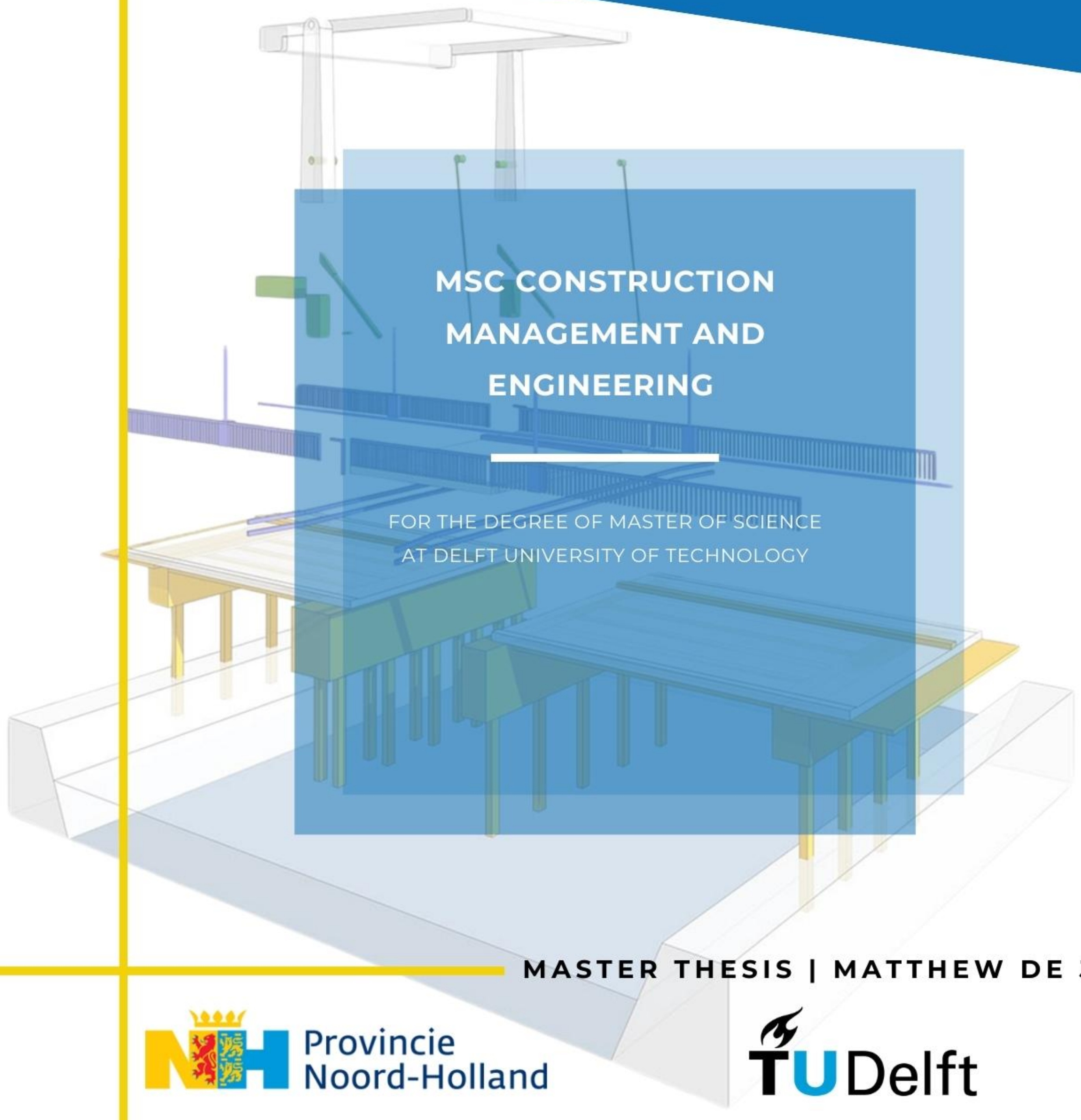
IFD

MAPPING THE TRANSITION TO INDUSTRIALISED BRIDGE CONSTRUCTION IN THE NETHERLANDS

PATHWAYS TO STANDARDISED IFD PRACTICES ACROSS THE SUPPLY CHAIN



MSC CONSTRUCTION MANAGEMENT AND ENGINEERING

FOR THE DEGREE OF MASTER OF SCIENCE
AT DELFT UNIVERSITY OF TECHNOLOGY

MASTER THESIS | MATTHEW DE JONG

Provincie Noord-Holland

TU Delft

Colophon

Title: Mapping the transition to industrialised bridge construction in the Netherlands: Pathways to standardised IFD practices across the supply chain

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CME 5200: CME Master thesis

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Preface

This document presents my master's thesis on the transition of industrialised, flexible, and demountable bridge construction in the Netherlands. The research was carried out in collaboration with the public client Province of North-Holland, an ambitious and forward-thinking regional authority aiming to establish a sustainable and industrialised bridge construction supply chain. This initiative reflects the province’s commitment to serving its citizens through innovative infrastructure that future-proofs public works and makes strides in modernising Dutch construction.

The thesis marks the conclusion of my Master's programme in Construction Management and Engineering and represents the end of my time as a student at the TU Delft.

First and foremost, I would like to express my sincere gratitude to my supervisors, Dr. Daniel Hall and Dr. Wenjuan Lyu, for their insightful guidance and continuous support throughout this process. Your expertise, encouragement, and critical feedback helped shape this research. I would also like to thank my graduation chair, Dr. Daan Schraven.

Special thanks go to Dr. Paul Waarts, my supervisor at the Province of North Holland, for providing me with the opportunity to work on this topic and for your trust, insights, and constructive dialogue throughout the project. I am also grateful to my colleagues at the Province, whose collaboration and open-mindedness greatly enriched my experience and understanding of the real-world complexities in the public construction sector.

Furthermore, I wish to thank all the participants who contributed to this research. Your willingness to spare some of your time and professional perspectives was vital for this research, and I deeply appreciate your openness and honesty.

Lastly, I would like to share my gratitude to my friends and family. Thank you for your patience, support, and for putting up with my endless complaining.

I hope this thesis makes a meaningful contribution to the ongoing development of sustainable infrastructure in the Netherlands and inspires further progress in the adoption of IFD.

Enjoy reading!

Sincerely, Matthew de Jong

Summary

The Dutch bridge infrastructure sector is facing an unprecedented renewal challenge, known as the Vervanging en Renovatie (V&R) task. This task is driven by the ageing of thousands of bridges and viaducts (TNO, 2023). Furthermore, the V&R challenge is intensified by resource constraints, including shortages of skilled labour and the growing scarcity of primary construction materials (Alsharef et al., 2024). Simultaneously, the Netherlands has set ambitious sustainability goals: achieving a fully circular economy by 2050 and reducing the use of primary raw materials with 50% by 2030 (RWS, 2023). These ambitions demand a fundamental transition from traditional linear construction models to circular and industrialised approaches. Currently, traditional bespoke construction is regarded as too slow and resource-intensive in order to achieve the required scale and pace needed for the V&R challenge while also meeting the circularity targets (Van Gils & beton&staalbouw, 2023).

In response to these challenges, there is a growing consensus that industrialised construction methods are a key part of the solution. A recent study by Brouwer (2024) identified a set of industrialised innovations as promising responses. Among them, Industrial, Flexible and Demountable (IFD) construction is viewed by supply-chain actors as particularly promising. Supported by the recently developed voluntary Dutch Technical Agreements (NTA 8085, 8086, 8089), IFD provides a framework for scalable, adaptable, and circular bridge delivery (EIB, 2023).

The concept of IFD construction, refers to a bridge-construction approach that applies industrial production to prefabricated demountable modules, designed with standardised interfaces and dimensions (as codified in the NTAs). These parts can be swapped, upgraded, or removed without damaging the structure. Industrial in IFD denotes off-site serial manufacturing. Flexibility refers to the capacity for modification and scalability throughout the structures life cycle. Demountability signifies a design intent that enables disassembly and high-grade reuse (NEN, 2024a).

However, despite its potential, the uptake of IFD and its associated standards remains fragmented and inconsistent. This raises the question of how adoption can be promoted to enable the transition towards standardised IFD practices. Therefore, the main research question guiding this study is:

"How can the adoption of unified standards among supply chain actors in the Dutch bridge construction industry be promoted to facilitate the transition to standardised IFD practices?"

This question is addressed through three sub-questions, covering: 1) the definition and implications of IFD principles, 2) knowledge gained from practice through case studies, and 3) barriers and interventions to adoption through additional interviews.

In order to be able to answer these questions, an abductive, exploratory, qualitative research design was used. Furthermore, theory and empirics were combined through a systemic combining approach (Dubois & Gadde, 2002). This iterative approach suited the exploratory and evolving nature of IFD and the NTAs. The research integrated 1) a multiple-case study of three IFD bridge projects, conform the NTAs commissioned by the Province of North Holland (Cruquius Bridge, N240B Bridge, and Stolperbrug) and 2) fourteen semi-structured interviews across the supply chain, including public clients, designers, contractors, and suppliers.

To be able to analyse the case studies, an evaluation matrix was developed to provide a structured framework for assessing each case's level of industrialisation, flexibility, demountability, and NTA conformity. This provided the necessary context and comparability between cases. The interviews were analysed through thematic coding and cross-case comparison to identify recurring barriers and enablers to IFD adoption.

The Cruquius Bridge (case A) served as the first IFD pilot project. Industrialisation was moderate, achieved mainly through prefabricated steel and M&E systems. Flexibility was low, because it was limited to vessel clearance and modular M&E components. Demountability was moderate to high, since the steel bridge and M&E systems were removable but reuse was limited by the concrete cast layer and asphalt connection. NTA 8086 was still under development and applied as guidance only, so compliance remained partial. The collaborative bouwteam model fostered learning and early contractor involvement, yielding strong lessons for future NTA development.

The N240B Bridges (case B) represented the most advanced application of IFD principles. The twin fixed bridges are designed to be fully demountable, supported by a disassembly manual and reuse scenarios. Industrialisation was high due to extensive prefabrication and design repetition. Flexibility was moderate to high, as modular elements allowed potential relocation and a scalable design was developed. Furthermore, the NTA 8085 use was near full compliance and was applied actively. However, the D&C contract limited early collaboration and optimisation. Also, an alternative modular product proposal was withdrawn, illustrating how procurement constraints and NTA use can restrict innovation.

The Stolperbrug (case C) is part of a framework agreement of four movable bridges. The first standalone tender failed due to poor market alignment, leading to a framework-based bouwteam approach, which enabled more realistic and iterative collaboration. Industrialisation was moderate, mainly through prefabrication and process repetition, while full product modularisation was not yet achieved. Flexibility was also deemed moderate, with ambitions formulated but not yet realised in the design. Demountability was moderate to high, similar to case A, with removable steel and M&E parts. NTA 8086 v2 was applied from the outset yielding high compliance, though some provisions required adaptation to project specifics.

Across all three cases, IFD implementation is progressing but uneven. Industrialisation remains focused on prefabrication rather than serial, product-based construction. Flexibility lags behind other principles, while demountability shows the most maturity. The NTA compliance is steadily improving. Additionally, the procurement models, especially collaborative frameworks and early contractor involvement, emerge as key enablers of IFD adoption.

The analyses of the interviews identified seven barrier themes: 1) institutional conservatism, 2) limited knowledge diffusion, 3) regulatory and procurement constraints, 4) weak client-side capacity, 5) organisational fragmentation, 6) NTA-specific limitations, and 7) lack of coordinated leadership and market signals. Proposed interventions fall into three categories. First, communication instruments (pilots, knowledge hubs, training, structured dialogue) build competence and convergence. Second, regulatory instruments (continuous NTA development, catalogue-based procurement, partial mandating) are useful as adoption matures. Third, economic instruments (co-funding and EMVI criteria rewarding lifecycle value) are valuable to incentivise adoption.

To conclude, the findings of this study show that effective NTA adoption relies on coordinated client leadership with a phased mix of systemic interventions. First, building awareness (creating visibility, signalling), competence and partnering through communication-oriented interventions can help NTA adoption. As the sector gains experience, consistency can be enhanced by institutionalising and aligning regulatory instruments by continuous refinement and gradual formalisation of the NTAs within procurement frameworks. Here, economic incentives can enhance financial feasibility.

Ultimately, the success of the IFD transition depends on governance alignment and sustained public leadership. By consistently applying and evolving the NTAs, public clients can transform isolated pilots into a unified, platform-based IFD supply chain. This way, IFD can be of value in undertaking the V&R challenge and achieving circular economy objectives.

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List of Abbreviations

BAU	Business-as-usual
CC	Circular Construction
EIB	Economic Institute for Construction (*Dutch:* Economisch Instituut Bouw)
EM	Evaluation Matrix
EMVI	Best Price-Quality Ratio (*Dutch:* Economisch Meest Voordelige Inschrijving)
IC	Industrialised Construction
IFD	Industrial, Flexible, Demountable
IHB	Industrialised House Building
IIC	Infrastructure Industrialised Construction
NEN	The Dutch Norm/Standard (*Dutch:* Nederlandse Norm)
NTA[1]	Dutch Technical Agreement (*Dutch:* Nederlands Technische Afspraak)
PNH	Province North-Holland
R&D	Research and Development
ROK	Framework agreement (*Dutch:* Raamwerkovereenkomst)
RWS	Ministry of Infrastructure and Water Management (*Dutch:* Rijkswaterstaat)
V&R	Replacement and Renovation (*Dutch:* Vervanging en Renovatie)
VO	Renewal Task (*Dutch:* Vernieuwingsopgave)

[1]In this thesis, references to NTA specifically refer to NTAs developed for IFD bridges, which include the NTA 8085, 8086 and 8089.

Chapter 1 - Introduction

Infrastructure is the backbone of economic growth and societal well-being (Rathnayaka et al., 2022). It enables trade, connects workers to jobs, powers businesses, protects communities from environmental threats and contributes to the reduction of economic disparity (Srinivasu et al, 2013). However, due to growing resource scarcity and environmental pressure, the global infrastructure sector faces pressing challenges that strain its ability to fulfil this vital role (Alsharef et al., 2024).

The construction industry consumes about 100 billion tons of raw materials annually and generates roughly one-third of the world's waste (Miller, 2022). This mostly linear consumption model is unsustainable, contributing to resource depletion and high carbon emissions. Such impacts highlight an urgent need to conserve materials, reduce waste, and lower the carbon footprint of infrastructure development.

Furthermore, a shortage of skilled labour is creating bottlenecks in infrastructure projects worldwide. Many countries report difficulty finding enough qualified construction workers, as an ageing workforce retires and fewer young workers enter the industry. Across Europe, building and other related professions are among those facing the most severe labour deficits (WEF, 2023). This labour shortage ultimately means that traditional on-site construction methods are increasingly hard to execute.

These global challenges, including resource scarcity, labour shortages and the climate crisis, are driving a revaluation of how we build and maintain infrastructure.

The goal of this chapter is to set the stage for this research. First, it outlines the problem context by relating the global issues discussed above to the Dutch infrastructure sector, including the role of Industrialised, Flexible, and Demountable (IFD) construction and the role of standardisation. Second, it identifies the research gap that this thesis seeks to address. Third, it presents the research questions (RQs) and finally, it introduces the overall research design of this thesis.

1.1 Problem context

This thesis is set within the context of the Dutch bridge infrastructure sector. To fully grasp the challenges of this sector, it is essential to bridge the gap between global challenges and the specific complexities faced in the Netherlands. Several national developments and sector-specific dynamics add to the urgency and relevance of this research.

1.1.1 Research context

The Dutch construction industry exemplifies the global trends mentioned above, while also facing distinct local pressures on its infrastructure. A significant concern is the ageing bridge infrastructure, many of which were constructed in the post-war period. Beyond decades of heavy use and environmental exposure, these structures were not designed to the current traffic loads and frequencies seen today (TNO, 2023). Thus, a large share of Dutch civil infrastructure has aged and is in dire need of renewal and renovation, a situation referred to as the renewal and renovation (V&R) challenge (*Dutch* "Vervanging en Renovatie").

In the upcoming decades, thousands of bridges, viaducts, and other structures across the country will reach the end of their technical or functional lifespan (Lantsoght et al., 2017; Van Gils & beton&staalbouw, 2023). As a result, public agencies at all levels (national, provincial, and municipal) are now confronted with the immense task of upgrading and replacing infrastructural objects. This is evident by a recent prognosis report by TNO, which highlights the urgency: keeping the Netherlands safe and accessible will require rapidly increasing investments in infrastructure renewal, rising from about €1.1 billion in 2021 to an expected €2–4 billion annually for the upcoming decades, see figure 1 below (TNO, 2023).

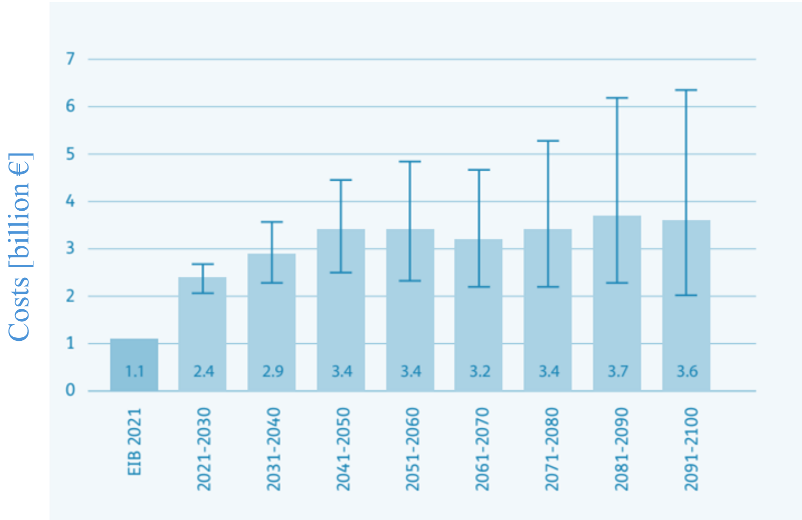


Figure 1: Prognoses on Civil infrastructure renovation and renewal costs [Billion € /Year] (TNO, 2023)

This wave of replacements and renovations poses not only an engineering but also an economic and logistical challenge. Budgetary constraints demand that solutions be cost-effective, and lengthy traffic disruptions must be minimised to avoid harming the economy. Traditional one-off construction approaches, designing and rebuilding each bridge in isolation, would be too slow and expensive to address the nationwide renewal backlog in time (Van Gils & beton&staalbouw, 2023). Consequently, there is a strong demand for efficient, scalable methods to deliver infrastructure projects faster and with less disruption. Dutch authorities and industry stakeholders recognise that a more innovative and programmatic approach is needed, rather than business-as-usual (RWS, 2024).

In addition to the V&R challenge, the Netherlands is pursuing ambitious sustainability and circular economy goals that directly impact infrastructure development. The Dutch government has set a national target to achieve a fully circular economy by 2050, with an interim goal of reducing the use of primary raw materials by 50% by 2030 (RWS, 2023). This means infrastructure projects are expected to prioritise the reduction and reuse of materials, recycling and other circular construction methods to minimise waste.

Given this context, the current state of infrastructure construction in the Netherlands is at a crossroads on how to handle the V&R challenge and reach its sustainability goals. Many projects still rely on conventional methods that may not scale well to the enormous renewal demand and sustainability goals. However, to meet these challenges, there is a pressing need to modernise Dutch infrastructure construction and strengthen the supply chain, so that projects can be delivered faster, more efficiently, and in line with sustainability ambitions.

In response to these challenges, there is a growing consensus that industrialised construction (IC) methods are a key part of the solution. In a recent study conducted by Brouwer (2024) titled ‘Exploring the Transition to Industrialisation in Dutch Infrastructure Construction’, Brouwer similarly delves into the V&R challenge. The research highlights a substantial demand for rehabilitation that currently surpasses supply capacities, advocating for an industrialised approach to infrastructure projects to streamline processes and improve efficiency. Brouwer identified a set of innovation types that, when integrated, show promise for facilitating industrialisation across traditional project lifecycle phases. This integration primarily revolves around digitalisation, parametric design practices and IFD construction. The latter innovation is the focus of this research.

1.1.2 Practical implications

IFD construction has thus emerged as a promising innovation to the infrastructure challenges described above and is gaining traction among stakeholders as a feasible way to meet future infrastructure demands (Brouwer, 2024). A definition put forward in the Dutch GWW (civil infrastructure) sector describes IFD as "*working with standardised interfaces that are factory-produced, can be installed quickly, and are suitable for reuse*" (ipvDelft, 2019). In essence, IFD construction is an approach that standardises and modularises infrastructure construction, allowing it to be assembled quickly, adapted over time, and ultimately taken apart for reuse (EIB, 2023). The three pillars of IFD capture its key principles (NEN, 2020a):

- Industrialisation means using factory-made components and repeatable processes (similar to prefabrication in manufacturing) to increase quality and efficiency.
- Flexible refers to the ability to mix and match components or upgrade parts of the structure in the future; the design is not a one-off, rigid design, but rather adaptable to new requirements or technologies.
- Demountable means that components are not cast in place permanently. Instead, elements can be disassembled at functional or technical end-of-life and potentially used in other projects.

Standardisation is at the heart of IFD. Much like building with Lego blocks, the concept relies on prefabricated components that fit together in a predetermined way and can be dismantled without any damage. In Chapter 2, these core principles are outlined in more detail.

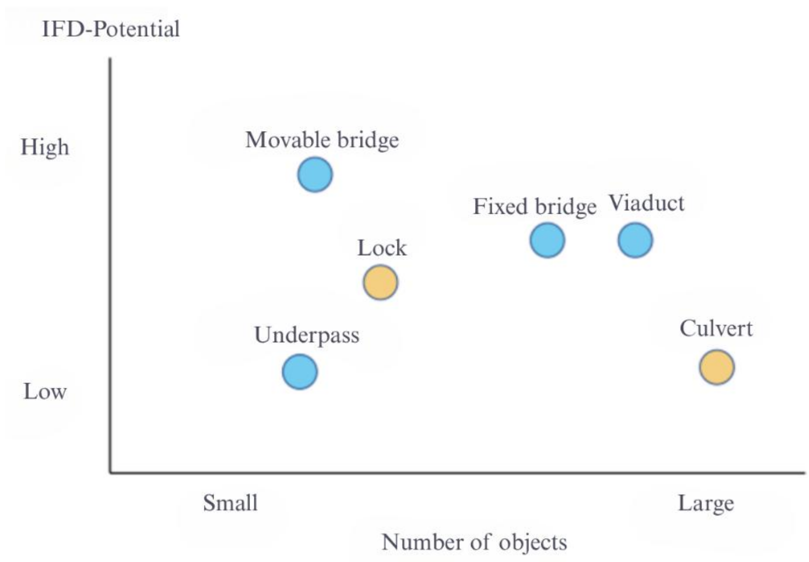


Figure 2: Market potential of IFD plotted against the number of objects for different infrastructure structures, adapted illustration (EIB, 2023)

The benefits of IFD construction are closely aligned with the current demands of Dutch bridge infrastructure, addressing both the V&R challenge and sustainability efforts. As highlighted by the EIB (2023), there is significant potential for IFD construction across various infrastructure assets, particularly for movable and fixed bridges and viaducts, as illustrated in Figure 2. Furthermore, research by TNO estimates the market capacity for IFD at €61.4 billion (TNO, 2023).

The IFD approach shifts construction from on-site to a controlled off-site factory environment, which significantly shortens on-site assembly times and thereby reduces traffic disruptions. Industry reports indicate that applying IFD principles such as prefabrication and standardised components not only accelerates project delivery and minimises public inconvenience, but can also reduce initial construction and maintenance costs by up to 15% when adopted at scale (EIB, 2023).

The public client Province of Noord-Holland (PNH), a frontrunner in IFD, reports that using IFD has allowed them to save on materials and design costs, also indicating that maintenance and future replacements can be done quicker and cheaper (Van Gils & beton&staalbouw, 2023).

In addition to reduced cost and construction time, IFD offers clear sustainability advantages. Because an IFD bridge's components are demountable and reusable, the approach inherently supports the circular use of materials as components can live multiple lives across different projects. This greatly extends the service life of materials beyond a single structure and avoids premature scrapping of valuable steel or concrete elements. As Paul Waarts asset manager for PNH explains, when all bridges share standardised parts, "*if something needs replacing, you could take that part from another bridge being retired, or easily make a new one*" (Rijksoverheid, 2024). Such interchangeability means far less raw material is needed over time, directly contributing to circular economy goals. Environmental impact is reduced not only through reuse but also through more efficient fabrication. Building in a factory setting generates much less waste (scrap can be recycled on the spot) compared to traditional on-site construction (Ortega et al., 2023). Lifecycle analyses show lower CO_2 emissions for IFD bridges versus conventional ones, thanks to optimised use of materials and fewer transport and construction activities on site (EIB, 2023). Thus, IFD construction aligns with climate and sustainability objectives by cutting material waste, enabling re-use, and reducing emissions.

Recognising these benefits, several organisations have launched a number of initiatives to promote IFD construction in bridge projects. One notable effort is the development of three standards for IFD bridges (fixed and movable) and IA&E (Instrumentation, Automation & Electrical) systems of movable bridges (NEN, 2020a; 2020b; 2024a). The public client PNH collaborated with the Dutch standardisation body NEN and other industry partners to develop a national standard for IFD bridge design. This standard is known as the NTA, which stands for Dutch Technical Agreement (*Dutch*: Nederlands Technische Afspraak) (PNH, 2023). The availability of this national standard is believed to be a major step toward mainstreaming IFD, as it ensures that all actors can work from a common playbook when pursuing IFD bridge construction. Appendix D provides further details on the current status and historical development of the NTA, as well as other industry initiatives. It delves deeper into the creation of this standard and the collaborative efforts that led to its establishment.

Apart from standard development, there has been the first key pilot project demonstrating IFD in practice. The renovation and renewal of a large movable bridge, the Cruquius Bridge in North-Holland, is being carried out by implementing IFD principles and the NTA (PNH, 2024). The bridge is partly rebuilt with modular components, aiming for a low-maintenance and circular outcome (Rijksoverheid, 2024). Early reports highlight that using uniform component sizes and connections greatly simplifies assembly and will allow parts to be swapped out in the future, extending the bridge's lifespan (Rijksoverheid, 2024). Perhaps the strongest endorsement comes from PNH's decision that "*from now on we will apply IFD to all our fixed and movable bridges*", as stated by the provincial executive for infrastructure (Van Gils & beton&staalbouw, 2023). It underscores a commitment to scale up IFD from isolated pilots to routine practice.

Overall, IFD construction presents a transformative approach that directly addresses the Netherlands' need for rapid, large-scale, and sustainable bridge replacement. Its modular, kit-of-parts philosophy can turn the looming replacement wave into an opportunity instead of reinventing the wheel for each project; engineers can draw on a library of proven components and focus on site-specific adaptations. The expectation is that this will not only save time and money but also produce bridges that are future-proof, easier to adapt, repair, and eventually recycle. The current initiatives (standards, pilot projects, provincial programs) demonstrate that momentum is building around IFD. Yet, as the next section discusses, there are still many hurdles and challenges to overcome before IFD is fully integrated across the Dutch infrastructure sector.

1.2 Research gap & problem statement

Although industry and pilot-project reports highlight clear benefits of IFD construction, its adoption in practice remains fragmented amongst the supply-chain actors. So far, the movement toward IFD has been driven by a few frontrunners such as public asset owner PNH and a handful of contractors and engineering firms, resulting in pockets of experience but not a uniform nationwide shift. The development of NTA guidelines is a step towards addressing the fragmentation, however, having a standard available does not automatically guarantee widespread use. One challenge is that the NTA guidelines are relatively new and not mandated, and thus bridge owners and supply chain actors may or may not choose to adopt.

It is common practice for the NEN to formalise an NTA into an official norm after three years (NEN, 2024b). However, this has not materialised due to insufficient adoption among public clients. Besides the fact that NTA is still in development, there are also gaps that the NTA doesn't fully address yet (NEN, 2020a).

This lack of adoption can lead to varying standards between projects: for example, one public client might require IFD-compatible design without the use of the NTA, while a neighbouring province requires IFD with the NTA. Such inconsistency means the full potential of industrialised production repetition and the ability to reuse components across jurisdictions is not realised. As Jeroen Olthof of PNH said "*IFD yields the greatest benefits if all infrastructure owners apply it together*" (Van Gils & beton&staalbouw, 2023). Currently, that unified application is non-existent; many clients and contractors are watching from the sidelines, hesitant to be early adopters.

Building a one-off bridge with custom design has been the norm for decades, shifting to a paradigm where bridges share components and designs requires a change in mindset and new competencies. For suppliers, investing in factory production or new tooling for IFD parts is a commitment that they might only make if they see a reliable pipeline of IFD projects ahead (EIB, 2023).

Additionally, procurement and policy adaptation have been slow. Public tender procedures often lag behind innovative practices. Until recently, tenders for bridges were very prescriptive (the agency specifies exactly what to build and how), leaving little room for contractors to propose modular alternatives (RWS, 2023). Some contracting authorities are trying more flexible, outcome-based procurement approaches, for example, asking bidders for a plan to deliver a "circular, demountable bridge" rather than a fixed design (RWS, 2023). However, not all agencies have adjusted their procurement frameworks to this new approach. Aligning multiple public bodies (municipalities, provinces, Rijkswaterstaat, etc.) on a common procurement strategy takes time. In fact, the need for better coordination led to the creation of a "Market Vision and Procurement Strategy for Circular Viaducts and Bridges", a guide developed jointly by government clients and industry on how to gradually change procurement towards circular (and by extension, IFD) solutions (Platform Bruggen, 2024).

In summary, the issue can be framed as follows: *How can the Dutch bridge infrastructure sector transition from isolated uses of IFD to a mainstream, standardised practice?* The central hypothesis is that the use of unified standards (NTA) and more industry collaboration is needed to overcome these barriers. If all stakeholders, public clients, designers, contractors, and suppliers work from a common playbook (technically via standards like NTA, and procedurally via aligned procurement and policies), the transition to IFD could accelerate greatly. Conversely, if each party continues to "do its own thing", the benefits of IFD will be diluted. Therefore, a coordinated effort is required to move from pilots to mass implementation. The research will investigate barriers to this transition, what is needed to achieve such unification and how to address the concerns of more reluctant actors.

1.3 Research questions

The central research question guiding the study is:

> *'How can the adoption of unified standards among supply chain actors in the Dutch bridge construction industry be promoted to facilitate the transition to standardised IFD practices?'*

In this study, adoption of the NTA refers to public clients consistently specifying NTA 8085/8086/8089 as requirements in bridge projects, suppliers offering NTA-conform and interoperable components, and designers and contractors engineering, assembling, maintaining, and deconstructing using NTA interfaces and IFD methods.

To answer the main research question (MRQ), three sub-questions have been formulated. The first sub-question (SQ) explores the concept of IFD construction within the Dutch bridge construction industry, and examines how its underlying principles and standards affect the current bridge construction supply chain.

SQ1: What is IFD, and what do its core principles imply for the current bridge construction supply chain?

Following, SQ2 evaluates case studies of IFD and NTA implementation, to identify key barriers to adoption as well as insights and lessons learned from real-world applications.

SQ 2: What lessons can we learn from IFD and NTA implementation in practice?

The final SQ focuses on barriers and interventions, aiming to identify what hinders and what supports the adoption of IFD and the NTA.

SQ 3: What are barriers and interventions to the IFD transition and the adoption of the NTA?

1.4 General research design

To conclude chapter 1, this section outlines the overall research design, the structure of the thesis and in which chapters the RQs are answered. Figure 3 illustrates how the RQs fit within the thesis.

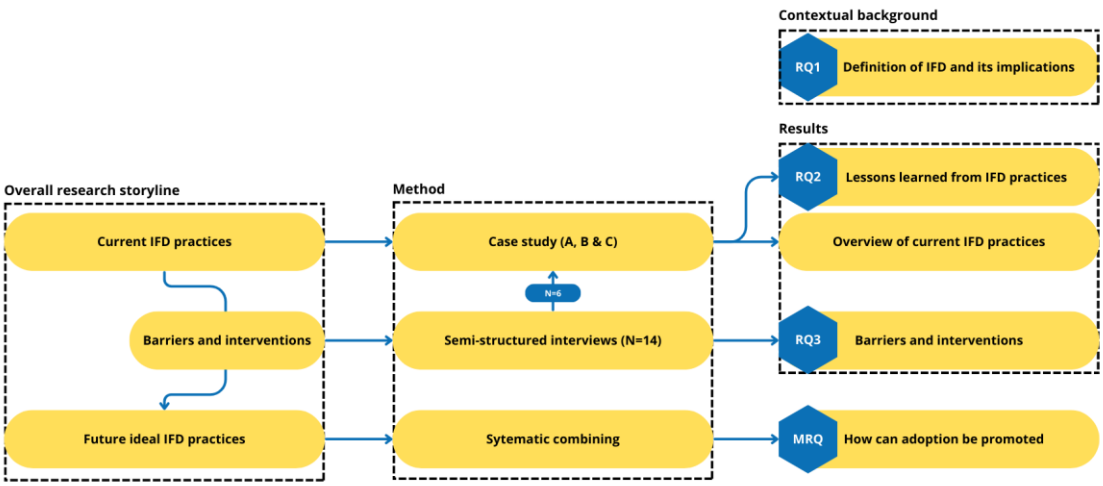


Figure 3: Simplified outline of the RQ's within the overall thesis

This thesis applies an exploratory, qualitative research design using an abductive, systematic combining approach by Dubois & Gadde (2002). Empirical work combines a multiple-case study of three bridge projects (Cruquius, N240b, Stolperbrug) with 14 semi-structured interviews across the supply chain. Case studies use an evaluation matrix to assess industrialisation, flexibility, demountability, and NTA alignment. Analysis proceeds within case and then across cases, integrating insights from the additional interviews. Figure 4 shows the research flow (activities, inputs, analysis, outputs).

	Sub-question 1	Sub-question 2	Sub-question 3
Activity	Literature review and document study.	Case study (N=3) research of IFD projects.	Semi-structured Interviews (N=14) with supply chain.
Input	Academic articles & grey literature: industry reports, standards, policy documents.	Interview transcripts, project data, workshop notes, industry reports.	Interview transcripts.
Analysis	Compare definitions and identify key concepts.	Thematic coding, cross-case comparison application of evaluation framework	Thematic coding.
Output	Definition IFD & its implications	Assessment of current IFD practices and lessons learned.	Barriers & intervention to the transition.

Figure 4: Research approach to the SQs, adapted illustration (Brouwer, 2024)

- SQ1 is addressed through a literature and document review that explores IFD concepts and their implications for the bridge construction supply chain. This forms the conceptual context of IFD (Chapter 2).
- SQ2 (Chapter 4) examines case studies of IFD and NTA implementation, identifying key findings and lessons from practice and also giving the reader and overview of the current status of IFD practices.
- SQ3 (Chapter 5) is informed primarily additional interviews (cross case interviews) with stakeholders across the supply chain, both those already engaged in IFD projects and those exploring solutions to the V&R challenge. Together, the case study and interviews are used to identify strategies to promote the adoption of IFD and the NTA.

The structure of the thesis is presented in Table 1.

Table 1: General thesis outline

Type	Chapter
Research introduction and context	Chapter 1 Introduction *Supporting Appendix D*
Conceptual background and methodology	Chapter 2 Conceptual background (SQ1) Chapter 3 Methodology *Supporting Appendices A - F*
Empirical data results	Chapter 4 Results case analysis (SQ3) Chapter 5 Results cross-case analyses (SQ4) *Supporting Appendix C*
Research interpretation	Chapter 6 Discussion
Concluding answers & implications	Chapter 7 Conclusion (MRQ; actionable recommendations)

Chapter 2 - Conceptual Background

This chapter provides the conceptual background by first defining IFD and explaining its core principles. It subsequently explores how IFD relates to or diverges from other construction and design strategies, and concludes by discussing how IFD challenges and reshapes traditional business-as-usual practices in the sector.

Additional historical context and the current status of the IFD transition in Dutch bridge construction, particularly the development of IFD standards NTA, are provided in Appendix D.

2.1 Definition IFD

IFD is a construction approach which can be related to theory on IC and CC. Currently, in the Dutch context it is primarily applied to civil structures, mainly bridges. The term 'currently' is used because the approach has its origins in building construction, as explained in Appendix D on the history of IFD.

In short, IFD bridge construction means applying industrial production methods with flexibility and disassembly in mind. It involves prefabricated modules assembled via standard interfaces, allowing components to be swapped or removed without damaging the structure. This approach aims to streamline construction and maintenance (through industrialisation), accommodate future changes in use or requirements (through flexibility), and facilitate end-of-life deconstruction for reuse (through demountability) (NEN, 2020a; 2020b; 2024b). The following section details each of these three core principles of IFD and how they are implemented, additionally focusing on the critical role of standardisation.

2.1.1 Core principles

The IFD approach is founded on three primary principles, each corresponding to a component of the acronym. While each principle addresses a distinct aspect of design, they are closely interrelated, with certain principles enabling or reinforcing others. In addition to explaining these principles, this section also highlights the foundational role of standardisation in enabling the effective application of the IFD approach.

Industrial

Industrialisation emphasises prefabrication and serial production (repeatability), meaning that as many parts as possible are built in a controlled factory setting and then brought to the site for assembly (NEN, 2020a; 2020b, 2024b). An enabling factor of the industrial principle is standardisation, and in the context of IFD within the Netherlands, this can be tied to the NTAs. As the initiators of IFD recognised early on that *“standardisation would be necessary to enable an industrial production process”* (GWWTotaal, 2023).

Flexible

Flexibility in infrastructure design refers to a system’s capacity to adapt or evolve as needs change over time (Rahla et al., 2021; GWWTotaal, 2023; NEN, 2020a). Within the context of IFD, the NTA defines flexibility through two interrelated dimensions: modifiability and scalability (NEN, 2020a; 2020b, 2024b). In broader academic literature, this is often described as adaptability.

Flexibility ensures that an IFD bridge is not a fixed, one-time solution, but a structure that can evolve throughout its service life. This includes being able to adjust, expand, or reconfigure the bridge when required. Importantly, flexibility depends on demountability, as components must be easy to remove, replace, or reassemble to enable such changes.

Thus, adaptability in the context of IFD is modifiability (also referred to as upgradeability, changeability or interchangeability), which allows for the modification or upgrading of parts of the structure throughout its lifespan (NEN, 2020a; 2020b, 2024b). This could include replacing outdated elements, integrating new technologies, or adapting the bridge to meet changing functional requirements without needing to rebuild the entire structure.

Complementing this is scalability, which refers to the ability to adjust the size or capacity of the structure such as by adding or removing spans in response to future demands, also see Figure 5 (NEN, 2020a; 2020b, 2024b). This supports infrastructure that can expand or contract based on context-specific needs, aiming to make it more efficient and future-proof.

Together, these features allow for:

- Spatial reconfiguration (e.g., adding/removing spans),
- Functional conversion (e.g., changing traffic type or capacity),
- Future-use scenarios (e.g., upgrading with new systems or design standards).

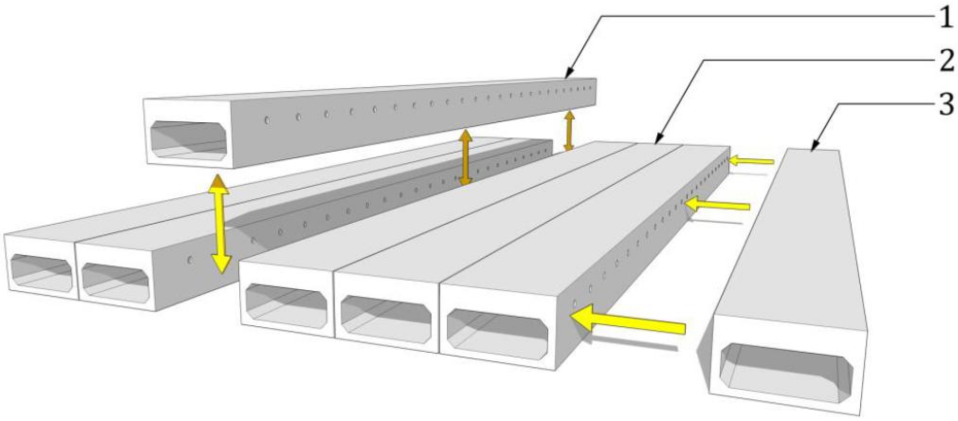


Figure 5: Adaptable design of modular girders (NEN, 2020b)

Demountable

Demountable focuses on a design for disassembly (NEN, 2020a; 2020b, 2024b). This principle facilitates the reuse of structural elements by creating a demountable structure. *"Demountability is extremely important. High-grade reuse is one of the circular strategies being targeted in the sector… That is possible if each component is detachable,"* notes one industry publication, stressing the importance of this principle (GWWTotaal, 2023). Equally as mentioned under the previous principle, demountability enables certain aspects of flexibility and therefore an important aspect to IFD construction.

Deconstruction ties directly into sustainability by supporting a circular use of materials. If a bridge is no longer needed at a location, it could be disassembled and its modules reused elsewhere, rather than demolished into waste. Even if the entire bridge isn't relocated, components can be recovered for high-quality reuse in new structures, thus extending their life and reducing demand for new raw materials.

Standardisation

Central to all three principles is standardisation, which is the cornerstone that enables industrial production flexibility in use and demountability. Its importance cannot be overstated, as it underpins many of the key elements in an industrialisation strategy (Larsson et al., 2013; Ortega et al., 2023). As Larsson et al. (2013) note, standardisation facilitates the implementation of practices such as prefabrication, experience feedback and continuous improvement of products and processes. A critical aspect of this is the development of standardised interfaces between modules, which ensures the interchangeability of component variants and supports modular design (Larsson et al., 2013).

While IFD in the Dutch context is primarily associated with the NTA framework, it is important to note that standardisation within IFD is not confined to these agreements. Alternative forms of standardisation can be developed and adopted, such as company-specific standards or sector-wide protocols. These can serve similar purposes by ensuring compatibility, repeatability, and efficiency across different projects and stakeholders.

For IFD construction, three Dutch Technical Agreements (NTAs) have been established by the Royal Netherlands Standardisation Institute (NEN), which is the Dutch national standardisation body. The three agreements are NTA 8085 for fixed bridges and overpasses, NTA 8086 for movable bridges, and NTA 8089 for the IA&E (Instrumentation, Automation & Electrical) systems of movable bridges. These agreements focus on the standardisation of component interfaces and dimensions (GWWTotaal, 2023; ipv Delft, 2024).

As long as the interface is consistent, the internal design of components can be modified or improved over time. Designers, manufacturers, and builders retain the freedom to optimise the shape, materials, and internal structure of components, provided that the connection points and dimensions comply with the defined standards (ipv Delft, 2024). This is to preserve room for innovation and project-specific requirements while ensuring system-wide compatibility. The NTAs deliberately avoid prescribing specific materials or architectural forms; a bridge may be made of steel, concrete, or composite, and be arch- or beam-shaped as long as the interface requirements are respected (GWWTotaal, 2023; NEN, 2020).

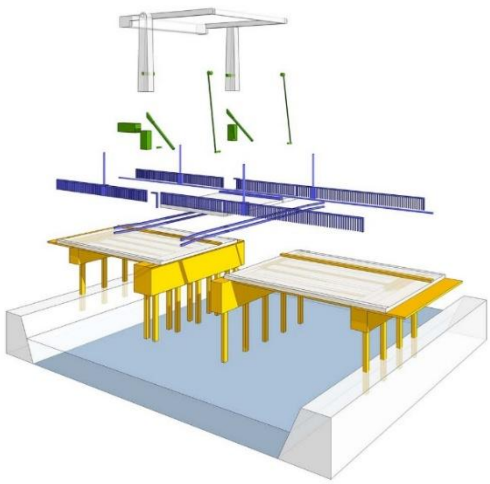


Figure 6: Illustrates the concept of a modular bridge with standardised interface connections, where each major component can be factory-made, swapped or removed independently. (IPV Delft, 2024)

2.1.2 Overlapping concepts and strategies

The principles of IFD share strong similarities with several established construction concepts. To better understand IFD, this section examines several related concepts and design strategies. While IFD encapsulates key elements of modularity, CC, and design for adaptability, it does not always fully encompass these strategies in their entirety (see Figure 7). This section analyses how IFD aligns with, or diverges from, key related concepts, namely: 1) Circular Construction, 2) Modular Construction, 3) Design for Quality & Maintenance, 4) Design for Adaptability, 5) Design for Disassembly & Reusability, 6) Design for Manufacturing & Assembly (DfMA), 7) Design for Disassembly & Adaptability (DfDA), and 8) Series-based construction. Clear comparisons are drawn for each, focusing on overlaps and differences in light of IFD's three pillars. A concluding summary highlights how each concept fits within or outside the IFD framework.

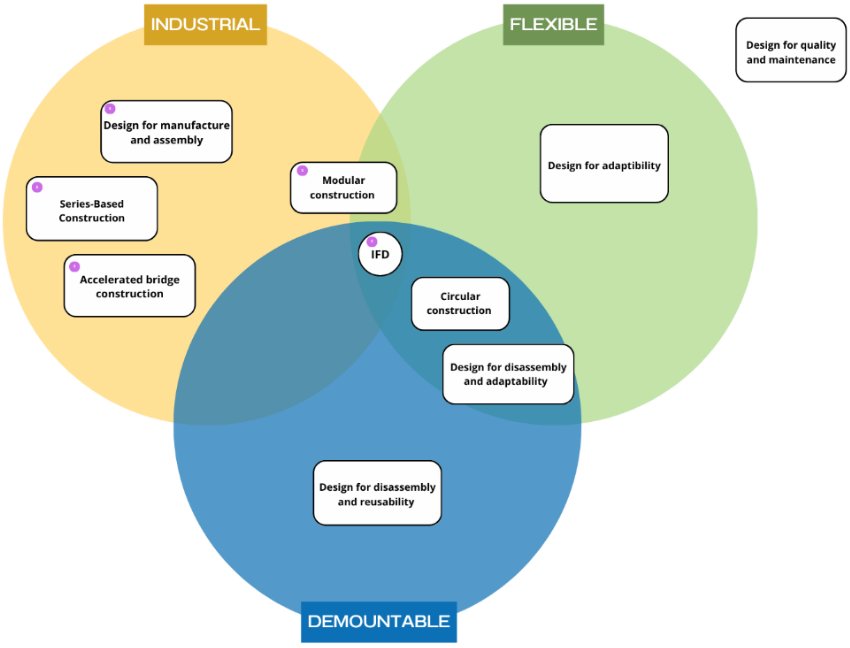


Figure 7: Venn diagram of concept and design strategies overlapping with the IFD principles. The purple circle indicates that standardisation is foundational for these strategies.

Circular construction

CC in infrastructure emphasises closed resource loops, extended service life, component reuse, and waste minimisation (Coenen et al., 2021; Platform CB'23, 2023). In practice, CC entails design strategies such as extending a structure's lifespan, increasing its adaptive capacity, and applying the "R-principles" (e.g. Reuse, Recycle) (Platform CB'23, 2023).

This overlaps with IFD's flexible and demountable principle. For example, designing for deconstruction and adaptability, means creating infrastructure *"from the outset to allow future changes and the deconstruction of components… including provisions for reuse and recycling"*(Bertino et al., 2021). The distinction lies in scope CC is a broad paradigm focused on environmental outcomes, whereas IFD also explicitly includes industrialised production. Still, one could argue that industrialisation contributes to circularity by reducing waste, aligning with the R-principle of Reduce.

Modular construction

Both IFD and modular construction rely on prefabricated, standardised components assembled on-site, but IFD places additional emphasis on long-term flexibility and disassembly. The key difference is that modular construction is often driven by efficiency and repeatability in construction, whereas IFD extends modularity to include interchangeability of parts and future disassembly. In other words, IFD can be seen as "modular construction for reuse", ensuring that modules are not only easy to assemble but also easy to take apart intact. Traditional modular bridges (e.g. many accelerated bridge construction projects) may use bolted or segmental elements for speed, but they are not always intended to be moved or reconfigured after installation (Aurier et al., 2023). Thus, IFD aligns with modular construction in prefabrication and rapid assembly, while adding a lifecycle perspective.

Design for quality & maintenance

DfQM focuses on extending a structure's lifespan and reducing ongoing maintenance requirements. By carefully selecting materials, well-considered detailing, and creating accessible components for inspections, this strategy reduces environmental impact by preventing premature repairs or replacements (Platform CB'23, 2023). Because it does not inherently involve demountability, flexibility, or industrialisation, this strategy does not overlap with IFD in the Venn diagram (Figure 7).

Nonetheless, IFD construction aligns with DfQM in several ways. Industrialised fabrication improves precision and consistency, reducing errors and the risk of early repairs (Ortega et al., 2023). Demountability further enables easier maintenance and replacement of deteriorated parts, linking directly to "design for maintainability," a key strategy for lowering lifecycle costs (Coenen et al., 2021). Finally, IFD's flexibility principle supports interchangeability, ensuring components can be upgraded or replaced efficiently over a bridge's lifespan.

Design for adaptability

Design for adaptability seeks to allow a structure to accommodate shifting functional needs over time (Platform CB'23, 2023). In bridge infrastructure, this means planning a structure so it can accommodate changing requirements over time (e.g. increased traffic loads, new functional demands, or repurposing) without full replacement. The parallel with IFD lies in the "Flexible" principle, as done in the section 2.1.1.

Design for disassembly & reusability

Design for disassembly and reusability specifically aims to create structures from elements that can be taken apart and reused elsewhere (Platform CB'23, 2023). This is identical to the demountable and flexibility principle of IFD. Nevertheless, demountable designs are not always industrially produced or standardised for multiple projects, meaning they might lack the "Industrial" features at the core of IFD.

Design for manufacturing and assembly

DfMA focuses on optimising designs for efficient off-site manufacturing with high productivity, and on-site assembly with minimal effort, cost, and error (Antoniou & Marinelli, 2020). IFD overlaps strongly with this strategy through its industrialisation principle, treating bridges less as bespoke projects and more as manufactured products by leveraging standardisation.

The key distinction is that DfMA alone does not guarantee future adaptability. While one could argue that design for assembly implies easier disassembly, this is not necessarily the case: a bridge may be designed for rapid assembly without any intention of dismantling it later. IFD explicitly extends DfMA by requiring both flexibility and disassembly, ensuring that structures are not only efficient to build but also adaptable and reusable.

Design for disassembly & adaptability

DfDA combines the previous strategies, aiming for structures that can both adjust to new requirements and be fully dismantled (Platform CB'23, 2023). This integrated approach is essentially the philosophy behind IFD. Instead of treating adaptability and disassembly as separate considerations, IFD treats them as intertwined: flexible design makes disassembly easier, and demountable design increases adaptability. The only distinction is that DfDA as a general concept doesn't mandate prefabrication or series production (industrialisation) it speaks to the design's characteristics, not how components are made. IFD goes a step further by insisting on an industrial production model to economically realize those characteristics at scale.

Series-based construction

Series-based construction, or '*seriematig werken'* in Dutch, refers to executing projects in a programmatic, repetitive manner to exploit standardisation and learning effects. Somewhat similar to design for manufacturing and assembly. This approach is highly compatible with IFD, and potentially necessary to fully realize IFD's benefits. Research on industrialised bridge construction finds that a "lack of repetition possibilities" has been a major barrier in traditional procurement of bridges (Larsson et al., 2013). IFD addresses this by providing standardisation that can be used across many bridges, thus encouraging clients to bundle bridge projects or adopt common designs. In a series-based paradigm, multiple bridges (for example, a region's worth of similar overpasses) would be designed using the same IFD modular kit (unified standard), manufactured in batches, and could perhaps be constructed in a continuous pipeline.

The analysis of overlapping concepts shows that IFD does not exist in isolation but integrates and extends several established construction strategies. CC, modularity, adaptability, and disassembly all align closely with IFD's principles of flexibility and demountability, while DfMA and series-based construction connect strongly to its industrialisation pillar. Other strategies, such as DfQM, only partially overlap. Ultimately, IFD can be understood as a synthesis of these approaches; it combines the environmental ambitions of circular construction, the efficiency of modular and DfMA methods, and the adaptability of disassembly-focused strategies, while uniquely embedding industrialisation and thus standardisation as a structural requirement.

2.2 Reshaping business-as-usual

Traditional "business-as-usual" (BAU) practices in bridge infrastructure have typically been linear and fragmented, with bespoke designs constructed on-site and eventually demolished at the end of their life, giving limited consideration to reuse, flexibility, or repetition. In contrast, IC and CC have emerged as transformative paradigms that challenge this status quo, offering systemic changes in how bridges are designed, procured, built, and managed across their life cycle. Because academic work on IFD is limited, we use IC and CC as the primary lenses to show how IFD reshapes BAU.

As discussed in Ch. 2.1.2, IFD can be understood as a combination of overlapping strategies. This section examines thus how IC and CC individually contribute to modernising bridge construction and how their principles are applied in IFD practice. Also looking into the role of standardisation and highlighting similarities of the IFD transition with other theories.

2.2.1 Industrialised construction

IC has been firmly established in the housing sector for several decades and has seen successful adoption across numerous countries. In contrast, the transition toward industrialisation in infrastructure construction, particularly in civil works such as bridges, has progressed much more slowly (Larsson et al., 2013). Despite this lag, valuable lessons can be drawn from the housing sector to understand how IC reshapes BAU practices in infrastructure construction.

At its core, IC can be viewed as a systematic approach to construction, wherein every phase from design to on-site assembly is carried out much like a manufacturing operation (Lessing, 2015). This paradigm significantly diverges from traditional construction practices, which typically regard each project as a unique, one-off endeavour involving fragmented stakeholders and temporary project teams

(Hall et al., 2021). Instead, IC relies on repeatable processes and standardised components, continually refined through feedback loops and continuous improvement (Meiling et al., 2012; Lessing, 2015; Costa et al., 2022). Kauppinen et al. (2024) further emphasise the minimisation of project-specific work throughout a building's life cycle, illustrating how the adoption of manufacturing-inspired methods can reduce rework, variability, and inefficiencies.

Although off-site manufacture and prefabrication are among the most visible features of IC, they represent only a fraction of the overall shift. As Hall et al. (2021) argue, IC goes beyond production alone and is a far more holistic and encompassing approach. In the Dutch context, similar themes are echoed in the grey literature on IFD construction, where the industrial principle is defined not only by prefabrication but by the systemic application of manufacturing logic to infrastructure development (EIB, 2023; NEN, 2024b).

Two recent systematic reviews, one by Costa et al. (2022) and another by Kauppinen et al. (2024), stress that IC constitutes a holistic transformation of how construction businesses operate. This theoretical orientation treats construction as a "new form of production and management" comprising multiple innovations (technical, organisational, and managerial) aimed at improving productivity and sustainability (Costa et al., 2022). In practical terms, this includes adopting standardised design solutions, technical systems, and process optimisation. This translates to organisational restructuring, business process redesign, supply chain planning, and resource redefinition (see Figure 8).

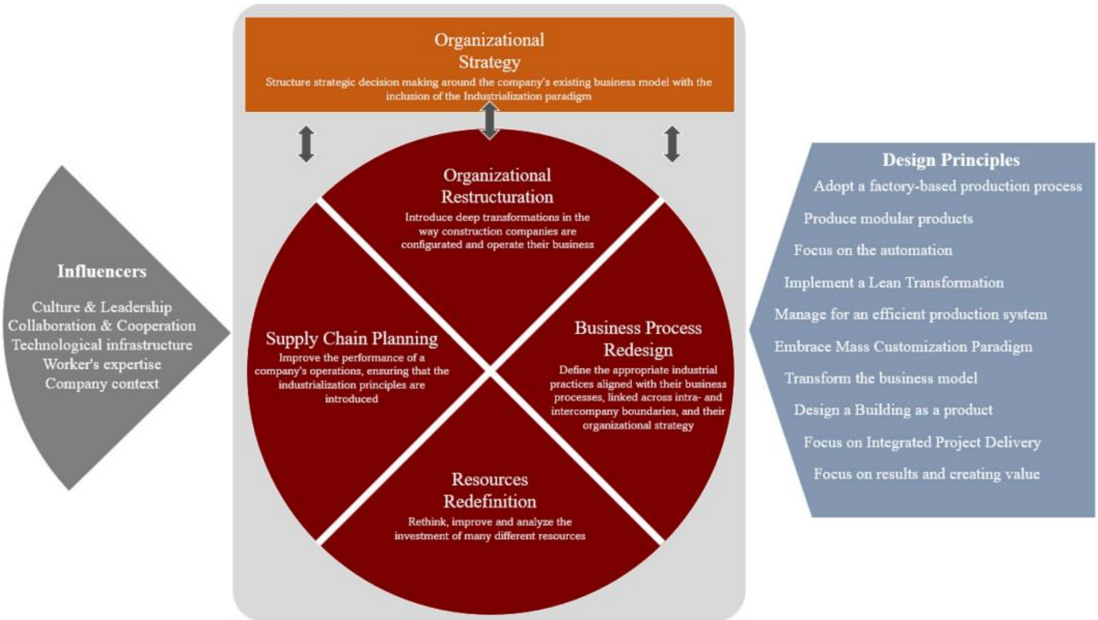


Figure 8: IC framework (Costa et al., 2022)

Although Costa et al.'s (2022) framework was developed with reference to the building sector, it is presented as an industry-wide conceptualisation of construction industrialisation. Unlike housing-based models such as Lessing's (2015) IHB, which Brouwer (2024) needed to adapt for infrastructure, Costa's focus on organisational transformation and supply chain integration makes it more readily transferable. Nevertheless, its application to infrastructure still requires contextualisation, since bridges and civil works involve different scales, stakeholder arrangements, and life-cycle demands than buildings.

In practice, these changes entail the following: organisational restructuring, as companies adopt new models to integrate design, production, and assembly processes, moving away from conventional siloed or hierarchical setups. In infrastructure, this often means breaking down the separation between engineering consultants, fabricators, and contractors to enable joint design-for-manufacture sessions at an early stage. Such transformations necessitate closer (vertical) collaboration between engineers, fabricators, and contractors during design development. Traditional sequential workflows give way to integrated teams where buildability and modularisation are decided upfront. Van Gassel et al. (2003), reflecting on an IFD pilot building, observed that "*IFD building requires co-operation and a multidisciplinary approach during the design process*," including carefully choosing design tools and organising design meetings with all stakeholders. These points are similarly illustrated in Case A Cruquius Bridge (see Appendix C), where a collaborative contract enabled expert alignment and co-design sessions.

Business process redesign replaces traditional sequential workflows with integrated and standardised procedures; for bridges, this can involve embedding modularisation and buildability decisions into digital design environments from the outset. Resource redefinition shifts the emphasis from on-site craft labour to capital-intensive prefabrication facilities, where heavy structural components such as steel or precast bridge elements are produced under controlled conditions. Finally, supply chain transformation requires early stakeholder integration, just-in-time logistics, and collaborative planning to ensure that large prefabricated elements can be transported, lifted, and assembled efficiently in highly constrained civil environments (Costa et al., 2022).

A key distinction between BAU and industrialised approaches is how learning is handled across projects. While traditional construction may generate valuable insights, these often remain tacit and are rarely formalised or systematically reintegrated (Negara et al., 2021). In contrast, Lessing's (2015) Industrialised House-Building (IHB) framework illustrates how feedback from completed projects can be actively captured and fed back into a broader system (technical and process platform) for continuous development (see Figure 9).

Over time, this enables the creation of robust, stable platforms for repeatable production. Such platform-based development is essential, encompassing both technical platforms, consisting of common modules or components applied across projects, and process platforms, which standardise workflows and data flows to support efficient delivery (Lessing, 2015). Essentially, this shift moves BAU from a project-oriented industry to a bridge product industry.

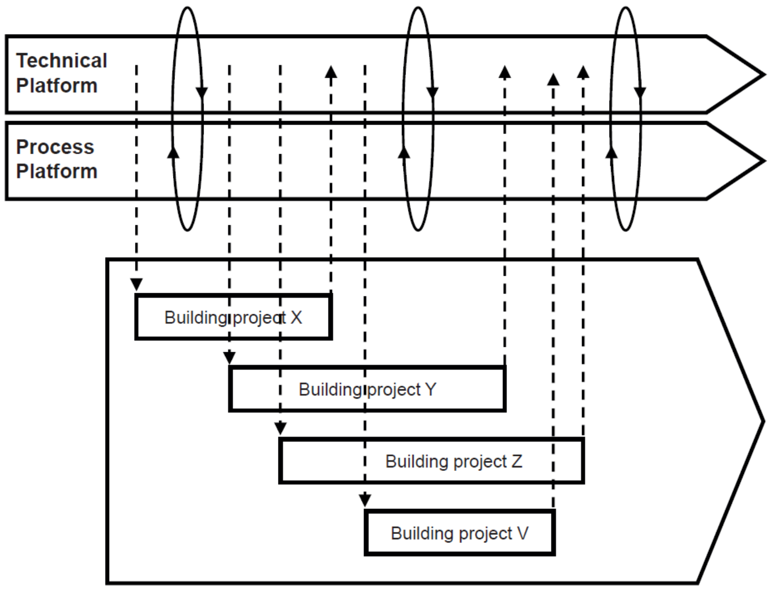


Figure 9: Development of standardised technical and process platforms supported by structured information flows (Lessing, 2015).

Continuous improvement is also explicitly embedded within the IHB framework as one of its nine interrelated constructs (see Figure 10). This inclusion signals a deliberate shift away from isolated, one-off projects toward a model where feedback from practice is systematically captured, analysed, and used to improve the technical and process platforms. In doing so, the framework transforms construction from a reactive activity into a proactive, evolving system (Lessing, 2015).

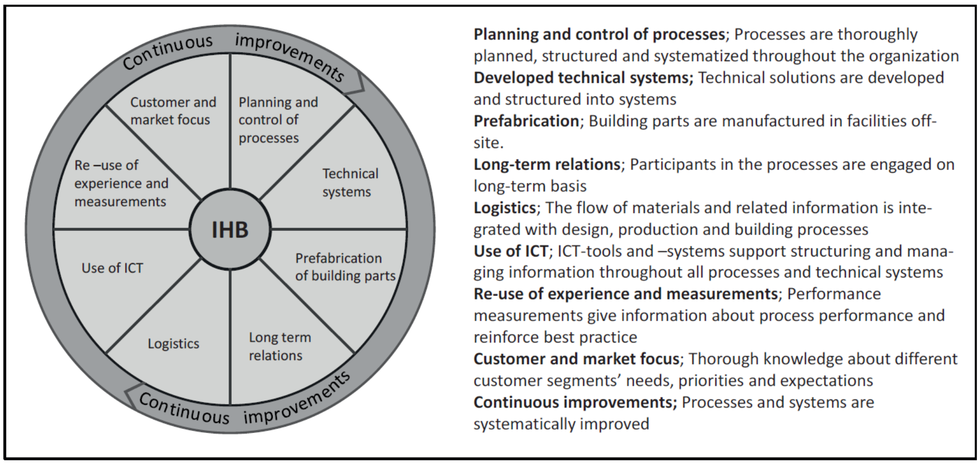


Figure 10: IHB Framework (Lessing, 2015)

Building on this foundation, Brouwer (2024) adapted the IHB framework for infrastructure through the proposed IIC framework. This version identifies two infrastructure-specific constructs: continuity and repetition of demand, and standardisation and norms. These constructs are seen as essential for shifting from unpredictable, project-based delivery toward programmatic, industrialised approaches. Continuity provides the predictability (removal of uncertainty) needed for supply chain partners to invest in prefabrication and automation. Similarly, this continuity of demand is achieved through standardisation.

In the context of IFD, these constructs are not optional; they are prerequisites. The IIC framework stresses that only through repeatable demand and shared standards can industrial actors develop interoperable, scalable, and demountable product platforms. This marks a significant departure from BAU, which remains dominated by a project-oriented industry characterised by fragmentation and uniqueness.

2.2.2 Flexibility and demountability

Implementing CC principles in bridge projects likewise demands profound changes to current practice, complementing the industrialised shifts. CC is closely tied to the principles of flexibility and demountability, which, as identified in the previous section, align closely with the DfDA strategy (see Ch. 2.1.2). Arguably, the first principle of industrialisation also promotes CC due to the reduction of waste linked to factory manufacturing. However, because IC is widely covered in the section above, this part will only highlight the remaining principles.

At the core of flexibility lies the assumption that future circumstances will change (Saari & Heikkila, 2008). Flexibility in design thus attempts to anticipate this change, whether in usage, function, regulations, or environmental conditions. In IFD, flexibility is somewhat enabled by demountability, and together they support adaptability (modifying existing elements) and interchangeability (swapping elements for others). These represent high levels of circularity on the R-ladder, specifically the strategies of "refuse" and "rethink." This goes directly against the grain of BAU, where a bridge is designed to be fixed (static design) during its lifespan.

However, designing for flexibility inherently involves a significant degree of uncertainty. The further one tries to anticipate needs or changes in the future, the less predictable the context becomes. As shown in Figure 11 (Saari & Heikkilä, 2008), types of flexibility become increasingly uncertain over longer time horizons. This is relevant not just in general construction, but equally in bridge infrastructure, where service lives often exceed 50 to 100 years. Attempting to pre-empt future loads, transport modalities, or design codes involves speculation, making adaptability a technically noble, but economically complex ambition.

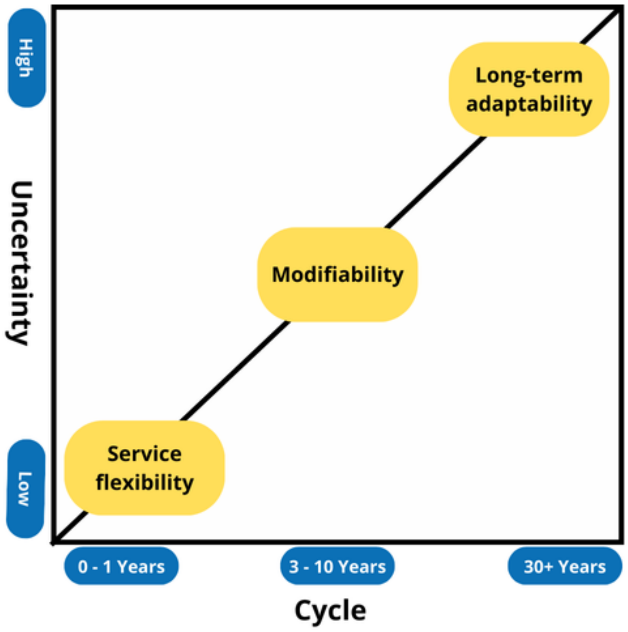


Figure 11: Flexibility becoming more uncertain as the year cycle increases, adapted based on Saari & Heikkila (2008)

A practical example of this dynamic is visible in the Netherlands. Girders from a viaduct on highway A9, originally built in 1968, are currently being reused. While the viaduct's functional life has come to an end due to increased traffic intensity and evolving infrastructure demands, the girders themselves still possess several decades of remaining technical life (TU Delft, 2025). This demonstrates both the longevity of structural components and the difficulty in predicting when and how they may become reusable. The recovery of the girders required additional effort, as the viaduct had not been designed for disassembly. If IFD principles had been applied at the time, features facilitating easier deconstruction may have been incorporated into the original design.

In this context, flexibility and demountability require a shift in the traditional project mindset. Engineers and asset owners must now consider not only how to build or assemble bridges but also how to disassemble or repurpose them decades later. End-of-life is no longer an afterthought managed by demolition teams; it becomes part of the initial vision. This may involve producing detailed disassembly plans during the design phase and integrating tools like material passports or digital tags, which document the material properties and facilitate future reuse assessments (Nationalebruggenbank, 2022). Thus, the scope of design broadens from cradle-to-grave to cradle-to-cradle.

Moreover, designing for modifiability implies an awareness of component lifespans. Short-life elements should not be inseparably integrated with long-life ones. IFD principles discourage this encapsulation and encourage layered design, where elements can be upgraded or replaced independently (Shoorl, 2023).

Another challenge lies in the economic evaluation of infrastructure projects. Designing for reuse or enabling careful disassembly often requires higher upfront costs, which can deter adoption when assessed through conventional cost-benefit analyses (Mlote et al., 2024; Ostapska et al., 2024). This highlights the need for new economic models that factor in life-cycle savings, long-term value retention, and environmental benefits. One way to support this shift is through circular procurement criteria. Clients can, for example, require a minimum percentage of recycled or reused materials, or assign additional value to bids that include plans for end-of-life reuse. Such an approach was applied in the tendering process for the Cruquius Bridge, where circularity was explicitly incorporated into the evaluation through weighted criteria (see Appendix C).

In parallel, policy developments in the Netherlands aim to make these sustainability considerations more formal and enforceable (RWS, 2025). There is growing momentum to include shadow costs of carbon and environmental externalities in infrastructure appraisals, making the long-term benefits of circular strategies more visible and economically competitive. These externalities are quantified through methodologies such as Life Cycle Assessment (LCA) and Environmental Cost Indicator (ECI) in the Netherlands also known as Milieu Kosten Indicator (MKI).

To stimulate adoption, public clients and policymakers are beginning to intervene. The Dutch Ministry of Infrastructure and Water Management has announced its intent to legally mandate the use of MKI in public procurement (RWS, 2025). From 2027 onward, public clients will be required to firstly include minimum environmental performance thresholds (expressed in MKI) for certain materials and for large infrastructure projects, use MKI as a formal award criterion within BPKV tendering procedures (RWS, 2025).

On the construction side, circularity demands a shift in how old structures are retired. Instead of sending crews to demolish a bridge, teams must practice deconstruction, carefully dismantling structures to preserve components. This would mean investing more time and labour at end-of-life, essentially performing construction in reverse. Contractors need to develop these capabilities and adjust their mindsets, as the goal is no longer speed at any cost, but maximisation of salvage.

Another aspect is what happens after retirement, thus the supply chain and logistics for reuse, as CC practice creates a new supply chain which loops bridge elements flowing back from old projects into new ones. This requires infrastructure such as component banks or marketplaces (e.g. the National Bridge Bank in the Netherlands) to connect those who have usable components with those who need them (Nationalebruggenbank, 2022). In practical terms, owners (or third parties) may establish storage yards to stockpile retired bridge parts. Inspection and certification protocols must be in place, as every retrieved element beam needs assessment to certify it for safe reuse.

Thus, new industry roles could emerge, for instance, a company which specialises in refurbishing and repurposing old structural components. Project planners would then consider reused materials during design. For example, if a set of standardised beams is available from the Bridge Bank, a new bridge might be designed to dimensions that fit those beams, rather than ordering new ones. This is a reversal of traditional supply thinking and requires a new mindset, which includes flexibility and communication between projects. The key shift is that the construction lifecycle extends beyond a single project, demanding coordination across multiple projects and timeframes.

In essence, CC calls for reimagining the life-cycle responsibility in bridge projects. No longer can stakeholders hand off a finished bridge and forget about it, but the end-of-life stage becomes part of the initial project vision. This whole-life thinking, backed by new practices in design, deconstruction, and reuse logistics, represents a fundamental broadening of what it means to build responsibly. Notably, the Netherlands is actively pursuing these circular construction methods, gradually shifting away from traditional business-as-usual practices.

2.2.3 Unified standard (NTA)

Standardisation has long underpinned many aspects of construction, from uniform design loads and safety factors to common contract forms and tendering procedures, some mandated by law, others adopted as best practice. Building codes (e.g., Eurocodes), material specifications, and procurement frameworks (such as UAV and UAV-GC in the Netherlands) are all forms of standardisation that promote baseline consistency, safety, and quality across projects (Chao-Duivis et al., 2013; Eurocodes, 2025).

However, in BAU bridge construction, even when national codes and regulations are consistently applied, each bridge remains a largely bespoke endeavour with unique geometries, detailing, and components tailored to the specific project context. As quoted by a bridge design firm, "*the hundreds of movable bridges in the Netherlands are almost all different in appearance and detailing*" (ipvDelft, 2023).

The NTA series developed for IFD represents a type of standardisation that explicitly targets the physical interfaces and dimensions of bridge components (NEN, 2024b). It serves as a strategic instrument to enable the benefits tied to IFD construction and standardising design, manufacturing and construction. As discussed in Ch. 2.1.1 and visualised in the Venn diagram, all IC strategies depend on standardisation, and the NTA embodies this principle in a form specifically tailored to the bridge sector. While Ch. 2.2.1 outlines many of the technical and production-related impacts, the focus here is on collaborative and organisational changes resulting from this unified approach.

By aligning stakeholders to a shared "playbook," the NTA reduces project-by-project variation and promotes consistency across the supply chain. Instead of defining new interfaces and specifications for each bridge, public clients prescribe NTA compliance as a contractual requirement. This means contractors must work with suppliers who can deliver NTA-compliant components, encouraging interoperability and a broader, more stable supply market.

For designers, this introduces a new working method; rather than inventing connection details for each project, they operate within predefined interface parameters. Design libraries can be reused and adapted, increasing efficiency while still allowing for site-specific adaptations.

For suppliers, standardisation tends to provide clarity and stability in demand (Larsson et al., 2013). Prefabricated elements can be produced in anticipation of future use, reducing lead times and enabling economies of scale. Components become more interchangeable, allowing stock parts to be deployed across different projects and clients.

Perhaps most significantly, the development of the NTA itself marks a cultural shift. Unlike traditional top-down regulations, the NTA was co-developed through supply chain collaboration (network level) involving public clients, engineering firms, contractors, and manufacturers (Bouwen met Staal, 2023; see also Appendix D).

2.2.4 IFD as a transition

According to the EIB (2023) the reported benefits of 15% reduced building costs and construction time, will only be seen if there is a broader industry adoption of the use of the NTA. But as described in the previous section there are many changes to the current bridge supply chain if they (the supply chain) were to transition to IFD and NTA use.

Similar to many other technological innovations, the implementation of IFD faces numerous hurdles that are not only technical but also institutional and cultural in nature, as it challenges the existing BAU practices. With such transformation inevitably come challenges and barriers.

A previous study by Brouwer (2024), which applied the Technological Innovation System (TIS) framework in a similar context, identified several systemic problems related to industrialisation and the Dutch V&R challenge (see Figure 12).

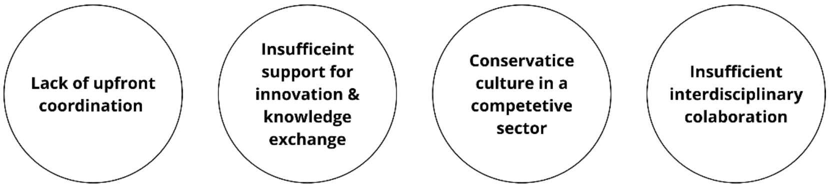


Figure 12: Systematic problems to transition to industrialisation in the Dutch Infrastructure construction (Brouwer, 2024)

Large-scale changes of this nature are often analysed through the lens of socio-technical transitions (STS), because they involve the co-evolution of technology, actors, institutions, and cultural practices. To make sense of such complex and dynamic processes, one can map the transition using the STS framework. For instance, the Multi-Level Perspective (MLP) provides powerful tools for understanding long-term transformation dynamics. It is particularly suited for analysing how new innovations develop within "niches" in this case, IFD and how they challenge dominant "regimes" such as BAU (Geels et al., 2002).

A characteristic of the infrastructure sectors including the Dutch construction industry is that they operate within a liberal market context (Sheffer, 2011). Consequently, much of the responsibility for innovation lies with the supply side, which is also expected to adopt new approaches such as IFD construction largely on its own initiative. Thus much is left to the supply side to innovate and thus also adopting IFD on their own accord. However, the Dutch market is highly fragmented, with numerous public organisations including municipalities, provinces, and national agencies each playing distinct roles. This fragmentation exists both horizontally, between different levels of government, and vertically, between public clients, contractors, and suppliers within the construction supply chain. Such a fragmented institutional and market structure makes it particularly challenging to for innovation diffusion (Sheffer, 2011).

To address the governance challenges inherent in such fragmented systems, adaptive or transition management approaches have been proposed. Bednar et al. (2018) offers a valuable finding on the importance of governance. Bednar (2018) recognises 4 distinct modes of governance: hierarchy, market, network, and community. Each of these arrangements implies a different distribution of authority, coordination mechanisms, and types of influence between actors. This distinction is particularly relevant for analysing the IFD transition, which based on both the interview findings and sector structure appears to operate primarily through market and network dynamics, though it also features elements of hierarchical governance in specific cases. For instance, although higher levels of government (e.g., provinces) may coordinate or fund infrastructure initiatives, their influence over local bridge design decisions especially when made at the municipal level is limited. While they may have formal power in areas such as zoning laws or regional mobility strategies, they cannot directly enforce the use of standardised approaches like the NTA or mandate IFD principles in local projects.

	Hierarchy	**Market**	**Network**	**Community**
Direction of Authority	top-down	circular (supply and demand)	horizontal	bottom-up
Initiating and Implementing Actors	federal, regional and local governments	government and market actors	government, private sector, and non-governmental experts	citizens, community groups, neighbourhood associations
Dominant Policy Instruments	legislation and regulation	supply and demand; government market intervention	negotiated agreements, codes of practice, voluntary programs	self-regulation, voluntary participation

Figure 13: Types of governance systems (Bednar et al., 2018)

To address this gap, it is essential to understand which governance structure is dominant in a given context, as this determines which intervention strategies are likely to be effective. Different systemic instruments such as regulations, financial incentives, or collaborative platforms vary in their impact depending on whether authority is centralised (hierarchical), distributed through voluntary cooperation (network), driven by market incentives, or embedded within shared community norms (Bednar et al., 2018). In contexts where hierarchical control is limited, soft governance instruments such as knowledge sharing, capacity building, co-design initiatives, and procurement support may be more appropriate and effective than traditional top-down regulation.

In parallel, applying an innovation diffusion framework such as the Technological Innovation System (TIS) (Wieczorek & Hekkert, 2012) provides a structured approach for identifying systemic problems that hinder innovation uptake and for linking these problems to targeted policy interventions (see Figure 14). The combination of governance analysis and innovation system thinking thus enables a more comprehensive understanding of how transitions such as the adoption of IFD can be effectively steered within complex, fragmented socio-technical systems.

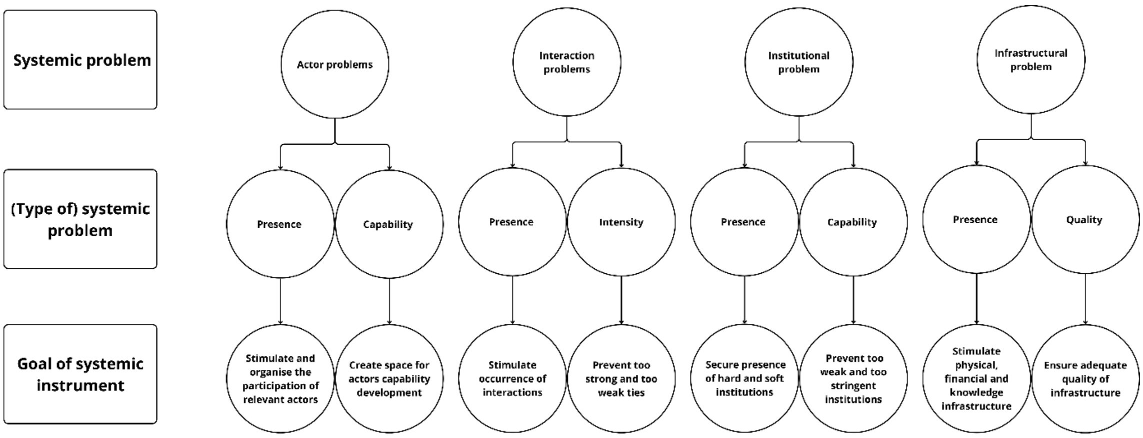


Figure 14: Own figure based on Wiezcorek en hekkert (2012) systemic problem, type of systemic problems and the goals that systemic instruments have in regard to these problems

Chapter 3 – Methodology

This chapter presents the qualitative and exploratory methodology used during this research. It first introduces the abductive research approach (systematic combining). Following, the multiple-case study design, including the creation of an IFD Evaluation Matrix, and additional interviews (referenced as cross-case analyses). Next, it explains the data collection procedures, followed by the analytic procedures. The chapter concludes with ethical considerations and the data management plan.

3.1 Abductive Research Approach: Systemic combining

The study follows an abductive, iterative research approach known as systematic combining, as described by Dubois and Gadde (2002, 2013), which is used for case research. This approach is well-suited for studying an evolving, complex phenomenon such as the IFD transition and aligns with the exploratory nature of the research. Rather than proceeding linearly from a fixed hypothesis, systematic combining emphasises continuous "matching" between theory and empirics, allowing the theoretical framework and empirical observations to develop together in a looping process (Dubois and Gadde, 2002). Figure 15 illustrates this, showing iterative feedback between the *empirical world*, *theory*, *analytical framework*, and *case studies* with added context of this research.

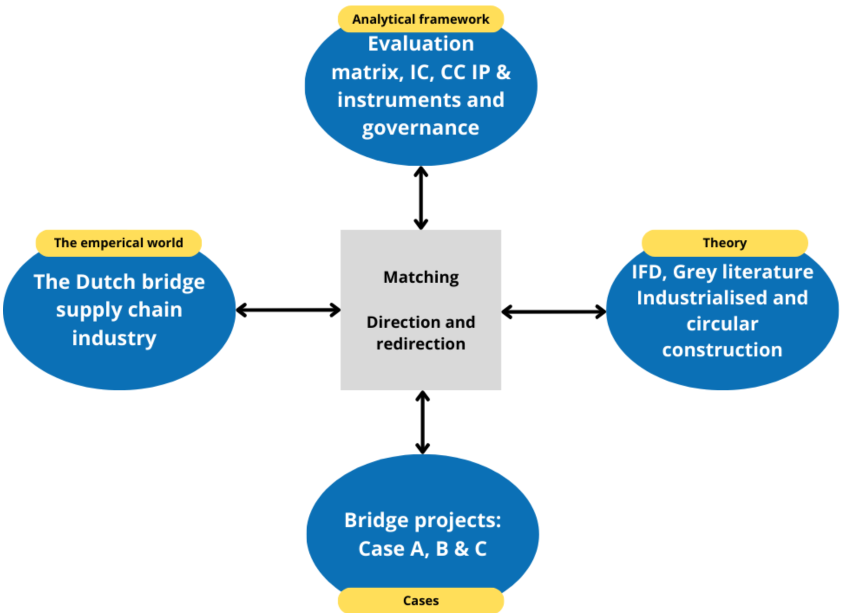


Figure 15: The Dubois–Gadde systematic combining cycle (adapted from their 2002 model), showing the iterative loops between "empirical world," "theory," "framework," and "case" in the context of this research

In practice, it means that the research design was not static; insights from data collection continually informed adjustments to the theoretical focus, and vice versa. In systematic combining, a "tight" framework reflects the researcher's preconceptions from theory, but it remains fluid enough to be revised ("loosened") as new empirical insights emerge (Dubois and Gadde, 2002, 2013). In this thesis, the starting framework was informed by academic literature on IC and CC (due to limited prior research on IFD specifically). This flexibility was crucial because the IFD transition is in a very early stage and thus a "moving target," with policies and industry attitudes evolving in real time.

The iterative nature of this process is best illustrated through several examples of how empirical findings reshaped the theoretical and analytical framing. For example, as empirical data accumulated, the framework was updated to incorporate relevant insights. When it became apparent that several governance structures play a role in the IFD transition, an additional theoretical component was integrated: Bednar et al. (2018)'s model of hierarchy, market, network, and community governance. Adding this lens helped distinguish how different procurement and collaboration arrangements shape IFD adoption, addressing a gap in the initial framework. By combining this governance perspective, the study refined its analytical lens to better suit the Dutch infrastructure context.

Also during the early stages of data collection, interviews with consultants outside frontrunner provinces revealed that awareness of NTA standards was highly uneven. Initially, these findings were coded as evidence of "limited communication." However, as more interviews confirmed this trend, it became clear that the issue could not simply be described as a lack of information flow but needed to be understood as a structural weakness of network governance. Without centralised coordination, knowledge diffusion relied too heavily on informal communities of practice, resulting in persistent gaps. This observation necessitated a reframing of the analysis to include governance perspectives on knowledge diffusion, which later formed an important theme in the discussion.

Another important adjustment stemmed from the supply side interviews. Several contractors repeatedly emphasised that they would only invest in new factory tooling if there was a predictable pipeline of IFD projects. At first, this was treated as supplier hesitation, but as the evidence accumulated, it became clear that this reflected the limits of market governance in the absence of stronger signals from hierarchy. In other words, relying solely on competitive markets is insufficient to stimulate systemic investment. Without regulatory mandates or consistent client leadership, the risks for suppliers remains too high. This led to the integration of innovation system perspective (Wieczorek & Hekkert, 2012) as part of the discussion and sharpened the theoretical framing around market formation as a systemic barrier.

3.2 Multiple-Case study design

3.2.1 Approach and case selection

To investigate IFD and NTA implementation in depth, the research employed a multiple-case study design. According to Yin's (2014) theory, each case serves as a replication experiment: some cases might be literal replications that yield similar results, while others offer theoretical replications and product different outcomes that highlight important contextual factors. This replication logic enhances confidence in results as consistent findings across cases provide reinforcement and divergent findings provide valuable insights into specific circumstances.

A case protocol was prepared for each project, which covered aspects such as procurement method, design standards, materials, and stakeholder roles. Also, multiple data sources were collected to ensure a rich, triangulated understanding (see Ch. 3.4.1).

The iterative nature of the systematic combining approach was embedded in the case design. Insights from early cases informed the focus of subsequent cases. This entailed that when an unexpected finding was noted in the first case, the next case's data collection probed that issue more deeply. For example, the first IFD pilot (Case A) highlighted the importance of an ambition document as a key enabler. This lesson was subsequently questioned in later case interviews by asking whether the presence and perceived value of such documents. In this way, the case studies were not isolated inquiries but part of a progressive learning sequence. Cross-case comparisons were conducted after within-case analyses to explore both common themes and key differences.

Notably, all selected cases were procured by the PNH. This scope was partly due to practical reasons (the researcher's internship at PNH) and strategic relevance: PNH is the first public-client to pilot IFD principles and the associated NTA standards in bridge projects. By focusing on this early adopter access to critical lessons learned and experience in this construction approach was provided. While this means all cases share a common client context (a possible limitation for broad generalisability), it also ensured that each case was directly relevant to the NTA implementation.

For the cases, the unit of analysis is the individual project. Although IFD is a construction approach which inherently deviates from single project executions, given that industrialisation emphasises serial production and automation, it was considered appropriate for this research. This decision reflects both the early stage of the transition, the availability of data on the NTA and its application in terms of development, adoption, and implementation.

The cases satisfy the following criteria;

- Inclusion of IFD Standards (NTA): selected cases had implemented one or more of the new Dutch Technical Agreements (e.g. NTA 8085, 8086, 8089) relevant to IFD. This ensured each case directly relates to the push for unified IFD standards.
- IFD bridge project (fixed or movable): the case must be a bridge project applying IFD principles either fixed or movable.

The three cases are presented in the table below. Further details can be found in Appendix C.

Table 2: Cases. Bridge Project, NTA used, type of bridge

Case	Bridge project	NTA Standard	Type
A	Cruquius Bridge	8086	Movable
B	N240b	8085	Fixed
C	Stolperbrug	8085 + 8086	Movable

3.2.2 Creation evaluation matrix

In order to evaluate the degree to which IFD principles are applied across different bridge projects, a qualitative assessment matrix was created (see figure 18). This evaluation matrix (EM) was send to either the contractor or consultant of the case to evaluate the project. Therefore, it involves a level of subjectivity. However, this was mitigated through triangulation which is highlighted in Ch. 3.5.1. This EM provides a simplified comparative framework that supports structured analysis of case studies by aligning them with core IFD principles and NTA implementation.

Rationale for the evaluation matrix

First, a suitable scale was considered. Given the emerging nature of IFD in infrastructure and the lack of standardised evaluation methods for bridge construction, a matrix was developed for this research to assess IFD implementation at the project level. The EM captures varying degrees of implementation by considering the three core IFD principles and the degree of alignment with relevant NTA guidelines (NTA 8085, 8086, and 8089).

To assess the degree of IFD implementation across projects, a value-based scoring system was developed for each of the three IFD principles. These individual scores reflect the extent to which each principle is embedded in a given project and together provide an overall indication of IFD integration. The matrix uses a range to which IFD is arranged in an ordinal scale, which is defined as follows:

- **BAU:** represents conventional, BAU practices, with no intentional implementation of IFD principles.
- **Low - Moderate - High:** represent incremental progressions in IFD integration.
- **Full**: represents full IFD compliance.

Industrialisation

The first principle in this EM is industrialisation. While several frameworks exist to assess industrialisation in the building construction sector, the literature on industrialised infrastructure construction remains limited. This requires a conceptual translation from building-centric models to an infrastructure context.

There are multiple holistic frameworks that identify important constructs to characterise industrialisation. For instance, Lessing (2005) developed the Industrialised House-Building (IHB) framework, which defines nine characteristic constructs to industrialisation. Another IC framework by Costa et al. (2022), evaluates the organisational strategy as highlighted by the previous section considering the changes to BAU. Although they are useful, these frameworks are best suited for vertically integrated organisations. These are typically large-scale producers who control design, production, and assembly in-house. They can also attain high level of industrialised processes.

In contrast, infrastructure projects (particularly bridge construction) are typically project-based, involve a wide range of stakeholders, and display limited vertical integration. Owing to the traditional view of construction as a unique, one-off endeavour characterised by fragmented stakeholders and temporary project teams (Hall et al., 2021), the direct application of these frameworks to case-based project comparisons proves challenging.

To ensure comparability across diverse projects and contexts, this EM adopts a simplified, project-level approach. However, it still accounts for organisational capabilities where relevant (e.g., access to automated production or use of platform-based design), thereby recognising that the builder's practices influences the level of industrialisation in a project.

Therefore, two straightforward frameworks are used. The industrial construction hierarchy developed by Goh & Loosemore (2016) is used as a base (see figure 16). This hierarchy defines 5 levels of industrialisation, focusing on how construction processes shift from traditional building site-based bespoke production to a complete modular construction. The framework is particularly suited for defining observable characteristics at the project level.

In parallel, Richard’s (2004) framework on the degree of industrialisation defines a continuum from manual production to prefabrication and ultimately reproduction. Richard’s framework complements Goh & Loosemore (2016) by offering a strategic lens to interpret higher levels of industrialisation, especially where design logic becomes repeatable and suitable for automation (see figure 17).

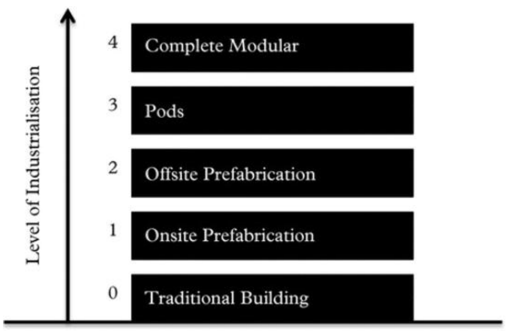


Figure 16: Industrial construction hierarchy (Goh & Loosemore, 2016)

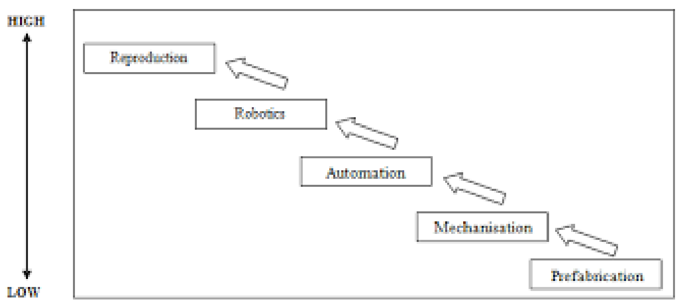


Figure 17: Degree of industrialisation (Richard, 2004)

These frameworks also align conceptually with the core principles outlined in the NTAs. The NTAs define industrialisation as the combination of prefabrication and repeatability (i.e., serial production). However, the NTA remains open-ended, and the specific degree of industrialisation is not clearly defined. In Richard’s terms, the standards could aim to industrialise anywhere between prefabrication and reproduction.

Given that IIC is still emerging, it is reasonable to place current practice at the threshold between mechanisation and automation. As such, Level 4 of the Richard (2004) framework represents an aspirational yet plausible future state, where bridge components are serially produced using repeatable, automated processes.

Thus, the evaluation adopts Goh & Loosemore's 5-tier hierarchy as a foundational structure, with integration of Richard's upper-level classifications. The scoring focuses primarily on the extent and type of prefabrication, the degree of design standardisation, and whether the project incorporates a repeatable, product-based logic.

The EM defines the following scale for industrialisation applied to IFD projects:

- **BAU:** the bridge is constructed entirely on-site using bespoke formwork, materials, and methods. No prefabrication is used and the project reflects conventional, labour-intensive practices.
- **Low IFD integration (Limited On-Site prefabrication):** the project incorporates some prefabricated components, but these are primarily fabricated or assembled on-site. Prefabrication is not systemic, and there is little standardisation.
- **Moderate IFD integration (Mixed On-/Off-Site Prefabrication with partial standardisation):** significant parts of the project are prefabricated, often off-site, and delivered for assembly. Some elements exhibit repeated dimensions or design logic, although the system is not modular. This level reflects growing industrial influence but remains tied to project-specific design.
- **High IFD integration (Modular or product-based prefabrication):** the project adopts a modular design philosophy, with components prefabricated off-site and designed for repeated use across projects. There is clear productization of elements, requiring higher levels of coordination and tolerance control.
- **Full IFD compliance (Serial production with repeatable design logic):** this represents full industrialisation under the IFD philosophy. Components are not only prefabricated but also produced through serial, repeatable, and potentially automated processes. Designs are product-based and standardised for high-volume or cross-project use.

Flexibility

The second principle in the IFD framework is flexibility. Flexibility refers to the capacity of an infrastructure asset to accommodate change over time, whether in terms of function, performance, or configuration.

However, measuring flexibility remains complex, particularly in the context of bridge infrastructure. Unlike buildings, where flexibility is often assessed through spatial re-use or change of interior layouts, bridges involve rigid structural systems and highly deterministic performance requirements. As noted by Mlote et al. (2024), even in building contexts, few assessment frameworks capture deeper structural adaptability, and most focus on surface-level space reconfiguration. This gap is even wider in infrastructure literature.

Moreover, flexibility is inherently interdependent with demountability. The ability to replace or upgrade an element (i.e., upgradability or interchangeability) depends on whether that component is demountable. However, high demountability does not automatically equate to functional flexibility. For instance, a bridge may be easily disassembled and reconstructed but only in its original configuration, without the ability to scale or repurpose it. Therefore, this EM distinguishes between component-level changeability and system-level adaptability.

Given these nuances, this study adopts a qualitative, structured scoring system that captures both the effort required to implement changes and the intentionality of the design to accommodate them. Projects are rated higher where flexibility is a strategic design consideration, not just an incidental result of modularity or removable parts.

This evaluation draws on the adaptability taxonomy of Askar et al. (2021), who define four core attributes relevant to flexibility:

- modularity: the use of discrete, interchangeable components;
- convertibility: the capacity to shift use or function;
- upgradability: the ability to incorporate future technological or functional improvements;
- scalability: the potential to expand capacity without a full redesign.

Based on these definitions and literature insights, the following levels are proposed for scoring flexibility:

- **BAU (Fixed Configuration)**: the structure is designed solely for a single, static use-case. No consideration is given to future upgrades, expansions, or alternate uses.
- **Low IFD Integration (Basic upgradability)**: the structure includes minor provisions for change, typically dependent on demountable components. These allowances are not fully integrated into a strategic flexibility plan and may require invasive interventions later.
- **Moderate IFD Integration (Targeted Adaptability)**: the structure includes explicit design features to support predictable future changes. Examples include extra width for lane expansion, scalable substructure designs, or modular deck panels enabling reconfiguration. Flexibility is intentional but limited to a narrow set of use cases.
- **High IFD Integration (Modular and convertible design)**: a system-level flexibility approach is adopted. The infrastructure is designed using modular principles that allow for expansion, contraction, or reconfiguration. Here, adaptability is driven by a design strategy, not just optional add-ons.
- **Full IFD Compliance (Fully Flexible System)**: the infrastructure is designed for full reconfiguration, relocation, or functional transformation. This level reflects the highest maturity of IFD implementation under the flexibility principle and aligns with “design for transformation” thinking in circular infrastructure.

Demountability

The third principle in the IFD framework is demountability. For the evaluation this principle builds on an existing assessment tool developed under the Dutch Beoordelingsmethodiek Losmaakbaarheid by De Circulaire Bouweconomie (2023). The tool evaluates individual connection types based on their accessibility, reversibility, and the degree of damage they cause during disassembly.

While the existing disassembly methodology provides valuable criteria, it is not directly designed for assigning a single score to a complete infrastructure object. In reality, a bridge comprises numerous structural elements, each with different levels of demountability. For example, bearings may be replaceable, while cast-in-place concrete piers are not. Consequently, assigning a universal project-level score requires simplification.

In this EM, a global score is proposed for each bridge case. This score is based on the overall demountability strategy evident in the project, the presence of accessible and reversible joints across key components, and the extent of recoverable and reusable elements without destructive techniques.

This holistic approach ensures consistency with the element-based logic of the original tool, while remaining suitable for comparative analysis across entire projects. The scale used here is adapted from the existing tool with modifications:

- **BAU:** the structure is designed for a single, static use-case with no provisions for future changes in layout, function, or capacity. This is typical of traditional bridge design, where performance is fixed from day one.
- **Low IFD Integration:** minor provisions for replacing or upgrading individual elements (e.g., bearings or barriers) exist, often relying on demountable connections. However, these changes are not integrated into a broader flexibility strategy and may require significant effort or invasive intervention.
- **Moderate IFD Integration:** most structural elements are accessible. Disassembly is possible with additional steps (e.g. temporary supports, selective cutting). Components can be removed with minimal or fully repairable damage.
- **High IFD Integration**: key components can be accessed and removed using planned, non-destructive processes. All structural parts are designed with reversibility in mind. No permanent or destructive connections are used.
- **Full IFD Compliance:** all elements are freely accessible and fully reversible without extra work. The system allows for total recovery, reuse, or relocation. No invasive tools or heavy machinery are needed beyond lifting or unbolting. This level reflects full alignment with circular construction objectives.

NTA implementation

Lastly, this evaluation considers the extent to which the project aligns with the NTA standards (NTA 8085, 8086, and 8089). There is no existing measure for the level of adherence to the NTA. Therefore, for the purposes of this evaluation, NTA implementation is expressed as a range (low to high). The range indicates the proportion of components or systems within a project that conform to the relevant NTA guidelines.

However, it must be noted that the NTA documents are still under development and not yet fully comprehensive, particularly in relation to bridge-specific components. As a result, the evaluation of NTA compliance in this study remains indicative rather than definitive. The score primarily reflects how consciously NTA principles have been applied, rather than a strict standardised measurement.

A more detailed and standardised method for measuring NTA compliance, possibly at the component or system level, would offer a more robust evaluation for future research. This could include integration into digital models (e.g., BIM validation tools) or benchmarking against certified reference designs once the NTA documents are fully adopted.

The IFD evaluation matrix

The resulting IFD EM consolidates the qualitative assessment scales for industrialisation, flexibility, and demountability into a single comparative tool. The matrix enables consistent evaluation across bridge projects, despite varying levels of maturity in IFD adoption. Supplementary NTA implementation offer further depth on the development of the NTA across the different cases, as well as highlighting gaps in the standards.

Principle	Business-as-usual	Low IFD Integration	Moderate IFD Integration	High IFD Integration	Full IFD Compliance
Industrialisation	Fully built on-site; bespoke design; no prefabrication.	Limited prefabrication, mainly executed on-site.	Significant prefabrication; some standardisation.	Majority prefabricated; modular or product-based approach.	Fully off-site produced system; repeatable design logic fully integrated.
Flexibility	Fixed Configuration: No consideration for change; fixed structure; no future-proofing.	Basic upgradability: Minor provisions for change, dependent on demountable components	Targeted Adaptability: Includes specific adaptation options (e.g., space for future widening).	Modular and convertible design: Modular components; aimed at future-oriented expandability through a clear strategy.	Fully flexible system: designed for reconfiguration, relocation, or expansion without major alterations.
Demountability	Designed for demolition; inaccessible; irreparable damage.	Accessible with extra steps, partially repairable damage.	Accessible with extra steps, fully repairable damage; material separation possible.	Accessible with extra steps, no damage to components.	Freely accessible without extra steps; no major work required.

Figure 18: Evaluation matrix for IFD bridge construction

3.3 Cross-case study design

To complement the within-case analyses and enable cross-case reasoning, the study included semi-structured interviews with stakeholders beyond the three cases (additional interviews). The purpose was to surface sector-wide patterns, boundary conditions, and recurring barriers or interventions for IFD and NTA implementation that are not attributable to a single project. These interviews are used in Chapter 6 to develop cross-case themes on the IFD and NTA transition.

3.3.1 Approach

The selection of interviewees was guided by the need to represent the full spectrum of actors influencing the IFD transition. Respondents included companies directly involved in drafting the NTA, contractors and consultants engaged in IFD pilot projects, as well as public clients who had not (yet) adopted IFD or NTA standards. Including non-adopters was particularly important, as it provided insight into the reasoning behind hesitancy or resistance, thereby broadening the explanatory scope beyond frontrunner practices.

All interviews were conducted using a semi-structured interview guide (see Appendix A). Conversations were audio-recorded with consent, anonymised with unique IDs (D-codes), and transcribed (see Ch. 3.5). Details on ethical safeguards and data management are provided in Ch. 3.6.

Analytically, additional-interview transcripts were coded together with case-interview transcripts (see Ch. 3.5), then mobilised in two ways: to test the generality of case-specific observations and to construct cross-case patterns reported in Chapter 5. Credibility was strengthened through triangulation with project documents and the evaluation matrix-based case profiles, iterative refinement of codes, and convergence of themes across actor groups. Case-bound interviews are listed with each case (Table 3); additional interviews are reported separately (Table 4) to prevent double-counting.

3.4 Data collection

Multiple data sources were collected for each case and complemented by semi-structured interviews with industry stakeholders, comprising both case-bound and additional cross-case interviews (see

Figure 19). Both streams used the same core interview guide. For case-bound interviews an extra module captured project-specific experience and IFD and NTA application (Appendix A, Section 4).

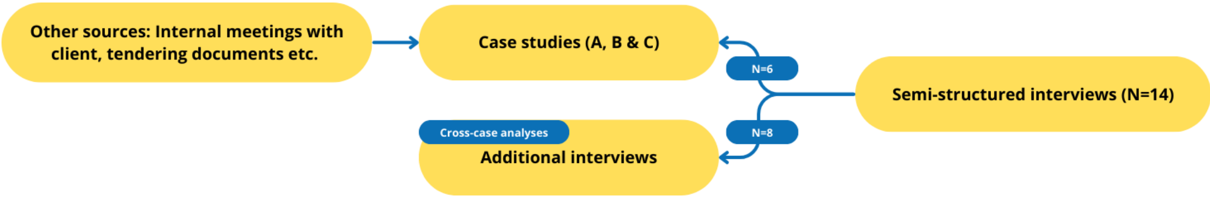


Figure 19: Data sources overview

3.4.1 Case study data

For each bridge case, a rich dataset was collected to document IFD and NTA implementation. This typically included: project documentation (tender documents, technical requirements, and any NTA-related specifications), publicly available information (industry reports, online articles about the project), and direct stakeholder inputs (see Table 3).

Table 3: Collected data for the cases

Case	Data collected
A	Internal meetings with client - notes made (A1), appointed contractor (D16) and consultant (D2). Tendering documents (A2), online information and industry reports (A3). Information presentation by contractor (Bruggen-festival) (A4), site visit (A5). Evaluation matrix (Evaluated by D2).
B	Internal meetings with client - notes made (B1), appointed contractor (D15), consultant (D2) and non-awarded contractor (D6). Tendering document (B2), internal documents (B3) and Evaluation matrix (Evaluated by D15).
C	Internal meetings with client - notes made (C1), appointed contractor (D12) and consultant (D4). Tendering document (C2), internal documents (C3) and online information (C4). Evaluation matrix (Evaluated by D2)

In each case, interviews were conducted with key participants: the public client or owner, the main contractor, and a consulting engineer or advisor involved (see Table 3). These interviews focused on the case's specific experiences with IFD principles and standards. Where possible, site visits or presentations were also included (e.g. Case A involved a site visit and a contractor presentation of their IFD approach). By triangulating documents, interviews, and observations for each project, the study captured both the formal intended application of IFD (from plans and standards).

3.4.2 Additional interviews

In addition to case-specific interviews, the research conducted semi-structured interviews with a wider set of stakeholders to gain general insights into the IFD transition. In total, 14 interviews were held across three main actor groups: public clients (bridge owners from various authorities), contractors (including bridge builders and component suppliers), and consulting or engineering firms (see Table 4).

Table 4: Types and amount of actors interviewed (including interviews for the case)

Actor group	Interviews	ID
Public clients (bridge owners)	4	D9, D10, D11, D14
Contractors	7	D3, D5, D6, D7, D12, D15, D16

• Including inhouse supply production (D5, D6) • Including case study (D6, D12, D15, D16)		
Consulting & engineering firms • Including case study (D2, D4)	3	D1, D2, D4

The semi-structured format followed an interview guide to cover key topics such as experiences with IFD standards, procurement strategies, technical challenges, and collaboration issues, while still allowing interviewees to introduce novel insights (see Appendix A). This type of questioning enabled the discovery of emergent themes (e.g. unanticipated organizational or policy barriers) that could then feed back into the evolving theoretical framework.

3.5 Data analysis

After data collection, a systematic analysis was undertaken in two streams: 1) case study analysis using an IFD EM and 2) interview analysis using thematic coding. These techniques allowed the study to assess IFD and NTA implementation qualitatively through schematic scoring and thematic interpretation.

3.5.1 Case analysis

To evaluate each case's level of IFD and NTA implementation in a structured way, the research employed a custom EM developed from academic IC and CC literature, as described in Ch. 3.2.2. This IFD EM qualitatively assesses the implementation of the core IFD principles. In addition to the core principles, the matrix also captured supplementary aspects important to the research objective: the degree of conformance to official NTA standards in the project.

Figure 20, illustrates the analytical process. First, case data were scored against the EM dimensions. The stakeholder received an explanation of the EM and then had to fill in the matrix based on their knowledge. Second, these scores were verified through triangulation by drawing on other stakeholder perspectives. For instance by verifying these scores with involved PNH actors and internal project documentation. This verification step was crucial, since the evaluation of the stakeholder inevitably involves an element of subjectivity. Therefore, triangulation provided a means of confirmation and, if necessary, adjusting preliminary assessments. Third, adaptation took place when inconsistencies or "faults" in the scoring emerged during the previous verification step. During adaptation, additional context was incorporated to either substantiate or correct the initial evaluation. This refinement ensured that the profiles captured a balanced and credible picture of each case.

Figure 20: Analysis of cases with the evaluation matrix

After adaptation, the EM results essentially portrayed a qualitative "scorecard" that highlighted the extent of IFD implementation and the role of the NTA per case. These case profiles were then compared across cases to identify both commonalities and divergences. The cross-case analysis enabled the identification of recurring strengths and weaknesses in IFD adoption. For example, it revealed whether certain principles, such as demountability, were consistently less or more developed than other principles of IFD.

In conclusion, by first conducting detailed within-case analyses using the EM and then systematically comparing results across cases, the research was able to draw conclusions about the current state of IFD implementation in Dutch bridge projects. This layered approach provided a nuanced understanding of how far the sector has progressed and what gaps remain. The additional data collected from interviews and other documentary sources further enriched the findings, allowing the evaluation to move beyond simple scoring and capture the broader contextual factors influencing IFD and NTA adoption.

3.5.2 Semi-structured interview analysis

The interview data were analysed using an inductive qualitative thematic analysis to extract key themes. All interview recordings were initially transcribed using Microsoft Teams' automated transcription function, followed by manual correction and refinement to ensure verbatim accuracy and deeper immersion in the data. The software ATLAS.TI was used to code the transcripts. The coding of the transcripts followed a six-phase thematic analysis framework outlined by Braun & Clarke (2006) (see figure 21).

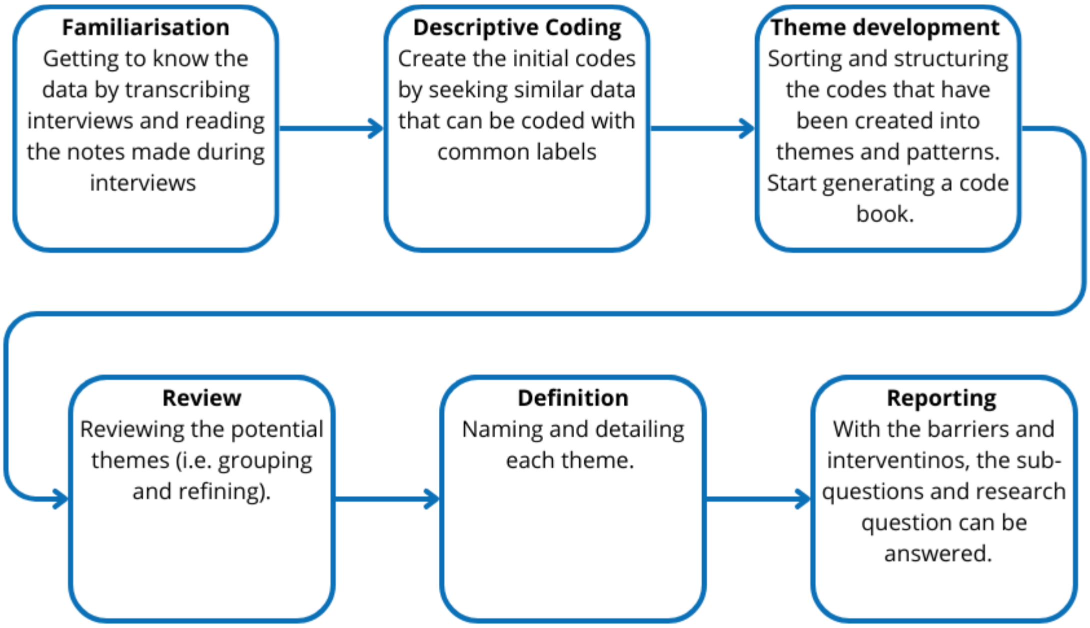


Figure 21: Six-step Thematic Analysis Flowchart, adapted based on Braun & Clarke (2006)

First, familiarisation of the data took place. During this phase the researcher is becoming familiar with the data by making notes during the interview and transcribing the interview afterwards. Second, descriptive codes were attached to the interview transcripts to capture recurring issues and observations in the respondents' own terms. This open, inductive phase allowed the data to be grouped under common labels, while illustrative quotes were highlighted for later use in the results chapters (Braun & Clarke, 2006). At this stage, no predefined model was imposed. Instead, codes functioned as empirical signposts pointing toward barriers and interventions in the IFD and NTA transition. Third, axial coding or theme development was applied to organise the descriptive codes into broader patterns and thematic clusters. For example, individual codes such as "unclear NTA guidance," "limited client awareness," and "fragmented knowledge sharing" were drawn together into higher-order themes. Simultaneously, a codebook of these emergent barrier and intervention themes was compiled (see Appendix F). Fourth, the researcher reviewed the themes made to evaluate whether the grouping and refining still follows logically from the original codes. Fifth, the evaluated themes were named. The sixth and final step entailed the consolidation and connection of themes and patterns back to the overarching research questions.

The thematic coding of interview data produced a set of key themes that captured both the barriers and the interventions shaping the IFD transition and NTA adoption (see Ch. 6). Combined with the case analysis and EM, the thematic analysis highlighted why certain dynamics emerged and how they were perceived by stakeholders.

3.6 Ethical considerations and data management

All research activities were conducted with careful attention to ethics and data integrity. The study followed the TU Delft Human Research Ethics Committee. The committee approved the Data Management Plan, ensuring compliance with institutional and legal guidelines. Prior to interviews, participants received information about the research and gave their informed consent (verbally and/or in writing) to participate and be recorded (see Appendix B). To protect confidentiality, all personal identifiers (names of individuals and specific organizations) were removed or pseudonymized in the transcripts. Each interview transcript was labelled with an anonymised code (e.g., D1, D2, etc.) for reference instead of real names.

Data security was rigorously maintained. Digital audio recordings and transcript files were stored on secure, access-controlled servers at TU Delft. Only the researcher had access to the raw data. After transcription and verification, audio recordings were deleted to prevent any unintended disclosure of identities. Transcript files, coded data, and analysis outputs were backed up in accordance with the data management plan. Throughout the project, the researcher upheld ethical standards of honesty, objectivity, and respect for participants' privacy.

Chapter 4 – Results Case Analysis

This chapter reports the results of the case analyses of the three bridge projects. For each case, the IFD EM profile (as completed by the contractor or consultant) and then substantiate the scores with project evidence, tender and technical documents, site observations/presentations, and semi-structured interview insights etc., following the methodology. Detailed background and source lists for each case are provided in Appendix C. After the three cases, an overview table consolidates key results and notes preliminary cross-case signals (similarities/differences).

4.1 Cases

4.1.1 Case A: Cruquius bridge project

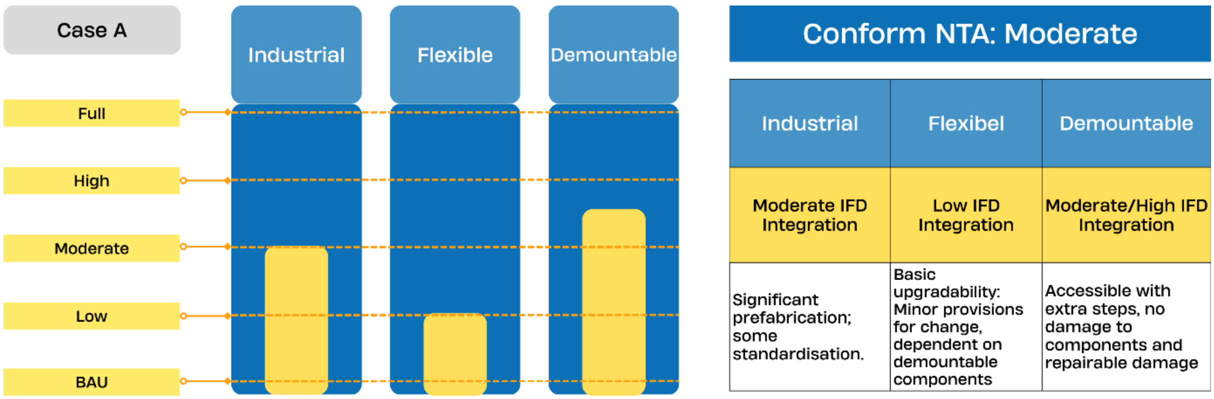


Figure 22: EM profile of IFD implementation Case A (D2)

Industrialisation in this project was moderate as it was limited mostly to prefabrication (D2). Logically the steel structure of the bridge was prefabricated as well as the mechanical and electrical systems. Additionally the approach bridge (*Dutch* "aanbrug") was prefabricated, although initially intended to be cast in place, this practically seen as to risky (D16). Most elements were project-specific and not part of any higher industrial levels, such as automation. This can be tied to several factors, first of all the bridge was only partially replaced for instance the existing substructure (the original abutment) was retained, further limiting opportunities for full IFD application (A5). Secondly, this project was seen as the first IFD pilot project served the goal of the implementation, proof of concept and further development of the NTA 8086 (A3; Platformbruggen, 2023). Standardisation was partially achieved through reference of the NTA 8086 although most elements remained project-specific (D2, A1).

The second principle flexibility was low. The design accounted for future navigational clearance (e.g., taller vessels), and some flexibility was built into the mechanical and electrotechnical systems through modular, upgradeable components (D16). However, the structural elements were not designed for future adaptation or extension, and no broader adaptability measures were included.

Demountability was relatively strong (moderate/high), particularly in the mechanical and electrical systems, which were designed to be removed, maintained, and reused. Equally the steel structure of the movable bridge is highly demountable (A4). In the fixed bridge section, the concrete girders were initially intended to be cast in place, but this was revised at PNH's request (D16). Girders were placed on bearings to allow potential reuse. However, the inclusion of a cast-in-place compression layer and seamless asphalt surface reduced disassembly ease. This was deemed necessary by the contractor as to prevent horizontal movement of the abutments, as this would risk the opening bridge becoming stuck

(D16). As a result, demountability was quantified lower, as the removal is possible for some elements without damage and the retrieval of the girders requires effort and may cause partial damage.

NTA compliance was moderate. During the first-phase of the UAV-GC contract, NTA 8086 was still under development (D2, see Appendix C) and was therefore treated as non-binding guidance rather than incorporated as a contractual requirement. Application was interpretive, but the project fed lessons back into the ongoing development of the standard.

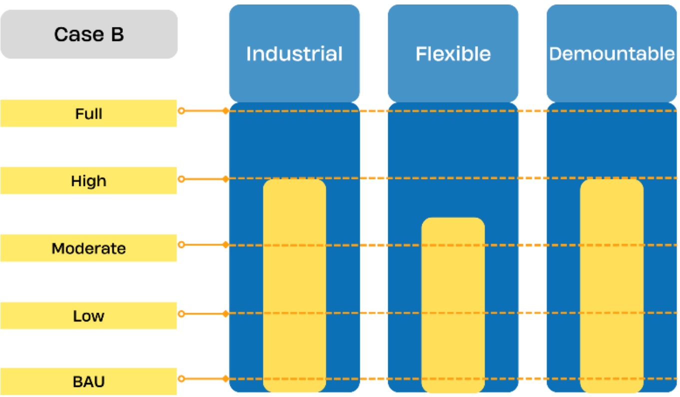
The pilot project resulted in many lessons learned for the integration of the NTA and application of IFD for future PNH bridge projects, these lessons learned can be recognised case B and C (B2, C2). Not only in the tendering documents, but also in the procurement approach for IFD bridge projects of the PNH (see figure 1, appendix C).

Interview insights highlighted the need for early integration of IFD principles and NTA, including a clearly defined ambition and including the NTA as a future tendering criteria. Specify NTA guidelines in the project's requirements and ensure they are integrated into the hierarchical project documentation.

The Bouw-team model was positively received, offering space for collaborative design development and alignment of expectations regarding the implementation of the NTA (A1). Stakeholders also emphasised the importance of regular design sessions, early expert involvement regarding the implementation of the NTA, and improved documentation throughout the project. Lastly mentioned was the need for a mindset change, to adopt a "design in series" approach to promote the reuse of design elements, which is believed to lead to significant cost savings (A3).

4.1.2 Case B: N240B

Appointed contractor (D15)



Conform NTA: High		
Industrial	Flexibel	Demountable
High IFD Integration	Moderate/High IFD Integration	High IFD Integration
Majority prefabricated; modular or product-based approach.	Targeted Adaptability: Includes specific adaptation options (e.g., space for future widening).	Accessible with extra steps, no damage to components.

Figure 23: Evaluation level of IFD implementation, Case B (D15)

Case B involves the replacement of two identical fixed bridges and also serves as a pilot for implementing IFD principles and further developing the NTA 8085 standard. The project is currently in the Definitive Design phase, with construction not yet started (D15). The bridge design includes modules for future IFD projects which is intended to be scalable.

Industrialisation in this case is high, though not full IFD compliance. The design includes the prefabrication of nearly all components; however, there is no mass or automated production, and no standardised external supply chain is in place. The repetition of two identical bridges enables reuse of the design and construction process, creating procedural efficiency rather than product standardisation (D15). As one contractor explained, the project does not enable a fully automated approach: "*We brought several prefab suppliers on board; they said, just tell us what to make and we can do it. But the market is far from offering standardised elements straight from a catalogue*" (D15).

At the same time, the contractor expressed caution around execution tolerances when working with a high degree of prefabrication. As one interviewee noted: *"The main issue is tolerances. How do we get it right without having to redo or rebuild parts several times?"* (D15).

Flexibility is moderate to high. While the bridge is not designed for direct in-situ functional changes, its demountable structure allows for relocation or reconfiguration in the future. The design also uses modular elements intended to be interchangeable, supporting adaptability. The contractor described: "*We designed 3 by 3 metre elements that are interchangeable and can be coupled with pre-stressing. These modules can be scaled up - 6, 9, 12, 15 metres - and are fully demountable"* (D15). This approach introduces potential for scalability, even if functional adaptability remains limited.

Demountability is high. The bridge is designed to be fully demountable, supported by a disassembly manual and future-use scenarios. "*All major elements are conceived as stand-alone units that can be retrieved without damage*" (D15).

NTA compliance is also high. The project contributes actively to refining NTA 8085, especially in testing demountable connections at the substructure level. However, as the contractor pointed out: "*Connections between pile foundations and the substructure are not yet fully addressed in the NTA. That gap shaped our tender, and lessons learned here should be fed back into the new version of the standard*" (D15). Despite this, internal meeting notes that such feedback mechanisms are not yet in place, even though the ambition exists (B1).

The use of a D&C contract model, combined with limited design time, was perceived as a barrier to developing a fully optimised IFD solution. As observed: "*If you really want to develop an IFD product, the client should avoid setting hard deadlines and instead prioritise product development. Of course, at some point you need a deadline, but more time upfront would help*" (D15). Interviewees suggested that a more iterative and collaborative process, with closer involvement of the client, designers, and suppliers, could have led to a more effective IFD product: "*If you bring the province's knowledge together with ours and the suppliers', sit together and shape it, you can create the optimal fixed bridge design*" (D15).

Alternative bid (D6)

A notable alternative bid was submitted by contractor D6 who proposed their system a standardised, modular bridge concept with a strong emphasis on industrial fabrication, rapid deployment, and complete demountability (D6). The system is based on a single-span steel bridge that can cover lengths up to 50 meters without intermediate supports. For the N240b tender, D6 proposed a 36-meter single-span structure without piers, offering advantages in speed of installation, reduction of substructure works, and potential reusability.

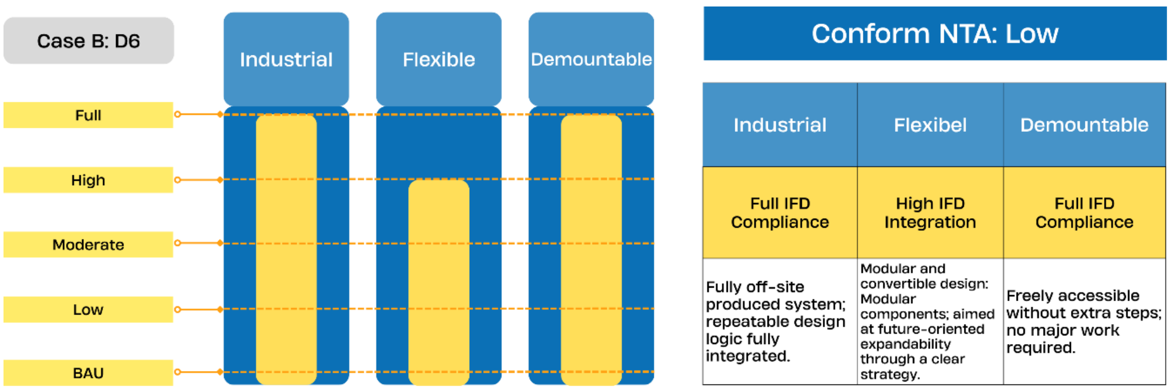


Figure 24: Evaluation level of IFD implementation (D6)

The D6 product demonstrated near full compliance with IFD principles, particularly in industrialisation, being a serially produced, off-the-shelf system based on standardised processes (D6).

Flexibility was rated moderate to high. The system is a modular, convertible design that can be expanded and adapted to some extent once installed. Its modularity allows it to be easily reconfigured, relocated, or reused at other sites. In addition, the system can be deployed in varied setup such as multiple spans or parallel viaducts offering further adaptability in planning and application (D6).

Demountability was very high. The bridge is fully disassemble without destructive work, and components can be reused multiple times with minimal material loss. Only the foundations are site-specific, but these too can be repurposed (D6).

Despite its strong alignment with IFD goals, the bidder ultimately withdrew from the tender. The main issue was a mismatch in span layout: PNH required three 12-metre spans, reflecting their strategy to enable future reuse in an area with many shorter-span bridges. The D6 system, however, was based on a single longer span, which could not be subdivided (B1). As the participant explained: "*The existing bridges all had spans in multiples of 12 metres. The reference design also prescribed three 12-metre spans. We wanted to go for a single span, but that was excluded early on*." (D6).

They further noted that the way NTA requirements were applied also narrowed down the available product options: *"We see the NTA as a guideline with classes, like clearance heights. You should comply with one of these classes, but in this project a specific class was prescribed. By doing that, you effectively prescribe certain products, like concrete box girders, while excluding other systems that could achieve the same span. That wasn't clear in the beginning, but once your product doesn't fit, you're out."* (D6).

This experience highlights a broader challenge in aligning innovative product-based solutions with the rigid criteria set out in reference designs and tender requirements. The appointed contractor (D15) echoed this sentiment more generally, reflecting: *"The real question is whether the product truly matches the demand."* (D15).

Still, not all effort was wasted. The alternative design led to innovations that can be reused elsewhere. As the interviewee explained: *"Initially, we didn't have demountable substructures, but we eventually developed them during the tender. So in that sense, it wasn't wasted effort - we can reuse the idea in the next tender. And we will take this forward into the next discussions on revisions of the NTA."* (D6).

4.1.3 Case C: Stolperbrug

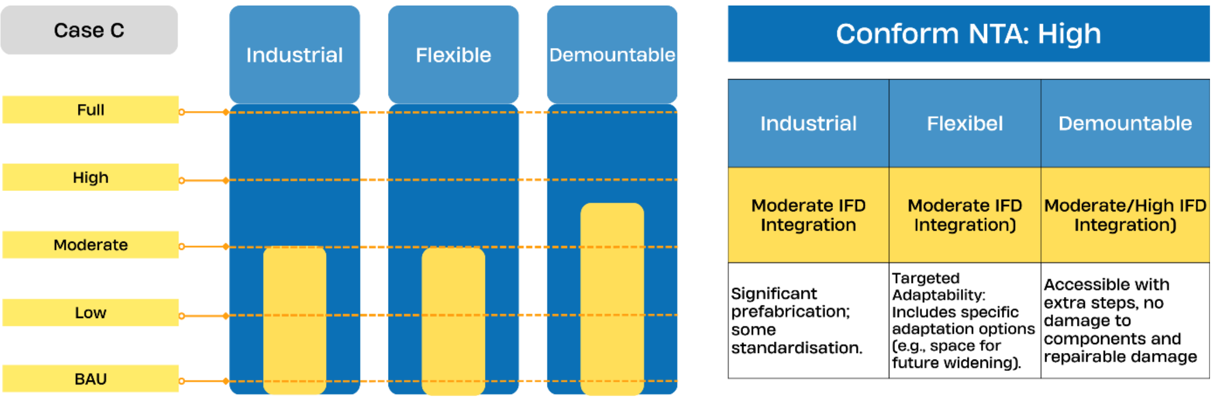


Figure 25: Evaluation level of IFD implementation Case C based on pre-Definitive Design (D2)

Case C is in the Definitive Design phase, with implementation not yet started. A key feature of this case is the transition from an initial failed standalone tender to a framework agreement, with the Stolperbrug serving as the first bridge to be delivered under this arrangement.

Industrialisation is currently moderate. A significant portion of the bridge will be prefabricated, and some standardisation is expected across the projects in the framework. However, the design remains largely project-specific, with no fully modular or productised approach in place. Efficiency gains are therefore expected more from process repetition than from product standardisation. As one interviewee noted: "*The cross-section is the same, so you don't have to think about it again. The mechanical parts should also be kept the same. That repetition is where IFD really comes in, even if on a smaller scale. I think it's a good development*." (D12).

Flexibility is not yet developed. Although included in the contractual ambition level, no concrete measures or design features supporting adaptability have been established so far. The design remains focused on fixed functional goals, with flexibility to be reassessed in later phases (D12).

Demountability is a key focus area. The use of a disassembly index is included in the design process, and some elements will be designed with disassembly in mind. Similar to Case A, the mechanical and electrical parts, as well as the steel structure of the bridge (C1), are demountable. However, further demountability appears challenging in practice due to constraints in the bridge configuration. For example, fixed connections were required to prevent structural interference between spans, which limited the potential for disassembly. As one participant described: "*You have 2 approach spans with the deck between them. To prevent them from moving towards each other and jamming the deck, we had to make a moment-fixed connection. But you can still take out the box girders where no pressure lies, remove the asphalt, lift out the girder, and use it somewhere else*." (D12). These findings mirror those of Case A, where partial demountability was achieved but certain structural constraints limited full reversibility of certain components.

NTA compliance is high, with the updated NTA 8086 v2 being used from the outset. The standard helps reduce design uncertainty and clarify expectations for contractors. However, full conformity is not yet achieved, as some NTA provisions are not fully suited to the project-specific context and therefore require adjustment or exclusion. This highlights that while the NTA provides a strong baseline, further refinement is needed to ensure alignment with diverse project conditions.

The shift to a framework agreement was regarded as a positive step, creating more realistic targets and enabling iterative learning (D12). The framework approach was also seen as better suited to current market conditions compared to the earlier standalone tender (A3). In addition, the use of a bouwteam structure within the project fostered closer collaboration between the client, designers, and contractors, supporting joint problem-solving during the design phase. While repetition across projects was welcomed, contractors emphasised that this primarily supports process efficiency rather than full industrialisation. As one interviewee explained: *"Architecturally it can look very nice, but with IFD you are moving more towards serial building - doing the same tricks repeatedly. That repetition is where we need to go. From a cost and risk perspective, that makes sense: for the client, it saves money and reduces risks."* (D12).

At the same time, contractors expressed caution about long-term reusability. As the contractor reflected: *"For contractors, it also reduces risks because you know what is coming. But what we build now at Stolperbrug, we won't reuse in eight years. Maybe after several decades you could reuse elements like the edge beams. But whether it will really prove future-proof, that remains to be seen."* (D12).

4.1.4 Overview cases

Table 5: An overview of all cases based on EM and other results

Theme / Criteria	Case A: Cruquius Bridge	Case B: N240B	Case C: Stolperbrug
Project context	Moveable bridge (partial replacement); nearing completion	Twin fixed bridges (full replacement); Definitive Design	Moveable bridge (first in framework programme); Definitive Design
Contract model	UAV-GC 2005 (bouwteam, 2-phase collaborative)	D&C (limited design time, no early involvement)	UAV-GC 2005 (bouwteam) within framework agreement (ROK)
Industrialisation	**Moderate:** prefabricated steel, M&E, and approach bridge; project-specific design	**High:** extensive prefabrication; twin bridges enabled design reuse	**Moderate:** prefabrication and framework-level repetition; no modular/product approach
Flexibility	**Low:** limited to vessel clearance and modular M&E	**Moderate - High:** demountable structure allows relocation; modular elements	**Moderate:** ambition in contract, but not yet translated into design
Demountability	**Moderate–High:** steel/movable parts removable; girders partly reusable, limited by cast layer/asphalt	**High:** fully demountable; manual and reuse scenarios included	**Moderate – High:** steel/movable parts removable; girders partly reusable, limited by cast layer/asphalt
NTA conformity	**Moderate** NTA 8086 in development, applied as guidance only	**High** active testing and refinement of NTA 8085	**High** NTA 8086 v2 applied from outset; some provisions ill-suited to project specifics
Procurement outcome	Competitive dialogue; yielded strong lessons for NTA and IFD implementation	Conventional tender; alternative modular bid withdrawn (D6)	Standalone tender failed (single bid mismatch); framework adopted for better market fit

4.2 Summary of Findings

The three cases reveal a gradual but uneven trajectory in the implementation of IFD and the NTA. Industrialisation was evident in all projects, though primarily through prefabrication and process repetition rather than through modular or catalogue-ready products. Case A showed moderate industrialisation, limited to project-specific prefabricated components, while Case B demonstrated higher levels by repeating the design of two identical bridges. Case C, under a framework agreement, indicated that repetition across multiple projects may yield process efficiencies, yet true productization and modularisation remain underdeveloped. Flexibility, meanwhile, remained the weakest principle across all three cases. Although contractual ambitions for adaptability were present, these rarely translated into tangible design features, with Case B offering the only moderate example through modular elements designed for relocation and an expandable design.

Demountability emerged as the most consistently advanced principle, particularly for mechanical and electrical systems, though structural constraints limited full reversibility in Cases A and C. By contrast, Case B achieved near-complete demountability, supported by a disassembly manual and future-use scenarios. NTA compliance showed clear progression across the cases: from partial and experimental use in Case A, to near-full compliance and active feedback in Case B, and structured application of the updated NTA 8086 in Case C, though with some provisions not fully suited to project-specific contexts. Finally, procurement approaches played a decisive role. Case A's collaborative bouwteam enabled learning, Case B's D&C contract restricted early innovation and excluded an alternative product-based solution (D6), while Case C's shift to a framework agreement, combined with a bouwteam, was seen as better aligned with market conditions and allowed more iterative development. Together, the cases illustrate a sector in transition: while key principles of IFD are being tested and refined, flexibility, reusability, and procurement alignment remain critical challenges for wider adoption.

4.2.1 Key Findings

From the case analysis, several key findings emerge:

1. **Industrialisation** is present but incremental, relying on prefabrication and design repetition rather than true modular (NTA conform) or product-based approaches.
2. **Flexibility** remains the weakest IFD principle; ambitions exist but are rarely reflected in concrete design features.
3. **Demountability** is the most advanced principle, though structural constraints (fixed spans, cast layers) for movable bridges still limit higher levels. Case B showcases that high levels of demountability are attainable.
4. **NTA conformity** is improving over time: from partial and experimental use (Case A) to near-full compliance with active feedback (Case B), and structured but not fully project-suited application (Case C).
5. **Procurement approach significantly influences outcomes.** Collaborative models (such as bouwteams and frameworks) facilitate iterative learning and alignment, which is especially advantageous for pilot projects where experimentation and knowledge sharing are key. Conversely, in traditional D&C tenders, the prescriptive specification of span layouts, NTA classes, or material choices can unintentionally overlook existing productised solutions. Therefore, it is not the contract form itself that rules out alternatives, but the manner in which requirements are expressed within it.
6. **Innovation barriers** arise from misalignment between prescriptive client demands (e.g., fixed spans, specific classes) and the emerging supply of product-based modular solutions. This indicates
7. **Market maturity is still limited.** Across all cases, contractors noted that the market does not yet offer standardised, catalogue-ready IFD (NTA) components. Prefabrication is possible, but industrial supply chains remain fragmented.

Chapter 5 – Results Cross-Case Analysis

This chapter presents the cross-case analysis of results, drawing on both the three case studies and the additional interviews. The additional interviews provide broader perspectives from the sector and highlight not only the key barriers to IFD implementation but also potential interventions to support the transition.

5.1 Barriers

Industry participants described a range of barriers that hinder the widespread adoption of IFD bridge practices and the NTA. Thematic analysis of the interview data revealed several recurring challenges. Each theme is grounded in the content of the interviews and illustrated with anonymised quotes from respondents. The findings are presented objectively, as insights derived directly from what the interviewees reported.

Theme 1: Institutional conservatism

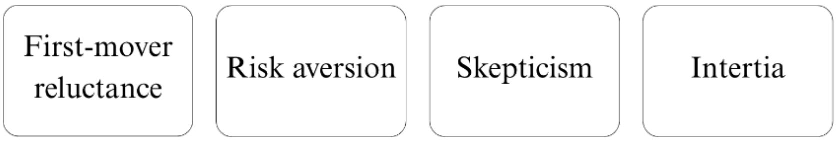


Figure 26: Barriers tied to conservatism: risk aversion, inertia, first-mover reluctance and scepticism.

A prominent barrier identified is conservatism in the industry, manifesting as reluctance to change established practices. Many stakeholders are wary of new approaches like IFD, preferring familiar methods even though they acknowledge the benefit of which IFD and standardisation can bring to bridge construction. As one interviewee explained, *"it's about the mindset… People need to think differently. Traditional thinking is above all a challenge.*." (D15)

This cultural resistance is can be tied to risk aversion actors fear potential failures or costs associated with unproven methods, indicating that there is too much uncertainty. Several interviewees admitted that although they agree with principle that IFD and the NTA are important, few are willing to take the risk or invest upfront in IFD without immediate returns (D2, D9 D14). As one respondent explained, many prefer to "*leave it alone for now*" (D4) rather than gamble on future benefits.

Another participant observed that some colleagues remain openly sceptical, with "*a lot of people still saying 'it can't be done'*" (D2) and even circulating internal memos listing reasons why IFD "*isn't a good idea"* (D2). Such accounts illustrate the scepticism to depart from traditional bridge design and construction, rooted in fear that IFD might complicate projects. One contractor described how even when IFD's advantages are presented such as lower costs and fewer errors clients remain hesitant "*If you sell to the client the benefits of less costs, less errors, they're going to tell you: 'Well, we have to see. The proof is in the pudding. I need to actually see it.*'" (D5).

In summary, resistance to change whether due to comfort with the status quo, fear of technical unknowns, or the "*cold feet*" (D3) syndrome of not wanting to be the first mover emerged as a significant hurdle across the supply chain. This inert behaviour can be seen for instance by public-clients (D10), indicating if the NTA is adopted more widely by others they would consider also adopting it.

Theme 2: Limited knowledge diffusion and demonstration

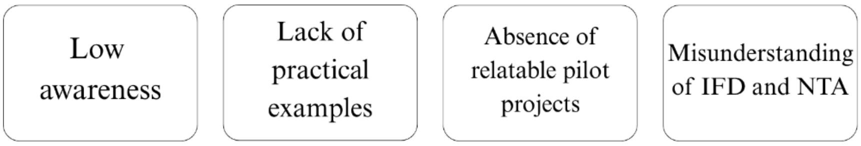


Figure 27: Barriers related too knowledge diffusion and demonstration

A further barrier is the simple lack of knowledge and concrete examples circulating in the industry. Even years after the introduction of IFD concepts, many professionals still have only a vague notion of what IFD entails in practice. Multiple interviewees observed that *"a lot of people still don't really know what IFD is."* (D2) One interviewer and educator noted that when they bring up IFD in courses for contractors or asset managers, *"they say: 'Oh yeah, I heard of that 5 years ago – but what exactly is it again?'* (D2). This illustrates that awareness may exist at a superficial level, but a detailed understanding is often absent among many practitioners.

Multiple interviewees noted that many stakeholders are either unaware of the NTA or unclear about its purpose and how they can contribute to or benefit from its use (D10). This lack of engagement slows the spread of standardised practices and weakens the collective learning process.

Part of the problem, as respondents identified, is the lack of readily accessible demonstration projects that stakeholders can relate to. The only well-known IFD pilot projects are large-scale and led by frontrunners. Local officials in other regions do not see those as relevant to their situation. *"Municipal managers don't see themselves reflected in projects like the Cruquius Bridge,"* (D1) one interviewee explained. An example followed this, *"They think: 'That's for Noord-Holland, not for us in our town. If we had a database of simpler IFD projects that municipalities could relate to, that would help "* (D1). The absence of diverse case studies, for example, simpler or smaller IFD projects that typical municipalities might undertake, means that many clients cannot visualise how to apply IFD in their own context. One expert sighed that since the initial pilots, *"I was hoping to have ten solid examples by now. Then I could show clients: 'Look, here's what's possible, and here's how we designed an even better IFD bridge for that case.' But we're not there yet. I really need those examples."* (D2) This comment reflects frustration that the knowledge diffusion and new IFD projects have been slow; success stories and lessons learned are not broadly available to convince sceptics.

Additionally, the lack of knowledge and examples contributes to the misinterpretation of the concept. Many stakeholders emphasised that every bridge project is different, which limits the perceived applicability of standardised solutions (D11, D14). This belief leads to a preference for bespoke designs, even in cases where standardisation could offer benefits. However, as noted by other stakeholders, this is a common misconception of the NTA, as standardising interfaces and dimensions considers the uniqueness (D1). Related to this, concerns were raised that standardisation might result in uniform, unattractive designs, evoking comparisons to "East Bloc" style infrastructure. As one participant reflected, *"Of course, the fear is that it's going to become like the East Bloc in the past. But I think some things do have to be standardised. And yes, do we really need every bridge to be unique?"* (D12). Ultimately, the same participant concluded that the NTA provides sufficient flexibility to allow for architectural variation and contextual adaptation, while recognising that not every bridge requires a one-of-a-kind design. Other interviewees (D1, D3) similarly emphasised that there will always be room for flagship projects to stand out, but not every simple bridge needs to be unique.

Theme 3: Regulatory framework

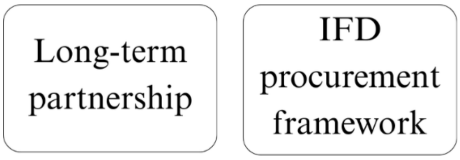


Figure 28: Legal and regulatory type barriers

Several challenges were identified regarding procurrent framework both the general concept of standardisation in bridge construction and the specific application of the NTA and IFD development.

Firstly, a barrier pertained to European and national procurement laws, were cited as obstacles to enabling supply chain integration, such as consistently working with the same contractor to industrialise production processes, "*Serial tendering is also sometimes somewhat hindered by regulations*" (D3). Current legislation somewhat limits the ability to streamline partnerships (between public client and contractor) or build long-term production efficiencies through repeated collaboration.

Secondly, barriers arise around product tendering or IFD procurement framework. As one participant explained, "*You can certainly develop something like a product, but if it doesn't align with the conditions and requirements of the client's demand, then it doesn't fit their needs. You can keep on developing endlessly, but you end up with something that serves no purpose. Supply and demand have to align. Development will only really take off once there is a clear direction that clients want to move towards*" (D15). This highlights the structural challenge of synchronising innovation with procurement requirements and client expectations. An example of this can be found in Case B, with the product of (D6).

This point was further emphasised *"From this product perspective, there is still a real step to take if we want to move towards standardisation. That means that at some point several parties will need to start developing standard products to give substance to that standardisation. The question, however, is whether we are giving enough room and platform for this to happen. In the discussion groups, yes - but not yet in practice."* (D6).

Theme 4: Client related barriers

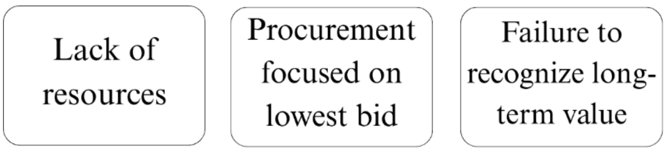


Figure 29: Barriers related to public

Public clients, such as municipalities and provinces, differ significantly in their capacity and enthusiasm for adopting new standards. Respondents noted that smaller municipalities are often focused on immediate issues, *"putting out fires"* (D9), and may lack the time, budget, or expertise to pursue innovative approaches. One public-sector participant acknowledged that municipalities are *"behind"* in circular and modular thinking (D10).

A key explanation given for this lag is the wider set of challenges currently facing local governments. As one interviewee noted "*But municipalities are currently dealing with much larger issues concerning their budgets, particularly in the social domain. We're seeing that there's simply too little money and capacity to take on trajectories like this, even from within the municipalities themselves*." (D10).

These clients frequently rely on external consultants to manage bridge tenders and will only consider IFD if it fits a low-cost, low-effort package. As one interviewee explained *"Smaller municipalities do* *not have the capacity (time and money) to demand sustainable bridge projects. They hire a consultant to help with a tender and, unless that consultant can provide a cheap bridge with a sustainable design, then IFD might be an option."* (D2). Additionally the lack of knowledge is also showcased by another consultant saying "*What you see is many clients asking, what exactly am I supposed to do with this NTA? … If we don't have a design yet, we can take the NTA and make some choices so it complies, but clients are unsure how to handle it."* (D1)

Limited resources consequently tie with another barrier procurement rules that prioritise the lowest initial cost, often ignoring long-term benefits such as reduced lifecycle costs, faster delivery, and improved quality (D10). This cost-driven approach discourages innovation and undermines the advantages of standardised design and construction.

Capacity constraints and cost pressures also mean that if IFD is perceived as requiring additional effort or investment, clients may simply opt out. Many also question the value of standardisation for one-off projects. As one client put it: *"If I only need one bridge, why would I standardise it?"* (D14). This illustrates a key challenge the systemic benefits of IFD, which rely on scale and repetition, are not compelling to individual clients focused on single, isolated projects.

<u>Theme 5: Organisational fragmentation and misalignment</u>

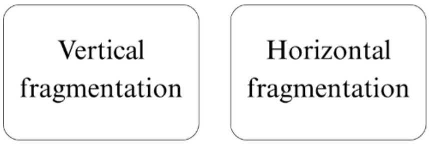


Figure 30: Barriers related to public

A recurring barrier to the adoption of IFD is the lack of alignment and weak communication among stakeholders, both within organizations and across project teams. Interviewees explained that differing interpretations and siloed communication often create confusion about what IFD requirements actually mean in practice. Within client organisations, departments frequently struggle to align their perspectives. As one engineer noted, *"the technical bridge engineer says one thing, the sustainability officer says another, and those demands only merge at the very end – often without fitting well together."* (D12)

Likewise, when multiple firms take on a project (client, contractors, designers), they often bring conflicting views on IFD. *"We were in a tender team with several parties. One said, 'We must do IFD,' another said, 'No way, it's not practical.' So we ended up trying to meet the requirement without really believing in it,"* (D1) . Such anecdotes reveal organizational misalignment, where lack of consensus leads to half-hearted implementation.

This compartmentalization also means that IFD principles may be championed by some individuals but not understood or prioritized by others, resulting in inconsistent application. Horizontally, across public stakeholders, there is also limited shared learning. As one respondent observed, *"But you do notice silos. These kinds of initiatives need to be shared more widely and advanced together. That's something the province could catalyse."* (D5). Another interviewee emphasised the same challenge across provinces: *"It doesn't add up much, does it? You deliver a nice bridge in one province, and then you go to another and they have completely different ideas. Then the benefits are minimal."* (D12).

Theme 6: NTA specific

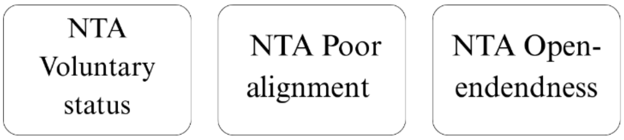


Figure 31: NTA specific barriers

Firstly, the non-binding nature of the NTA weakens its authority and results in inconsistent adoption across clients and projects. Because its application is voluntary, many public agencies choose not to use it, especially when there is no strong external incentive to do so. Since its application is voluntary, many public agencies choose not to use it, particularly in the absence of strong external incentives. As several respondents noted, beyond being a technical guideline, the NTA lacks a mandate from higher authorities to enforce or standardise the use of IFD (D3, D4). Without national policy or consistent requirements, many agencies overlook the NTA.

Another significant issue is that the NTA is still under development and contains notable gaps. Even the documents themselves acknowledge areas that require further elaboration and consensus. Equally mentioned that the NTA for instance does not cover "*sideway overpasses*" (D11). This undermines confidence in the NTA as a reliable and complete standard. Additionally, concerns were raised about the lack of alignment among the existing NTA documents (e.g., for movable and fixed bridges). Their miscoordination complicates implementation and makes it harder for designers, contractors, and clients to follow a unified approach.

Several respondents criticised the NTA for being too open-ended. While its flexibility aims to foster innovation, it often leads to vagueness and inconsistent interpretation. One interviewee called it "*an open-source development*" that "*allows a lot of room for interpretation*" (D2). This flexibility has resulted in various actors defining IFD differently, reducing interoperability. As one expert noted, "*Honestly, I would have preferred if concrete IFD modules were prescribed like, 'This is an IFD module, build this*'" (D2). However, another public client cautioned that overly prescriptive standards could shift too much design responsibility to the client: "*If you really want to do it well, you'd want to specify much more. But the more you prescribe, the more design responsibility you assume. That's always a tricky balance* " (D10). Equally, another contractor highlighted: "*Because if we have a programme with 5 different design firms that will reinterpret IFD, then all the homework that you did is worth nothing, because you're shifting the goalposts every time… They don't get the benefits."* (D5)

The lack of clear prescriptions also discourages prefab manufacturers and contractors from investing in industrial production lines, fearing their products may not align with differing interpretations (D5). This highlights a broader issue of fragmentation: without a strict, universal standard, regions develop their own IFD requirements. One respondent remarked, "*You want to tighten the framework so that designs for Woerden, Enschede, or Haarlem are at least equivalent. But that's still really difficult*" (D6).

Theme 7: Lack of coordinated leadership & structural market signals

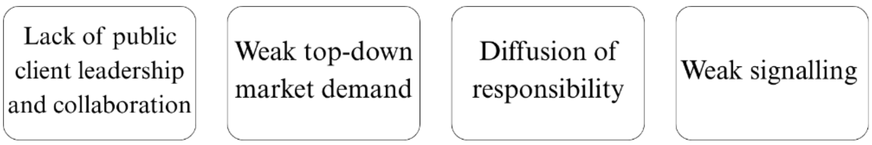


Figure 32: Lack of coordinated leadership and institutional mandate

A major barrier to the broader adoption of IFD is the lack of clear, consistent leadership from public clients, particularly in setting expectations, interpreting standards, and creating structural demand.

This leadership gap manifests in several ways, including a lack of public client leadership and collaboration, weak top-down market signals, and a diffusion of responsibility across stakeholders.

Interviewees emphasized that contractors and engineers generally follow what is requested in tenders and rarely take the initiative to introduce IFD themselves. There is a widespread view that unless IFD is explicitly demanded, it is unlikely to be pursued: *"If the client doesn't ask for it, not much happens."* (D5)

Many respondents highlighted the importance of top-down market demand. As one noted, *"If public clients started requiring IFD principles in their tenders, that would immediately push others to adopt it. A client mandate would change priorities overnight."* (D3) Another added, *"If we want IFD to really be adopted, the demand needs to be structural, consistent, and come from above."* (D9) The lack of such structural demand means innovative proposals are often left unused *"As engineering firms on the market side, we need contractors to come up with initiatives, but it all has to fit within the frameworks set in the tender. If I have an idea that the client isn't asking for - or doesn't dare to ask for - then it never gets off the ground."* (D3)

Contractors themselves recognize the need for clear and consistent market signals: *"Contractors see the asphalt running out; we all need to become more circular. Concrete too must become more sustainable. Contractors will adapt - but only if the market demands it. If there's no demand, what should they adapt to?"* (D2) This lack of coordination and commitment makes it unlikely that contractors will invest in IFD systems without reliable, repeatable demand.

The absence of strong leadership is also tied to a diffusion of responsibility. Stakeholders often assume that someone else whether larger clients, the national government, or the market will take the lead. As one participant observed, *"I think provinces and RWS can take the lead, and municipalities will follow. But you do notice silos. These kinds of initiatives need to be shared more widely and advanced together. That's something the province could catalyse."* (D3) Similarly, others questioned whether contractors could realistically take the lead: *"I don't really see how contractors would take the lead in applying IFD. They just follow what's asked. Sure, we could always try suggesting alternatives -but those are rarely accepted, and the effort often isn't worth the cost."* (D7)

A lack of collaboration between clients further limits progress. As one interviewee explained, *"If clients collaborated more, we'd see the benefits of IFD more clearly. You could build ten bridges with a single design, or learn quickly from one to the next."* (D1) Several interviewees also pointed out that while some public clients are exploring IFD and using the NTA, even setting up projects (D1, D2, D10), these efforts are not well signalled to the wider industry and therefore remain relatively quiet.

5.2 Interventions

Having identified the barriers in the previous chapter, participant were also asked various questions on how to overcome these challenges and promote the adoption of unified IFD standards. Interventions are a mix of instruments that can be used and also other steps that need to be taken according the interview participants.

The results are organized by three categories of instruments; Economic, Legal and Regulatory, and Communication reflecting the major areas in which measures to stimulate IFD uptake were identified. Within each category, several subcategories of interventions emerged from the interview data. The analysis below synthesises these interventions, clarifies their practical implications, and illustrates them with representative quotes from the interviews.

Theme 1: Economic

An economic intervention has aims to influence behaviours through market-based mechanisms and financial incentives. In the interviews the following measures were mentioned on how to promote IFD, see table 6.

Table 6: Economic interventions

Intervention	Responsible Actor(s)	Comment on Practical Implementation
Subsidies or grants	National government (relevant ministries), provincial authorities	Can be implemented by setting up national/provincial grant programs to co-fund IFD pilot projects or innovations.
Tax-based incentives	National government (tax authorities, finance ministry)	Finance ministries could introduce tax deductions or VAT exemptions for reuse components or circular design features (such as IFD).
Procurement incentives	Public procuring agencies (municipalities, provinces, national infrastructure agencies)	Public clients can revise tender criteria to reward IFD use, e.g., through EMVI scoring or awarding price reductions.

Subsidies or grants

Interviewees mentioned the importance of financial support mechanisms, such as subsidies and grants, to lower the entry barrier for adopting IFD principles (D1 D6, D11). These were seen as essential to de-risking innovation and incentivising the use of modular, demountable bridge. Specifically how this should be implemented was unclear from the interviews.

A common theme was "challenging" the market to encourage IFD uptake. For example, one respondent noted: *"But there is always room to keep challenging the market and use marktprikkels to get contractors and engineering firms to do more than they currently do."*D1 This reflects the idea of using market incentives (often referred to by the Dutch term *marktprikkels*) such as competitions, pricing structures or R&D that push suppliers to offer IFD solutions.

The practical implication is that with targeted subsidies, contractors and suppliers might be more willing to develop standardised bridge elements, and clients would face less budgetary hurdle in specifying IFD requirements.

Tax-Based incentives

Although mentioned less frequently, a few respondents pointed out the potential of tax-related incentives *"There should be a way to reward circularity fiscally. Right now, the tax system doesn't really distinguish between linear and circular designs."* D14. These could include VAT reductions for reused components or tax deductions linked to modular design investments. While no interviewee explicitly detailed a tax scheme, the underlying idea is to leverage the tax system to make innovative circular solutions financially advantageous and thus giving and advantage to the IFD approach. However, this was not a dominant theme in the interviews, suggesting that stakeholders focused more on direct procurement-related incentives than on abstract fiscal policy changes.

Procurement incentive

Many interviewees suggested that public clients should create financial rewards or competitive advantages for projects that incorporate IFD. For example, one participant proposed rewarding contractors for working with IFD through tendering incentives: *"Perhaps you can even give a discount on the bid price if a contractor can show they use IFD. ... If you can prove you're building IFD, then it becomes very attractive"* D12. Such procurement incentives (for example, using award criteria in

Best Value procurement or EMAT/EMVI scoring to give an edge to IFD-based proposals). This is something which the PNH is already incorporating and their IFD procurement strategy, see Appendix C.

Theme 2: Legal and regulatory

Legal and regulatory interventions refer to changes in laws, standards, and formal procedures that can facilitate the adoption of IFD and the NTA. These measures are mostly top-down hierarchical types of interventions, where a higher authority needs to step in to make this change. Though, the NTA development measure is done under the network governance as done during its initial development.

Table 7: Legal and regulatory interventions

Intervention	Responsible Actor(s)	Comment on Practical Implementation
Procurement frameworks (Product catalogue)	National government policymakers	Set up national or regional procurement frameworks that allow municipalities to select from pre-approved IFD bridge designs (a product catalogue).
NTA development	Standard bodies (NEN) with industry experts; supported by government funding and oversight	Continue funding and coordinating NEN working groups and development of the NTA.
Mandatory NTA (norm)	Government policymakers (national or provincial agencies)	Government to integrate NTA into national procurement law or guidelines to enforce use in public infrastructure projects.

Procurement frameworks (Product catalogue)

In addition to technical rules, participants highlighted procurement regulations and contracting mechanisms as key areas where interventions could accelerate the IFD transition. A frequently mentioned idea was the development of a product catalogue, often described as an ideal outcome or even the ideal form of the standardised NTA product. One contractor illustrated this vision: "*For example, you could look in a brochure, select a bridge from different contractors, and in that way choose the right bridge. From this product perspective, there is still a real step to take if we want to move towards standardisation. That means that at some point several parties will need to start developing standard products to give substance to that standardisation*." (D6).

Rather than each municipality tendering a single bridge project independently, one interviewee explained: *"You could tender for a product database (catalogue) of bridges. Then clients can choose bridges from that framework, or hold a mini-competition. It saves on tendering costs, ensures product quality, and allows contractors to reinvest in improvements."* (D2)

This approach suggests a centralised, pre-approved catalogue of modular bridge designs from which local authorities could effectively "shop" without having to run a full tender for every project. Another participant described it more vividly as an *"IKEA of bridge building"* scenario "*go to the catalogue, pick a standard bridge (specifying length, width, etc.), have it delivered and assembled, and you have your bridge*" (D3). However, there were doubts if such a system would require adjustments to procurement regulations, as EU law currently limits the extent to which catalogue-based frameworks could be applied. At the same time, Case B illustrates that within a D&C contract, if not too many prescriptive requirements are set, such an approach could be feasible. The alternative bid by D6, which offered a product-based modular bridge system, provides an example of how catalogue-ready solutions might be introduced in practice, provided that tender specifications leave sufficient room.

NTA development
Continuous development of the NTA is seen as a critical step in overcoming current barriers to adoption. Interviewees widely agreed that if the industry guided by standardisation bodies (NEN) can finalise and consolidate standard designs and specifications. "*We must keep funding the NEN working groups so contractors, fabricators and engineers all define the IFD parts together.*" (D2). As another participant stressed: *"I think there are still a few steps needed for further development, and the NTA still needs to be developed further."* (D6).

A recurring theme was the need for the NTA to remain a living standard or open-source standard, evolving over time to integrate project feedback, technical advancements, and new insights from practice (D1, D2). As highlighted in the case results, structured processes must be established to ensure that lessons learned in projects are systematically fed back into the NTA (B1). Without such mechanisms, valuable practical knowledge risks being lost. Equally contractors are willing to add to this development with their own initiatives *"if there is demand to open it up more, we could, for example, work on an addendum to the NTA for steel-concrete bridges… we'd have to discuss how we can make that more open."* (D6)

Alongside this, filling in the gaps of the current documents is necessary to reduce ambiguity. Another important area is the improved alignment between the various NTA documents. Ensuring consistency across these standards. One contractor mentioned; *"Collaboration across the supply chain is key. We need to get designers, contractors, and suppliers all involved early to develop and agree on IFD components together. That way, everyone is on board and capable when it comes time to build."* (D1)

Mandatory NTA (norm)

Some interviewees (D9, D12) suggested that ideally a hard legal measure, transitioning the NTA from a voluntary guideline into a binding legal norm, would represent a significant shift in regulatory approach but could also provide the strong, top-down mandate that is currently missing. As one participant noted, *"Maybe the NTA and IFD should be promoted from The Hague, so to speak. And that it is, as it were, prescribed and perhaps even incorporated into the calculation rules or building regulations."* (D12).

At the same time, concerns were raised that the sector is not yet ready for such a step. As one respondent explained, *"You could mandate the NTA, however there is a lot more adoption needed to consider this"* (D9). This view is echoed by the NEN, who stressed that only if adoption becomes more mainstream could making the NTA mandatory be considered a viable option.

Theme 3: Communication

Communication-based interventions were highlighted as essential for building awareness, trust, and momentum behind IFD bridge construction. Many said that the goal behind communication is also to stimulate and organise participation among actors. Many of the challenges to IFD adoption stem from unfamiliarity or scepticism/conservatism, so interviewees stressed the importance of demonstration projects, knowledge sharing, training, and leading by example to convince stakeholders (mainly public clients) of IFD's benefits. Unlike economic or legal tools, these measures focus on influencing perceptions and capabilities through information and experience. The interventions pertaining to communication was also the most frequently mentioned.

Table 8: Communication interventions

Intervention	Responsible Actor(s)	Comment on Practical Implementation
Pilot projects & demos	Early-adopting clients (provinces, large municipalities, RWS) in partnership with contractors	Clients partner with contractors to build and evaluate IFD bridges, then document and disseminate findings to peers.

Knowledge sharing & awareness	Knowledge institutes, industry associations, and government agencies	Organize roadshows, workshops, and a central online repository to spread knowledge.
Training and education	Knowledge centres and professional bodies (with support from government and early adopters)	Offer targeted training for public procurers, engineers, and contractors on applying NTA standards and IFD.
Lead by example and collaboration	Major public clients (provincial authorities, RWS, big municipalities)	Provinces and agencies visibly commit to IFD by using it in own projects and sharing results with smaller clients.
Ongoing dialogue	All stakeholders (clients, contractors, designers, standards bodies)	Convene multi-stakeholder working groups to discuss standard interpretation, gather feedback, and build consensus.

Pilot Projects

Interviewees repeatedly stressed the importance of successful pilot projects and "iconic" examples to showcase the viability of IFD in bridge construction. Several participants lamented that, to date, only a few IFD bridges have been built and publicized. As one expert noted, *"Ultimately we just need many more examples. Now we have the Cruquius bridge, the Cruquius bridge and the Cruquius bridge. I honestly expected that from 2018–2019 to now we would have ten good examples. I really need those. – with ten examples, I could go to all my clients and say: look, this is already possible, we learned from it, and it can be even better next time. … Unfortunately, we don't have that many examples yet, and I really need them"* (D2).

This statement illustrates a common sentiment practical demonstration is needed to overcome scepticism. Participants explained that seeing an IFD bridge successfully implemented with acceptable cost and performance helps convince other municipalities that "*it's not that much extra effort and it delivers a lot of benefits*" (D2). In essence, "*concrete and compelling pilot projects are always the most effective" in persuading people"* (D9). Such projects serve as proof-of-concept, reducing the "*cold feet*" (D3) (initial fear of the unknown) among potential adopters. One interviewee emphasised, "*We also believe in this 100%. But getting everyone on board and making them believe takes time. That happens by putting these kinds of projects* (reference towards Case B) *on the market and letting people see and realise: oh yes, it can be done this way as well."* (D15).

One respondent enthusiastically said, *"We should build a lot of these bridges and shout from the rooftops about them, show that standardization works and really offers advantages"* (D3). The implication is that scaling up the number of pilot projects and widely publicizing their outcomes can create a bandwagon effect. This highlights the communication side of demonstration projects not only doing them, but actively broadcasting their success.

Knowledge Sharing & Learning

In tandem with pilots, structured knowledge sharing was seen as vital. Interviews revealed concern that many public agencies and contractors currently operate in silos regarding IFD, with each learning on their own (see previous section on horizontal fragmentation).

Several participants argued for the creation of platforms to exchange lessons learned, best practices, and technical knowledge about IFD bridge construction. As one interviewee urged, *"Initiatives like this need to be shared more broadly and advanced together"* (D5), referring to PNH's ongoing IFD projects.

More horizontal communication between public client, essentially learning from each other's experiences, or contractors and engineers openly discussing results would accelerate improvement. Some suggested organizing regular forums or a *"roadshow"* (D3) where successful IFD projects are presented in various regions, allowing local officials and engineers to directly see and discuss outcomes. Others mentioned the idea of a knowledge hub or database (potentially overlapping with the technical idea of a product catalogue) where information on standard designs and past projects could be accessed easily by all stakeholders (D2).

In practical terms, this could take the form of workshops, inter-municipal working groups, or online platforms, potentially coordinated by a province or an industry association. The goal is to break down information barriers and ensure that valuable insights are disseminated across the bridge-building community. *"It would help if there was a central body or consortium that provided standard IFD designs or a library of components. If we had clear, ready-to-use standards, it'd be easier for everyone to adopt rather than each firm reinventing the wheel."* (D2)

Training and education

Closely related to knowledge sharing is the need for training and education to build up expertise in IFD construction. A few interviewees noted that the unfamiliarity with IFD principles among client organizations and even some contractors points to a skills gap (see previous section). They observed that many municipal engineers or project managers simply have never been exposed to designing with IFD or using the new standards.

As one interviewee remarked, clients sometimes react with confusion when IFD is introduced *'What am I supposed to do with the design?'* (D2). This highlights the need for guidance and practical tools to support public clients in understanding IFD. Another participant suggested that *"workshops, guidelines or trainings on how to apply the NTA in procurement would help clients feel more confident"* (D1).

Lead by example and collaboration

Another communication-related strategy highlighted was the power of leading by example. Many interviewees argued that larger public clients such as the provinces or the national infrastructure agency (RWS) need to act as champions of IFD and visibly commit to it, in order to inspire confidence down the line. *"I think the provinces and Rijkswaterstaat can be frontrunners and then the municipalities will follow"* (D5).

By taking a "first mover" role, these major clients demonstrate that IFD bridges are viable. For instance, when a province successfully implements a series of IFD bridges and makes it a standard practice, it creates a powerful example that others can emulate "*leading by doing*" (D11).

In practice, "leading by example" could mean that a province not only uses IFD in its own bridge projects but also actively involves municipal officials in those projects (for example, through joint working groups or showcase events). One suggestion from an interviewee was that *"the PNH could pick up a project together with a municipal client and then present it to other municipalities – that might work even better"* (D1) for spreading adoption. This underlines that championing is not just about doing it first, but also about mentoring and encouraging others. The overall insight is that strong leadership and visible commitment from the top of the public sector can lend legitimacy to IFD, create momentum, and effectively communicate to all stakeholders that "*the public client need to indicate this is the direction we are going,"*(D5) thereby accelerating broader uptake.

Ongoing dialogue

Fostering a continuous dialogue between stakeholders clients, contractors, engineers, and standard developers about IFD implementation and the constant development of the NTA. This ties into the legal and regulatory type of intervention in the continuous development of the NTA.

One interviewee described the value of convening conversations where each party can discuss how they interpret and experience the IFD guidelines: *"Why isn't it being applied more? You could find out by starting the dialogue: how does the client read this [the standard]? How does the contractor read it? The architect? What do you think works well, what not? Ultimately you'd arrive at a request that everyone can live with… I think that dialogue can play an important role"* D1 This suggests establishing forums or working groups that regularly bring together different perspectives to align expectations and share feedback on IFD projects or the further implementation of the NTA.

Indeed, maintaining open communication channels was also mentioned in the context of standard development as the IFD standard evolves; continuing to involve contractors and other practitioners in the discussion ensures the end product is practical and widely accepted. *"We must keep funding the NEN working groups so contractors, fabricators and engineers all define the IFD parts together"(*D2).

5.3 Summary of Findings

Barriers

Findings from the semi-structured interviews complement the case insights by exposing 7 major categories of barriers hindering the broader uptake of standardised IFD:

1. **Institutional Conservatism**: Widespread resistance to change and risk aversion, especially around unfamiliar or untested methods.
2. **Limited knowledge diffusion & lack of relatable demonstrations**: Awareness often stops at buzzword level; few small, locally relevant pilots exist, many clients and practitioners can't see how to apply IFD/NTA in their context
3. **Regulatory framework:** Procurement rules hinder serial collaboration and standardisation and IFD procurement model of 'shopping' for a bridge not possible.
4. **Client-Side Constraints**: Especially in smaller municipalities: scarce time/budget, reliance on consultants, and award criteria emphasizing lowest upfront price over lifecycle value dampen demand for IFD.
5. **Organisational fragmentation and misalignment**: Siloed departments and mixed messages within client organizations, and limited shared learning across public clients, plus divergent views across tender teams, reduce consistency and turn IFD into a box-ticking exercise rather than a shared goal.
6. **NTA specific barriers**: NTAs are voluntary, still developing, somewhat misaligned and open-endedness gives uncertainty.
7. **Lack of coordinated leadership & structural market signals**: No strong, consistent top-down mandate; responsibilities diffuse across RWS/provinces/municipalities; limited visible champions, collaboration and weak signalling.

Interventions

Interviewees identified a range of economic, legal-regulatory, and communication-based interventions to address these barriers:

- **Economic**: Targeted pilot/co-funding and training subsidies to de-risk early adoption; procurement EMVI/MEAT criteria that reward IFD outcomes; selective fiscal measures (e.g., VAT/deductions for reuse) to improve lifecycle economics.
- **Legal/Regulatory**: Procurement frameworks/catalogues that let clients “buy” from pre-approved modular designs; continued NTA development and alignment with clearer reference solutions at interface level; consider partial mandating of core NTA interfaces once adoption further matures.
- **Communication**: Scale pilot projects and make results visible; build a shared knowledge hub; deliver hands-on training for procurers/designers; lead by example (provinces/RWS) and maintain structured multi-stakeholder dialogue to converge on consistent interpretations.

Chapter 6 - Discussion

The discussion chapter presents an integrated interpretation of the main findings in the previous results and analysis Chapter 4 and 5. It begins by outlining the key insights derived from the research, offering a critical interpretation of these results. Subsequently, it aligns these findings with the existing body of literature, drawing connections between observed trends and established theoretical frameworks. Following, suggestions for future research and finally limitations and strengths of the thesis.

6.1 Main Findings

The findings from this research reveal a complex interplay between technical innovation and diffusion, systemic barriers, and governance context in the Dutch infrastructure sector. Figure 33 below provides an overview of the main findings. In this chapter, these results are interpreted in light of existing literature on systemic innovation and governance. The discussion first relates the empirical findings to the analytical framework namely Wieczorek and Hekkert's (2012) systemic problems/instruments logic improved with Bednar et al.'s (2018) governance overlay to show how the IFD transition aligns with and adds to theory. It discusses key theoretical contributions of the study, highlighting how IFD challenges or extends current understandings of systemic problems and governance modes. Next, practical implications are drawn for regulation frameworks and procurement practices by mainly Larsson et al. (2013), considering if there is another path to IFD procurement and standardisation.

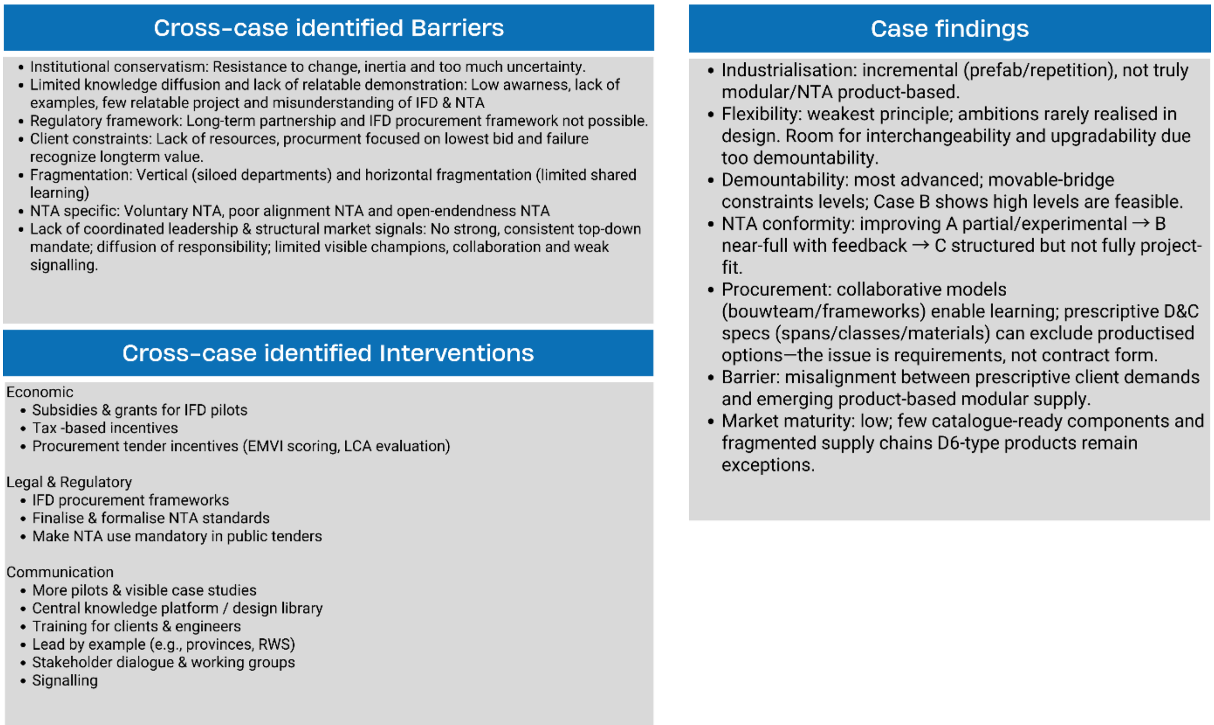


Figure 33: Main findings of research

6.1.1 Interpretation main findings

Across the three cases and the interviews, it is clear that the IFD transition is underway but not yet regime-forming. Implementation is strongest at the project level (one-off designs that borrow IFD ideas) rather than at the product/industry level (repeatable, standardised solutions pumped through stable supply chains). In diffusion terms, practice sits between early pilot uptake and an "early majority" that would require more certainty in demand as per the quotes of the supply side, essentially to increase uptake industry frontrunners need to address the barriers and utilise the identified interventions.

This pattern explains the case EM scores:

- Industrialisation: moderate. Prefabrication and repetition occur, but serial production and platformed supply chains are rare. Case B's twin bridges and somewhat Case C capture process repetition more than product platforming.
- Flexibility: weakest. Teams hesitate to spend now for uncertain future option value; guidance on where flexibility pays is thin. This aligned with Saari & Heikkila (2008) as the knowledge or certainty to which you know change will occur in functionality or intensity decreases (thus increased uncertainty over time).
- Demountability: comparatively strongest. It is tangible, design-controllable, and easier to justify to clients and verifiers than open-ended flexibility.
- NTA conformity: the document is improving but still incomplete. NTA compliance was found to improve significantly when standards were referenced early in the design process, as seen in Case B and C.

Notably, the D6 bid in Case B reflects how cross-case interviewees described the ideal scenario for IFD transition and NTA adoption. Stakeholders envisioned a future "product catalogue" model in which public clients could purchase modular bridge systems off-the-shelf rather than commission bespoke designs. Similarly, interviewers suggested a new procurement framework (legal and regulatory intervention) to allow this type of 'shopping'. At the same time, the case exposed a risk of unintended exclusion or perhaps too many demands: when tenders apply narrow interface classes or prescriptive criteria, viable standardised products can be ruled out at the outset, as per the interviewer "*but once your product doesn't fit, you're out*." (D6). This may also deter other suppliers from adopting IFD/NTA, reinforcing a perception that "*the real question is whether the product truly matches the demand*" (D15). Essentially, the construction market is seen as a liberal market and is meant to give room for innovation but however perhaps the demands public clients make or because of our procurement system (rules, regulations, norms etc.) essentially block this intention.

Empirically, the system behaves as market-demand governance as the supply side indicated that they will follow clear, repeated client signals, but will not front-run without them. There will always be outliers to this notion and seek opportunity in the transition, perhaps being an early majority, this is evident from the frontrunners and also D6 from case B and for instance, the IFD Colombia bridge (Appendix E).

Nonetheless, a majority will operate in this idea (that they will follow with signals), which was reinforced in interviews, particularly regarding Barrier 7 (lack of coordinated leadership and institutional demand). Contractors and engineering firms described themselves as responders rather than initiators of change, emphasising that public clients must lead by explicitly demanding IFD solutions. Importantly, this stance does not reflect outright resistance (Theme 1: Institutional conservatism), but rather a cautious wait for consistent signals that justify investment. Sheffer D.A (2011) ties this too the characteristics of the construction products being costly and durable resulting in susceptibility to demand fluctuations and the effect being reluctance to invest and technology risk aversion (other studies such as Larson et al. (2013) see this as conservatism). Essentially there is too much uncertainty which creates this demand fluctuation. Larsson et al. (2013) similarly mentions this as a barrier to standardised and IC practices as lack of repetition, and ties is directly to public clients as responsible actor. This notion highlights a clear direction by who the transition could be steered.

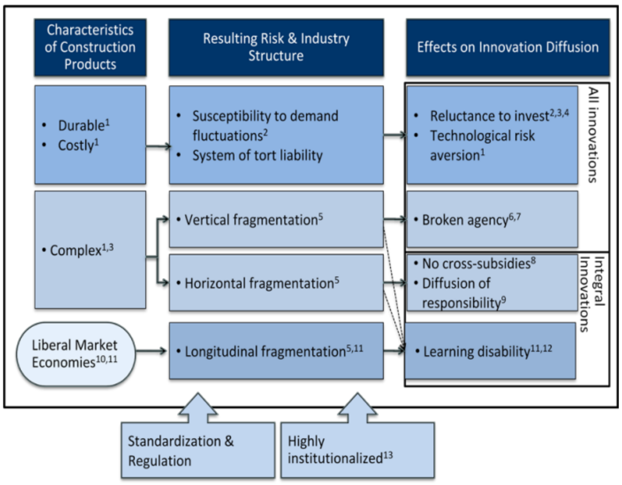


Figure 14:Barriers (resulting risks) to innovation in the construction industry with problems caused due to these risks (Sheffer D.A , 2011)

This dynamic positions public clients as critical enablers of systemic change, but many public clients are not currently equipped or incentivised to take on this role. Smaller municipalities often lack the technical expertise, resources, or strategic capacity to incorporate IFD into procurement (Theme 4: client-related barriers) and others are still not convinced. Responsibility therefore falls to larger, better-resourced clients such as provinces or national authorities to act as frontrunners and enable broader adoption across the sector. While these actors have the capacity to orchestrate signals, they operate within network governance and hold limited hard levers (Bednar et al., 2018). As such, the identified communication instruments are best suited to use in this type of governance sphere. This was an expected outcome.

Other interventions, such as legal and regulatory changes, require hierarchical action at the national level and are unlikely to materialise until adoption increases. For example, mandating the NTA (Theme 6) is an intervention which can only be considered adoption of the NTA increases as currently the NTA has been developed in a network (collaboration) essentially reflecting a network codification. Economic instruments such as tax breaks are also unlikely to play a role in the short term, with procurement incentives or subsidies remaining the most feasible levers.

Furthermore not surprising that some barriers and interventions align essentially, being able to be paired. Obviously example barrier is the incomplete NTA barriers, and in the intervention, legal and regulatory measures on the continuity of work of the NTA. Equally, what should be considered are some barriers that can be somewhat addressed directly others fall under a similar category of direction.

6.1.2 Interpretation and implications of the findings with existing literature

Theme 1:

The empirical results resonate strongly with the systemic innovation literature. Many of the identified challenges correspond to well-known systemic problems that can hinder technological transitions. For example, the widespread institutional conservatism and risk aversion observed among stakeholders (Theme 1) reflects a “soft institutional failure”, wherein cultural-cognitive institutions (mindsets, norms) impede change. Equally identified by Brouwer (2024) as a systemic barrier and Larsson et al. (2013) on the barriers to standardisation of products. Stakeholders admitted a “reluctance to change established practices” and a preference for familiar methods despite recognizing IFD’s benefits. This aligns with literature describing how entrenched norms and uncertainty avoidance can slow innovation adoption (a soft institutional barrier) (Wiezoreck & Hekkert, 2012). Similarly, the barrier of limited knowledge diffusion and demonstration (Theme 2) corresponds to a knowledge infrastructure problem i.e. insufficient circulation of information and examples in the system, this is equally seen by Brouwer (2024) as systemic problem labelled as insufficient support for innovation & knowledge exchange. Many practitioners have only a vague idea of IFD even years after its introduction, and "*still don't really know what IFD is*" (D2), indicating a failure in the system's ability to effectively share lessons and evidence. Or even more so the lack of accessible pilot projects beyond a few flagship cases further hampers learning, echoing the importance of demonstration projects in diffusion theory. In innovation system terms, this is a functional weakness in knowledge diffusion and learning that inhibits positive feedback loops.

Several structural system failures are also evident. Interaction (network) failures manifest as fragmentation and misalignment among actors (Theme 5). The study found weak coordination both "within organizations and across project teams," leading to inconsistent interpretations of IFD requirements and "*half-hearted implementation*" (D1) when partners disagree. This is a classic weak network failure, where actors are not sufficiently aligned to pursue a common innovation goa (Wiezoreck & Hekkert, 2012). At the same time, there are hints of strong network failures in pockets for instance, if a small group of frontrunners closely collaborate, it may inadvertently exclude others, though in this case the dominant issue is more about too little connection rather than too much exclusivity.

Another structural issue is the incomplete institutional framework around IFD. The NTA standard itself a form of hard institutional intervention currently lacks formal authority (voluntary use only). This presents a hard institutional failure (Wiezoreck & Hekkert, 2012). There is no binding regulation or policy compelling adoption, and gaps in the standard mean it does not yet function as a comprehensive rule-set. In fact, respondents noted that without a mandate or higher-level directive, many agencies "simply overlook the NTA," resulting in inconsistent uptake.

Additionally, market structure failures are apparent. The research highlighted that the supply chain has not developed ready-made IFD/NTA conform components or "catalogue-ready" solutions due to uncertainty of demand. Contractors and manufacturers are hesitant to invest in modular product lines when each client might interpret standards differently and no guaranteed market exists. This aligns with the notion of capacity and market failures i.e. missing capabilities in firms and a growing market that has not yet formed around the new standard. In summary, the findings confirm that IFD adoption is impeded by multiple interlocking systemic problems, spanning institutional, interaction, and infrastructure dimensions of the innovation system. This provides empirical support to Wieczorek & Hekkert's framework, which stresses identifying such systemic problems as a precursor to targeted interventions.

Crucially, the study also demonstrates how the governance context modulates these systemic issues and the choice of solutions. By overlaying Bednar et al.'s (2018) governance perspective, we see that the Dutch infrastructure sector exhibits a mix of governance modes, with a notable emphasis on network governance. Bednar et al. (2018) distinguish between hierarchy, market, network, and community modes of governance. In the IFD program, many initiatives (such as the NTA development and "open source" knowledge sharing) have been driven by collaborative, network-oriented arrangements rather than top-down authority. This has implications for how far certain interventions can go. For instance, under a decentralized network governance regime, a purely hierarchical instrument (such as a national mandate requiring IFD) is hard to implement because authority is distributed provinces or the national government cannot simply impose standards on autonomous municipal projects. Thus, softer instruments such as voluntary agreements, guidelines, and joint knowledge platforms have been the primary tools so far, consistent with what Bednar et al. (2018) term "communication instruments" suited to network governance. Our findings illustrate this: the NTA is a consensus-based standard (essentially a voluntary technical agreement) and its promotion relied on persuasion and piloting rather than regulation. While this network-based approach enabled broad stakeholder involvement and initial buy-in, it also led to voluntary uptake only, meaning many actors remain unconvinced or uninvolved. The result is patchy adoption a known challenge when operating in a non-hierarchical context. Interviewees noted, for example, that provinces have limited formal power over municipalities' bridge choices, so progress depends on coordinative efforts and shared vision rather than orders. This aligns with Bednar et al.'s (2018) argument that understanding the dominant governance mode is "crucial for selecting appropriate intervention strategies". In short, the governance lens helps explain why certain systemic problems persist: fragmentation and inconsistency in IFD uptake can be traced not only to a lack of awareness or capability, but also to the diffuse authority structure in the Dutch public infrastructure landscape. It also underscores that any systemic instruments proposed (e.g. new policies or support measures) must fit the governance environment to be viable. The combination of the two theoretical lenses systemic problems and governance modes thus provides a richer explanatory framework for our findings, ensuring that both the "what" (barriers and solutions) and the "how" (the way coordination happens) are taken into account.

Overall, the empirical evidence both supports existing theory and points to areas of extension. It reaffirms that IFD, as a innovation in construction, faces classic systemic barriers that need combined policy intervention validating the usefulness of frameworks such as Wieczorek & Hekkert's (2012). At the same time, the case highlights nuances such as the importance of multi-actor governance dynamics (per Bednar et al. 2018) that traditional innovation system analyses might underemphasise.

Based on the above reflections, this research offers several contributions to the academic understanding of systemic innovation and governance in infrastructure transitions. The key theoretical contributions are:

The study extends Wieczorek & Hekkert's (2011) systemic innovation framework by demonstrating how introducing a technical standard (NTA) as a systemic instrument can both address and reveal systemic problems. In line with theory, the NTA was intended to tackle an institutional failure (lack of common standards) and facilitate market formation. Our findings show that this systemic instrument indeed filled a crucial gap it provided, for the first time, a technical "playbook" for IFD that stakeholders could commonly refer to. However, the cases also highlight that a single instrument is not a silver bullet; deploying the NTA exposed other bottlenecks (e.g. limited knowledge, conservative culture, misaligned incentives) that require additional interventions. This contributes to theory by illustrating the interdependence of systemic instruments: a technical standard alone had limited impact without complementary measures such as training, demos, or incentives, reinforcing the notion that systemic failures must be addressed with a portfolio of coordinated instruments. Moreover, the IFD case challenges the assumption that once a standard or technology is available, the system will automatically adjust. Instead, it shows that voluntary standards need active support to achieve widespread adoption, thereby extending the systemic-instrument logic to emphasize implementation and uptake, not just design. In sum, this research underscores that systemic innovation policies must go beyond creating tools (standards, platforms) to also foster the conditions for their uptake (e.g. mandate or incentivize their use, enable actor capabilities) a critical nuance for the literature on Technological Innovation Systems and transition management.

A second contribution lies in bridging innovation systems analysis with governance theory. By applying Bednar et al.'s (2018) governance typology, the study shows that the mode of governance fundamentally shapes transition dynamics and required interventions. The IFD transition in Dutch infrastructure demonstrates that network-based governance, while valuable for early-stage innovation (fostering collaboration and consensus), may struggle to enforce system-wide change. Our cases revealed that a collaborative, bottom-up approach led to important achievements (development of NTAs, pilot projects, knowledge networks) under a voluntary basis. However, the lack of hierarchical reinforcement has resulted in uneven adoption many public clients and firms remain on the sidelines. This finding contributes to theory by highlighting the need for hybrid governance approaches in scaling up innovations and adoption. Specifically, it suggests that transitions may require a shift from predominantly network governance towards a mix that includes selective hierarchical or market mechanisms over time. For instance, as the innovation matures, hierarchical measures (e.g. national standards, funding conditions) might be introduced to accelerate diffusion, while market-based incentives (e.g. procurement rewards, subsidies for standard solutions) can motivate industry investment. This complements Bednar et al.'s framework by illustrating that governance modes are not static alternatives but can be sequenced or combined to suit different transition phases. The interplay observed between initiatives such as (IFD Colombia bridge), voluntary networks, and hopes for national direction provides a richer picture of governance in transitions than a one-size-fits-all model. Thus, this study nuances governance theory by empirically showing that successful innovation diffusion may depend on aligning multiple governance modes leveraging the strengths of each. It calls attention to the governance "mix and shift" as a dynamic aspect of transition management, contributing to a more adaptive governance paradigm.

Theme 2:

Theme 3 (Regulatory framework) aligns with Larsson et al. (2013), who identify the inability of contractors and clients to form long-term relationships as a primary barrier to IC and standardisation. That barrier rooted in a liberal, transactional market links directly to Sheffer (2011)'s notion of longitudinal fragmentation, which produces a sector-wide learning disability across projects. Our Case C echoes this: the framework agreement covering 4 similar movable bridges enabled learning across projects and the incorporation of lessons from one project to the next, with potential for design reuse. However, this primarily reflects procedural learning, not the platform building associated with IC or product development (Lessing, 2015). Put differently, current arrangements still fall short of the manufacturing logic that IFD seeks to realise (NEN, 2024b).

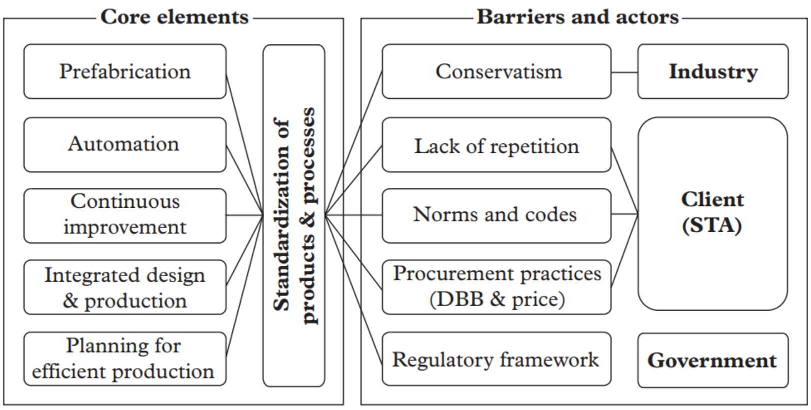


Figure 35: Perceived barriers to increased IC and standardisation related to actors who could remove them (Larsson et al., 2013)

The NTA aims to address this gap by enabling platform development through interface and dimensional standardisation. Yet limited adoption and the absence of formal feedback loops to channel practice-based insights back into NTA revisions constrain its impact. Even so, Case B (the "failed" D6 tender) offers a glimpse of platform-oriented feedback loops: "*Initially, we didn't have demountable substructures, but we eventually developed them during the tender. So in that sense, it wasn't wasted effort - we can reuse the idea in the next tender. And we will take this forward into the next discussions on revisions of the NTA*." (D6).

Procurement practices compound these issues. Larsson et al. (2013) flag lowest-bid selection as a barrier to standardised construction. Our Theme 4 (client-related barriers) finds a similar pattern: many municipalities lack capacity to engage with IFD and the NTA, nudging them toward lowest-cost criteria and away from innovation. Beyond price, our data show that rigid, prescriptive criteria including how NTA classes are specified can narrow product options and inadvertently pre-select other options: *"We see the NTA as a guideline with classes, like clearance heights. You should comply with one of these classes, but in this project a specific class was prescribed. By doing that, you effectively prescribe certain products, like concrete box girders, while excluding other systems that could achieve the same span. That wasn't clear in the beginning, but once your product doesn't fit, you're out."* (D6). The appointed contractor (D15) echoed this sentiment more generally, reflecting: *"The real question is whether the product truly matches the demand."* (D15).

Taken together, this broadens Larsson et al.'s (2013) procurement barrier from lowest-bid to also include over-prescription and criteria rigidity within a project-oriented regime that struggles to accommodate product-based solutions. As long as infrastructure is treated as a custom product every time, the shift toward an industrialised, product-based (IFD) construction market will remain difficult.

IFD products could, in principle, occur under D&C contracts, but it would require very little criteria-based specification on dimensions for instance. A new IFD-oriented procurement approach may therefore be needed.

Relating this to the identified interventions: in our case, the hierarchical governance (laws, formal procedures) and market-based tendering has not yet evolved to support IFD. The study's evidence aligns with this logic stakeholders envisioned a procurement framework enabling a "product catalogue" approach, modular bridge systems bought off-the-shelf rather than bespoke each time. Such a shift would likely require hierarchical interventions (policy changes or new regulations) to permit standard products in public procurement.

6.2 Suggestions for future research

The results point to multiple opportunities for further research. First of all, future studies should explore how procurement and contracting models can be reimagined to facilitate platform-based, repeatable IFD solutions. This could involve investigating the feasibility of a "product catalogue" approach for bridges under public procurement law. For example, research could analyse legal and economic mechanisms to allow public clients to procure standardised bridge modules (perhaps via framework agreements, innovation partnerships, or changes in EU tender directives) without violating competition rules. Such work would directly address the regulatory misfit identified in our study and could provide practical roadmaps for policymakers on enabling off-the-shelf modular infrastructure, essentially operationalising the "IFD shopping" concept envisioned by stakeholders. Comparative research might look at other countries or sectors (e.g. prefabricated housing) that have made progress in catalogue-based procurement for lessons applicable to bridges.

Furthermore, to test the generalisability of the findings, research in diverse contexts is needed. One suggestion is a comparative case study or survey across multiple Dutch provinces and municipalities, examining how smaller or less-resourced clients manage (or struggle with) IFD implementation. In parallel, study projects that apply standardisation differently (e.g., alternative interface standards, firm-specific standards). Additionally, a longitudinal study following current IFD pilot projects into their operational or end-of-life phase would be highly valuable. Such research could track whether the anticipated benefits such as ease of component replacement or actual reuse of demountable parts are realised over time. It would also document how maintenance and end-of-life processes evolve for IFD structures, providing feedback to improve NTA standards or design guidelines. Essentially, this future work would move beyond the early adoption phase and evaluate IFD in the medium to long term, informing whether the early promise translates into sustained impact. Moreover, longitudinal analysis could monitor how the network of actors and institutions around IFD changes: for instance, do more suppliers start offering standard IFD and NTA conform components? Do educational curricula begin teaching IFD concepts? Such questions go beyond the scope of the small window through which this research has looked, but answering them will be key to understanding and steering the transition.

6.3 Limitations and strengths

While the study provides valuable insights, several limitations must be noted regarding generalisability and data constraints.

First, the research is based on a multiple-case study of three bridge projects within a single regional context (Province of North-Holland). As such, the findings are context-dependent and may not readily generalise to all infrastructure projects or other regions. All three cases were led by the same public client (PNH), meaning that certain client-specific practices or priorities could have influenced results. Future studies should investigate a broader range of client organisations including smaller municipalities and national agencies to see if the identified barriers and enablers hold true elsewhere.

Second, the cases were at early stages of IFD deployment and NTA development (two were still in the design or construction phase during the research). This limited the ability to observe long-term outcomes such as the actual demountability and reuse of components. The study captures perceptions and short-term results, but the real test of IFD especially in regards too flexibility and demountability (e.g. whether a demountable bridge actually gets dismantled and repurposed in a decade) will only be evident over a longer time period. Thus, the evaluation of "success" is based on expected benefits rather than demonstrated life-cycle performance.

Third, the sample of interviewees, while diverse across the supply chain, could be expanded. The interviews included public clients, engineers, contractors, and a few integrated firms, but supplier/manufacturer perspectives were only indirectly covered. The suppliers were represented through the two larger integrated contractors that have in-house fabrication and supply capabilities, thus limiting the depth of insights into stand-alone suppliers. Since component producers are critical for industrialising IFD and adopting the NTA, their views on challenges (e.g. investing in new product lines) were not deeply explored; this is a gap that could be addressed with additional interviews or surveys focusing on suppliers.

Fourth, there is an inherent response bias risk in interview-based research as stakeholders might have presented an overly optimistic or defensive view of their own role. This is somewhat mitigated through triangulation (cross-verifying claims with project documents and other interviewees) and anonymity to encourage openness. Nonetheless, some biases may persist (for example, contractors underemphasising their resistance, or clients overstating their commitment to innovation).

Finally, given that academic literature on IFD specifically is essentially non existent, the study had to rely on industry reports and grey literature for certain data (such as cost figures or timeline claims for IFD). These sources are not peer-reviewed, which could affect the reliability of some background information. Such data was treated cautiously and focused on empirically validated insights, but this lack of published research on IFD is itself a limitation it underscores that the study is among the first of its kind, and thus its conclusions should be seen as exploratory.

In summary, these limitations suggest care in using these findings: they are most applicable to similar contexts (Dutch civil infrastructure with proactive regional clients) and current conditions (early-stage transition). The strength of the study is in depth and rich qualitative insight, but it covers a narrow range of contexts.

Chapter 7 - Conclusion

This study set out to address the fragmented and inconsistent adoption of the IFD construction approach in the Dutch bridge construction sector. The main objective was to explore how unified standards, particularly the Dutch Technical Agreements (NTAs), can be promoted to facilitate a a standardised approach to IFD construction. The research aimed to identify barriers and interventions across the supply chain, assess IFD implementation in real-world projects through case studies, and propose strategies for mainstream adoption.

7.1 Main research question

'How can the adoption of unified standards among supply chain actors in the Dutch bridge construction industry be promoted to facilitate the transition to standardised IFD practices?'

This study reveals that the adoption of unified standards specifically the Dutch Technical Agreements (NTA 8085, 8086, and 8089) can be effectively promoted through coordinated, programmatic client leadership combined with a phased mix of systemic interventions that align technical, organisational, and institutional dimensions of the bridge construction sector.

Pathways to Promote Adoption

Firstly, building awareness (creating visibility, signalling), competence and partnering through communication-oriented interventions. Strengthening knowledge diffusion, interpretative alignment, and cross-supply chain collaboration is crucial to creating visibility and confidence around IFD and NTA practices. Scaling up the number of pilot and demonstrator projects, such as the Cruquius Bridge, can create visibility and serve as communicative examples (e.g. roadshows and events) that normalise the use of NTAs while building confidence among more hesitant clients and contractors. However, these pilots must be embedded within a broader learning structure to ensure that lessons are captured, evaluated, and transferred beyond individual projects.

Establishing a national IFD knowledge hub, supported by training programmes for procurers, designers, and contractors, can centralise experiences and build shared competence. In parallel, structured dialogue between NEN, provinces, contractors, and suppliers is essential to converge interpretations of the NTAs and strengthen inter-organisational partnerships. Public clients such as the provinces and Rijkswaterstaat should lead by example, signalling a consistent commitment to IFD implementation and thereby providing the market with the clarity and direction currently lacking. Equally, frontrunners across the supply chain public and private alike should not move in silence but leave a clear trail and, signalling their direction to the wider sector to encourage alignment and collective momentum.

Secondly, institutionalise and align through regulatory instruments. As the sector gains experience with IFD implementation, standardisation should evolve from voluntary guidance into a partially formalised framework that provides consistency. Continuous refinement (updating) and alignment of the NTAs are essential to maintain technical coherence and interoperability across projects. This iterative development process should be supported by an ongoing dialogue between NEN, public clients, and market actors to clarify the specification of IFD elements and ensure that updates reflect practical lessons from implementation. Embedding NTA conformity within tender documents and design frameworks is a crucial step towards institutionalising its use. Ultimately, institutionalisation requires a gradual but deliberate transition from voluntary participation to partial mandating of core

NTA interfaces once sector maturity and market readiness have increased. This approach can lock in interoperability and consistency while preserving competition on performance and innovation.

Thirdly, to sustain this transition, economic instruments must make NTA adoption financially attractive and viable. Introducing EMVI criteria that reward lifecycle value, demountability, and circular performance can help embed sustainability and reuse principles into procurement decisions. Complementary co-funding or targeted subsidies can offset the initial investment costs associated with industrial tooling, standardisation, and early NTA adoption. These incentives will enable both clients and suppliers to commit to IFD practices with greater confidence and reduce the perceived financial risks of innovation.

To conclude, the success of NTA adoption depends not solely on technical readiness, but on governance alignment and coordinated leadership across all levels of the public and private sectors. However, in the early stage of this transition, public client and supply side frontrunners have a large role to play. Transitioning to standardised IFD practices requires public authorities to act as market orchestrators: repeatedly applying the NTAs, fostering cross-project learning, and signalling continuity of demand through strong partnerships and collaborative frameworks. Continuous development and regulatory alignment of the NTAs are essential to maintain technical coherence, interoperability, and confidence in their application.

7.2 Sub-questions

To support the MRQ, this section revisits the three SQs that guided the research. Each sub-question addresses a distinct layer of the IFD transition: first, defining the concept and its implications for the Dutch bridge construction supply chain; second, drawing lessons from the practical implementation of IFD and the NTA in pilot projects; and third, identifying the key barriers and corresponding interventions required to accelerate adoption. Together, these SQs form a coherent narrative that connects the theoretical foundations of IFD with the empirical findings from case studies and stakeholder interviews, culminating in actionable conclusions for policy and practice.

Starting with SQ 1***: What is IFD, and what do its core principles imply for the current bridge construction supply chain?***

IFD is a bridge construction approach that applies industrial production to prefabricated modules, designed with standardised interfaces so parts can be swapped, upgraded, or removed without damaging the structure. IFD stands for Industrial, Flexible and Demountable. Industrial means serial, off-site manufacturing. Flexible means modifiable and scalable over the life cycle. Demountable means designed for disassembly and high-grade reuse. Standardisation (e.g., NTA 8085/8086/8089) underpins all three by fixing the interfaces.

For the supply chain, this represents a paradigm shift: design moves from bespoke, one-off projects toward product-platform thinking and repeatable manufacturing. Engineers must coordinate early with fabricators, suppliers need to invest in prefabrication capacity and clients must specify NTA compliance to guarantee interoperability. Standardisation underpins collaboration and economies of scale, but also constrains design freedom. The transition requires new competencies, digital integration, and long-term coordination across projects. Ultimately, IFD challenges the fragmented, project-centric BAU model by demanding cross-organisational alignment, programmatic procurement, and continuous feedback between projects to realise an industrialised, circular bridge ecosystem.

Followed by SQ 2***: What lessons can we learn from IFD and NTA implementation in practice?***

The 3 case studies demonstrate that the implementation of IFD and the NTA in practice is progressing, but unevenly and with several challenges. Industrialisation is largely achieved through prefabrication, while flexibility remains aspirational and demountability is progressing where technically feasible.

NTA compliance evolved from optional guidance to near-full use, demonstrating growing maturity yet also confusion due to voluntary status and evolving versions. Collaborative procurement (bouwteams, framework agreements) proved essential for integrating suppliers early and aligning on standardised solutions. Conversely, rigid D&C contracts was seen as less optimal for innovation development. Furthermore, the strict use of the NTA in case C led to withdrawal of modular bids. Projects confirmed that repeated NTA use strengthens learning and interoperability, while isolated pilots limit scalability and thus the real potential of IFD. Overall, the case studies revealed that while IFD and the NTA provide valuable tools for standardisation and circularity, their full potential will only be realised when procurement frameworks, market maturity, and knowledge feedback loops are better aligned.

Lastly SQ 3*: What are the barriers and interventions to the IFD transition and the adoption of the NTA?*

Results of this study revealed 7 barrier themes recuring: 1) institutional conservatism, 2) limited knowledge diffusion, 3) procurement and regulatory constraints, 4) weak client capacity, 5) organisational fragmentation, 6) NTA-specific limitation, and 7) lack of coordinated leadership or market signals.

Correspondingly, three themes of interventions were identified. First, communication-type interventions were most frequently cited. These include developing a pipeline of small, local, and highly visible pilot or demonstration projects. Establishing a shared knowledge hub and organising roadshows or workshops were also suggested. Training programs for procurers and designers on applying IFD and the NTA are essential. Provinces and RWS can provide leadership by example through repeated use of IFD. Finally, ongoing multi-stakeholder dialogue is needed to ensure consistent interpretation and application.

Secondly, legal & regulatory type of interventions. Framework agreements and product catalogues can enable clients to purchase pre-approved modular bridges through mini-competitions. Continued NTA development and alignment are important, including closing gaps, harmonising movable and fixed bridge documents, and publishing clearer reference interfaces with feedback loops. Once adoption has matured, partial mandating of core NTA interfaces may be appropriate.

Lastly, economic type of interventions. These include targeted subsidies or grants to de-risk early projects and support standard module development. Procurement incentives, such as EMVI or MEAT scoring tied to verifiable IFD outcomes, can further stimulate adoption. Selective fiscal instruments, like VAT reductions or deductions for reuse, can also help shift lifecycle economics in favour of IFD.

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Appendix A: Interview Questions

Dutch interview guide

Sectie 1: Onderzoek en introductie interview
Stel jezelf voor
Allereerst bedankt dat u vandaag de tijd heeft genomen. Ik ben momenteel bezig met mijn afstudeerscriptie als onderdeel van de master Construction Management and Engineering aan de TU Delft. In samenwerking met de Provincie Noord-Holland richt ik mij op het begrijpen hoe organisaties omgaan met, of juist besluiten om niet te kiezen voor, IFD-benaderingen en de bijbehorende NTA-standaarden.
Door ervaringen, barrières en kansen met betrekking tot IFD te onderzoeken, hoop ik aanbevelingen te kunnen doen om bredere marktparticipatie in IFD-gebaseerde projecten te stimuleren. Om dit doel te bereiken voer ik interviews uit met verschillende actoren in Nederland. Tijdens het interview stel ik vragen over onderwerpen zoals de IFD-ervaring van uw organisatie, standaardisatie, samenwerkingen, inkoop, uitdagingen en kansen. U wordt aangemoedigd om vrijuit en in detail te spreken. Ik kan aanvullende vragen stellen om bepaalde onderwerpen verder te verkennen.

Het interview zal ongeveer 60 minuten duren. Ik wil graag benoemen dat uw deelname volledig vrijwillig is en dat er geen foute antwoorden. **Heeft u vooraf nog vragen voordat we beginnen?**

Mag ik uw **toestemming** om deze sessie op te nemen? De opname helpt om niets belangrijks te missen tijdens de analyse. Alles wordt anoniem verwerkt en verwijderd na afloop van het onderzoek.

Sectie 2: Introductie van de deelnemer
Q1: Kunt u zichzelf kort voorstellen (functie, organisatie, achtergrond)

- Voordat we meteen diep in de vragen duiken, zou ik het interessant vinden als u iets wilt delen over wat u op dit moment leuk vindt aan uw functie, of misschien een interessant project waar u recent aan hebt gewerkt?
- Gebaseerd op uw rol binnen de keten denkt u dat deze positie uw kijk op of ervaring met IFD beïnvloedt? Zo ja, op welke manier?

Extra Vraag – Hoe ben je betrokken bij IFD?

Sectie 3: Sectorontwikkelingen & huidige IFD-landschap
Vraag 2:
Q2: Welke belangrijke trends of uitdagingen ziet u momenteel in de Nederlandse infrasector? En hoe merkt u die in uw dagelijkse werk of in besluitvorming?
Vervolg:

- Welke rol of toegevoegde waarde ziet u voor IFD binnen deze context?
- Welke aspecten van IFD vindt u daarbij het belangrijkst en waarom?

Sectie 4: Ervaring met IFD en NTA's
Q3: Bent u betrokken geweest bij een project waarin IFD en/of NTA-standaarden vereist of gestimuleerd werden?

Zo ja: Wat was uw ervaring? En zou u overwegen opnieuw aan een project mee te doen waar een NTA-verplichting geldt?
Wat waren volgens u de succesfactoren of struikelblokken?

Q4A: Wat waren de praktische uitdagingen bij het toepassen van IFD op de bouwplaats of tijdens de uitvoering?
Q5A: Zijn er risico's of onzekerheden verbonden aan IFD/NTA's die u terughoudend maken om in de toekomst nogmaals aan IFD-projecten deel te nemen?

Zo nee:

Q4B: Zijn er risico's of onzekerheden verbonden aan IFD/NTA's die u terughoudend maken om aan zulke projecten mee te doen?

Sectie 5: Organisatorische gereedheid

Q6: Hoe bereidt uw organisatie zich momenteel voor op de (verdere) implementatie van IFD en/of het werken met NTA-standaarden?

- Hebben jullie al interne aanpassingen gedaan (trainingen, digitale systemen, proceswijzigingen) om aan te sluiten bij IFD of gestandaardiseerde aanpakken?
- Wat is volgens u belangrijk voor een organisatie om succesvol met IFD aan de slag te gaan?
- Welke interne veranderingen zouden nodig zijn om de gereedheid te verbeteren?

Sectie 6: Barrieres, kansen en interventies
Q8: Wat zou uw organisatie (en andere organisaties) helpen om IFD en NTA's effectiever te adopteren?
Denkrichtingen:

- Zou de Provincie of een andere opdrachtgever meer kunnen doen (duidelijkere eisen, prikkels, meer vraag genereren)?
- Wat voor soort tools of ondersteuning zou het meeste verschil maken?
- Welke rol ziet u voor samenwerking binnen de keten? Denk aan co-creatie, vroege betrokkenheid, gedeelde risico's.

Q9: Hoe zou u voorstellen om de introductie van IFD/NTA's in aanbestedingen te verbeteren of de ondersteuning in de praktijk te versterken?
Vervolg:

- Zijn er concrete stappen of maatregelen die bredere adoptie zouden stimuleren?
- Hoe kunnen opdrachtgevers en opdrachtnemers beter op elkaar afgestemd raken?

Sectie 7: Toekomstvisie
Q10: Als u 5 à 10 jaar vooruit kijkt, hoe zou IFD er idealiter uitzien in Nederlandse infraprojecten, en wat is er nodig om daar te komen?
Denkrichtingen:

- Wat zijn volgens u belangrijke mijlpalen of succesfactoren om daar te komen?
- Hoe kunnen uniforme standaarden (zoals NTA's) breder worden gestimuleerd?
- Welke rol speelt beleid hierin, en wat zou nodig zijn vanuit overheden of brancheorganisaties?

Afsluiting
Extra vragen:

- Zijn er IFD-gerelateerde onderwerpen die we nog niet besproken hebben, maar die u belangrijk vindt?
- Heeft u nog vragen of suggesties voor mij of het onderzoek?

Bedankt voor uw waardevolle inzichten.
Geef eventueel aan wat de volgende stappen zijn (bijvoorbeeld: dat je mogelijk nog contact opneemt voor een follow-up en dat ze een samenvatting van de onderzoeksresultaten ontvangen indien gewenst).

Appendix B: Informed Consent Form

Je wordt uitgenodigd om deel te nemen aan een onderzoeksstudie met de titel *" Mapping the Transition to Industrialised Bridge Construction in the Netherlands: Pathways to Standardised IFD Practices Across the Supply Chain "*. Deze studie wordt uitgevoerd door MSc-student Matthew de Jong (TU Delft), onder begeleiding van Daniel Hall, Wenjuan Lyu en Daan Schraven (TU Delft), en Paul Waarts (Provincie Noord-Holland).

Het doel van dit onderzoek is om te verkennen hoe Industrieel, Flexibel en Demontabel (IFD) bouwen van bruggen kan overgaan van geïsoleerde pilotprojecten naar een gestandaardiseerde en gangbare werkwijze binnen de Nederlandse infrastructuursector. De studie richt zich op het identificeren van belangrijke stimulerende factoren, belemmeringen en strategieën voor het implementeren van IFD-praktijken binnen de gehele bouwketen.

Je wordt uitgenodigd voor een semi-gestructureerd interview van ongeveer 45-60 minuten. Het gesprek zal gaan over jouw professionele ervaringen en inzichten met betrekking tot geïndustrialiseerd bouwen van infrastructuur en IFD-praktijken.

Het interview of gesprek wordt opgenomen in audioformaat en daarna getranscribeerd. De transcriptie zal worden geanonimiseerd. Alle geluidsopnamen, transcripties en persoonsgegevens worden opgeslagen binnen de beveiligde digitale infrastructuur van de TU Delft. Als onderdeel van het verificatieproces worden gegevens over professionele functies verzameld; deze worden echter gegeneraliseerd om identificatie van specifieke personen te voorkomen. Zoals bij elke (online) activiteit is het risico op een datalek nooit volledig uit te sluiten. Wij zullen echter ons uiterste best doen om de vertrouwelijkheid van jouw antwoorden te waarborgen. De verzamelde gegevens worden twee jaar na afloop van het onderzoek verwijderd.

Jouw deelname aan dit onderzoek is volledig vrijwillig, en je kunt op elk moment besluiten om te stoppen. Je bent vrij om vragen over te slaan. Samengevatte transcripties worden vóór de anonimisering toegestuurd aan de geïnterviewde om te controleren of de verzamelde gegevens correct zijn en goedgekeurd zijn voor verder gebruik. Indien deelnemers het niet eens zijn met de verzamelde gegevens, worden deze binnen 7 dagen verwijderd.

Tot slot willen we je bedanken voor je deelname aan dit onderzoek. Als je vragen hebt, kun je op elk moment contact opnemen met [redacted] of de verantwoordelijke onderzoeker Daniel Hall via [redacted].

Als je de informatie hebt gelezen, begrepen en al je vragen zijn beantwoord, kun je hier tekenen:

Naam van deelnemer	**Handtekening**	**Datum**

Ik, als onderzoeker, heb de informatie accuraat voorgelezen aan de potentiële deelnemer en, voor zover ik kan beoordelen, ervoor gezorgd dat de deelnemer begrijpt waarvoor hij/zij vrijwillig toestemming geeft. .

Matthew de Jong		*15/04/2025*
Naam van onderzoeker	Handtekening	Datum

Appendix C: Cases

This appendix shows the different bridge renewal projects which the asset owner PNH has initiated, all these projects had a weighted IFD criteria as an award criteria (EMVI criteria). These projects are grouped in table 1 below.

Table 1: IFD Project conducted by the public client PNH with exception of the first project

Bridge / Project	Type	NTA Standard	Timeline	Status
Case A: Cruquiusbridge	Moveable bridge	NTA 8086 Concept/ V1	2023-2025	Construction (near completion)
Case B: N240b	Fixed bridge	NTA 8085	2024–2026	Definitive Design
Case C: Stolperbrug	Moveable bridge	NTA 8086 v2	2024–2027	Definitive Design

The layout of each project description is done in the following way, first a project overview considering a brief description of the project itself, following the tendering objectives both regarding IFD and non IFD criteria. For the Case A: Cruqiusbridge will also consider the contractual structure because of the specific detail regarding the NTA development during this process which becomes clear in that following parts. Additional subchapters are considered for project where information was available.

PNH IFD Procurement method

On the client side, a consistent procurement approach is used, integrating IFD and the NTA throughout the process (see Figure 1). In the formulation phase, a consultant supports the inclusion of IFD and NTA in the specifications. These are reflected in the EMVI tender criteria, alongside ECI values, reduced environmental nuisance, and other sustainability goals.

A competitive dialogue allows bidders to present their vision on IFD and related aspects, with contract award based on EMVI scores and dialogue outcomes.

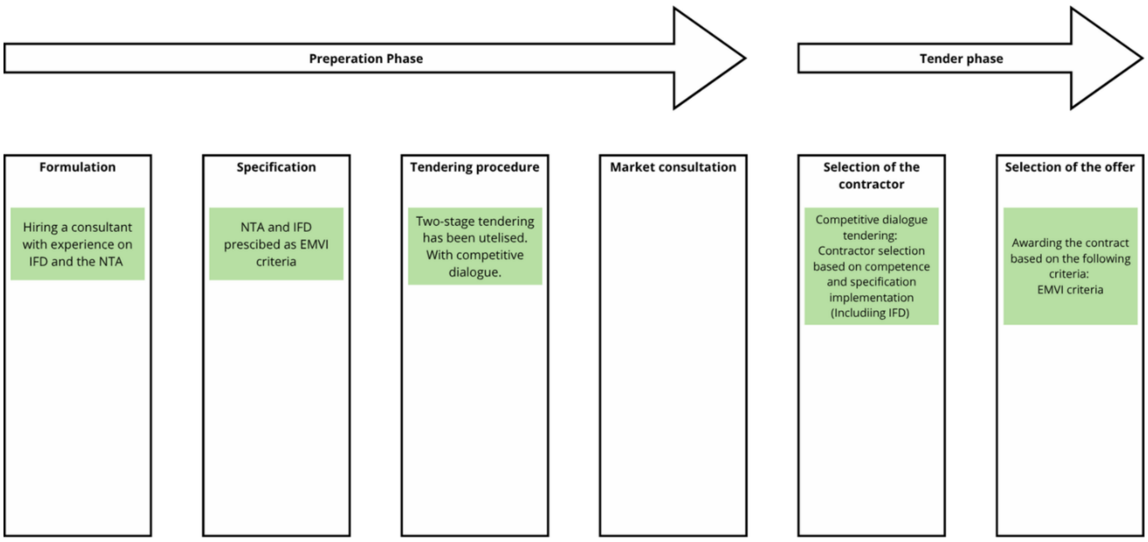

Figure 1: Phases of procurement and implementation of IFD/NTA, adapted based on Akshay A. (2020)

Case A: Project Cruquiusbridge

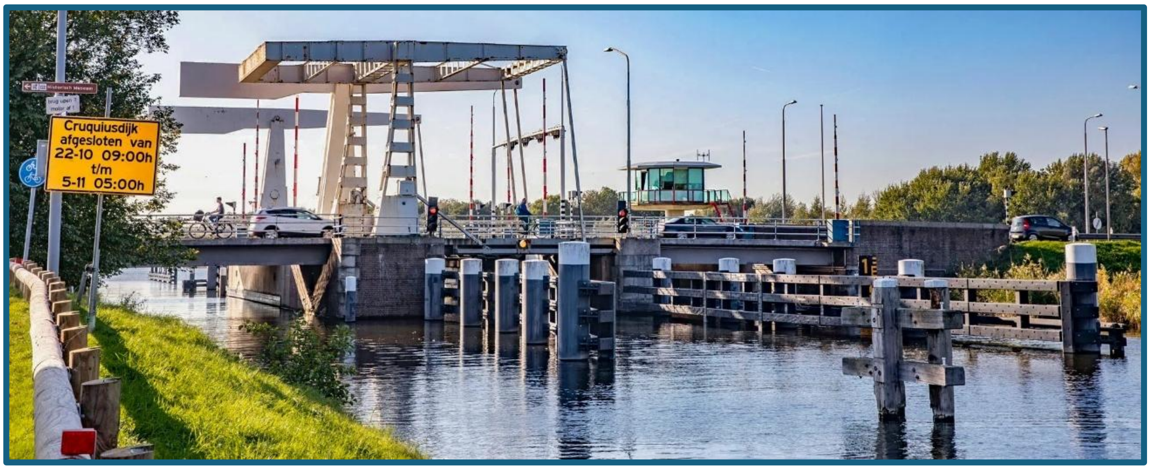

Figure 2:Image of the Cruquiusbridge, copyright of (bloemendaalredactie, 2022)

Project Overview

The Cruquiusbridge is situated on the heavily travelled Provincial Road N201, connecting Heemstede and Hoofddorp in the PNH. Constructed in two parts Bridge A dating back to 1932 and Bridge B added in 1971 the structure has long served a critical transportation function in the region. After decades of use, Bridge A has reached the end of its service life and needs to be replaced, while Bridge B requires major maintenance to ensure it can operate reliably for another 30 years. The project, overseen by the PNH, reflects a commitment to accommodating the intense traffic demands of the area and fulfilling modern sustainability requirements.

Table 2: Key Details of the Cruquius Bridge Renewal Project (Data source TenderNed (2021).

Item	**Details**
Status	Ongoing (Construction started 2023, expected completion 2025 Q4)
Project Name	Renewal of the Cruquius Bridge
Location	Heemstede, North-Holland (on the N201 between Heemstede and Hoofddorp)
Client	PNH
Contractors	Van Hattum & Blankevoort / Hollandia Infra
Technical Consultant	Witteveen+Bos
Type of Bridge	Movable (bascule / “ophaalbrug”)
Year Built	- Bridge A (east side): 1932 (requires replacement)
	- Bridge B (west side): 1971 (major maintenance)
Ambitions	- Circular construction (IFD, NTA 8086)
	- Energy-neutral design
	- Low-maintenance
Contract Model	- Competitive dialogue for tender
	- UAC-IC 2005 (UAV-GC 2005) with bouwteam
Fixed Budget	€ 20.000.000 (price is not an award criterion, focus on quality/innovation);
Notable Features	- Reuse of steel from the old bridge
	- Thermal Sprayed Aluminium for long-lasting coatings

Main Sustainability Goal	Minimise material usage, reduce environmental impact, and balance bridge energy consumption
IFD Application	Demountable design to allow future reuse of components
NTA	NTA 8086

Innovation and Pilot Role

The Cruquius Bridge project served as the first pilot for the NTA 8086 standard for movable bridges. It contributed significantly to the further development of the NTA and has generated a wide range of lessons learned. These lessons are now shared across various learning networks and events to inform other stakeholders about the practical implementation of IFD construction.

It is considered a pioneering IFD pilot project aligned with the NTA 8086, and it also serves as a test case for future circular and energy-neutral tenders in the civil infrastructure sector.

In line with PNH's broader goals, this project also aims to expand and deepen knowledge in innovation and sustainability within the region, and to adopt and share new developments and insights.

Tendering Objectives

The Province of North Holland formulated several selection/award criteria for the project;

Table 3: Tendering Objectives Case A (Data source TenderNed (2021).

Criterion Type	Name	Description
Quality	Circular Construction	Maximise reusability of components and materials, adhering to IFD/NTA 8086. Reduce use of primary raw materials and adopt a future-proof, adaptable design.
Quality	Energy Neutrality	Ensure total annual energy consumption is compensated by local, renewable production.
Quality	Low-Maintenance Design	Maximise availability and minimise life-cycle costs.
Quality	Minimal Nuisance	Reduce disruptions during construction and operation through efficient planning.

Contractual Structure

The contractual structure is based on UAC-IC 2005 (UAV-GC 2005). Below is a schematic based on Chao-Duivis et al. (2013) showing the relationship between the client (PNH), main contractor (Van Hattum & Blankevoort), technical consultant (Witteveen+Bos), and subcontractors.

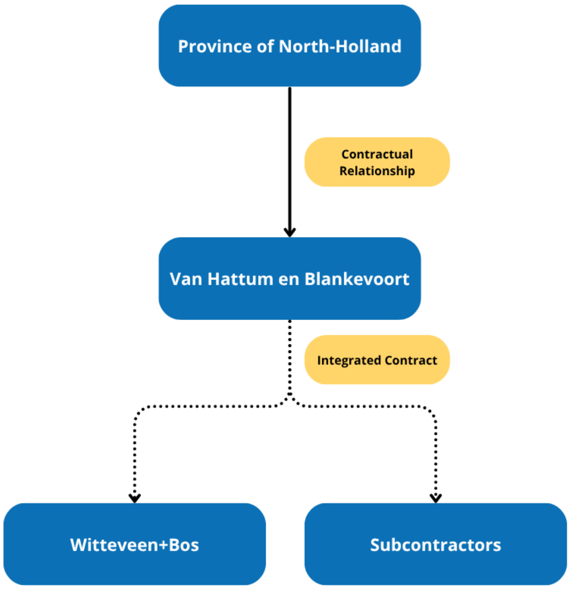

Figure 3: Own Schematic of relationships actors according to UAC-IC 2005, figure based Chao-Duivis et al. (2013)

This type of procurement route allows for early contractor involvement and is sometimes referred to as a two-phase procurement process. It allows the contractor to be conditionally appointed before the full scope and pricing of the construction works have been finalised.

The project follows a two-phase contract model, see figure below:

Phase 1: Design/Preconstruction (Bouwteamovereenkomst)

- The selected contractor collaborates with PNH in a project-specific "Bouwteam."
- Jointly refine requirements, produce an integrated Definitive Design and optimize cost management, risk allocation, and sustainability solutions.

Phase 2: Execution Phase (Uitvoeringsovereenkomst)

- If consensus is reached on price, scope, and design solutions during the Bouwteam phase, a follow-up contract for actual construction is awarded under UAV-GC 2005.
- The Client retains the option to withdraw if final terms are not acceptable. In such a case, design intellectual property (IP) transfers to PNH, with fair compensation provided for the design work.

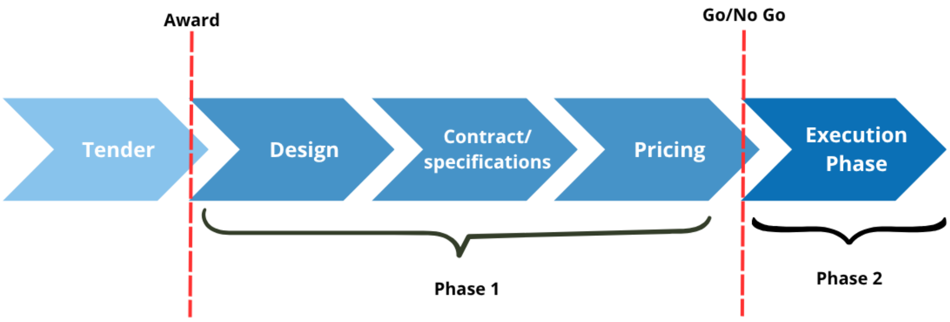

Figure 4: Bouwteam structure, based on and adapted Adjust (2024)

Case B: Project N240b

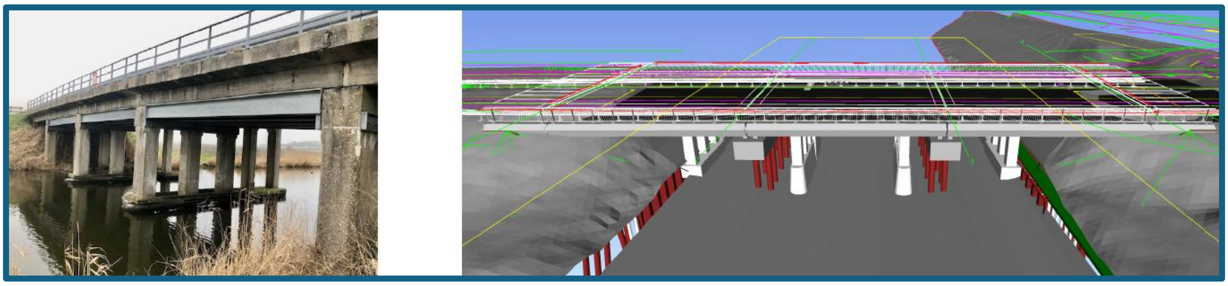

Figure 5: Image of the N240b Bridge and design

Project Overview

The N240b project involves significant infrastructural improvements to the N240 road in the municipality of Medemblik, North Holland. The project includes the replacement of two identical set of bridges which are the existing traffic and bicycle bridges (14H02, 14H03, 14H04, and 14H05), major maintenance on road and bicycle path surfaces, and safety upgrades to the road and intersections within the system boundaries. The bridges will potentially be temporary due to the changing dynamics in the surrounding area of the agro-industry and will therefore be designed to be fully demountable. It further serves as a pilot project in the further development of the NTA 8085, specifically adding to substructure design interfaces.

Table 4: Key Details of N240b project (TenderNed, 2025b).

Item	Details
Status	Ongoing: Tender is awarded, Definitive Desing is to be delivered
Project Name	N240b
Location	Medemblik, North Holland, Netherlands
Client	PNH
Contractors	K Dekker
Type of Bridge	Fixed bridge
Span Bridge	36 meters
Ambitions	- Apply IFD/NTA 8085 for future reuse
	- Environmental cost indicator (MKI) used in assessment
	- Align with PNH goal to reduce CO_2 emissions by 55% and raw materials by 60%
Contract Model	Design and construct (DC)
Notable Features	Two identical bridges, designed to be fully demountable
IFD Application	Large focus on and demountable aspect and serve as a pilot project for IFD construction.
NTA	NTA 8085

Tendering Objectives

Table 5: Tendering objectives case B(TenderNed, 2025b).

Criterion Type	Name	Description	Weight
Cost	Sustainable Execution	MKI (environmental cost) calculation for asphalt and terrain elevation	10%
Quality	IFD Application	Explanation of IFD principles used in execution	40%
Quality	Disturbance & Phasing	Plan to minimise disruption to residents and farmers	30%
Quality	Risk Management	Measures for 3 risks within PNH’s influence	20%

Case C: Project Stolperbrug

Figure 6: Left Impression of the new Stolperbrug, right the current Schagerbrug

Project Overview

These stolperbrug are part of a framework agreement involving a total of 4 movable bridges, 3 of which will be constructed according to IFD principles. The fourth bridge will undergo major maintenance only (TenderNed, 2025b).

Initially, the Stolperbrug was tendered as a standalone project in early 2023 (TenderNed, 2024). However, the Province of North Holland decided to terminate this original tender. This decision was driven by limited market response and misalignment between the province’s expectations and the approach proposed by the market parties. In particular, the implementation of IFD principles by the initially involved contractor did not sufficiently align with the province's vision. Specifically, the proposed level of demountability an essential component of the IFD concept was not in line with the long-term adaptability and circular ambitions that the province had set out.

To better meet market needs and ensure an efficient long-term solution, the province opted for a framework agreement with a contractor. This long-term collaboration aims to facilitate the serial renewal of multiple bridges, preparing them for the next 100 years. Construction of the stolperbrug is expected to take place between 2025 and 2027. In the meantime, the bridge remains safe for use and will be maintained by the province until the new bridge is operational.

Although the framework agreement includes 3 bridges designed according to IFD principles, this document will focus solely on the Stolperbrug, as the contractor has not yet commenced work on the other projects. At the time of writing, the definitive design for the Stolperbrug is in the process of being submitted.

Table 6: Key Details of the framework agreement including the Stolperbrug (TenderNed, 2025a).

Item	Details
Status	Ongoing: Tender awarded;
Duration	Expected 8 – 10 years
Project Name	Framework agreement Movable Bridges
Location	North Holland
Client	PNH
Contractors	Contractor combination Reimert-Beentjes
Technical Consultant	Original design Witteveen+Bos
Type of Bridge	Movable bridge
Year Built	- Stolperbrug (replacement of Stolperbasculebrug 1936)
	- Schagerbrug (potential replacement)
	- Waardebrug (replacement)
	- Zwanenbrug (major maintenance)
Contract Model	- Competitive dialogue for tender
	- UAC-IC 2005 (In Dutch referred to as 'Bouwteam ' or UAV-GC 2005)
Contract Value	€ 120.000.000
IFD Application	Application of NTA 8086

Tendering objectives

Table 7: Tendering objectives Case C (TenderNed, 2025a).

Criterion Type	**Name**	**Description**
Quality	Sustainable Execution	MKI (environmental cost) calculation for asphalt and terrain elevation
Quality	IFD Application	Explanation of IFD principles used in execution. As circular as possible, in line with the principles of IFD construction as outlined in NTA 8086
Quality	Disturbance & Phasing	Plan to minimise disruption. A comprehensive risk dossier, including identification and management of project risks

Appendix D: Current Status and History IFD and NTA

The development of IFD construction for bridges in the Netherlands has been driven by industry collaboration and emerging public policy priorities, rather than academic research alone. This section outlines the history of IFD's evolution and its current state of adoption, highlighting key milestones such as the 2016 initiative that kick-started the movement, the publication of NTA guidelines, and pilot projects such as the Cruquius Bridge that are putting IFD into practice.

While the term IFD construction is relatively new in the context of Dutch infrastructure, the core principles have existed in practice for decades. Although these earlier developments were not formally labelled as IFD, they clearly embody its foundational ideas.

A well-known historical example is the Bailey Bridge, developed during WW2. This modular, prefabricated bridge system was designed for rapid military deployment and reflects all three principles of IFD. The components were mass-produced on an industrial scale, designed to be assembled and disassembled without damage, and adaptable to various configurations by extending or widening the structure (Adams, 2022).

Figure 1:Bailey Bridge in use during WW2 (Adams, 2022)

Inspired by this model, companies such as Janson Bridging have developed their own modular bridge systems that also align closely with IFD principles (Janson Bridging, 2025). Their use of prefabricated, reusable elements often offered through bridge leasing models reflects a clear commitment to flexibility and demountability, tailored to the needs of temporary or rapidly deployable infrastructure.

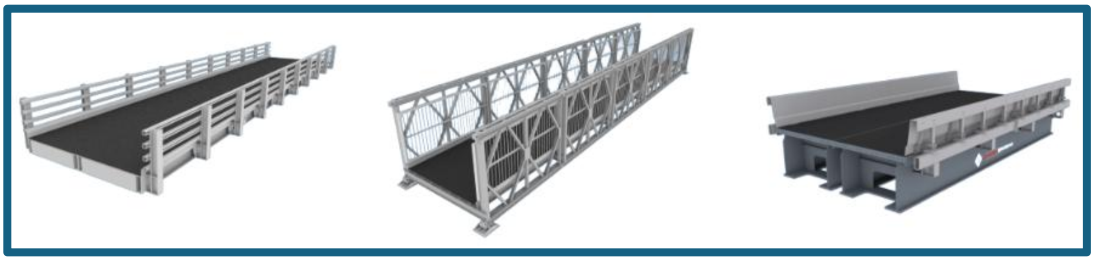

Figure 2:Several types of standardised modular bridges from the company Janson Bridging (Janson Bridging, 2025)

Early Origins (1990s): The name and concept of building in an IFD manner has roots in the late 20th century. Around the late 1990s, the Stuurgroep Experimenten Volkshuisvesting (SEV) introduced IFD principles in the Dutch housing sector (Bouwen met Staal, n.d; Westra et al., 2003). At that time, it was an innovative approach to prefab housing, greeted with optimism for a "sunny future" (Bouwen met Staal, n.d). However, as the construction boom of that era subsided, interest in IFD construction diminished and it largely fell off the radar for about a decade (Bouwen met Staal, n.d). This period is noteworthy because it shows that the ideas behind IFD modularity, flexibility, and disassembly are not entirely new, but their application needs the right context and demand to flourish.

2016 Revival for Infrastructure: The turning point for IFD in civil infrastructure came in 2016, against the backdrop of a national infrastructure challenge. The Netherlands faces a massive task of replacing and renovating thousands of bridges and viaducts, many of them built in the post-WWII era and reaching end-of-life simultaneously, the VO. In that year, *"IFD in the GWW (civil infrastructure) was started on the initiative of, among others, Paul Waarts of the Province of Noord-Holland"* (Bouwen met Staal, n.d). The Province of Noord-Holland, dealing with a particularly large inventory of ageing bridges recognised that a business-as-usual approach (treating each bridge as a unique project) would be unaffordable and impractical to meet the impending demand (Bouwen met Staal, n.d). If every one of the ~380 public bridge owners in the country procured bespoke designs, it would strain the market's capacity and budgets. The IFD approach offered a way to standardise and speed up bridge delivery. Thus, in 2016, a consortium of public agencies and industry partners launched an initiative to explore IFD for bridges and locks, framing it as both an efficiency measure to speed up construction and minimise construction nuisance (Bouwen met Staal, n.d; NEN, 2024b). Coincidentally, IFD also overlapped well with circularity goals in construction and later IFD was also used to address these circularity goals. This initiative can be seen as the start of a modern IFD program specifically aimed at infrastructure, marking the transition of IFD from a concept into an organised development effort.

2018–2021 Development of NTA Standards: One of the first outcomes of the IFD initiative was to formalise the approach into guidelines that the whole industry could follow. As the initiators of IFD recognised early on that *"standardisation would be necessary to enable an industrial production process"* (GWWTotaal, 2023). Rather than a top-down regulation, the choice was made to create NTA, through the NEN (the Dutch Standardisation Institute). NTAs are consensus documents, quicker to develop than official standards, and serve as interim standards that stakeholders agree to use. Work on the first NTA for IFD bridges began in 2018, with leadership by provinces (notably North-Holland and Overijssel) and participation from engineers, contractors, and NEN experts (ipv Delft, 2024). By 2019, the initial specifications had been drafted, focusing on a particular type and size of bridge. The effort culminated in NTA 8086, the first technical agreement for IFD construction of movable bridges, which was published in early 2020 (after a draft in 2019) (NEN, 2020a). NTA 8086:2020 lays out standardised interface dimensions and details for key connections in common types of movable bridges (such as bascule and drawbridges) (NEN, 2020a). It accounts for existing norms and covers interfaces between substructure, superstructure, and mechanical parts, ensuring that these elements can connect uniformly (NEN, 2024B). The intent was that public clients could reference this NTA in tender documents for new bridges, and industry could confidently design interchangeable modules around it (NEN, 2024a). Following NTA 8086, a complementary NTA for fixed bridges and viaducts was developed: NTA 8085, published in mid-2020 (NEN, 2020b). NTA 8085 extended the IFD principles to non-movable (static) bridges, again specifying standard interface designs but for components such as decks, piers, and bridge furniture (railings, etc.) typical of overpasses and small spans. These documents provided the first technical basis for actually implementing IFD in real projects, effectively translating the IFD philosophy into engineering requirements.

In parallel, the IFD initiative emphasised knowledge sharing and refinement often referred to as 'open source'. The NTA process itself was iterative for instance, the first version of NTA 8086 was recognised as a concept with further development (version 2.0) planned to broaden its scope (more bridge types, multiple size classes) (ipv Delft, 2024). This collaborative standards-making ensured that lessons from pilot applications and calculations could be fed back into updated guidelines (ipv Delft, 2024). By standardising one interface at a time (in focused "raakvlakteams" or interface teams), the stakeholders could gradually cover more aspects of bridge design (Bouwen met Staal, n.d). Notably, the interfaces were categorised by classes to avoid a one-size-fits-all; for example, different size classes were defined so that small bridges wouldn't be over-dimensioned by a standard meant for larger ones (ipv Delft, 2024). This shows a nuanced approach: standardisation where beneficial, but still allowing scaling.

As of 2023–2024, the IFD standardisation has expanded into the realm of bridge control systems. A new NTA, NTA 8089, was issued to address IFD for Industrial Automation & Electrical (IA&E) installations of movable bridges (NEN, 2024b). This guideline aims to standardise the interfaces of the operating systems, the sensors, the motors, the control software, electrical components. By doing so, it extends the IFD approach beyond just the physical structural components to the technological components of bridges, potentially allowing plug-and-play replacement of control modules and easier upgrades of bridge electronics. With NTA 8085, 8086, and 8089 now in place, the IFD framework in the Netherlands covers superstructure, substructure, bridge equipment, and control systems (GWWTotaal, 2023). These NTAs are not formal Eurocodes or laws, but as the literature stresses, *"clearly not official standards, but purely technical agreements"* (GWWTotaal, 2023; NEN, 2024a). These They serve as recommended practices that progressive clients and builders can adopt. In fact, the PNH has already *accepted the NTAs as a standard* in its own projects (GWWTotaal, 2023), effectively making compliance with IFD principles a requirement in provincial bridge procurements. This early adoption by a major regional authority has been a catalyst for others to follow or at least take IFD seriously.

Pilot Projects and Implementation: While standards are essential, demonstrating IFD in actual projects is what truly validates the approach. A number of pilot projects and early implementations have emerged in recent years, also appendix C.

- The Cruquius Bridge replacement in Noord-Holland is one of the first IFD projects. This is a movable bridge (part of the N201 arterial road) that the province is renewing with ambitious sustainability goals. The province explicitly used a competitive dialogue procurement to incorporate IFD principles, citing that *"the Province embraced the principles of IFD construction, as outlined in NTA 8086, making the Cruquius Bridge one of the first movable bridges in the Netherlands to utilise this approach"* (European Commission, n.d.). The design and contract for Cruquius Bridge require modular, demountable construction the bridge is being built as a set of demountable modules that can be easily separated if needed. This project, which started construction in 2023 and is expected to complete in early 2026, has been held up as a proof-of-concept for IFD at full scale. It even won the KoopWijsPrijs 2021, a Dutch procurement award, for its innovative circular and modular approach, indicating the recognition of IFD principles in delivering a circular bridge solution (Platform Bruggen, 2021). The relevance of Cruquius Bridge lies in demonstrating that IFD is not just a theoretical ideal but workable in a complex, heavily trafficked infrastructure project. Early indications suggest that the approach has allowed contractors to propose creative solutions for reusing materials and minimising disruption, aligned with the project's aims of being circular, energy-neutral, and low-maintenance (European Commission, n.d).

- Another early project is the Stolperbrug in the Province of Noord-Holland. Its design was developed completely according to IFD principles (cited as one of the first fixed bridges to do so) (GWWTotaal, 2023). The Stolperbrug, designed by engineering firm Witteveen+Bos, applied the NTA 8085 guidelines, meaning its spans, supports, and connections conform to the standard interfaces. While smaller in scale than Cruquius, it showcases IFD for fixed bridges and serves as a template for future designs where multiple contractors could supply standard parts.

- The IFD Columbia project illustrates applying IFD principles to a movable bridge for a private Colombian developer. Instead of using the NTA 8086 standard, SPIE and IPV Delft employed their own Hollandse Brug system originally created to simplify and economise Dutch public bridge projects. Here, the bridge was broken into modular components sized to fit into 3 shipping containers. A step-by-step assembly manual enabled local contractors to install the bridge with minimal on-site support.

Despite these promising developments, it is important to note that IFD adoption is still in its early stages. The market share of bridges built to full IFD specifications remains very small. Estimates suggest that as of the mid-2020s, only “a little over 0%” of new bridge projects actually incorporate IFD, essentially a tongue-in-cheek way of saying it’s just beginning (GWWTotaal, 2023). The EIB market analysis commissioned by the PHN and others found that about 70% of upcoming bridge replacements (by value) could potentially be addressed with IFD standard designs, yet currently almost none are, indicating a huge growth potential, (EIB, 2023; GWWTotaal, 2023). The implication is that there is significant room (and need) for wider implementation.

Academic and Industry Context: In reviewing literature for IFD in bridges, one finds that the knowledge base is dominated by grey literature such as technical reports, standardisation documents (NTA 8085/8086/8089), conference presentations, and industry articles rather than peer-reviewed academic papers. The NTAs themselves are a form of codified industry consensus, and many insights are documented in trade publications or websites (for instance, GWW Totaal, Bouwen met Staal, Platform Bruggen). In academic terms, IFD bridges can be related to concepts such as IC and CC methods, DFD and modular construction, as done in 2.1.2, which do have research literature, but the specific application and the Dutch context mean much information comes from project reports and policy studies.

In conclusion, the current status of IFD in the Netherlands is that of an innovative approach moving from pilot phase toward potential mainstream adoption. The period from 2016 to 2024 has seen IFD go from concept to concrete guidelines and real bridge projects, thanks largely to proactive government agencies and industry frontrunners.

Appendix E: IFD Products

IFD Colombia bridge

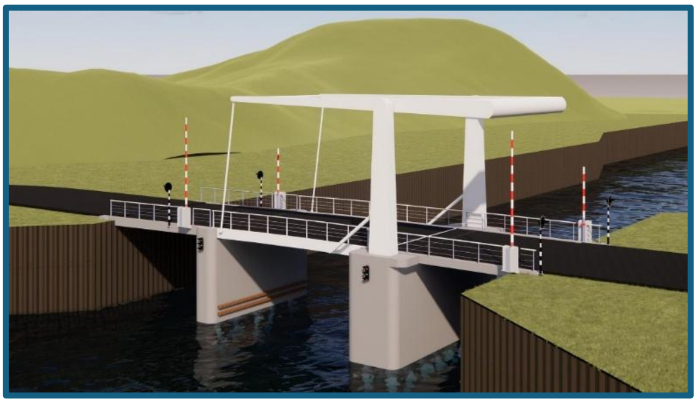

Figure 1:Impression of IFD Columbia Bridge by IPV Delft

The IFD Columbia project exemplifies how IFD principles can be applied to the design and delivery of a moveable bridge for a private client in this case, a Colombian project developer without a formal public tender process (CvdB, 2025).

Rather than adopting the NTA 8086 standard, Spie and IPV Delft drew upon their own standardised approach known as the Hollandse Brug system. This system was originally conceived to reduce complexity and cost for Dutch public authorities (municipalities, provinces, water boards) seeking a reliable moveable bridge solution (CvdB, 2024).

In this instance, the bridge was designed as a kit of parts suitable for overseas container transport to Colombia. The components, including the main bridge deck (the "val"), the hamei structure, the counterweight mechanism, the guardrails, the drive system, and other mechanical-electrical elements, were broken down into modules that fit neatly into three shipping containers (CvdB, 2024). The instructions were provided in a step-by-step guide similar to an assembly manual so that local contractors on-site could handle construction themselves with minimal or no on-site assistance from Spie.

IFD Aspects in the Colombia Project

- **Industrial:** Prefabrication and modular manufacturing streamline the production process, enabling easier transport and assembly.
- **Flexible:** Although based on the "Hollandse Brug" standard, the design was adapted for overseas shipping constraints, including containerization. Adaptability in design is possible but current structure is not adaptable.
- **Demountable:** Splitting the bridge into container-sized components means the structure can be fully disassembled, transported, and reassembled promoting easier future modifications or relocations if necessary. The substructure is however concrete which is poured in situ by the local contractors in Colombia. Although the structure is demountable, the bridge its goal is not to relocate but it is however possible, other parts are easily demountable for future maintenance, as additional part have been provided which have a short technical life span.

This model demonstrates how a standardised, kit-based moveable bridge can offer a private client a turnkey, scalable infrastructure solution that is both cost-efficient and relatively straightforward to ship and construct internationally.

Appendix F: Codebook Cross-Case analysis

This appendix presents the codebooks used in the thematic analysis of the semi-structured interviews: one for barriers and one for interventions.

Table 1: Codebook related to barriers

Aspects	First-order themes	Definition	Codes
Barrier	Institutional conservatism	The tendency of established institutions (like governments, companies, or organizations) to resist change and maintain existing structures practices, and traditions, even when new approaches might be more efficient or beneficial.	First-mover reluctance
			Risk aversion
			Skepticism
			Intertia
	Limited knowledge diffusion and demonstration	Insufficient sharing of lessons, guidance, and visible pilots/demos, leaving teams unaware of how to apply	Low awarness
			Lack of practical or relatable examples
			Misunderstanding
	Regulatory framework	Misalignment, ambiguity, or gaps in laws/standards/procurement	Long-term partnership
			IFD procurement framework
	Client related barriers	ublic client capacity, capability, budget, or time constraints that prevent consistent programmatic specification of NTAs/IFD.	Lack of resources
			Procuremnt focused on lowest bid
			Failure to recognize long-term value
	Fragmentation	Dispersed responsibilities and misaligned incentives across civil,	Vertical
			Horizontal
	NTA specific	Issues inherent to the NTAs (immature scope, ambiguous wording, evolving versions, limited coverage) that hinder uptake.	Voluntary
			Poor allignment
			Open-endndness
	Lack of coordinated leadership & structural market signals	Absence of joint leadership and stable, market signals, leading to fragmented efforts and underinvestment.	Lack of public client leadership and collaboration
			Weakt top-down market demand
			Diffusion of responsbility
			Weak signalling

Table 2: Codebook related to interventions

Aspects	First-order themes	Definition	Codes
Intervention	Economic	Financial levers that change costs, risks, or rewards to de-risk and accelerate NTA/IFD adoption (e.g., subsidies, tax measures, procurement incentives).	Subsidies or grants
			Tax-based incentives
			Procurement incentives
	Legal and regulatory	Rule- and contract-based levers that define obligations and interfaces, reduce ambiguity, and enable/mandate interoperable	Procurement frameworks (Product catalogue)
			NTA development
			Mandatory NTA (norm)
	Communication	nowledge- and relationship-based levers that build capability and alignment by showing how to apply NTA/IFD (e.g., pilots, guidance, training, leadership, ongoing dialogue).	Pilot projects & demos
			Knowledge sharing & awareness
			Training and education
			Lead by example and collaboration (signalling)
			Ongoing dialogue