supply and demand mismatch’ as a general constraint, whereas the case studies showed that the mismatch is often the result of early design decisions made without considering donor steel. Both built environment projects required designs to be adapted to the available steel grades (S355 to S235), whereas the infrastructure projects benefited from the timely availability of suitable donor steel (Kanyilmaz et al., 2023).

In contrast to the interviews, another major obstacle emerged from the case study research: ‘Certification and design standardization’, which occurred in each case but had varying impacts.

In the cases where high-quality donor steel was available with MP's/CE (enabler), the certification structured the verification process rather than preventing reuse. In contrast to cases where documentation was incomplete, certification requirements led to additional testing, delays, and cost uncertainty (Kanyilmaz et al., 2023; Dunant et al., 2018).

Remarkably, 'Lack of collaboration and transparency' was identified as the second overhead obstacle in the interviews, but did not appear as an obstacle in any of the case studies. In contrast, it appeared in the cases as an enabler: 'strong collaboration structure'. This contradiction is emphasized as a key insight of this research, showing that the obstacles are not fixed conditions, but are shaped by organisational choices and project governance (Tingley et al., 2017).

To conclude, the integration of the exploratory interviews and case study findings illustrated that the added value of this study lies in explaining why the obstacles persist in theory, even though they are manageable in practice. Contextualising the abstract obstacles through empirical research shows that donor steel obstacles are primarily organisational rather than technical, repeating historical practices where steel reuse was common under different economic and governance conditions.

5.2 Reflection on the implications and contributions

This section will reflect on the thesis's contributions to the literature and practice, with specific focus on the added value of the empirical obstacle identification (interviews) and contextual interpretation (case study).

First, from an academic perspective, this thesis contributes to the literature on circular construction and material reuse strategies by elaborating beyond the abstract obstacle categorisations. Previous studies have identified the five obstacles, which are technical, policy, regulatory, social, and economic-related obstacles, but not their relative severity or manifestation in practice. This thesis not only presents their ranking in relative severity but also illustrates that the practical relevance of these obstacles depends strongly on project-specific conditions. The case study research showed that organisational and economic decisions often determine the criticality and manageability of the technical obstacles.
In essence, the key contribution lies in the empirical grounding of the obstacles. The research explains why donor steel remains difficult to apply despite its environmental benefits by analysing how these obstacles materialise in real projects. For instance, cost uncertainty is not only a financial issue but is strongly influenced by interrelated factors such as testing requirements, risk allocation, timing, and logistics. The identification of these interactions adds depth to the existing literature, which treats the obstacles as discrete issues.

Second, from a practical perspective, this thesis contributes by emphasizing solution directions that implicitly form real projects. Although this thesis does not prescribe a solution or framework, the cases demonstrate that early stakeholder alignment, early integration of digital and sustainability tools, and client sustainability ambition consistently help to reduce uncertainty. The existing theoretical claims are supported by these insights, but also refine them by showing their effectiveness under certain conditions.

Third, placing these findings in a broader context clarifies the persistence of donor steel obstacles. Historically, steel reuse was a common practice, particularly during WWII, driven by material scarcity and economic necessity (Addis, B., 2006). Currently, the difficulty of reuse does not stem from technical impossibility, but from the evolution of linear construction processes, risk-averse governance structures, and fragmented responsibilities. Nowadays, donor steel obstacles reflect organisational and institutional shifts rather than a lack of technological capability.
Current donor steel practices need to be reconnected to this historical perspective, as this thesis illustrates that circular construction does not require new principles but rather reconfigures existing practices. The case study research shows how current projects already navigate this transition, offering insights into how reuse can be reintegrated into modern construction processes.

To conclude, the thesis contributes to an in-depth understanding of why donor steel application remains challenging and how empirical insights from practice can refine and contextualise the existing theory.

5.3 Study limitations

The limitations of this study can be divided into two categories: methodological and scope-related limitations.

First, from a methodological perspective, this study is based on exploratory interviews and case study research. The exploratory interviews identified stakeholders' current perceptions and experiences of the obstacles, while the case study examined the manifestation of the obstacles, digital solutions, and collaboration in completed projects. Therefore, this research does not include longitudinal or process-oriented observation of donor steel integration over time in a project. The study provides insights into perceptions and experiences of obstacles, but not into how they evolve dynamically over the course of ongoing projects or across multiple project phases. Moreover, the study does not account for the transformation of the current construction sector or for how stakeholder behaviour can change at a broader societal scale. Resulting in the limited ability of this method, a qualitative and exploratory approach, to assess causal relations and quantify the general impact of specific obstacles or enablers across society over time.

Second, regarding scope-related limitations, the study focuses on four cases across two construction domains: two infrastructure and two built environment projects. While this distinction allows comparison at the sectoral level, the study does not further differentiate between specific project typologies within these domains. Different project typologies, such as bridges, rail infrastructure, offices, housing, or schools, may face specific technical, regulatory, and organisational conditions that influence the feasibility of donor steel. These typology-specific dynamics were outside the scope of this study and were therefore not identified in the findings. Additionally, the number of cases is limited, therefore making them insufficient to claim broad generalizability across the construction sector.

Future research could address these constraints by examining a broader range of project types with a process-oriented observation, thereby incorporating dynamic factors, such as ongoing regulatory and policy processes.

6. Conclusion

This chapter presents the conclusion of this thesis, structured per sub-question, followed by a comprehensive answer to the main research question. Finally, recommendations for future research are provided.

The main research question of this thesis was:

"How can applications of digital solutions and conditions for collaboration in the early design stages help to address the identified key obstacles to integrating donor steel in circular construction projects?"

To answer this main question, the following sub-questions were addressed.

6.1 Conclusions to sub-questions

SQ1: What key obstacles hinder the integration of donor steel in construction projects?
The research identified five main obstacles, obtained from the literature review, validated and ranked through the exploratory interviews and case study research (§ 5.1.1, § 5.1.2). The most frequently mentioned obstacles in both the exploratory interviews and case study data were:

- **Cost and economic uncertainty,** related to testing, risk allocation, and redesign.
- **Supply & demand mismatch,** sourcing available and suitable donor steel.

Two additional barriers appeared in the top three of either the exploratory interviews or the case study research, but not in both:

- **Lack of collaboration and transparency,** as an overhead obstacle by the interviews, but seen as the main enabler by the case studies.
- **Certification and design standardization** (case study) due to quality constraints.

These findings indicate that the organizational and economic barriers dominate the purely technical and regulatory constraints.

SQ2: How do applications of digital solutions influence the identification and mitigation of these donor steel obstacles in early project stages?
The research found that BIM models, material testing, and structured digital documentation (such as MP's) have the greatest positive impact on donor steel applications (§ 2.2). The case studies confirm the literature by presenting 'Early integration of digital and sustainability tools' as the main decisive enabler. These digital solutions support the early identification, design integration, and technical assessment of the donor steel components. They facilitate compliance with the certification requirements of NEN-EN 1993 and NTA 8713. However, their impact depends strongly on early application; if introduced later in the process or not embedded within the collaborative workflows, the digital tools have limited influence.

SQ3: What conditions for collaboration in contract and procurement phases enable or constrain donor steel integration?
The research found that early stakeholder engagement, collaborative contract and procurement forms, and explicit client sustainability ambitions are decisive factors in enabling steel reuse (§

2.3, § 5.1.2). Contract forms such as Design Teams, Alliances, and DBM/DBFM contracts facilitate shared risk management, early stakeholder engagement, joint problem-solving, and transparency, all of which are features of the IPD model. In contrast, traditional procurement models constrain donor steel integration by limiting early dialogue and flexibility. Additionally, the client's willingness to accept risks and uncertainty, and to support circular ambitions, emerged as a critical success factor in the case studies (§ 5.1.2).

SQ4: How can insights from the previous research questions be synthesized into general findings that support early decision-making on donor steel projects?

Insights from the literature review, exploratory research, and case study research were synthesized by linking perceived obstacles to their manifestation in practice, clarifying which obstacles are decisive in the early project phases and under which conditions they become manageable. Integrating the ranked interview obstacles with observed case study dynamics shows that donor steel feasibility is primarily shaped by economic, organisational, and collaborative decisions rather than by technical constraints alone. The emerging findings (§ 5.1.3) support early decision-making by elaborating how key obstacles interact (Figure 5.1), how enablers such as early digital integration and strong collaboration mitigate uncertainty (§ 5.1.2), and why donor steel obstacles persist in theory while remaining manageable in practice.

6.2 Conclusion to main research question

This research concludes that digital solutions and collaborative conditions support the application of donor steel and help address the identified key barriers to its application, only when applied early and in combination. Digital solutions enable identification, documentation, and assessment of donor steel, but their value is unlocked through early collaboration, client commitment to sustainability, and suitable procurement strategies. By showing the manifestation of these elements in the early project phases, the findings help future projects reduce uncertainty. In a broader context, the results indicate that donor steel integration requires reconfiguring existing construction practices rather than introducing entirely new principles. This echoes the historical precedent of steel reuse being scaled under different governance arrangements and economic drivers (Addis, 2006). Similarly to the case studies, which showed that contemporary reuse becomes feasible when early decisions, collaboration structures, and risk allocation are organised to support it.

6.3 Recommendations

Based on the findings and limitations of this study, the following recommendations are:

- **Future research:** Longitudinal and process-oriented research across multiple project typologies could generate more generalisable findings to create a coherent framework that can provide actionable guidelines for future donor steel applications.
- **Practitioners:** Should explicitly consider donor steel in the early design and procurement phases, integrate digital and sustainability tools early, and support early stakeholder engagement to reduce uncertainty and prevent late-stage rejection.
- **Policymakers and regulators**: Offer clarity and consistency in certification procedures and documentation requirements, to reduce the perceived certification and regulatory risks and facilitate wider adoption of donor steel within existing frameworks.

Appendix A

A. Interview protocol in Dutch and English

A.1 Interview opzet Nederlands

Introductie

1. Naam van de onderzoeker – Kathalijne van Rooij

2. Onderzoeksgebied – MSc. Architecture, Urbanism, and Building Sciences & Construction Management & Engineering

3. Onderzoeksdoel – Inzichten verkrijgen van verschillende perspectieven over de obstakels in het hergebruiken van staal, donorstaal, en wat de beste strategie is om deze obstakels te kunnen verminderen dat wat overblijft acceptabel is.

4. Toestemmingsformulier ondertekenen.

Openingsvragen

1. Wat is jouw rol binnen je bedrijf en welke noemenswaardige ervaringen heb je bij andere bedrijven opgedaan?

2. Wat is jouw ervaring met het hergebruik van materialen en met hergebruik van staal in het algemeen?

Kernvragen

3. Ondanks de voordelen, heeft hergebruik natuurlijk ook nadelen, wat zie jij als obstakels omtrent hergebruik?

Ik heb vijf obstakels geïdentificeerd op basis van een literatuuronderzoek. Ik ben voor elk van deze benieuwd wat jouw visie hierop is.
- ‘Vraag en aanbod van donorstaal’
- ‘Certificering en ontwerp standaardisatie’
- ‘Afwezigheid van wettelijke kaders en regelgeving’
- ‘Kosten voor hergebruikte materialen’
- ‘Samenwerking en transparantie’

4. Welke van deze obstakels ben je het mee eens en welke ben je het niet mee eens, en waarom?

5. Wat voor soort aanpak lijkt jou het meest geschikt om met deze onzekerheden om te gaan en waarom? (integraal of stukje voor stukje)?

Afsluitende vragen

6. Als deze strategieën worden toegepast in de praktijk, hoe denk jij dat de toekomst van hergebruikte materialen eruitziet?

7. Als je nog iets wilt toevoegen, kun je dat nu laten weten.

A.2 Interview set-up English

Introduction

1. Name of the researcher – Kathalijne van Rooij

2. Research field – MSc. Architecture, Urbanism, and Building Sciences & Construction Management & Engineering

3. Research goal – To gain insights from different perspectives about the obstacles in reusing donor steel, and to find the best strategy to reduce these obstacles to an acceptable level.

4. Sign the consent form.

Opening questions

1. What is your role within your company, and what notable experiences have you had at other companies?

2. What is your experience with the reuse of materials and with the reuse of steel in general?

Core questions

3. Despite the advantages, reuse also has disadvantages. What do you see as obstacles regarding reuse?

I have identified five obstacles to the application of donor steel. For each of these, I would appreciate your perspective.

- ‘Supply and demand of donor steel’
- ‘Certification and design standardization’
- ‘Lack of legal frameworks and regulations’
- ‘Cost of reused materials’
- ‘Collaboration and transparency’

4. Which of these obstacles do you agree with and which do you not agree with, and why?

5. What type of approach seems most suitable to you for dealing with these uncertainties, and why? (integrated or step-by-step)?

Closing questions

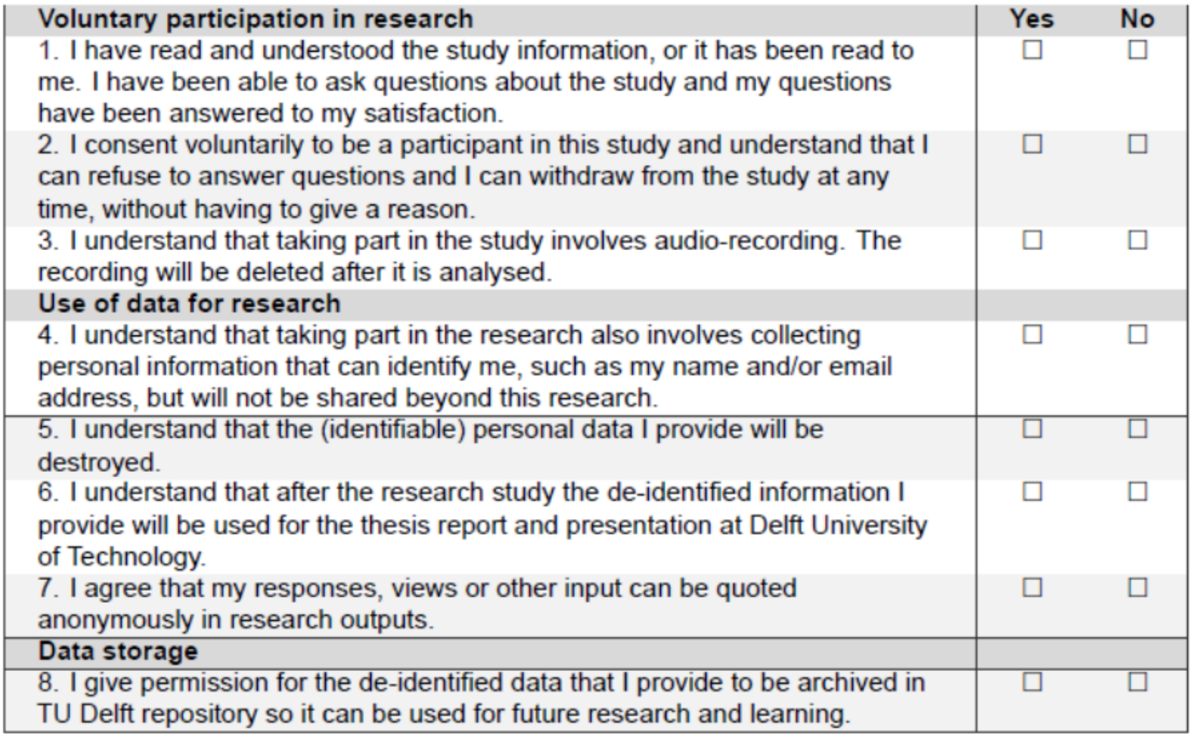
6. If these strategies are applied in practice, what do you think the future of reused materials will look like?

7. If you would like to add anything else, you can do so now.

Appendix B

B. Informed consent form

Please tick the appropriate boxes.



Voluntary participation in research	Yes	No
1. I have read and understood the study information, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves audio-recording. The recording will be deleted after it is analysed.	☐	☐
Use of data for research		
4. I understand that taking part in the research also involves collecting personal information that can identify me, such as my name and/or email address, but will not be shared beyond this research.	☐	☐
5. I understand that the (identifiable) personal data I provide will be destroyed.	☐	☐
6. I understand that after the research study the de-identified information I provide will be used for the thesis report and presentation at Delft University of Technology.	☐	☐
7. I agree that my responses, views or other input can be quoted anonymously in research outputs.	☐	☐
Data storage		
8. I give permission for the de-identified data that I provide to be archived in TU Delft repository so it can be used for future research and learning.	☐	☐

Name of participant:____

Signature:_____________________________ Date:___________________________

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Researcher: Kathalijne van Rooij

Signature: KRooij Date:___________________________

Appendix C

C. Case study research: ‘Comparative reflection framework’

The comparative framework will focus on the ‘replication logic’ described by Yin (2018) and the ‘cross-case analytical process’ outlined by Creswell (2013); see § 3.2 for more information. The comparison dimensions correspond to the ‘five obstacles’ and the ‘five technologies and assessment tools’ identified in the literature review (Chapter 2). The five analytical dimensions that were set up from this literature review are:

C.1: **Technological integration**
- Referring to the integration of digital solutions in § 2.2.

C.2: **Design and planning process**
- Referring to the stage and design strategy of the donor steel integration.
- Referring to the ‘supply and demand’ obstacle in § 2.1.1.

C.3: Collaboration and governance
- Referring to the collaborative conditions in § 2.3.
- Referring to the ‘collaboration and transparency’ obstacle in § 2.1.5.

C.4: Economic and logistical feasibility
- Referring to the ‘certification and design standardization’ obstacle in § 2.1.2.
- Referring to the ‘costs and economic uncertainty’ obstacle in § 2.1.4.

C.5: Regulatory and certification constraints
- Referring to the ‘certification and design standardization’ obstacle in § 2.1.2.
- Referring to the ‘absence of legal frameworks’ obstacle in § 2.1.3.

C.6: Outcome and lessons learned
- Summarizing the key enablers, key obstacles, and influence of digital solutions of the project.

This individual in-depth analysis of each case will provide the necessary outcomes and lessons learned to facilitate a cross-case analysis (Creswell, J.W., 2013).

C.1 Technological integration

This analytical dimension examines how the technologies were applied to identify, document, and evaluate the donor steel components. The application, consideration, or overlooking of donor steel here is also evaluated by answering the following questions:

- Which sort of steel components were considered and eventually used in the project?
- Why and how was this choice made in the design and planning phases?

After analyzing the choice of steel components, the application of these technologies is evaluated.

The questions for the application analysis of the technologies will be:

- Were identification technologies, such as real capture methods or BIM, applied for steel/ donor steel mapping?
- Were the material properties verified through testing or existing material passports?
- Was data integrated into the design tools or circularity assessments (e.g., LCA, ECI)?

The data to answer these questions will be sourced from various documents, including project documents, meeting notes, tender applications, BIM or 3D models, and stakeholder interviews.

C.2 Design and planning process

This analytical dimension examines the design and planning process, including the reuse consideration stage and its impact on design flexibility. To evaluate the design and planning process, the following questions will be answered:

- In which stage was reuse introduced (e.g., concept, preliminary, detailed design)?
- Which strategy was used for the structural design with reuse applications:
    1. *'Design and search strategy'*: The structural design is made first, and later the needed donor steel components are searched.
    2. *'Design for reuse strategy':* The donor steel components were identified first, and with the available components, a design was made
- How did the availability of donor steel influence the structural design?
- How did timing affect the feasibility and project planning?

The data to answer these questions will be sourced from various documents, including project documents, design meeting notes, planning schedules, and stakeholder interviews.

C.3 Collaboration and governance

This analytical dimension examines collaboration models and governance structures, and their impact on the reuse process. To evaluate the collaboration models and governance structures, the following questions will be answered:

- Were the stakeholders (e.g., contractors, designers, engineers, sustainability or circularity advisors) aligned early in the process?
- Did the trust and communication between the stakeholders influence the acceptance of donor steel?
- Was the decision-making in the project supported by integrated project delivery or traditional contracts?

The data to answer these questions will be sourced from various documents, including project documents, project governance reports, tender process notes, and stakeholder interviews.

C.4 Economic and logistical feasibility

This analytical dimension examines the financial and practical feasibility of the donor steel application in the project. To evaluate the financial and practical feasibility of donor steel, the following questions will be answered:

- Were the donor steel components cost-effectively compared to new steel components?

- Did testing, transport, or storage pose any challenges for the application of donor steel?
- Was the client willing to pay for the sustainable benefits of the donor steel application?

The data to answer these questions will be sourced from various documents, including project documents, cost estimates, procurement documents, and stakeholder interviews.

C.5 Regulatory and certification constraints

This analytical dimension examines how regulatory frameworks, safety standards, and certification procedures influenced the feasibility of donor steel. To evaluate these regulatory and certification constraints, the following questions were answered:

- Did Eurocodes or the NTA 8713 influence the project feasibility?
- Was CE marking or testing required to validate the application of donor steel?
- How was the structural safety assured to the client?

The data to answer these questions will be sourced from various documents, including project documents, engineering documentation, material testing reports, and stakeholder interviews.

C.6 Outcome and lessons learned

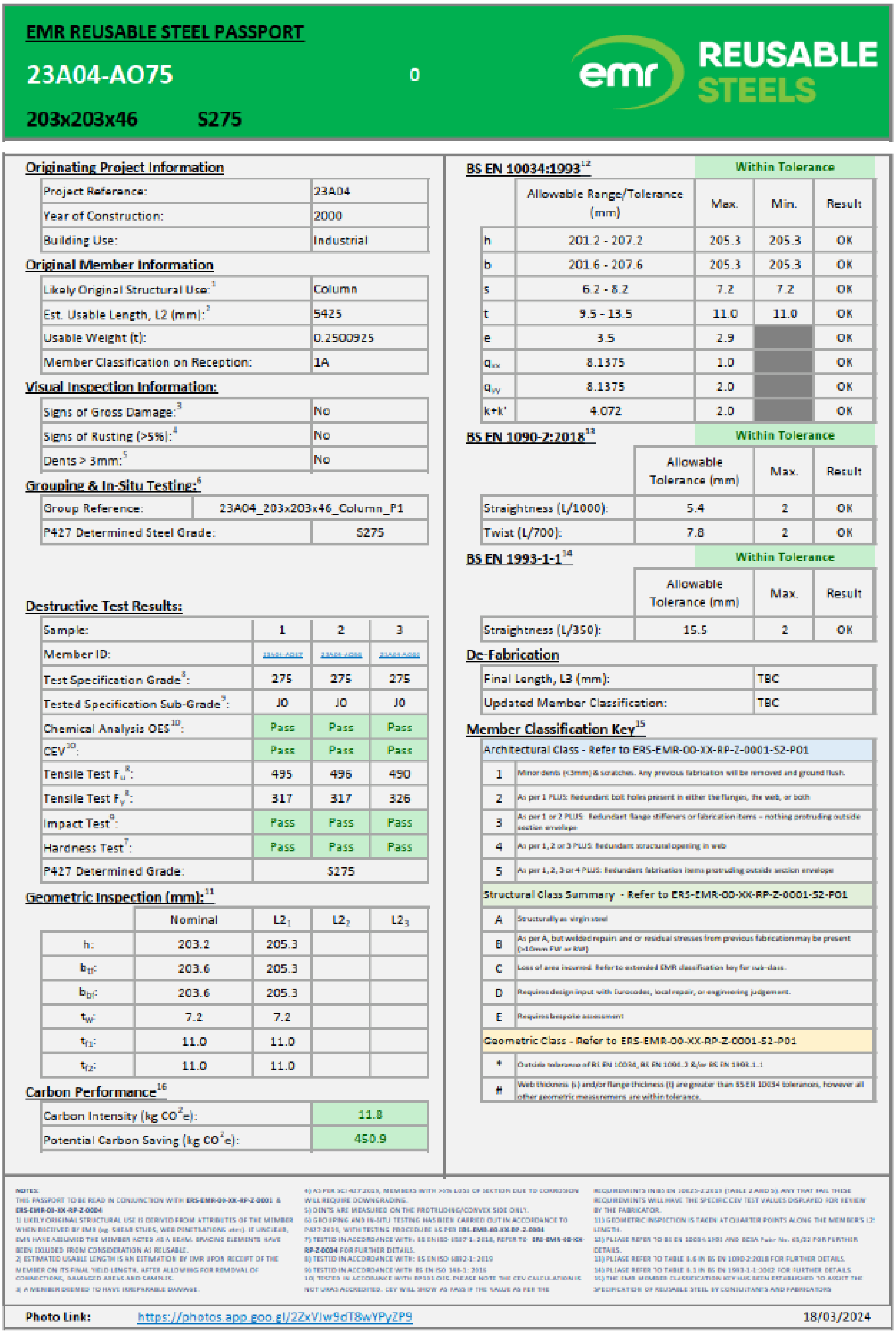
This subchapter summarizes the key insights, success factors, and obstacles for each case study. Moreover, transferable lessons for future donor steel projects have been identified. The following indicators will be summarized:

- *Key obstacles* (chosen from the five identified obstacles in the literature review → § 2.1)
- *Key enablers* (e.g., early digital integration, strong collaboration, transparency, client ambition → § 2.2 & § 2.3)

In § 4.1.6, all case studies will be compared using a 'cross-case analytical process' outlined by Creswell (2013), following the five analytical dimensions described in C.1–C.6.

Appendix D

D. Example: Material passport Landstations *(De Kok Schaalbouw, 2023)*



EMR REUSABLE STEEL PASSPORT

23A04-A075 0

203x203x46 **S275**

REUSABLE STEELS

Originating Project Information

Project Reference:	23A04
Year of Construction:	2000
Building Use:	Industrial

Original Member Information

Likely Original Structural Use:[1]	Column
Est. Usable Length, L2 (mm):[2]	5425
Usable Weight (t):	0.2500925
Member Classification on Reception:	1A

Visual Inspection Information:

Signs of Gross Damage:[3]	No
Signs of Rusting (>5%):[4]	No
Dents > 3mm:[5]	No

Grouping & In-Situ Testing:[6]

Group Reference:	23A04_203x203x46_Column_P1
P427 Determined Steel Grade:	S275

Destructive Test Results:

Sample:	1	2	3
Member ID:	[illegible]	[illegible]	[illegible]
Test Specification Grade[8]:	275	275	275
Tested Specification Sub-Grade[9]:	J0	J0	J0
Chemical Analysis OES[10]:	Pass	Pass	Pass
CEV[10]:	Pass	Pass	Pass
Tensile Test F_u[8]:	495	496	490
Tensile Test F_y[8]:	317	317	326
Impact Test[9]:	Pass	Pass	Pass
Hardness Test[7]:	Pass	Pass	Pass
P427 Determined Grade:	S275		

Geometric Inspection (mm):[11]

	Nominal	$L2_1$	$L2_2$	$L2_3$
h:	203.2	205.3		
b_{tf}:	203.6	205.3		
b_{bf}:	203.6	205.3		
t_w:	7.2	7.2		
t_{f1}:	11.0	11.0		
t_{f2}:	11.0	11.0		

Carbon Performance[16]

Carbon Intensity (kg CO^2e):	11.8
Potential Carbon Saving (kg CO^2e):	450.9

BS EN 10034:1993[12] Within Tolerance

	Allowable Range/Tolerance (mm)	Max.	Min.	Result
h	201.2 - 207.2	205.3	205.3	OK
b	201.6 - 207.6	205.3	205.3	OK
s	6.2 - 8.2	7.2	7.2	OK
t	9.5 - 13.5	11.0	11.0	OK
e	3.5	2.9		OK
q_{xx}	8.1375	1.0		OK
q_{yy}	8.1375	2.0		OK
k+k'	4.072	2.0		OK

BS EN 1090-2:2018[13] Within Tolerance

	Allowable Tolerance (mm)	Max.	Result
Straightness (L/1000):	5.4	2	OK
Twist (L/700):	7.8	2	OK

BS EN 1993-1-1[14] Within Tolerance

	Allowable Tolerance (mm)	Max.	Result
Straightness (L/350):	15.5	2	OK

De-Fabrication

Final Length, L3 (mm):	TBC
Updated Member Classification:	TBC

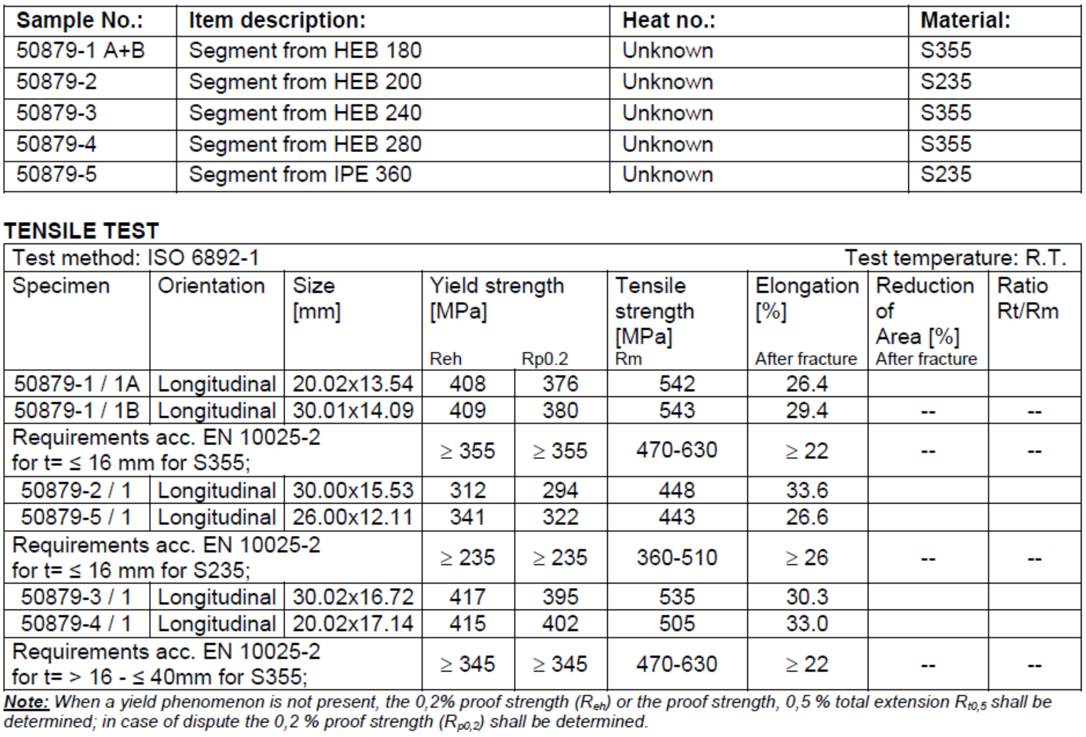
Member Classification Key[15]

Architectural Class - Refer to ERS-EMR-00-XX-RP-Z-0001-S2-P01	
1	Minor dents (<3mm) & scratches. Any previous fabrication will be removed and ground flush.
2	As per 1 PLUS: Redundant bolt holes present in either the flanges, the web, or both
3	As per 1 or 2 PLUS: Redundant flange stiffeners or fabrication items – nothing protruding outside section envelope
4	As per 1, 2 or 3 PLUS: Redundant structural opening in web
5	As per 1, 2, 3 or 4 PLUS: Redundant fabrication items protruding outside section envelope
Structural Class Summary - Refer to ERS-EMR-00-XX-RP-Z-0001-S2-P01	
A	Structurally as virgin steel
B	As per A, but welded repairs and or residual stresses from previous fabrication may be present (>10mm FW or BW)
C	Loss of area incurred. Refer to extended EMR classification key for sub-class.
D	Requires design input with Eurocodes, local repair, or engineering judgement.
E	Requires bespoke assessment
Geometric Class - Refer to ERS-EMR-00-XX-RP-Z-0001-S2-P01	
*	Outside tolerance of BS EN 10034, BS EN 1090-2 &/or BS EN 1993-1-1
#	Web thickness (s) and/or flange thickness (t) are greater than BS EN 10034 tolerances, however all other geometric measurements are within tolerance.

Photo Link: https://photos.app.goo.gl/2ZxVJw9dT8wYPyZP9 18/03/2024

Appendix E

E. Test report of donor steel beams building REC-P *(Blijlven, 2022)*



Sample No.:	**Item description:**	**Heat no.:**	**Material:**
50879-1 A+B	Segment from HEB 180	Unknown	S355
50879-2	Segment from HEB 200	Unknown	S235
50879-3	Segment from HEB 240	Unknown	S355
50879-4	Segment from HEB 280	Unknown	S355
50879-5	Segment from IPE 360	Unknown	S235

TENSILE TEST

Test method: ISO 6892-1 Test temperature: R.T.

Specimen	Orientation	Size [mm]	Yield strength [MPa] Reh	Rp0.2	Tensile strength [MPa] Rm	Elongation [%] After fracture	Reduction of Area [%] After fracture	Ratio Rt/Rm
50879-1 / 1A	Longitudinal	20.02x13.54	408	376	542	26.4		
50879-1 / 1B	Longitudinal	30.01x14.09	409	380	543	29.4	--	--
Requirements acc. EN 10025-2 for t= ≤ 16 mm for S355;			≥ 355	≥ 355	470-630	≥ 22	--	--
50879-2 / 1	Longitudinal	30.00x15.53	312	294	448	33.6		
50879-5 / 1	Longitudinal	26.00x12.11	341	322	443	26.6		
Requirements acc. EN 10025-2 for t= ≤ 16 mm for S235;			≥ 235	≥ 235	360-510	≥ 26	--	--
50879-3 / 1	Longitudinal	30.02x16.72	417	395	535	30.3		
50879-4 / 1	Longitudinal	20.02x17.14	415	402	505	33.0		
Requirements acc. EN 10025-2 for t= > 16 - ≤ 40mm for S355;			≥ 345	≥ 345	470-630	≥ 22	--	--

Note: *When a yield phenomenon is not present, the 0,2% proof strength (R_{eh}) or the proof strength, 0,5 % total extension $R_{t0,5}$ shall be determined; in case of dispute the 0,2 % proof strength ($R_{p0,2}$) shall be determined.*

Appendix F

F. Preliminary quotation and cost difference donor and new steel REC-P

(Blijlven, 2022)

Gebruikt staal

Aankoop 13.445kg HP staal x 1,05=	€	14.117,25
Transport HP staal naar straler	€	325,00

HP staal weet niet uit hoeveel batches het staal komt, omdat het gebruikt staal is.

De kosten voor 6 stuks trekproeven bedragen:	€	1.500,00
Stralen balken	€	4.595,00
Transport straler naar Blijleven	€	325,00
Totaal prijs	**€**	**20.862,25**

Nieuw staal

Wij hebben het volgende in onze begroting opgenomen voor inkoop nieuw staal.
Zie ook uitreksstaat in de bijlage van de balken die we eruit kunnen zagen.

Begroting / offerte: 12045kg x 1,18 euro per kg =	**€**	**14.213,10**
Verschil gebruikt staal t.o.v. nieuw staal	**€**	**6.649,15**

Deze prijs is excl.: BTW

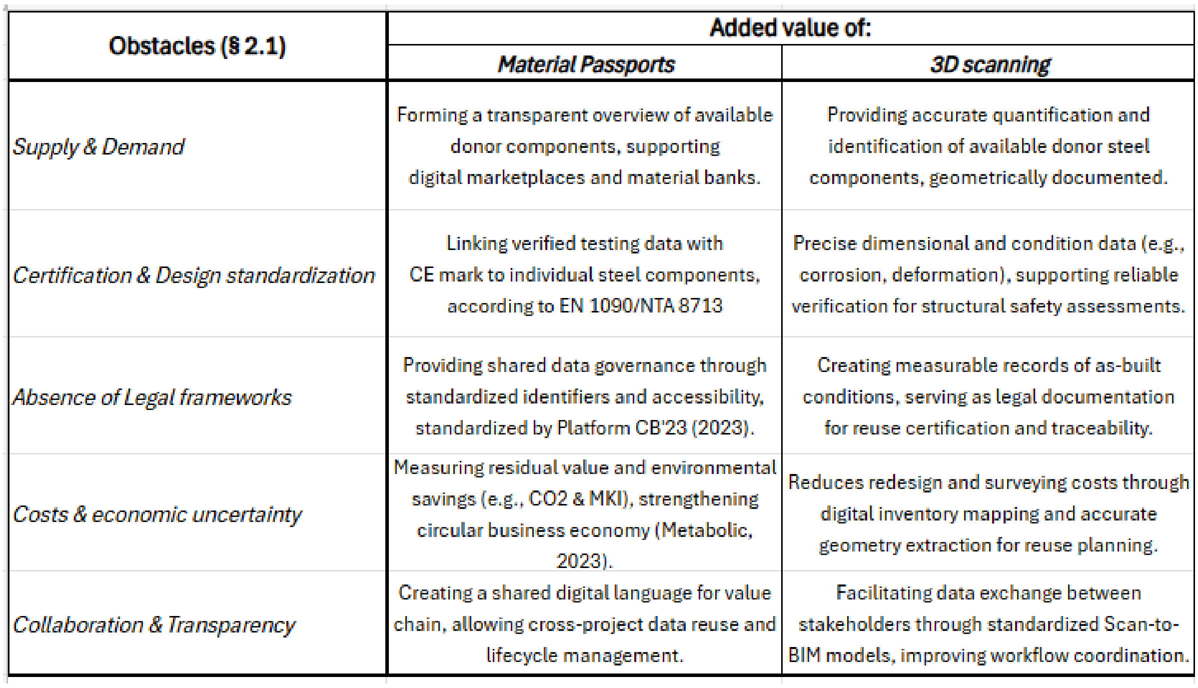
Levertijd: In overleg
Betaling: Binnen 14 dagen na factuurdatum.

In verband met de in korte tijd sterk wisselende prijs van staal op de wereldmarkt, kunnen wij hier op dit moment geen vaste prijs voor afgeven. De in de offerte/opdrachtbevestiging hiervoor opgenomen prijs betreft dan ook de prijs ten tijde van het opstellen van dit document. Mocht op het moment van de inkoop van het betreffende materiaal een andere prijs aan ons in rekening gebracht worden dan waar wij bij het opstellen van de offerte/opdrachtbevestiging mee gerekend hebben, dan behouden wij ons het recht voor om deze prijsstijgingen aan u in rekening te brengen. Wij vragen uw begrip voor deze situatie.

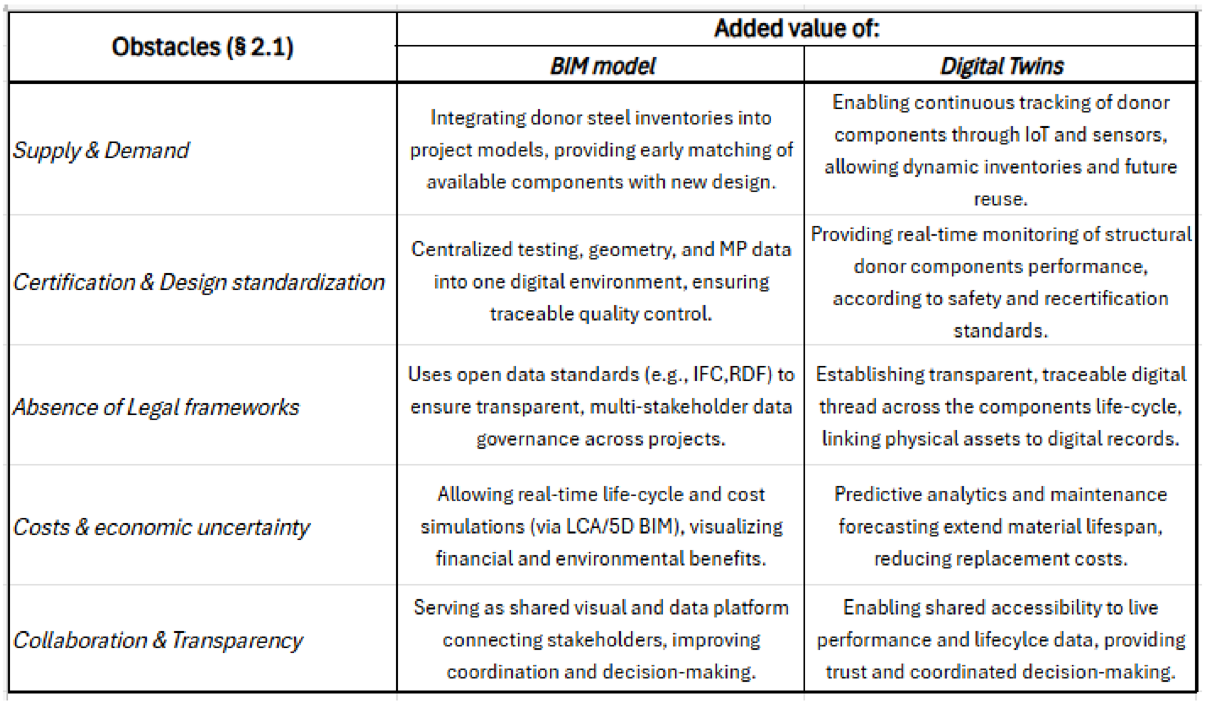
Appendix G

G. Detailed summary table obstacles (§ 2.2)

Table G.1: Summary of the added value for each technology for each obstacle in § 2.1 (detailed)



Obstacles (§ 2.1)	**Added value of:**	
	Material Passports	***3D scanning***
Supply & Demand	Forming a transparent overview of available donor components, supporting digital marketplaces and material banks.	Providing accurate quantification and identification of available donor steel components, geometrically documented.
Certification & Design standardization	Linking verified testing data with CE mark to individual steel components, according to EN 1090/NTA 8713	Precise dimensional and condition data (e.g., corrosion, deformation), supporting reliable verification for structural safety assessments.
Absence of Legal frameworks	Providing shared data governance through standardized identifiers and accessibility, standardized by Platform CB'23 (2023).	Creating measurable records of as-built conditions, serving as legal documentation for reuse certification and traceability.
Costs & economic uncertainty	Measuring residual value and environmental savings (e.g., CO2 & MKI), strengthening circular business economy (Metabolic, 2023).	Reduces redesign and surveying costs through digital inventory mapping and accurate geometry extraction for reuse planning.
Collaboration & Transparency	Creating a shared digital language for value chain, allowing cross-project data reuse and lifecycle management.	Facilitating data exchange between stakeholders through standardized Scan-to-BIM models, improving workflow coordination.



Obstacles (§ 2.1)	**Added value of:**	
	BIM model	***Digital Twins***
Supply & Demand	Integrating donor steel inventories into project models, providing early matching of available components with new design.	Enabling continuous tracking of donor components through IoT and sensors, allowing dynamic inventories and future reuse.
Certification & Design standardization	Centralized testing, geometry, and MP data into one digital environment, ensuring traceable quality control.	Providing real-time monitoring of structural donor components performance, according to safety and recertification standards.
Absence of Legal frameworks	Uses open data standards (e.g., IFC,RDF) to ensure transparent, multi-stakeholder data governance across projects.	Establishing transparent, traceable digital thread across the components life-cycle, linking physical assets to digital records.
Costs & economic uncertainty	Allowing real-time life-cycle and cost simulations (via LCA/5D BIM), visualizing financial and environmental benefits.	Predictive analytics and maintenance forecasting extend material lifespan, reducing replacement costs.
Collaboration & Transparency	Serving as shared visual and data platform connecting stakeholders, improving coordination and decision-making.	Enabling shared accessibility to live performance and lifecylce data, providing trust and coordinated decision-making.

Appendix H

H. Detailed data information of Chapter 4: Results

H.1 Detailed Cross-case analysis table: case study research

Table H.1 (4.13): Cross-case analysis of C1-C6 for the four case studies, with red key obstacles and green key enablers.

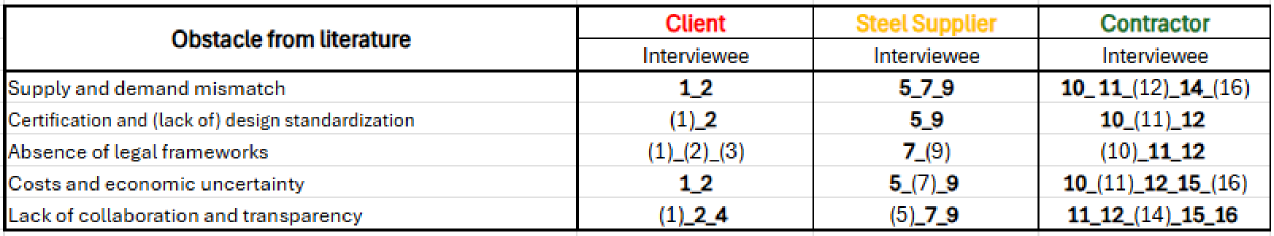
		Offshore Grid – 2GW Landstations	***Railway bridge Witte Paarden***
C1: Key technologies used		Material passport, BIM model, 3D scans / VR, ECI &LCA, Digital twin	Material testing, BIM model, ECI & LCA
C2: Reuse integration phase	Early (contract or design)	Contract phase	Contract phase
Reuse strategy	Design & Search'/'Design for reuse' strategy	Design & Search strategy	*Design for reuse strategy*
C3: Governance/ collaboration model	IPD model / Traditional model (TM)	Framework agreement (IPD)	Bouwteam (IPD)
Stakeholder alignment & communication	Early alignment & high transparency	High transparency & shared learning	High transparency & shared learning
C4: Economic feasibility	Cost efficiency	saving 98% CO2	saving 72.565 kg CO2
Logistical feasibility	Testings	weldability tests	microcracks, welding, ultrasonic
C5: Certification constraints	NTA 8713 (gevolgklasse 3) / Eurocodes (NEN-EN..)	NTA 8713 (gevolgklasse 3)	Eurocodes (NEN-EN1993-1-9)
	High requirements client	High (more than regulatory)	High
C6: Conclusion *Key bottlenecks*	Supply and demand mismatch		
	Certification and design standardisation	X	X
	Absence of legal frameworks		
	Cost and economic uncertainty	X	
	Lack of collaboration and transparency		
Key enablers	Early integration of reuse in the contract phase	X	X
	Availability of high quality donor steel with MPs/CE	X	X
	Client sustainability ambition supports reuse.	X	X
	Client willingness to pay for the circular solutions		
	Early integration of digital and sustainability tools.	X	X
	Strong collaboration structure/contract	X	X

		Building REC-P Roeterseiland	***Community School De Kameleon***
C1: Key technologies used		Material testing, BIM model, ECI & LCA, MPG	Material testing, BIM model, ECI & LCA, MPG
C2: Reuse integration phase	Early (contract or design)	Detailed design phase	Detailed design phase
Reuse strategy	Design & Search'/'Design for reuse' strategy	*Design & Search strategy*	*Design & Search strategy*
C3: Governance/ collaboration model	IPD model / Traditional model (TM)	Engineering & Construct (TM)	Design, Build, Maintain (IPE)
Stakeholder alignment & communication	Early alignment & high transparency	High transparency & shared learning	High transparency & shared learning
C4: Economic feasibility	Cost efficiency	specifics not conducted	specifics not conducted
Logistical feasibility	Testings	yield, tensile, elongation, chemical	tensile, yield, elongation, material
C5: Certification constraints	NTA 8713 (gevolgklasse 3) / Eurocodes (NEN-EN..)	Eurocodes (NEN-EN10025-2, 10210-1, 10219-1)	Eurocodes (NEN-EN10025-2,10210-1, 10219-1)
	High requirements client	Normal (regulatory)	Normal (regulatory)
C6: Conclusion *Key bottlenecks*	Supply and demand mismatch	X	X
	Certification and design standardisation	X	
	Absence of legal frameworks	X	
	Cost and economic uncertainty		X
	Lack of collaboration and transparency		
Key enablers	Early integration of reuse in the contract phase		
	Availability of high quality donor steel with MPs/CE		
	Client sustainability ambition supports reuse.	X	X
	Client willingness to pay for the circular solutions	X	
	Early integration of digital and sustainability tools.	X	X
	Strong collaboration structure/contract	X	X

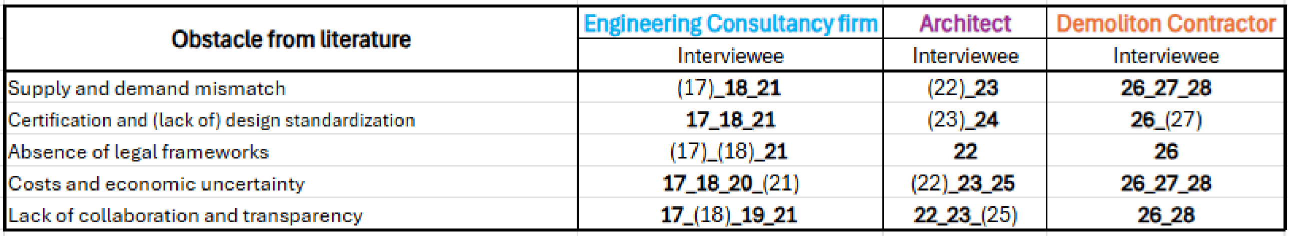
H.2 Detailed result table: exploratory interviews

Table H.1 presents the stakeholders from the interviewees who agreed with or mentioned the five identified obstacles from the literature review. The interviewee numbers listed in the row for a particular obstacle indicate that the interviewee mentioned that obstacle themselves during the conversation and agrees with it. Moreover, if the interviewee's number appears in parentheses, the interviewee agrees to this obstacle but did not raise it on their own; they only confirmed it after the researcher asked during the interview.

Table H.2: Comparison between the obstacles in the literature review and those mentioned by



Obstacle from literature	Client	Steel Supplier	Contractor
	Interviewee	Interviewee	Interviewee
Supply and demand mismatch	**1**_**2**	**5**_**7**_**9**	**10**_ **11**_(12)_**14**_(16)
Certification and (lack of) design standardization	(1)_**2**	**5**_**9**	**10**_(11)_**12**
Absence of legal frameworks	(1)_(2)_(3)	**7**_(9)	(10)_**11**_**12**
Costs and economic uncertainty	**1**_**2**	**5**_(7)_**9**	**10**_(11)_**12**_**15**_(16)
Lack of collaboration and transparency	(1)_**2**_**4**	(5)_**7**_**9**	**11**_**12**_(14)_**15**_**16**



Obstacle from literature	Engineering Consultancy firm	Architect	Demoliton Contractor
	Interviewee	Interviewee	Interviewee
Supply and demand mismatch	(17)_**18**_**21**	(22)_**23**	**26**_**27**_**28**
Certification and (lack of) design standardization	**17**_**18**_**21**	(23)_**24**	**26**_(27)
Absence of legal frameworks	(17)_(18)_**21**	**22**	**26**
Costs and economic uncertainty	**17**_**18**_**20**_(21)	(22)_**23**_**25**	**26**_**27**_**28**
Lack of collaboration and transparency	**17**_(18)_**19**_**21**	**22**_**23**_(25)	**26**_**28**

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