Exploring the transition to industrialisation in Dutch infrastructure construction

A Technological Innovation Systems perspective on innovative opportunities and systemic barriers in the bridge rehabilitation challenge

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Preface

In front of you lies my master thesis on industrialisation in the Dutch infrastructure construction context. This research was executed for De Bouwcampus, after initiation by collaborative efforts with TNO and the TU Delft, who aspire to further the body of knowledge on this subject. Without the daily efforts made by De Bouwcampus to realise transitions in the construction sector, this research would not have been conducted. Therefore, my gratitude goes out to Thijs and the others. This thesis report marks both the conclusion of the Construction Management & Engineering master programme, and my time as a student.

I would like to express gratitude to my thesis committee for guiding me through the process of writing this thesis. First and foremost, I would like to thank my first supervisor Daan for consistently showing the process and structure when I lost the bigger perspective. Also, thank you Thijs and Alexander for showing me the practical relevance of my study, by allowing me to partake in workshops and company visits. Those excursions away from my computer helped tremendously in my connection to the subject, and the eagerness to contribute to your daily efforts by finding useful results. Furthermore, I would like to thank my second supervisor Daniel for guiding me in my first experiences of conducting interviews and for the pleasant discussions regarding the framework I adapted for my research. Lastly, thank you Martijn for acting as chair and giving your independent opinion on the most important moments.

I could not think of a more suitable group of people to guide me through all research phases. The combined knowledge you have on all elements of this research is impossible to match, which meant that I could always fall back on any of you for additional knowledge.

Lastly, I would like to thank the people close to me for putting up with the moments I was thinking out loud, and for creating distractions when needed. I could not have done it without you all.

Tom Brouwer *Delft, 18th of June 2024*

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Summary

The construction sector is vital for the functioning of society, and is facing big challenges. The restricting effects of current and growing shortages in both physical and human resources are emphasised by the extensive material and energy use that characterises construction activities. In addition, the construction sector seems to have an inherent problem with developing and modernising, indicated by a continuously low productivity growth compared to other sectors.

The Dutch construction industry is not exempt from having to deal with these challenges, and are even facing additional complications. In addition to the effect of the abovementioned factors, the Dutch construction sector is currently under pressure because of the housing deficit, the increased costs of construction activities, and restricting nitrogen policies. On top of these developments, the emergence of a complex and challenging situation in rehabilitation requirements of infrastructure assets can be seen as a catalyst for change. This rehabilitation challenge, also known as the V&R challenge, forms the focus of this research.

Research context

A majority of bridge infrastructure assets were constructed between the 1950s and 1960s, which means they are approaching the end of their life expectancy. Consequently, all these infrastructure assets require either renovation or complete replacement, which must be done in addition to the general operation and maintenance related activities and the construction of new bridges. As a result of these assets reaching the end of their service life, the sector expects a spike in demand for construction activities. The supply capacity of the current infrastructure construction system is expected to be insufficient compared to the surge in demand generated by the V&R challenge related assets. Hence, there is a need for a transition in the approach and execution of infrastructure projects, in order to maintain the quality and availability of the current infrastructure network. For this transition, the concept of industrialisation is often mentioned as a solution. In a well-functioning industrialised construction system, numerous benefits can be identified, of which increased productivity is the mentioned the most.

Research scope

To transition to a new construction system, integration of innovations and new technologies is crucial. In the current construction sector, there are sufficient individual innovations and optimalisations within traditional subprocesses. However, collective innovation and system transitions through integration and harmonisation of innovative efforts is underrepresented. Therefore, this research conducted an analysis of the concept of industrialisation in the Dutch bridge infrastructure context. The research contributes to existing literature by addressing how the industrialisation process fits to the fragmented nature of the infrastructure sector, using the value chain as the unit of analysis. This way, value chain integration is assessed in regard to the need for harmonisation and the required insights in the dynamics of structural sector dimensions. The research aim was to gain insights to address how (system) innovations and

sector characteristics affect the potential to transition to an integrated industrialised value chain for infrastructure construction. Therefore, the main research question was:

What (combinations of) innovations or technologies contribute to the transition towards an industrialised value chain for Dutch bridge rehabilitation, and what systemic barriers affect their development and diffusion in the market?

Research method

To answer the research question, a context specific methodology based on a qualitative approach was applied. Based on a literature review and desk study, an assessment on suitable framework was concluded by the adaption as the Technological Innovation Systems (TIS) approach. The TIS analysis consists of a structural and functional analysis, which are coupled to review system blocking mechanisms. In turn, these blocking mechanisms were summarised into systemic problems that are in turn used to describe the systemic barriers. To support the TIS approach with industrialisation as the focal technology, industrialisation had to be defined in the infrastructure context. Therefore, established definitions for industrialisation from other fields were used to propose conditions for the infrastructure context. This set of proposed conditions is referred to as the Industrialised Infrastructure Construction (IIC) framework, and should mainly be interpreted as a tool for the TIS analysis, as the TIS analysis is conventionally conducted with a clearly defined technology. In addition, a classification framework to keep track of innovations and new technologies was applied. The required data to analyse the defined frameworks and TIS approach was gathered through conducting fourteen semi-structured interviews. Concluding the methodology, data analysis was done using a combination of open coding and deductive coding, using themes derived from the operationalised frameworks.

Results

In general, the results of this research showed that nearly all current efforts in regard to innovations and emerging technologies have the potential to contribute to the transition towards an industrialised value chain. Over forty types and forms of innovations and technologies were identified, of which over twenty were categorised using the faceted innovation classification framework. Yet, it was concluded that there is no singular combination of innovation or technologies that constitutes an industrialised value chain. This was concluded as contextual factors play a large role in the applicability of specified innovations. Yet, a set of overarching innovation types showed complementary potential for industrialisation, across the traditional project life cycle phases, connected through digitalisation innovations. This set consists of a combination of asset data innovations that provide input for parametric design practices, which can in turn be aligned with broad standardisation and IFD standards, ensuring a manufacturing plan for the prefabrication of components.

The limited understanding of the complete concept of industrialisation also restricted the solidity of conclusions, as it lead to varied interpretations of the research subject. As the lack of acknowledged definition was expected, the research methodology described the process of defining industrialisation in the research context as the first step. Both the theoretical and empirical analysis resulted in a proposed set of conditions that form the framework that could define what constitutes industrialised infrastructure construction (IIC framework), emphasising the importance of seven conditions for a functioning industrialised construction system. These seven conditions, derived from an established framework for industrialised house-building and factors from the infrastructure context, are: Continuity & repetition by demand, standardisation & norms, long-term relations, prefabrication of components, integrated logistics and use of ICT. The final condition, continuous improvements, affects all others. Even though further scrutiny on these constructs is needed, they form a proposal for the foundation of the requirements for a construction system and its actors to be able to transition to an industrialised construction approach. The seven identified constructs are interrelated and interdependent, and all are required to be on a sufficient level in order for an industrialised system to be able to function properly. Both the continuity & repetition by demand construct and the standardisation & norms construct were found to be a necessary change in reworking the industrialisation concept from a housing construction related context to an infrastructure related context.

In regard to the TIS analysis, seven key functional processes for development and diffusion of industrialisation technologies were evaluated. Out of seven, five scored insufficient. These insufficient scores showed that the development and diffusion of innovations and technologies to support industrialisation were limited by inadequate entrepreneurial experimentation and knowledge exchange, too little guidance of the search, insufficient mobilisation of resources, and a general resistance to change and lack of legitimation. These functional barriers were subjected to further analysis combined with the structural dimensions of the demarcated TIS, resulting in the formulation of four systemic problems.

First, there is a lack of upfront coordination & long-term planning leading to unstructured workloads and differentiated and unique project tenders. As a result, efforts to industrialise have little benefits. Asset owners without the ability to develop knowledge themselves have little tools to change the traditional approach, and market parties do little to plan long-term strategies that exceed the level of individual projects.

The second systemic problem was identified to be insufficient support for innovation & knowledge exchange. In the current form, knowledge exchange between competitors and other disciplines falls short to enable collectively aligned development of innovations.

The conservative culture in a competitive sector was found to be the third systemic problem, as it has broad implicit negative effects on the development of various types of innovative efforts. A general emphasis on proven methods was observed, combined with risk adverse behaviour in regard to unvalidated technologies or approaches.

Finally, the level of interdisciplinary collaboration was found to be insufficient and thus form the final systemic problem. A general shortage of interactions and collaboration was identified between actor types, material disciplines, and even departments within organisations. Consequently, it can be argued that this leads to a suboptimal exploitation of opportunities and a disregard for potential for potential complementary elements.

To stimulate transitional efforts, these systemic problems have to be mitigated through policy instruments and organisational strategies, in addition to further research to fill emerging knowledge gaps.

Reflection

The results should be considered in combination with the limitations. For one, the broad scope as a result of defining industrialisation as a focal technology, resulting in the use of multiple frameworks to ensure all contextual factors were analysed. In addition, the TIS was analysed using a unvalidated framework to define the focal technology, resulting in extra required interpretative steps. Lastly, the number of interviews could have been higher considering the unit of analysis being the complete value chain. Yet, despite the identified limitations, the results are argued to indicate signs of generalisability to other infrastructure applications.

For the future

In terms of recommendations, both academic and practical perspectives were described. For academic purposes, six potential research directions were provided for researchers in this area of expertise. Of those, further assessment and validation of the proposed IIC framework is essential, as well as research to make the wide effects of culture on sustainable innovation explicit. The proposed IIC framework requires further justification and validation, in order to acquire general acceptance. In its current form, the IIC framework is a mere research tool.

Recommendations for the using the results of this research for practical purposes were defined in two categories of actors. The first being all identified actor groups that were defined in the TIS demarcation, and the second being asset owners specifically. For all actors that are relevant to bridge rehabilitation efforts, the importance of increasing interdisciplinary collaboration and efficient knowledge exchange was emphasised, along with the explicit need to keep developing new approaches to improve their business case. For asset owners specifically, the need to translate the urgency of the V&R challenge into practical implications for the supply-side of the sector is most important. In addition, implementing broad standardisation and effective bundling of projects through framework agreements or other forms of long-term commitment is of crucial importance.

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V&R	Vervanging & Renovatie (replacement & renovation): rehabilitation
RWS	Rijkswaterstaat (Directorate General for Public Works and Water Management)
IHB	Industrialised House-Building
O&M	Operation & Maintenance
R&D	Research & Development
QDA	Qualitative Data Analysis
IIC	Industrialised Infrastructure Construction
TIS	Technological Innovation System
MIS	Mission-oriented Innovation System
MLP	Multi-Level Perspective
BIM	Building Information Modelling
IFD	Industrial, Flexible, Dismantlable
NTA	Nederlandse Technische Afspraak (Netherlands Technical Agreement)
DMP	Data Management Plan
HREC	Human Resource Ethics Committee
SP	Systemic Problem (TIS analysis output)

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CH1

Introduction

It is seldomly disputed that the construction industry is of crucial importance to the functioning of modern society. It employs over ten million people in the EU alone to ensure the availability, quality and safety of the built environment (Eurostat, 2023). Like many other industries, the construction industry is facing challenges because of changing global and local factors. Current construction activities are characterised by extensive material and energy consumption (Braun, Hall & Mueller, 2021), resulting in a responsibility for a large share of the total global waste production and CO2 emissions (Gerding, Wamelink & Leclercq, 2021). In addition, the material and energy consumption create a susceptibility for future shortages, which are predicted to increase (Mckinsey & Company, 2018). Even if potential future shortages in energy and material are left out of consideration, the construction industry is already experiencing the effects of shortages in the availability of skilled labour (Eurostat, 2023).

The potential disrupting effects of the abovementioned factors are emphasised by a characteristic that seems to be inherent to the construction sector: low productivity growth or lack of productivity growth. While statistics show that other sectors have gradually increased their productivity output over the years, this is not the case for the construction sector (Mckinsey & Company, 2017); (Rathnayake & Middleton, 2023). While the causes for this lack of productivity growth are ambiguous, it can have detrimental effects on future construction activities when combined with the current and future shortage of skilled labour.

Overall, the significant challenges that the industry faces also result in many drivers for change, which in turn lead to opportunities for innovations (BPIE, 2021). Different authors agree that change is imminent in the construction sector, and the benefits of digital technologies, automation, platformisation and manufacturing approaches are widely accepted and rarely disputed (Oti-Sarpong et al., 2022). Nevertheless, no singular approach to exploit these benefits is generally accepted by all, which opens up possibilities for research into system transitions combined with the concept of industrialisation.

This chapter represents the starting point for this thesis report. First, the general challenges as introduced above are specified to the Dutch context, resulting in a more practical problem for which research is required. Second, the concept of industrialisation is introduced, followed by the identification of a knowledge gap, the resulting problem statement, and the formulation of research questions. This chapter concludes with a description of the research design and the general structure of this thesis.

1.1 Problem context – setting the scene

This thesis report is conducted within the context of the Dutch construction sector. Hence, to understand the problem, the link from the general challenges to Dutch specific complexities has to be made. In addition, there are important national factors adding to the relevance of this research project.

Dutch construction activities are currently characterised by a few significant events and developments that set the scene for this research. Like the global challenges, Dutch construction companies face higher business costs through increased material, energy and labour costs. In addition, the energy & sustainability transition is greatly influential in numerous ways, as climate adaptive construction becomes increasingly important. While dealing with those developments, construction activities are affected by national nitrogen policies, which have a restricting effect on traditional construction logistics and on-site activities (TNO, 2024). Finally, the vast housing deficit is perhaps the most known and urgent matter, as it is not expected to decrease over the coming years (Gopal et al., 2022). It is important to note that this deficit is mostly caused by external factors such as population growth and urbanisation amongst other reasons, and less so through the shortcomings of the construction sector. However, the current housing shortage means that there are high ambitions in regard to the required construction capacity. In other words, delivering the number of projects that are required to solve the shortage is a big challenge by itself. Yet, while the abovementioned factors are all problematic on their own, a clear catalyst for transitional change is lacking. While one could say that the challenge of building enough homes to solve the deficit is a sufficient driver for such a change on its own, there is one crucial development still lacking in the list of challenges as mentioned above.

That development is represented by the replacing and renewal challenge in Dutch infrastructure assets, commonly referred to as the V&R challenge (V&R opgave in Dutch). For writing purposes, replacing and renovation will be referred to by the collective term ‘rehabilitation’. In short, the V&R challenge can be traced back to the delivery of a high number of infrastructure projects between the in the fifties and sixties of the previous century. As a result, a vast number of infrastructure assets of different types have already reached or are at the end of their service life, meaning renovation or replacement activities are required (TNO, 2023). The most relevant elements concerning the V&R challenge will be elaborated upon in the next section.

1.1.1 Practical research context

So far, it has been identified that Dutch construction faces complex challenges in both its building and infrastructure sector. This section describes more context as to the size of the V&R challenge, and its effects on society. As mentioned briefly in paragraph 1.1, the V&R challenge consists of a vast number of infrastructure assets requiring urgent renovating or complete replacement. To grasp the scale, an overview is provided in table 1, showing the estimated replacement costs of seven types of infrastructure assets.

Table 1: Overview of total civil asset replacement & renovation costs 2021-2100 (TNO, 2023)

Type of asset	Number [#]	Replacement costs 2021-1200 [Million EUR]	
Bruggen & viaducten	88.501	90.196	**53%**
Tunnels & onderdoorgangen	2.550	19.727	12%
Duikers	344.729	39.819	23%
Damwanden	29.826	10.086	6%
Gemalen	7.973	1.081	1%
Steigers	63.238	8.022	5%
Stuwen	50.229	949	0%
Totaal		**169.881**	**100%**

Most notable, the total replacement costs for all civil asset types would be close to 170 billion euros. Table 1 also shows that the bridges and viaducts are the biggest contributors to the V&R challenge, representing more than 50% of the costs. Over 85% of these bridges and viaducts are owned by the national government and municipalities (TNO, 2023).

In addition to the long-term nature of the V&R challenge, unavailable infrastructure is already affecting society through delays and inconveniences. To illustrate, the high-profile Brienenoord bridge in Rotterdam is in need for urgent renovations due to being deemed unsafe, which would result in major delays for more than two million road users, for a period of over four years (NOS, 2024).

Yet, the part of the V&R challenge that barely reaches the general public through news outlets constitutes the biggest part of the workload. The challenge is characterised by a high number of low complexity assets and a low number of high complexity assets. The Brienenoord bridge exemplifies a high complexity asset due to its size, technical components, and impact on mobility during downtime. An example of the V&R challenge in lower complexity assets is the relatively small town of Pekela, for which the municipality decided to remove 21 out of 34 bridges due to the costs of renovation (Grimmon, 2024). Due to large protests, the municipality managed to formulate a plan to retain 28 out of the 34 bridges, with hopes of financial support from higher authorities. All in all, both examples indicate the diverse and disrupting effects of V&R related assets.

1.1.2 Practical problem

This section argues that the V&R challenge in Dutch infrastructure provides an opportunity for collective improvement in a sector that has an urgent need for it. It does so by describing the most important characteristics regarding the V&R challenge. Thereafter, the concept of industrialising the infrastructure rehabilitation supply chain is introduced as a way to shape the transition that is required to move from the traditional approach towards an approach that is viable in the long-term.

For the context of this thesis, four specific elements in the V&R challenge are especially relevant. First, the most important takeaway is that the V&R challenge represents an amount of work that renders the conventional approach to infrastructure projects unfeasible. If the worst-case scenarios become reality, it would mean that the demand for construction capacity in the specific field of infrastructure construction exceeds the supply. In other words, even if all suppliers, contractors and subcontractors would combine their capacities and got to work on replacing and renovating, it would most likely still not be enough to maintain the current quality of infrastructure. Second, the Dutch construction sector is not exempt from the European trend of shortages in skilled labour (Nationale Bouwgids, 2021). Consequently, this means that the labour intensive, on-site focused traditional approach to construction projects represents a sub-optimal situation. Third, Dutch policies on Nitrogen strongly favour the minimisation of on-site activities, to decrease disruption on the area surrounding construction sites, and to minimise nitrogen deposition into nature.

Lastly, developments as described in 1.1 result in the need for a more integral approach, where more consideration is given to factors such as material and energy use or circularity goals. In present day, infrastructure projects are often seen as unique and individual projects, requiring specific expertise in each project phase. Consequently, the process is very linear and fragmented (Van Rijt et al., 2010), which in turn leads to a lack of learning capacity.

If the status quo remains, societal disruptions through unsafe or unavailable infrastructure will undoubtedly increase over the coming years. Overall, the V&R challenge necessitates a different way of working, which is underlined by different branch organisations (De Bouwcampus, 2021). A transition has to be made towards a construction approach that meets ambitions in productivity, optimises material and energy use, encompasses innovative techniques, and so forth. While such a transition would be beneficial in any form of construction, the V&R challenge presents a unique opportunity to align construction sector parties towards a common goal. While such a transition can be achieved through multiple pathways of change, this research report is centred around the concept of industrialisation. Given the share of bridges and viaducts assets in the complete V&R challenge as mentioned in the previous section, this type of asset is the focus for this research.

1.1.3 Industrialisation & value chain as unit of analysis

Industrialisation is a very broad and historical term, with definitions specified in numerous different fields of work and study. This section merely provides the arguments for its applicability in an (infrastructure) construction setting. For a more detailed definition of industrialisation in this thesis, see the conclusion of chapter two.

The necessity of adapting industrial concepts to the construction sector has been concluded in multiple articles and reports (Ji et al., 2017; Feng et al., 2021; Luo et al., 2021). In a construction setting, the main benefits of an industrialised production chain for construction can be summarised by improvements in project performance, cost efficiency, safety, quality, and productivity (Eriksson et al., 2014). Naturally, these advantages are only achieved when the industrialised production system is functioning as intended, which depends on a lot of factors. Industrialising a non-manufacturing type sector is a complex task (Eriksson et al., 2014), which holds true for infrastructure construction. Given the size of the V&R challenge, no individual company can achieve an industrialised production chain by itself and fulfil the required capacity. Hence, a collective approach to this transitional process is required, in which industrialisation is achieved through a combination of expertise and innovations. From this perspective, this research is intended to contribute to closing the knowledge gaps as described in section 1.2.

As stated, industrialisation is not achieved by a singular organisation. Hence, for this research, the value chain is defined as the unit of analysis. Meaning, the concept of industrialisation is not tested by assessment of one party within infrastructure construction, but by the complete chain of value creation by all relevant sector parties. The definitions of supply chain and value chain result are ambiguously used in literature. For this research, the value chain definition by Ruddock (2008) is applied. His definition accounts for the basic process, as well as the external process that add to value creation from the first to the final project stage.

1.2 Knowledge gap & problem statement

Combining the general and Dutch context, there is a need for the construction sector to change and exploit new technologies and concepts, but efforts so far show that the actual implementation in practice remains hurdled. To withstand and thrive under current and future challenges, the construction sector must transform itself towards more sustainable and industrialised forms of construction. Yet, innovations that serve as the backbone of potential transformations are historically difficult to implement in the construction sector, due to its fragmented and project-based nature amongst other factors (Sepasgozar et al., 2016; Hilbolling et al., 2021). While emerging technologies are developed and adapted by individual stakeholders within the construction value chain, they rarely pose an integrated solution that benefits all parties (Mckinsey & Company, 2018). Hence, the question presents itself as to how system wide innovations that result in integrated solutions can be achieved in a value chain with the abovementioned restricting characteristics. In this area, literature is lacking knowledge concerning the specific capabilities and vulnerabilities within value chain parties and the technical expertise they possess to contribute to system wide innovations.

This general challenge shows similarities with the challenge that is currently faced in the Netherlands. The Dutch infrastructure construction sector and its clients are facing a big challenge in the form of renovating and replacing bridges and their supporting infrastructure, as a significant part is coming to the end of their designed lifecycle. Given the number of individual bridges that require work within the same timeframe, the traditional approach of considering each bridge as a separate and unique project is unfeasible. Yet, the task at hand also provides an opportunity to implement new concepts such as industrialised construction to bridge construction, given the number of simultaneous projects in the near future. There is a window of opportunity for the implementation of construction concepts with characteristics such as modularity, sustainability, circularity, and efficiency through means of (niche) innovations. However, that would require the value chain parties within bridge renovation and construction activities to combine their individual efforts and expertise to create an integrated solution. Finding integrated solutions by assessing (partially) isolated innovations is something that is hard to find in literature, as well as applying concepts of industrialisation to infrastructure related challenges.

1.2.1 Knowledge gap

History shows that construction has a low productivity growth compared to other sectors, which can –amongst other things- be contributed to the difficulty in which innovations and new technologies are adapted. Whether that difficulty is caused by the sectors fragmented nature (Gerding, Wamelink & 6 Leclercq, 2021; Van den Broek, 2020), the public element of infrastructure construction leading to risk adversity (Rose & Manley, 2012), or other factors remains subject for discussion. While there is ample literature on advancing knowledge on emerging technologies, literature on how the actual value chain will invest and implement them and the challenges that are paired with that is underrepresented (Oti-Sarpong, Pärn, Burgess & Zaki, 2022). Despite emerging technology and major investments, there is a lack of integrated solutions that affect the main clusters within the construction value chain (Mckinsey & Company, 2018). This effect is explained by numerous authors, who mention causes like innovation undervaluing and the dynamic and unpredictable production environment amongst many others (Sepasgozar et al., 2016). In addition, previous research primarily focuses on single actor or project phase technology, while research on integrated solutions across a project life cycle or the value chain is lacking. The exception to the latter being housing construction, where the implementation of industrialised concepts is far more mature compared to the industrialisation of infrastructure (Eriksson et al., 2014). Meaning, there is an opportunity to add to the knowledge regarding complexities and dynamics for implementing industrialisation in the infrastructure construction value chain. In other words, more knowledge on multi-technology synergy in construction value chains is needed (Liao, Yang & Quan, 2023).

Overall, research that deals with the fragmented nature of the infrastructure sector, that attempts to integrate the value chain to ensure harmonisation and that gains insight how actors interrelate and interact with each other in an industrialisation process would fill a knowledge gap (Costa et al., 2023). To do so, empirical exploratory studies using a conceptual framework should be preferred over further theoretical research.

To summarise, even though organisations in the construction value chain are implementing emerging technologies or their own innovations, the perspective of ensuring complete value chain integration of complementary solutions is underrepresented in literature. In addition, the potentially disrupting or contradictory effects of combining different innovations pursued by different value chain actors is not yet assessed for the complete value chain.

1.2.2 Problem statement

The knowledge gap as identified in the previous section, combined with the problem description in paragraph 1.1, results in the following problem statement:

The construction sector faces challenges in implementing new technologies and achieving sustainable and industrialised forms of construction due to its fragmented nature and project-based approach. Despite efforts, integrated solutions benefiting all parties within and outside the construction value chain are lacking. This challenge is echoed in the Dutch infrastructure construction sector, particularly in renovating and replacing bridges, where traditional approaches are unfeasible. Implementing industrialisation in this context represents a transition where value chain parties are collectively required to change their approach. However, literature and practical examples that apply the value chain as the unit of analysis are scarce. Therefore, gaining insights is needed to address how (system) innovations and sector characteristics affect the potential to transition to an integrated industrialised value chain for infrastructure construction.

1.3 Research questions

The research questions serve as the foundation for the structure of this thesis report. In the chapters to come, the sub-questions provide the necessary information to form conclusions on the main research question in chapter six. Following the knowledge gap and problem statement, the main research question is:

"What (combinations of) innovations or technologies contribute to the transition towards an industrialised value chain for Dutch bridge rehabilitation, and what systemic barriers affect their development and diffusion in the market?"

To answer the main research question, four research sub-questions were formulated. First, the theoretical context needs to be analysed in order to form the theoretical foundations. Hence, the first sub-question is:

SQ1: How should infrastructure construction industrialisation be defined, and what elements from theory are required to analyse the transition to an industrialised construction chain for Dutch bridge infrastructure projects?

First, a definition for industrialising construction has to be established. In addition, the research context is used to assess which other elements or frameworks from theory should be utilised to construct a methodology to answer the main research question. Hence, keywords as transition, industrialised construction chain, and bridge infrastructure projects are mentioned here. The conclusions from the second chapter of this report can be seen as the output for this question.

SQ2: How to assess industrialisation in the context of bridges in the V&R challenge in order to capture both the context-specific definition of industrialisation and the transitional process it requires?

The second sub-question uses the findings from chapter two to construct a detailed research methodology. This sub-question is formulated to ensure that the data collection approach fits the research ambitions. Hence, the context of V&R challenge bridges is mentioned, as well as the specified definition for the infrastructure context. The second sub-question differentiates between both capturing the definition and the transitional process of industrialising a project-based sector. Therefore, the transition from a traditional construction approach towards an industrialised approach is mentioned explicitly. The output for sub-question two is an implementable research approach, which deals with both the data collection and data analysis steps.

SQ3: What are the key conditions to industrialise V&R challenge bridge projects, what innovations or new technologies are currently being developed that could contribute, and which TIS elements represent blocking mechanisms for the transition towards an industrialised value chain?

Sub-question three synthesises the results of the research. The first sub-question prescribes which main areas should be assessed, and the second sub-question prescribes how they should be assessed. Consequently, the third sub-question gives the results of the assessment itself, and their corresponding analysis. This will be done through a combination of the three framework elements as given in chapter two. The output of this sub-question can be found in the conclusions from chapter four.

SQ4: What insights does the TIS analysis in the context of the V&R challenge provide for innovation driven transitions towards industrialised infrastructure construction?

To conclude the sub-questions, SQ4 generalises the results from chapter four, in order to formulate broader implementations regarding the relevance of this research. In other words, the answer to this sub-question will be interpretive. This sub-question is answered in chapter five.

1.4 General research design

To close chapter one off, this section will briefly address the main research design and thesis outline. As mentioned throughout all sections above, this research is centred around the notion of industrialising infrastructure construction. It will do so by taking the urgent V&R challenge and gathering data from the key actors across its generalised supply chain.

It can be noted that the concept of industrialising is very broad, and the V&R challenge represents a very big case with many different elements. In addition, the concept of industrialising is relatively new to the infrastructure construction sector, as is the urgency of the V&R challenge. As a result, this thesis report is of a broad explorative nature. It will attempt to consider a broad range of information sources, in order to find the bottlenecks and most crucial areas in regard to the subject of industrialisation. Then, perhaps, future research can be designed to provide detailed analysis on smaller elements, by adapting a narrow scope definition.

Given the explorative and broad nature of this research, a qualitative approach was given preference over a quantitative one. Initially, a literature study will be conducted to ascertain how the analysis of industrialisation in a supply chain context should be designed. Then, to collect data, interviews will be conducted with experts and organisations that are active within the V&R challenge, across the supply chains for projects within the challenge. In turn, the collected data will be tested against frameworks as decided in chapter two. These frameworks provide structure to the analysis, in order to filter subjectivity and bias.

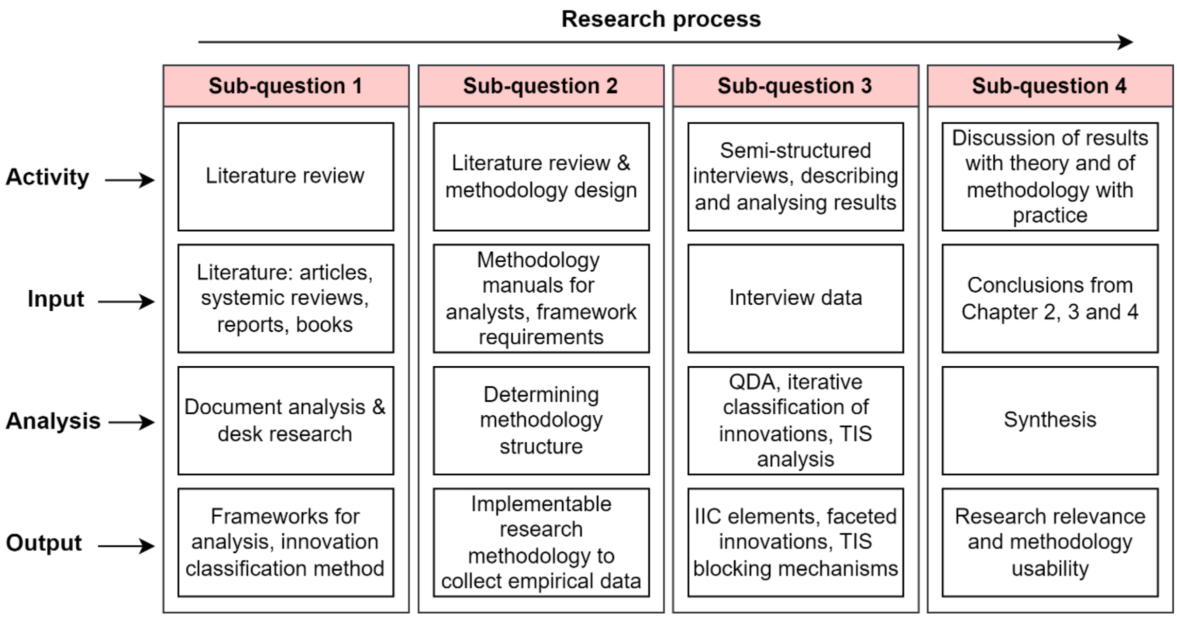


Figure 1: Research process overview (Own illustration, based on Dingelstad, 2021)

The research steps are founded on the principle that addressing each sub-question collectively contributes to answering the main research question. The sub-questions are phrased to follow the natural trajectory of research, beginning with theoretical elements and ending with conclusions and discussions based on empirical data. Four sub-questions have been defined, resulting in a research process overview consisting of four steps as well. Figure 1 shows the research steps, along with the main activities for the researcher, the required input, the types of analysis and the desired output. SQ1 is answered through means of literature studies, and followed by the methodological chapter that answers SQ2. The second sub-question is answered by constructing a methodology for research that fits both the conclusions from theory and the practical research context. In turn, the answer to SQ3 is a synthesis of the most important empirical findings that were observed by conducting the research in practice. Finally, SQ4 combines the research results with both the implications from theory. In addition, it relates to the potential scale-up and diffusion of an industrialised production chain, and the fundamental TIS methodology, in order to assess the general relevance of this research.

1.4.1 Thesis outline

This report is made out of four main parts, consisting of the research introduction, followed by the formulation of the theoretical background and methodology, the case results and analysis from the V&R challenge case study, and closed off with the research interpretation. Table 2 provides an overview for the general outline, showing the overarching themes and relevant research sub-questions.

Table 2: General thesis outline

Thesis outline		
Research introduction	Preface Chapter 1 - Introduction	
Theoretical background & methodology	Chapter 2 - Literature study Chapter 3 - Research methodology	(SQ1) (SQ2)
Case results & analysis	Chapter 4 - Results & analysis Appendices for data sources	(SQ3)
Research interpretation	Chapter 5 - Discussion Chapter 6 - Conclusion	(SQ4) (MQ)

CH2

Literature review

This literature review is conducted to grasp the theoretical context of this research, and consequently forms the basis for the research design required to gather the necessary empirical data in later research phases. Since the first chapter provided little detail as to the definition of industrialisation in this thesis, this section will more concisely define the concept and its relevant elements. First, the working definition for construction industrialisation is introduced, followed by an evaluation of terms with partially overlapping characteristics to. The definition will be supported by describing factors that enable or restrict the applicability of the industrialisation concept in the research context.

Literature was also studied to get a better understanding of transition frameworks and to help decide which approaches to studying innovation-induced systems change would be the best fit for this research. The final decision process can be found in section 2.2, followed by the conclusion on the first research sub-question section 2.3.

2.1 Defining industrialisation

Industrialising is a very broad term, with a vast variety of applications across many sectors. As a result, the term is ambiguously used in literature with different backgrounds. The existence of other concepts with partially overlapping values complicates the definition even further. Therefore, formulating a definition for industrialisation within the context of construction is an essential research activity, which can be found in this section. First, an overview of different definitions is provided, followed by a description of the most comprehensive definition. That definition is compared to overlapping concepts, to aid its clarity in the research context. Then, the definition is tailored to the infrastructure-specific research context. To conclude, a classification framework is introduced to adapt a structured approach to documenting innovations and new technologies that fit the proposed definition.

2.1.1 General principles

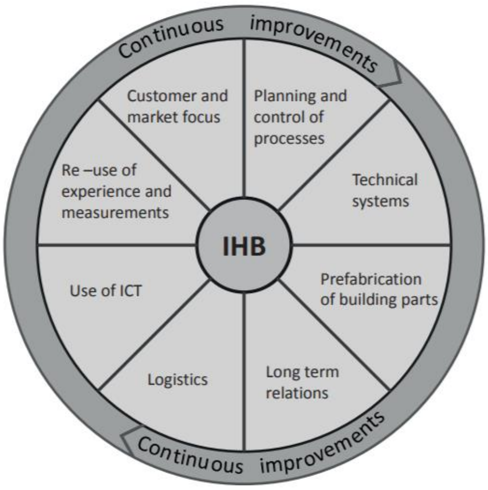
In short, industrialised construction represents an approach to construction activities that utilises methods and processes that are traditionally found in manufacturing or industrial engineering sectors (Goh & Loosemore, 2016). By doing so, crucial project objectives such as cost, time, quality, safety and environment can be improved upon. The basic premise of industrialising construction is that there is a lot to be learned from manufacturing industries regarding product development, production processes and supply chain management (Eriksson et al., 2014).

One simply phrased definition that is often quoted is made by Fathi et al. (2012), who describe industrialised construction as a "construction technique in which components are manufactured in a controlled environment (on or off-site), transported, positioned and assembled into a structure with minimal additional site works." Yet, it can easily be argued that current construction practices fit this definition. Hence, a more concise definition is required. The most recent systemic review on construction industrialisation defines it as a new, innovation-driven form of production and management, with the objective of improving productivity and sustainable development in the construction industry (Costa et al., 2023). In their definition, industrialised construction is stimulated by adapting individual, yet interrelated, innovations from construction, industrial engineering, and management-related practices. Using this definition, it is then argued that industrialising construction requires an organisational transformation, as underlined by other authors on the matter (Wuni & Shen, 2020; Wang et al., 2020). Costa et al. (2023) argue that the abovementioned organisational transformation for industrialising construction in any context can be achieved by following ten design principles, as depicted in figure 1.

Construction industrialisation design principles	
1. Adopt a factory-based production process	6. Embrace mass customisation paradigm
2. Produce modular products	7. Transform the business model
3. Focus on the automation	8. Design a building as a product
4. Implement a lean transformation	9. Focus on integrated project delivery
5. Manage for an efficient production system	10. Focus on results and creating value

Figure 2: Construction industrialisation design principles (Costa et al. 2023)

While Costa et al. (2023) describe their design principles as suitable for any context, they are notably based on housing construction. This observation holds true for a significant part of the literature, as the emphasis is mainly placed on the construction of housing (Lessing, 2015; Li et al., 2020; Attouri et al., 2022), and only rarely placed on infrastructure (Larsson et al., 2014; Eriksson et al., 2014). Lessing (2015) provides a framework to define Industrialised House-Building (IHB) that is not comprised of housing-specific terms. Even though the work of Lessing (2015) has been used in constructing the ten design principles as found in figure 1, they show interesting differences. Lessing formulated a characterisation of IHB that is comprised of twelve constructs, which form a holistic framework that showcases the most important aspects of IHB (Lessing, 2015). However, the last three constructs are omitted in this review, as they are only relevant at the internal company decision making level. This demarcation results in the nine constructs found in figure 2. The constructs are intentionally lacking a clear sequence, as they represent a set of requirements for industrialised housing construction when combined (Lessing et al., 2005; Lessing, 2015).



Planning and control of processes; Processes are thoroughly planned, structured and systematized throughout the organization
Developed technical systems; Technical solutions are developed and structured into systems
Prefabrication; Building parts are manufactured in facilities off-site.
Long-term relations; Participants in the processes are engaged on long-term basis
Logistics; The flow of materials and related information is integrated with design, production and building processes
Use of ICT; ICT-tools and –systems support structuring and managing information throughout all processes and technical systems
Re-use of experience and measurements; Performance measurements give information about process performance and reinforce best practice
Customer and market focus; Thorough knowledge about different customer segments' needs, priorities and expectations
Continuous improvements; Processes and systems are systematically improved

Figure 3: Framework for Industrialised House-Building (Lessing, 2015)

Continuous improvement is an important factor to prioritised in all constructs. Without continuous improvement, the benefits of an industrialised system are limited (Soderholm, 2010; Lessing, 2006; Lessing, 2015). In general, Lessing (2015) argues that each of the eight constructs need to be integrated and reinforced by continuous improvement (the final construct) to establish IHB.

Both the IHB framework by Lessing and the ten Industrialised construction design principles by Costa et al. were considered to use as the basic industrialised construction framework in this research. In general, the IHB framework provides a well-argued, overarching definition of all required elements for an industrialised housing construction system to work. In addition, the description of all constructs does not present clear conflicts when considered from an infrastructure construction perspective. Yet, further evaluation will have to determine whether all IHB framework elements are applicable within the context of infrastructure. However, overlapping concepts are defined first, as they can cause misinterpretations regarding the focal concept of industrialisation.

2.1.2 Overlapping concepts

While there is ample literature to be found on construction industrialisation, the previous section shows that a clear and mutually agreed upon definition is still lacking. As a result, consensus on off-site manufacturing approaches is lacking, leading to disagreements on its overall definition (Ayinla et al., 2019). Consequently, multiple terms exist that can either be seen as a category within the overarching theme of industrialisation, or partially overlapping with elements from industrialisation. In addition, it is important to understand that the concept of industrialisation is inherently connected to other emerging technological/organisational concepts (Jin et al., 2018). Therefore, the following section describes the other relevant terms, and shows how they relate to the core concept of industrialisation.

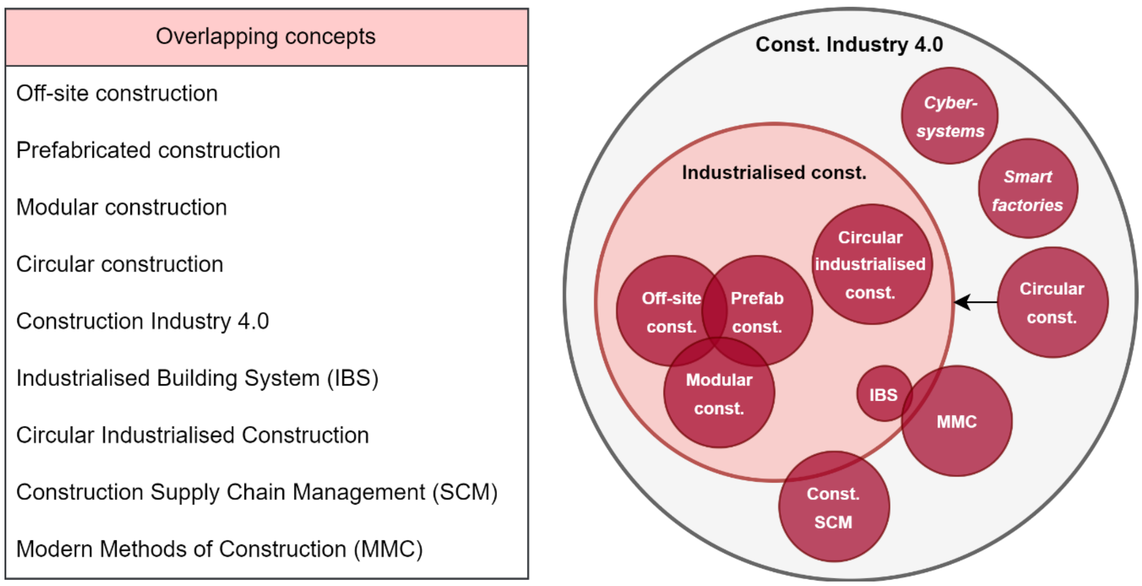


Figure 4: Visualisation of overlapping terms and concepts

Figure 3 shows which concepts completely fall within the overarching theme of industrialised construction, concepts that partially overlap and concepts that fall outside the definition of industrialised construction. Most notably, it shows how 'Construction Industry 4.0' is an overarching theme of developments in the construction sector. Construction industry 4.0, also referenced to as the 'Fourth Industrial Revolution', represents the development of 'smart' factories, production methods, and manufacturing processes (Demirkesen & Tezel, 2022). As a result of the broad definition, industrialisation is not the sole concept. Construction Industry 4.0 also encompasses future technological advancements such as cyber-physical systems and smart factories, which are not an inherent part of industrialised construction. Another thing to note is that industrialised construction differs from circular industrialised construction, as it does not inherently contain ambitions for circularity within its definition.

Literature on Industrialised Building Systems (IBS) is also reviewed and placed in the wider scope. IBS is a combination of prefabrication and industrialised construction and is a term that is mainly used in Malaysia (Kamar et al., 2011). The use of IBS is intended to by complementary to traditional activities, as an evolution in construction rather than a revolution. Yet, the most recent reports show that there is little progress on the use of IBS, because of crucial blocking factors such as ineffective policies and stakeholder reluctance (Al-Aidrous et al., 2023). Nevertheless, IBS is connected to Modern Methods of Construction, which is used as an umbrella term for innovations in both offsite and on-site activities (Nawi et al., 2014).

Figure 3 also depicts the three concepts of off-site construction, prefab construction, and modular construction. To clarify their place within industrialisation, the simplified hierarchal model by Goh & Loosemore (2016) shows how these three concepts relate to each other. Overall, the hierarchal model as depicted in figure 4 shows that there are levels of industrialisation, of which prefabrication is not the highest level that can be achieved.

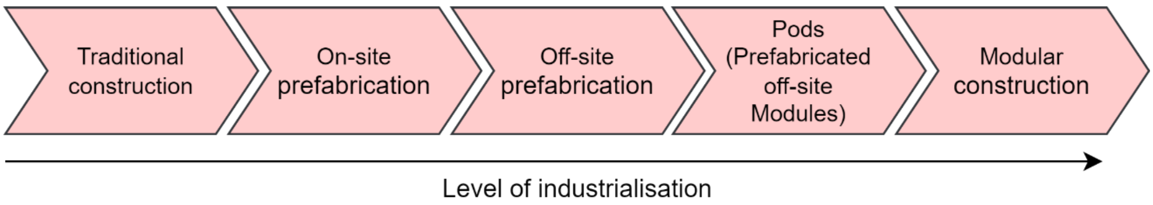


Figure 5: Hierarchal model on industrialisation levels (Goh & Loosemore, 2016)

2.1.3 Housing construction and infrastructure construction differences

After reviewing general construction industrialisation literature, it is concluded that the ten design principles by Costa et al. (2023) and the IHB framework by Lessing (2015) provide the most complete and comprehensive definitions for construction industrialisation. Between the two, the IHB framework is found to be a better fit for this research compared to the ten design principles for two main reasons. First, the IHB constructs leave more room for interpretation compared to the more concisely formulated design principles, which is deemed beneficial given the novelty of the industrialisation concept in the Dutch infrastructure context. Second, the IHB is less all-encompassing compared to the design principles, which aids feasibility in assessment. Overall, the description of all constructs in the IHB framework does not present obvious conflicts when considered from an infrastructure construction perspective. Yet, the IHB framework represents the nine constructs required for establishing and maintaining an industrialised production system that are specific for housing construction, instead of infrastructure construction (Lessing, 2015).

There are significant differences between general housing and office construction and infrastructure construction. Since the IHB framework is based on the construction of housing, its applicability to the infrastructure context can’t be assumed, and has to be reviewed. To do so, the IHB framework is assessed in four steps. First, a comparison between housing and infrastructure construction characteristics is made in table 3. Then, in line with these characteristics, each framework component is evaluated whether they are to be incorporated for the infrastructure context or not. Third, new framework components are identified and added, as well as the necessary rephrasing of IHB framework definitions. After that, the final theoretical framework for infrastructure industrialisation is constructed, which will form the foundation of further steps in this thesis. The main differences between housing construction and (bridge) infrastructure construction are depicted in table 3.

Table 3: Differences in characteristics - housing & bridge infrastructure construction

Characteristic	Housing construction	Bridge infrastructure construction
Project functions	Mostly private assets	Mostly public assets
Complexity	Architectural variety & customisation	Structural & logistical considerations
Stakeholders	Public agencies as regulatory institution	Public agencies as asset owner
Demand	Clear & high demand (housing deficit)	Ambiguous & uncertain for V&R. High urgency, low priority
Finance structure	Mostly private	Often public
Contracts	Primarily Build-operate/own-transfer	Often Design-Bid-Build
Impact on environment	Local to construction site	Wider - decreased mobility
Industrialisation maturity	High	Low

First and foremost, infrastructure assets are public, while housing construction related activities are mostly private. Consequently, infrastructure related construction has public agencies as asset owners, while public agencies function mainly as regulatory institutions in housing construction. The difference between public and private also results in a different finance structure and contract form. For the last three characteristics, project complexity is based on different sources, infrastructure construction has wider impact on the construction site environment. For example, bridge unavailability may restrict mobility and logistics for many users. Lastly, as the maturity of industrialisation in the infrastructure context is low compared to the housing industry, exemplified by section 2.1.1.

2.1.4 Industrialised Infrastructure Construction (IIC)

Keeping the differences between the abovementioned types of construction in mind, each of the nine IHB framework constructs was assessed for their applicability to a bridge construction context. It should be noted that ‘construction’ as used in the IIC abbreviation is used as an overarching term for both renovation and replacement activities. As expected, most of the constructs are arguably relevant for both perspectives, with the exception being the construct ‘Customer and market focus’. The relevance of this construct for the construction of housing is obvious. Yet, while one could argue that the client or asset owner is the customer in question, the description of differing needs for different customers does not align fully with infrastructure projects. This is attributed to the difference in constructing public goods versus private projects.

In infrastructure projects, the customer is both the client and thus asset owner. Hence, customer and market focus was removed.

At this stage. five constructs were deemed vital for both IHB and Industrialised Infrastructure Construction (IIC), being Use of ICT, Integrated logistics, Long-term relations, Prefabrication, and Continuous improvements. Digitalisation is an important topic in all areas of business, including construction. Especially for industrialisation, digitalisation of information and communication is required in both the project context as the general collaborative context (EIB, 2023). The same argument applies for the integrated logistics constructs, as fragmented logistic processes in all phases of a project or programme would be detrimental to the ability to industrialise. Though just named 'Logistics' in the IHB framework, the meaning of this construct in the infrastructure framework context is equal to its meaning regarding housing construction. The construct was named 'Integrated logistics' to make its content more visually explicit in the framework.

The importance of long-term relations is underlined by Costa et al. (2023), who state that cooperation is a core element of industrialising construction. This argument extends from housing to infrastructure, as it emphasises the importance of learning capacity and commitment. Compared to long-term relations, short-term collaborative activities restrict the ability to implement structural and systemic innovations (Tidd, 2010). Naturally, prefabrication is a crucial element to industrialise, and something that is already being done within the constraints of project conditions. However, the construct name has been changed from prefabrication of building parts towards prefabrication of asset components.

To conclude the unchanged constructs, the importance of continuous improvements is undeniable, and also serves as one of the key benefits of industrialisation. As with any new approach, improvements will have to be made. The advantages of industrialisation are only experienced when the production system is constantly receiving updates and improvements, in order to find increases in productivity and efficiency. Naturally, using experience and performance measurements to reinforce best practice is equally important in infrastructure construction compared to housing construction. Yet, for the infrastructure framework, it is attributed to the general concept of continuous improvements.

Two IHB constructs were combined and summarised as a new construct. This new construct, Standardisation & norms, is comprised of both Planning and control of processes, and Developed technical systems. Standardisation or platformisation are often mentioned in literature as core concepts for industrialisation. In the IHB framework, it was not explicitly mentioned.

Even though the IHB framework is well-embedded in housing construction, the infrastructure context called for either more explicit mentioning of an element or an addition of an element. Hence, two new constructs were added, being Flexibility in design and Continuity & Repetition by demand. First, flexibility in design was added as a framework criterium, also covering dismantlability. It is argued that flexibility is operationalised by design for deconstruction, so constructing of infrastructure assets that can easily be dismantled if needed (instead of permanent installations). Research by RWS in 2016 showed that almost 90% of bridges owned by RWS were demolished before reaching the end of their designed lifespan (RWS, 2016). In this application, flexibility means that changes in early project stages can easily be made, while enabling deconstruction for repurposing, thus contributing to circularity in construction activities.

Continuity & repetition by demand is argued to be a crucial requirement for current construction systems to transition towards an industrialised production system (Larsson et al., 2014). Without this construct, value chain parties will not be able to adapt their strategies and approach in a longer timeframe, as they conduct their business one unique project at a time.

The main goal of section 2.1 was to define industrialisation for the research context, in order to formulate a consistent foundation to analyse the research questions. All abovementioned changes to the original IHB framework by Lessing (2015) result in the newly proposed framework to define the conditions for industrialised infrastructure construction. The IIC framework can be seen in figure 5. It should be noted that this framework is primarily constructed to aid the assessment of the research subject in this thesis, and does not constitute a validated framework such as the IHB framework by Lessing. While the construct of continuous improvements is moved for visualisation purposes, its meaning and application remains equal to the IHB framework. IIC only works when all constructs are continuously improved, in order to achieve the advantages that an industrialised construction chain would provide.

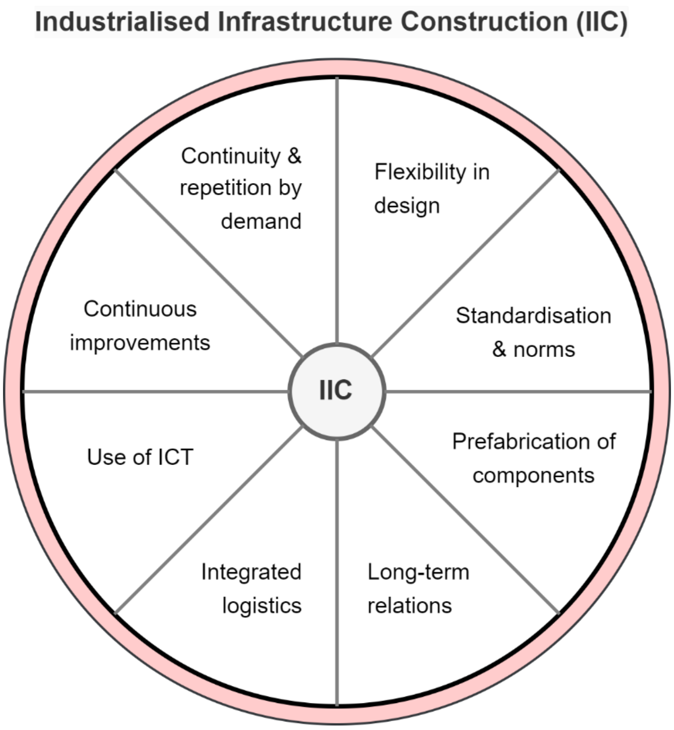


Figure 6: Proposed framework for Industrialised Infrastructure Construction (Own illustration)

Following the IIC framework, it is clear that to have an industrialised value chain and comply with the continuous improvements construct, traditional techniques have to be optimised, and the effects of new technologies and innovations have to be exploited. In addition, the way those new technologies and innovations relate to each other and to existing techniques have to be reviewed. Hence, the next section provides a structured way to classify these new techniques and innovations in a way that enables them to be assessed in chapter four and five.

2.1.5 Classifying innovations in the construction sector

To achieve a successful implementation of industrialisation in the current construction process, the adaptation of innovations is essential (Attouri et al., 2022). Consequently, the question should be asked which emerging innovations contribute to the transition towards an industrialised value chain. In addition to these emerging innovations, current developments in technologies and techniques are also relevant, as they could complement or contradict the potential to reach an industrialised value chain. As mentioned, a structured way to make inventory of these relevant techniques and innovations is required. By doing so, information from different source types such as construction reports, mission statements, and empirical findings can be summarised in a way that allows for later consideration.

The classification method for this research is an adapted version of the five-faceted innovation classification framework by Delarue et al., (2022). The original framework prescribes the use of five facets to define technological innovations, being asset life cycle, the sector (discipline), form (material or immaterial), business function and location.

Table 4: Adapted classification framework elements (based on Delarue et al., 2022)

Adapted innovation classification framework	
Element	Example
Name	BIM, 3D laser scanning, IoT material passports, Composite components
Form	Material, Product, Component, Equipment, Process, Service
Location	Office, Digital collaboration, Factory, On-site, Multi-site
Asset life cycle	Planning, Design, Manufacturing, Construction, O&M, Deconstruction
Estimated maturity	Low, Medium, High

The adapted framework elements are depicted in table 4. Since the classification is not the centre of this study, the framework has been simplified to four facets, of which three are unchanged. The estimated maturity facet was added to show whether an innovation or technique is ready to be implemented on a larger scale or requires more development.

2.2 Transition frameworks for value chain analysis

Fundamentally, industrialising the infrastructure construction production chain requires a collective reconfiguration of the conventional supply chain. As mentioned before, there is no lack of individual initiatives to improve on productivity, quality, and sustainability. However, there is a lack of integrated efforts to find solutions on current challenges. In addition, the efforts that are currently being made by chain parties lack a scientifically embedded theory or framework for structuring information and processes. Hence, this paragraph argues that analysing the research subject case by adapting a system transition theory/innovation driven transition framework is the best approach to assess this initial phase of systems transition in infrastructure construction.

Theory on innovation driven transitions is divided into two approaches, being the socio-technical transition approach and the innovation systems approach (Twomey & Gaziulusoy, 2016). Meelen and Farla (2013) identify the same approaches slightly more concise, finding literature that either relates to the Multi-Level Perspective (MLP) or relates to Technological Innovation Systems (TISs). The socio-technical approach overarches other theories such as the Multi-Level Perspective (MLP), Multi-phase model, Transition Management (TM) and Strategic Niche Management (SNM). The innovation systems approach has been defined in the national, regional, sectoral and technological context. However, frameworks for Mission-oriented Innovation Systems (MIS) have also been constructed as a result of 'challenge-based innovation missions' (Hekkert et al., 2020). Figure 6 gives an overview of the theories on system innovation and transition theories. Disruptive innovation theory is left out of scope as its fundamental assumption that sustainable innovations exceed the consumers ability to absorb them will not be met within the context of this research (King & Baatartogtokh, 2015).

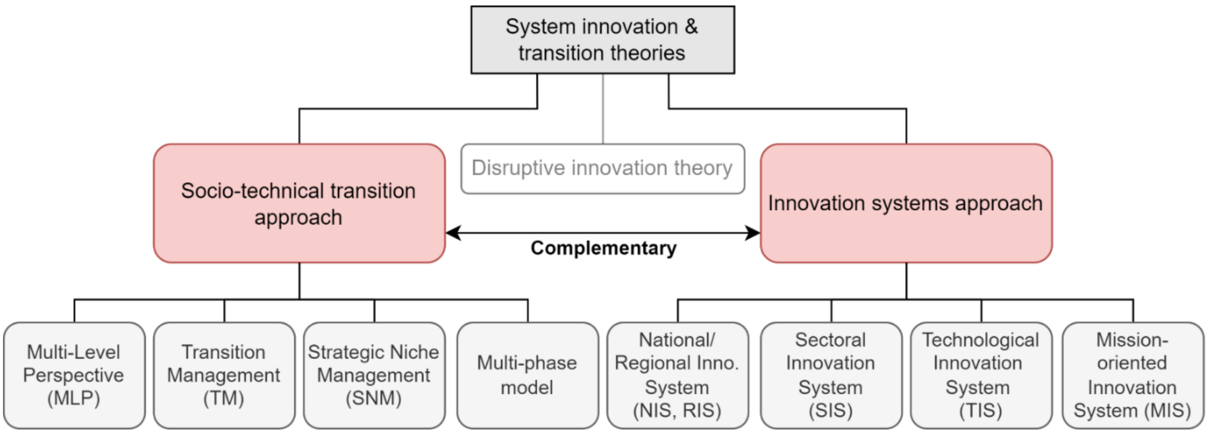


Figure 7: Transition theories (Twomey & Gaziulusoy, 2016; Meelen & Farla, 2013; Lachman, 2013)

These theories are touched upon briefly to assess their fit to the case in this research. It should be noted that the transition approaches below are largely complementary (Twomey & Gaziulusoy, 2016). To start, the Multi-Level Perspective is the most used approach within the category of socio-technical transition theory. It describes transitions as outcomes of alignments in the levels of niche-innovations, sociotechnical regimes and the landscape (Geels, 2007).

Transition Management approaches transitions from a managerial point of view. Therefore, TM neglects a lot of relevant influences from both inside and outside the transition realm (Shove & Walker, 2007). In addition, TM is already incorporated in Dutch policy design, without results (Lachman, 2013). Strategic Niche Management focuses on the process of technological niches gradually overturning the dominant regime by experimenting and learning (Geels & Schot, 2007). The question that presents itself is whether industrialisation and its accompanying elements represent a niche. One definition of a niche technology is that its desirability can’t be taken for granted (Twomey & Gaziulusoy, 2016).

National, Regional & Sectoral Innovation Systems do not provide specific propositions, only conceptual frameworks for transitions. The national and regional innovation systems are more relevant for policymakers (Edquist, 2006). In turn, SISs prioritise knowledge development over the importance of the use of new technologies and its diffusion (Geels, 2004).

Technological Innovation Systems pinpoint bottlenecks in the transition process by breaking down systems into their elements, and then assessing whether they are fulfilling their purpose (Lachman, 2013). This process is done using the seven functions of TISs (Hekkert & Negro, 2009). Candido et al. (2023) identify an absence of studies using TISs, caused by the difficulty of forming networks for cooperation in technological innovation. In turn, this difficulty is caused by sector characteristics such as being loosely coupled and favouring productivity while hindering innovation (Candido et al., 2023).

Mission-oriented Innovation Systems are most suited to challenges relating to societal challenges and use missions to stimulate innovation-driven change (Hekkert et al., 2020). Even though the V&R case deals with challenges in climate action, managing the environment, resource efficiency and shortages in raw materials, its primary concern seems to be construction productivity. Yet, Hekkert et al. (2007) explicitly describe how MISs are applicable for systems with a defined mission covering multiple societal functions. Therefore, it is argued that classifying the V&R case as a societal challenge itself is an overstatement. Consequently, the MIS framework is not the right fit for further analysis of the research case.

Even though elements of the theory may be adapted, SNM does not fully encompass the research case characteristics as well. It is questionable whether the fundamental principle is met, given that there seems to be a consensus amongst sector parties regarding the benefits of industrialisation. However, this consensus will have to be validated in a later stage.

Ultimately, that leaves MLP and TIS for further consideration. While both theories have shortcomings, four arguments as to why TIS is a better fit to this research compared to MLP are provided. First, MLP gives less attention to different actor roles and strategies, interactions between actors, and the agency of actors (Meelen & Farla, 2013). Second, MLP does not clearly describe how niches can break out into regimes (Aldersey-Williams et al., 2020). Both arguments are considered vital for the complete assessment of the Dutch bridge infrastructure construction value chain. Third, TIS is better capable of exposing bottlenecks in transition efforts, as it evaluated by applying seven functions to a deconstructed system (Lachman, 2013). Fourth and final, TIS provides a validated framework with seven functions, resulting in a clear basis to construct a detailed research design. Details of the TIS as a research methodology are described in chapter three, together with its required analysis steps. Points of critique focused on the TIS are discussed in chapter five.

2.3 Conclusion on the first sub-question

This chapter concerned the first research sub-question, which required the theoretical definition of infrastructure construction industrialisation and the tools to analyse the transition to an industrialised construction chain for Dutch bridge infrastructure projects. The first research sub-question was: *How should infrastructure construction industrialisation be defined, and what elements from theory are required to analyse the transition to an industrialised construction chain for Dutch bridge infrastructure projects?*

In regard to how infrastructure construction industrialisation should be defined, an established framework for industrialised house-building was used as a starting point. Representing a set of conditions (or constructs) for industrialised infrastructure construction, the Industrialised Infrastructure Construction (IIC) framework was conceived based on the IHB framework by Lessing (2015), research reports from the Dutch infrastructure context, and an assessment of general infrastructure construction processes and parties. At this stage, the proposed IIC framework consists of 8 constructs, all of which are argued to be essential for a well-embedded and properly functioning industrialised value chain for Dutch infrastructure replacement and renewal activities. Hence, these constructs can be seen as conditions, or requirements.

Though argued through literature and research context specific factors, the proposed IIC is unvalidated at this point. The framework will either be confirmed, or disputed based on the empirical insights that will be gathered in later phases of this research.

For the elements needed from theory to analyse the transition to an industrialised system, it was deemed essential to have a structured way of classifying innovations and new technologies. The faceted innovation classification approach is considered to be a good fit. Yet, given the urgency of the research case, practical usability of innovations is also considered to be important information. Hence, an estimation of maturity was added. Innovations and their interrelations with other (new) technologies and approaches are crucial to the successful implementation of industrialisation and systemic innovation.

To analyse the transition process, the Technological Innovation Systems (TIS) approach was considered the best fit out of all systemic innovation and transition theories. TIS allows for structured analysis of the system using seven functions (processes) that are crucial for development and diffusion of combinations of innovative efforts that together constitute Industrialisation. It is also identified that the TIS framework has shortcomings that could have an impact on the robustness of conclusions. These limitations will be discussed in chapter six.

To conclude, the research methodology that is to be described in the next chapter will analyse two main elements. First, the research design is intended to evaluate whether the eight industrialisation constructs for infrastructure are observable in the defined TIS and in (combinations of) emerging innovations, and in what way. Second, the TIS framework will be adapted using industrialisation as the focal technological innovation. By looking at industrialisation as one innovation (with multiple possible ways to achieve it), it allows the researcher to assess industrialisation in terms of development and diffusion and explain dynamics through the seven key processes. By doing so, inducements and blocking mechanisms for the implementation of industrialisation can be identified, and general recommendations can be constructed to exploit or reduce them.

CH3

Methodology

Following the findings from literature, this chapter describes all elements regarding the research methodology, and the way the research will be conducted in practice. It does so by introducing the main research steps with their corresponding research activities, followed by the operationalisation of the relevant frameworks for further analysis. Then, the interview setup is discussed, containing the fit of interviews to the methodology and the participant groups. To close off, an overview of data related processes can be found in section 3.6, followed by the answer to the methodological research sub-question in section 3.7

3.1 Methodological process

To design the methodological process, a brief revisit to the research questions is required. As provided in chapter one, the four research sub-questions are:

SQ1: How should infrastructure construction industrialisation be defined, and what elements from theory are required to analyse the transition to an industrialised construction chain for Dutch bridge infrastructure projects?

SQ2: How to assess industrialisation in the context of bridges in the V&R challenge in order to capture both the context-specific definition of industrialisation and the transitional process it requires?

SQ3: What are the key conditions to industrialise V&R challenge bridge projects, what innovations or new technologies are currently being developed that could contribute, and which TIS elements represent blocking mechanisms for the transition towards an industrialised value chain?

SQ4: What insights does the TIS analysis in the context of the V&R challenge provide for innovation driven transitions towards industrialised infrastructure construction?

The way these sub-questions are assessed was visualised in the introduction chapter, in figure one. While figure one provides a clear overview, there are four important things to note. First, expert consultation and expert validation are two activities that will be applied to the analysis on areas that remain unclear during the conduction of this research. It is expected that analysing the current infrastructure chain will be paired with implicit elements that are going to require further elaboration by sector experts. Hence, that is the reason they were added to this figure. Second, the first sub-question is answered in the conclusion of chapter two. Those conclusions form the theoretical and scientific basis for the research methodology, which this paragraph is about. A more elaborate description of individual elements within the methodology can be found in sections 3.3 and 3.4.

Since figure 1 serves as the process overview, it encompasses elements that require further specification. These specifications can be found in the subsequent paragraphs. The main elements that require elaboration are the methodology for conducting semi-structured interviews and the corresponding qualitative data analysis, the testing procedure for the proposed IIC framework with empirical data, the integration of the adapted faceted classification of innovations with other frameworks, and the delineation of steps for the structural-functional TIS analysis, along with their operationalisation. These elements are detailed in the next sections. A complete overview of the interview protocol can be found in the third appendix.

3.2 Operationalised frameworks for analysis

The main conclusions from chapter two consist of a theoretical framework for industrialised infrastructure construction, an iterative faceted classification tool for innovations that are relevant to construction activities, and the decision to perform a TIS analysis using industrialisation as the focal technology. The bottom row of figure 8 shows three main elements to analyse the research scope at the centre of the figure. This section operationalises the abovementioned frameworks and analysis tools from chapter two to ensure that the data collection is aligned with their respective information requirements.

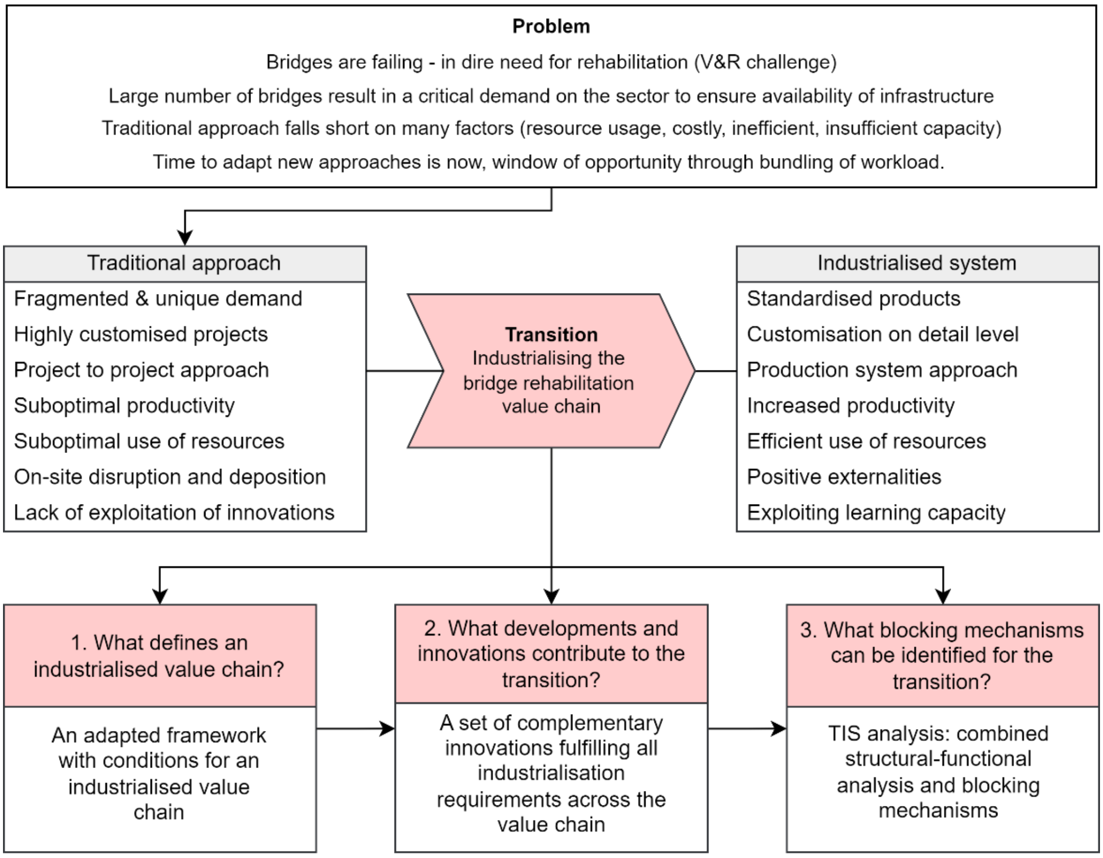


Figure 8: Research context translated to research methodology

Normally, studies that apply the TIS framework follow a simple structure, by first deciding on the focal technology and the demarcation of the system, followed by an analysis of both structural and functional system dimensions, in order to formulate systemic problems by summarising system blocking mechanisms. In this research, industrialisation is regarded as the focal technology. Consequently, performing the TIS analysis is complicated by the varied perspectives on industrialisation and what industrialisation consists of in an infrastructure context. Therefore, testing the definition and conditions for an industrialised value chain is represented by the first box on the bottom row of figure 8, and is done using the proposed IIC framework as defined in the previous chapter. Subsection 3.3 provides further elaboration in this regard.

The first two chapter showed that a transition from a traditional approach requires collective and harmonised implementation of innovations and new technologies. Hence, the second box in figure 8 depicts the need to understand what innovations and new technologies are emerging in the sector. In other words, whether there are directions from technology that complement the definition of industrialisation. Since chapter two already introduced and specified the classification method, it will not be discussed further in this chapter.

By properly defining the first and second box, it enables the researcher to correctly perform a TIS analysis, with the goal of identifying blocking mechanisms for furthering the industrialisation concept in the defined research context. The precise methodological steps required for this TIS analysis can be found in section 3.4.

3.3 Assessment of IIC definition

From a methodological perspective, the IIC framework is applied to ensure that there is clear technology definition for industrialisation for this TIS study to be conducted around. Chapter two defined the constructs that will be used to assess both innovation and system characteristics. However, this does not mean that the IIC framework is definitive, and it will probably require improvements. Hence, the industrialisation concept is also assessed during the data collection process, to enable discussion about its relevance in chapter five.

As mentioned before, the proposed IIC framework currently consists of eight constructs that were derived from both theory and research context. By using the value chain as the unit of analysis, this proposed framework is to be tested against the perceptions and expectations of real-world actors. The research participants will be questioned directly on their definition of industrialisation within their own scope of business. Nevertheless, it can be assumed that those definitions are the result of their position within the construction chain. Therefore, assessing the reactions of participants when indirectly introduced with elements which they fail to produce themselves could result in more diverse findings. Yet, doing so introduces a risk to induce a degree of suggestive bias or leading bias, which is unwanted in terms of reduced rigor and trustworthiness (Galdas, 2017).

For this reason, not one of the eight IIC constructs was asked in the form of a direct question to the research participants. Instead, its eight constructs were implemented both as indicators and themes, trough indirect questions and follow-ups. That way, insights are gathered whether the constructs are considered to be important, and how interviewees define each construct. In addition, the questions inquire whether the constructs are observable in the current system, and if so, how they score. In addition, if there are clear observations of IIC elements in the second segment of the interview, those will be taken into consideration as well. Table 5 shows how the interview setup attempts to maximise the probability of proposed constructs being discussed, without leading the interviewees.

Table 5: Operationalised IIC framework constructs for interviews

IIC framework operationalisation in interviews	
Continuity & repetition by demand	Indirectly asked through follow-up of question 5
Flexibility in design	Inherent characteristic of answer to question 4
Standardisation & norms	Asked in follow-up of question 7
Prefabrication of components	Inherent characteristic of answer to question 4
Long-term relations	Asked in question 8 & 9
Integrated logistics	Inquired indirectly through follow up on innovations
Use of ICT	Inquired by frequency of ICT related oberservations
Continuous improvements	Indirectly asked in the final question of segment 1

Chapter five will reflect on the proposed IIC framework, and its relevance compared to the established IHB framework. Hence, when multiple interviewees emphasise the importance of any factor that is not defined in the proposed IIC framework, those arguments will be reviewed there.

3.4 TIS analysis

As concluded in chapter two, the TIS framework was considered the best fit for this research. Literature provides different iterations for TIS analysis, of which s et al. (2008), Hekkert et al. (2011) and Wieczorek & Hekkert (2012) arguably present instructions with the clearest analytical steps. While there are differences, all three approaches describe a combination of a structural and functional analysis of the focal TIS, which for this report is represented by industrialisation.

This research will follow the TIS analysis steps as constructed by Wieczorek & Hekkert (2012), with small context-specific adaptations. They describe five stages for analysis. First, structural dimensions and their capabilities need to be mapped. Second, a coupled structural-functional analysis is conducted, resulting in functional barriers, argued through the formulation of blocking mechanisms. Third, systemic problems are identified. TIS is often implemented to the field of policy analysis, for which a fourth and fifth step are defined (goals and design of policy instruments). However, given the unmature status of the focal TIS and the framing of the main research question, emphasis is placed on the first three steps.

3.4.1 Structural TIS analysis

After defining the focal TIS, the next step is to assess the TIS structure. Wieczorek & Hekkert (2012) define four structural dimensions, being actors, institutions, interactions, and infrastructure. However, the literature on TIS studies is inconclusive regarding whether and how to include infrastructure as a structural dimension. For the application of TIS in this research project, it was decided to focus on the first three dimensions, being actors, institutions, and interactions. The infrastructure dimension was removed for three reasons. First, the definition is designed for a clearly defined, single technology. In this research context, the focal technology is represented by industrialisation, which is actually a combination of multiple innovations and technologies in many different forms. Second, the infrastructure dimension does not have a solid position as a structural TIS element, and examples of TIS studies exist which leave it out of consideration (e.g. Steen et al., 2019). Time and resource constraints also played a part. To analyse the three extra subcategories would require even more data collection, which was considered unfeasible given the elaborate data requirements from interview participants.

In some TIS guides, technology is seen is the first system component that requires mapping (Hekkert et al., 2011), while other framework applications are conducted in a different way (Wieczorek & Hekkert, 2012). Yet, the TIS analysis is mostly applied for innovation concepts that are unambiguously perceived by TIS actors, which is not the case for the concept of industrialisation. Hence, the technology element is defined by taking the relevant industrialisation elements as tested by the proposed IIC framework, and combining them with current innovation and investment trajectories found through the classification process.

The three structural TIS dimensions are actors, institutions, and interactions. Hence, to analyse the structural dimensions of the TIS in chapter four, insights have to be gathered on who the relevant actors are, and what capabilities they have. Then, both ‘hard’ and ‘soft’ TIS institutions are reviewed, and all factors that fall in between. Finally, the way actors interact within the TIS closes off the structural analysis.

3.4.2 Functional TIS analysis

As stated, the TIS framework identifies seven key processes for the development and diffusion of innovation, which are represented by the seven TIS functions. This research will follow the function definitions as specified by Wieczorek & Hekkert (2012), which are not significantly different from the definition by Bergek et al. (2008) or Hekkert et al. (2011). The seven functions are shown in table 6, along with a description. Combined, these functions can be seen as criteria to score the TIS on its ability to perform well.

Table 6: TIS function overview

TIS functions (summarised from Bergek et al. (2008), Hekkert et al. (2011) & Wieczorek & Hekkert (2012)	
F1 - Entrepreneurial experimentation	Turning potential of new developments into concrete action
F2 - Knowledge development	R&D and knowledge development in the form of 'learning by searching, learning by doing'
F3 - Knowledge exchange	Exchange of information in networks - 'learning by interacting, learning by using'
F4 - Guidance of the search	Activities positively affecting the clarity and process of selection amongst alternatives
F5 - Market formation	Articulation of demand & creation of space for new technologies
F6 - Resource mobilisation	Allocation of sufficient resources, for both financial and human capital
F7 - Counteract resistance to change /Legitimation	Creation of legitimacy via various means

The functions as depicted in table 6 are well-embedded in literature. Hence, they are unchanged for this specific application. The functions will be scored and compared between actor groups, as defined in section 3.5.1. Score differentiations within actor groups are considered out of scope.

To score each function, a set of diagnostic questions was formulated, and depicted in table 7. Since the interviews are conducted in Dutch, the questions were originally constructed in Dutch as well. The questions can be found in their original format in appendix three. These questions are based on examples from literature and amended to suit the research context of this thesis (Bergek et al., 2008; Hekkert et al., 2011; Wieczorek & Hekkert, 2012). To score the functions, a five-point Likert scale was adapted, ranging from very weak (1) to very strong (5), with neither weak nor strong (3) representing a neutral attitude. This Likert score scale was constructed by combining previous TIS analysis manuals (Wieczorek & Hekkert, 2012; Hekkert et al., 2011) with Likert scale best practice (Joshi et al., 2015). It was decided not to add a choice option along the lines of ‘Don't know’. Instead, no answer was noted if that was the case. Following other TIS studies, function scores below three mean that the function is insufficient and thus represents a negative influence on the TIS.

When all functions are scored, and arguments to support the scores are documented, the final phase of the TIS analysis in this research application is to find the blocking mechanisms problems that constitute the systemic problems for the TIS to develop and be diffused in the market. This step is described in subsection 3.4.3.

Table 7: TIS functions and diagnostic questions for assessment

TIS functions & diagnostic questions	
F1 Entrepreneurial experimentation & production	1.1 Are there enough diverse actors within the bridge infrastructure chain innovating and experimenting? 1.2 Is there sufficient innovation within the bridge infrastructure chain by parties capable of large-scale production? 1.3 Is there sufficient consideration given to scaling up existing innovations? 1.4 What is the status of the further development of innovative experiments/Living Labs?
F2 Knowledge development	2.1 Is enough knowledge being developed to stimulate the concept of industrialisation? 2.2 Is the quality of knowledge developments related to innovations sufficient? 2.3 How does existing knowledge (development) relate to barriers for collective innovation in the chain?
F3 Knowledge exchange	3.1 What is the level of knowledge exchange among actors in the same category? (Clients/contractors/suppliers) 3.2 What is the level of knowledge exchange between science and the chain? 3.3 Are the lessons learned from old projects/initiatives shared with the chain? 3.4 How does the method of knowledge exchange relate to barriers for collective innovation in the chain?
F4 Guidance of the search	4.1 Is there a clear understanding of the ways in which industrialisation should develop in the sector? 4.2 What are the expectations regarding the techniques and innovations for industrialisation? 4.3 Are there clear and stable policy objectives regarding collective system innovation in the sector? 4.4 Are actors in agreement regarding challenges and required changes for industrialisation? 4.5 How does (the absence of) a collective vision relate to barriers for collective innovation in the chain?
F5 Market formation	5.1 Is the current and expected market size sufficient for an industrialized system? 5.2 How does (insufficient) market size relate to barriers for collective innovation in the chain?
F6 Resource mobilisation	6.1 Does human capital pose a barrier to collective innovation in products and processes? 6.2 Does financial security pose a barrier to collective innovation in products and processes? 6.3 Do physical resources (raw materials/infrastructure) pose barriers to collective innovation? 6.4 Is the current form of the chain sufficiently developed to implement innovations behind industrialisation?
F7 Counteract resistance to change (legitimation)	7.1 Is there resistance to (collectively) implementing innovative techniques in parts of the chain? 7.2 Is there resistance to industrializing the bridge infrastructure chain? 7.3 Are there regulatory barriers for collective initiatives in innovations?

3.4.3 System blocking mechanisms

It is expected that there will be scores below the mean of the Likert scale. These low function scores indicate that the TIS is not performing well enough in that area. It is argued that low scoring functions are the consequence of shortcomings in structural TIS dimensions. These shortcomings in are either presence related, or capability related. Meaning, problems may be caused by the lack of presence of structural elements, or by insufficient quality within the structural dimension properties. In short, the cause for low function scores is explained by describing either actor's problems, institutional problems, and interaction problems. By coupling these shortcomings in structural dimensions with functional barriers, system blocking mechanisms can be formulated. In turn, these are summarised into systemic problems. An overview of this part of the TIS analysis is provided in figure 9.

Figure 9: Overview of functional segment in TIS analysis (Wieczorek & Hekkert, 2012)

3.5 Interview setup

Thus far, theory has been the greatest contributor to all conclusions. Yet, finding the deeper dynamics behind the functioning of the system in practice is something that is only achieved by collecting empirical data. Hence the semi-structured interviews and their subsequent analysis are a crucial part of this research methodology.

Semi-structured interviews were chosen after a broader consideration of fundamental research design theory. First, the decision was made to conduct qualitative research over quantitative research. Qualitative research is preferred in situations where more emphasis is placed on understanding the context of the problem, amongst other reasons (Almeida, Faria & Queirós, 2017). Given the lack of maturity that the concept of industrialisation has in the context of infrastructure project in the Netherlands, it was concluded that the characteristics of qualitative research were a far better fit for this research compared to their quantitative counterparts. Yet, applying qualitative methods means a potential vulnerability to bias. Therefore, any form of bias will be monitored during the execution of this methodology. Five types of bias are identified, being Halo, Horn, Affinity, Conformity and Confirmation bias (Bergelson et al., 2022).

Consequently, the type of qualitative research had to be decided, for which the use of surveys and conducting interviews were considered. Given the exploratory nature of this research, conducting interviews is preferred over the use of surveys, as concluded by Jain (2021) as well. Interviews allow more in-depth exploration and the exploration of unexpected perspectives on the subject matter. In addition, interviews are more suited to the limited number of relevant actors in the context of this research. Out of all interview types, semi-structured interviews are the best fit. Semi-structured interviews are especially suited for situations where probing, open ended questions are asked to find out what individuals in a group think, amongst other situations (Adams, 2015). If you consider the bridge infrastructure a group that's made of different types of group members, this definition applies. In the V&R context, it is interesting to see where interviewees identify their own priorities.

3.5.1 Interview participants

To conduct the research as described in the previous section, research participants had to be selected. Given the research aim of mapping a potential industrialised bridge construction value chain, each actor category and their interests had to be sufficiently represented in the participant list. Six categories of participants were identified, as shown in table 8. This category differentiation is a generalisation, as each organisation is unique in its contribution to the construction system, and some organisations will have overlapping activities with other categories. It should be noted that interviewees agreed to participate anonymously. Hence, all elements that could hint to a specific organisation are removed. Even though the data analysis is performed on participant category level, conflicts or contradictions within groups are equally important. For the collection of data, 14 interviews were conducted, of which the reference numbers can be found in table 8 as well.

Table 8: Actor groups and interview number references

Actor group	Interview numbers
Clients (asset owners)	D1; D7; D12
Contractors	D6; D9; D10; D11
Engineering & architectural organisations	D3; D8
Suppliers & manufacturers	D4; D14
Knowledge institutes & branch organisations	D2
Technological startups	D5; D13

The first participant group consists of clients, who own the assets that form the cause of the V&R challenge. There is a high number of clients, each with significant differences in terms of the number and type of assets they own. Therefore, the selection of interviewees within this category was made using two criteria. The first criterion concerned the probability of research specific knowledge on their assets. The second criterion was simply their probability of participation, measured through any form of earlier contributions or commitment to the problem context.

The second group represents the contractors and is arguably the most important one given their experience, knowledge, and ability to use that knowledge to implement innovations. Yet, while contractors may compete for the same tenders, there are differences between them. To see how they relate to each other and to other organisations in the bridge infrastructure chain, four contractors were interviewed.

Like contractors, engineering and architectural firms have a great degree of knowledge on the types of assets that are relevant to this case. While some contractors provide their own engineers, independent organisations for engineering remain a vital group to collect data from. Therefore, they make up the third actor group. The fourth group represents suppliers and manufacturers. These companies are of crucial importance to the current supply chain, but even more so when the traditional supply chain is transferred into an industrialised value chain.

The fifth group, knowledge institutes and branch organisations, are key in context-setting regarding the operational requirements for innovation. This group includes network and platform organisations as well, which are categorised within the branch organisation group. They have the means to align parties within the sector, using tools as norms and sector agreements. The final group is made of technical startups. Startups are relevant since they are the incubators of niche innovations, which could be the key in achieving an industrialised value chain in the future. They may have experiences in what it takes to force change in a system within a sector that is - or used to be – traditionally passive in adapting innovations.

3.5.2 Interview fit to research process

The interview is conducted in two separate segments yet conducted in one sitting. Figure 10 shows the general process of each interview, and its approach, themes, and form of analysis.

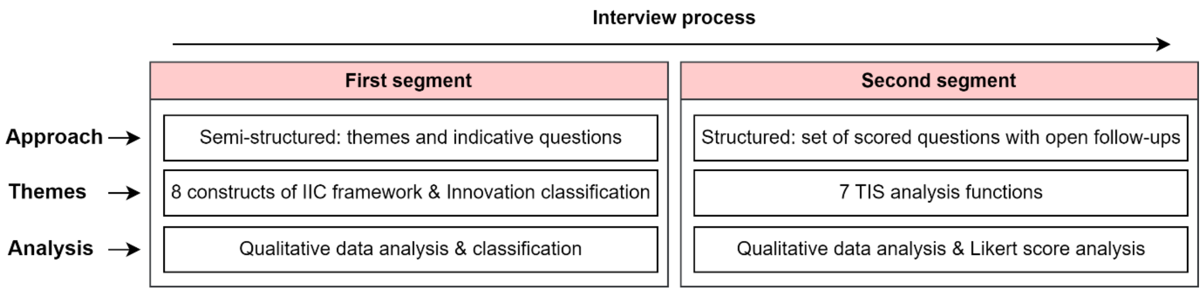


Figure 10: Interview process with specifications (own illustration)

To frame the interview themes, the methodologies were evaluated to determine which information should be gathered for complete and correct analysis. Given the more explorative nature of the IIC framework, the interviews were conducted in a less structured way. Consequently, the more analytical nature of the TIS framework allowed for a more structured approach in the interview. As a result, each interview consisted of a semi-structured segment followed by a segment with structured questions. For the second segment, the structured questions allowed for the implementation of a Likert scale for improved comparability between interviewee perceptions.

3.6 Data management

This section briefly touches up on data related activities. Besides desk research and literature studies, which formed the base for the first and second chapter, a lot of qualitative data was gathered from interviews with organisations in the demarcated system. Hence, thorough data management practices are of crucial importance. In total, the summarised and anonymised interview data from both segments would constitute to over eighty pages of text. Hence, the initial plan of adding the data to the appendix was not a preferred option. Therefore, if required, the anonymised interview data is available through contacting the first supervisor of the thesis committee.

3.6.1 Data analysis

For analysis of interview data, the five-phase process for Qualitative Data Analysis (QDA) was used to construct an approach that fit the specifics of this research. After comparison with competing approaches, such as Qualitative Content Analysis (QCA), Thematic Analysis, and Reflexive Content Analysis (RCA), QDA provided the best source of inspirations. Authors on QCA seem to have conflicting interpretations on its operationalisation. Most considered QCA an inductive approach (e.g. Finn, 2022), while some state it is based on both inductive and deductive efforts (e.g. Williamson et al., 2018). While RCA was constructed as a reaction on contradictory methodologies in QCA (Nicmanis, 2024), its emphasis on constant reflection can be argued to be redundant. The designed interview approach for this research is inherently iterative, meaning reflection is embedded in the process. Given the use of two frameworks (IIC and TIS), a primarily deductive approach was considered a better fit to this research design and context. This was found in the five-phase process, of which the first two analysis phases are deductive (Bingham, 2023). The five-phase process is shown in figure 11.

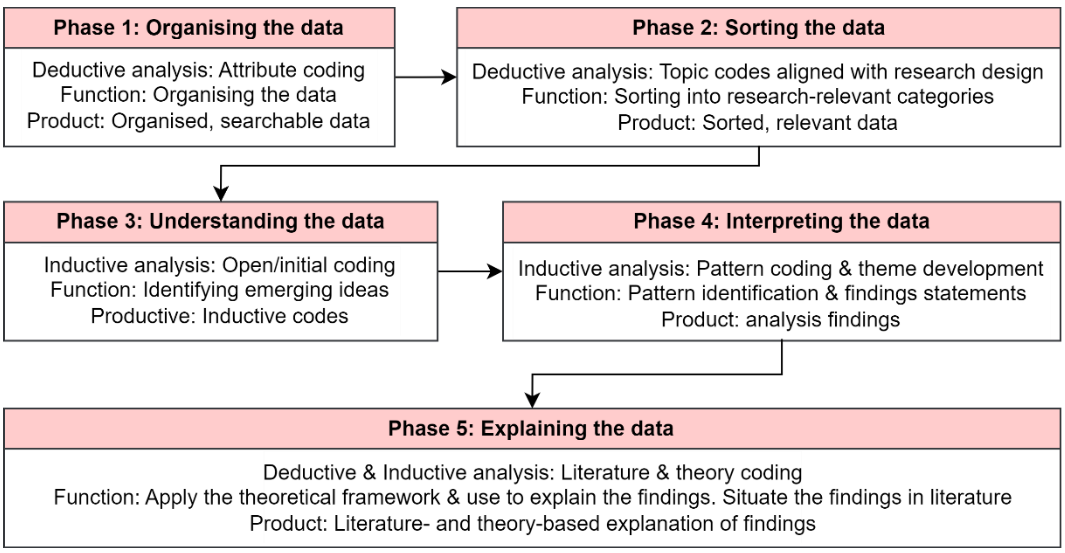


Figure 11: Qualitative Data Analysis – five phase process (Own illustration, based on Bingham, 2023)

Phases one, two and three were applied unaltered. Answers from interviewees were bundled per question as described in the interview format. The themes from the interview protocol allowed for a structured way of categorising interesting statements. In addition to applying framework elements from both the IIC framework and the TIS framework as deductive codes to analyse the data, open coding was also applied. This was done using online coding software (ATLAS.ti), which allowed for convenient comparison.

3.6.2 Data Management Plan

This research is conducted with an approved Data Management Plan (DMP) by the HREC committee of the TU Delft. In this plan, the agreement can be found regarding the approach for collecting and handling the interview data. First, all research participants were asked for their informed consent, by going through the informed consent form as approved by the data steward. As stated in the informed consent form, interview data will be anonymised and only stored on the TU Delft OneDrive. After processing the interview data, original interview recordings were deleted. All additional ethical considerations can be found in the HREC approved data management plan.

3.7 Conclusion on the second sub-question

The second sub-question is: *How to assess industrialisation in the context of bridges in the V&R in order to capture both the context-specific definition of industrialisation and the transitional process it requires?*

The methodology elements as mentioned in the previous sections fill all unknowns in the second sub-question. The context-specific definition of industrialisation is captured by inquiring on the constructs as proposed by the IIC framework. By extension, a transition towards industrialisation requires insights in the emerging technologies, which is incorporated through the classification tool. Lastly, the transitional process it requires is covered by the TIS analysis, which combines structural system characteristics with actor perceptions on how well the system scores on the processes that are required for the transition.

So, the way in which the assessment is conducted can be described in four steps. First, the scene is set regarding the perception of interviewees on the V&R challenge and the future viability of current processes, as it can't be assumed that all parties are in agreement about the concept of industrialisation and the need for it in the context of bridge infrastructure rehabilitation. Then, the reader is introduced with the demarcated TIS. This is done by describing all relevant structural dimensions of the system, in the structural part of the TIS analysis. The structural analysis is conducted prior to the evaluation of the IIC constructs, to introduce the reader with the characteristics of the system that is analysed. Hence, following the structural dimensions, an assessment of findings regarding the IIC constructs is done. Fourth, the analysis of system functions is performed, which in turn lead to the system blocking mechanisms when combined with relevant elements from the system structure. Normally, one would not split the structural and functional parts of the TIS analysis. However, given the adaption of industrialisation as the focal technology, there is an added step to properly define the technology prior to conducting the functional analysis.

CH4

Results & Analysis

This chapter describes all research results that were collected after conducting the research as presented in chapter three. It does so by following the same sequence as prescribed in chapter three, starting with the structural analysis as required by the TIS framework. However, this chapter is introduced by validating the significance of the V&R challenge, which was done by a general question at the start of each interview. Following, results regarding the proposed IIC framework and the observed innovations are used the further define industrialisation. This chapter is concluded by the functional TIS analysis and the conclusion to the third research sub-question.

General perception of the V&R challenge

To assess the general perception of the V&R challenge within the supply chain, interviewees were questioned regarding their views on the V&R challenge, its implications, and general attitude from the perspective or the organisation they represented. The key takeaways for the first question can be found below.

The opportunities that the V&R challenge presents for the sector to move forward are acknowledges by some, as is the need for a collective effort to mitigate the potential effects of V&R related bridges being unavailable. In general, all interviewees agreed that a significant increase in workload as a direct result of aging bridge infrastructure is to be expected. Some parties were preparing to act on the implications of the V&R challenge (D1; D6), and some parties are ready for the increased workload, having completed the preparatory phase of their concept (D8; D11). The workload would be divided in both (partial) replacement activities and renovation activities. Multiple participants acknowledged a shift in their approach when comparing the initial introduction of the V&R challenge and the current situation. At the start, priority was given mostly to the replacement of bridges (D7; D9). Over time, developments in all corners of the construction sector constituted a shift towards prioritising renovation, life extending measures, and other, cheaper alternatives (D1; D8; D11).

Three main causes for this shift were described, of which more available and higher quality data on existing bridge infrastructure is the first (D7). In addition, budget restrictions were mentioned as a cause to change approach, as complete replacement inherently requires a higher initial investment (D7). Lastly, there was a lack of consideration for sustainability elements such as material and energy usage and on-site disruption in the initial introduction of the V&R challenge case (D1). Later, when those factors received consideration, moving away from complete replacement towards renovation wherever possible was given the preference. Nevertheless, some interviewees showed scepticism towards the focus on renovation, as they argued that the only thing that it accomplishes is a delay in the bulk of work that is required (D6; D8). In addition to renovating and replacing, some asset owners mentioned scaling down bridge functionality levels, in order to extend their service life. By doing so, the frequency in which the bridge in question has to endure (heavy) loads is dramatically reduced, at the cost of reduced mobility and logistics.

The urgency of the V&R challenge is debated by some, as prognosis reports are not translated to practical work (D6; D9; D10). In other words, the V&R challenge is still perceived to be of low priority for some parties within the infrastructure sector. Interviewees also provided more details on the diversity of the V&R challenge. On multiple occasions, the significant differences between big asset owners and smaller asset owners were emphasised. As mentioned in the first chapter, the V&R challenge is characterised by a high number of low complexity assets and a low number of high complexity assets. Smaller asset owners are collectively responsible for the high number of low complexity assets, while the bigger asset owners individually have the responsibility over high complexity assets. On the one hand, big asset owners are responsible for bridge assets that have high impact during downtime for construction activities. On the other hand, smaller asset owners are responsible for a high number of bridge assets that have little and localised impact during downtime.

Long-term viability of current practices

To assess whether the organisations within the infrastructure construction chain were aligned in the need for change, the second theme was defined as the long-term viability of the current construction approach. In other words, interviewees were asked whether they perceived the current way of working and current trend of developments to be sufficient to deal with upcoming challenges.

In general, the proposition that the current way in which infrastructure projects are initiated, executed and delivered is not viable in the long term was undisputed amongst interview participants. Naturally, the reasons as to why they felt that way were varied. A wide array of factors that reduce the long-term viability of current approaches were found and described below. The order in which they are stated also indicates the frequency in which they were mentioned by other interviewees. It was also observed that many of the challenges that were described in section 1.1 were mentioned by the interviewees, such as shortages in many areas of construction and climate adaptive construction.

The way in which current construction processes are initiated also result in a varying demand for specific construction activities. Asset owners are rarely aligned with other neighbouring asset owners, which can result in two similar projects being designed and executed in a different way, merely because there is a municipal border between the two types (D10). Consequently, in current practice, a lot of projects are designed and executed in such a way that the end product is highly customised. Meaning, bridge projects with comparable characteristics may have significant differences in construction details. An example is that there are hundreds of types of available methods for seam transitions (D12). Naturally, this is unwanted when demand for bridge construction activities surges.

To close off, current practices provide little chance to consider strategic activities that exceed the project level. Meaning, the scope of optimalisations within the process is often demarcated at the project delivery. Lastly, some parties argued that current practice prescribes a lot of planning processes and documents that serve as conditions prior to starting a project. As a result, a lot of specific decisions are made that define the execution of the project, leaving little flexibility. This was also argued to be a hindrance (D1).

4.1 TIS – structural analysis

As mentioned, the complete value chain for Dutch bridge rehabilitation functions as the unit of analysis for this research. The TIS has a larger scope, as it is defined by the set of actors and rules that influence the speed and direction of technological change in a specific technological area (Hekkert et al., 2007). Therefore, mapping the structural dimensions and capabilities of the system forms the basis for developing the subsequent sections in this chapter. As mentioned in chapter three, the structural dimensions of the TIS in this research context are actors, institutions, and interactions.

4.1.1 System actors

This section answers the questions as presented in 3.4.2, regarding which organisations present the set of relevant actors for the TIS and what their capabilities are in regard to the concept of industrialisation. Analysis of this structural element is complicated, as it hinders the anonymity that served as a condition for interview participation. Therefore, detailed description of each individual actors' business is left out of scope.

Six categories of actors were defined to be relevant for the demarcated TIS, being asset owners, contractors, engineering & architectural organisation, suppliers & manufacturers, knowledge institutes & branch organisations, and technological startups.

Asset owners

For the research case, the largest variety of actors is found in the asset owners' category. From the top down, you have Rijkswaterstaat (RWS), followed by the twelve provinces and 342 municipalities, among which are the big four (Amsterdam, Rotterdam, Utrecht, The Hague). In addition, ProRail owns bridge assets to sustain the train infrastructure, and water agencies manage the remaining bridge infrastructure. Combined, these asset owners are responsible for the availability of Dutch bridge infrastructure.

The most important singular asset owner is RWS. RWS is responsible for 1134 bridges, many of which are placed in intensively used highway or national road infrastructure (Ministerie van Infrastructuur & Waterstaat, 2023). On a slightly smaller scale, this also applies to assets managed by the provinces. Both RWS assets and some assets managed by provinces show three characteristics. First, the argument that is at the foundation of the V&R challenge: A high number of bridge assets was built around the same time, thus requiring work at around the same time too. Second, RWS and provincial assets are generally bigger compared to municipal bridges, resulting in a higher complexity to renovate or replace and a broader consideration of disciplines. Third, RWS and provincial have a high impact on mobility and logistics when they become unavailable.

Naturally, the big four (G4) municipalities of Amsterdam, Rotterdam, Utrecht and The Hague are important asset owners, as they all manage a large number of bridges, and have large organisational capacity. Yet, the other 338 municipalities are insignificant when considered individually, as they mostly manage simple bridge assets. In addition, they are said to have little knowledge on the state of their infrastructure, they rely on external parties for technical knowledge, and tend to have little financing to address problems in their infrastructure. Yet, the most important factor for the consideration of municipalities in the TIS is that their assets are not built around the same time but expanded gradually through town expansion. Hence, in regard to the capabilities to influence the TIS, bigger asset owners showed significantly more ability to stimulate the development of new approaches compared to individual municipalities.

Contractors
Besides asset owners, contractors are the most obvious relevant actor type for the defined TIS. In the current value chain format, contractor responsibility can vary from mere execution to complete design, planning, execution and O&M. Hence, they also represent the organisations that are tasked with operationalising new technologies and innovations in practice. Currently, the contractors can be seen as the main source for practical expertise and experience.

In the Dutch V&R challenge context, there is a small set of big contractors, accompanied by a high number of smaller, specialised subcontractors. Each of the big contractors has a base level of expertise and resources that allows them to undertake bridge projects of most sizes. However, the big contractors have different specialisations and speciality resources which set them apart in their fit for specific projects.

It was also identified that there is a difference between contractors that merely manage projects and assign tasks to subcontractors, and contractors that both manage and execute the projects by assigning their internal project teams. This differentiation seemed to mainly be caused by the size of projects that those organisations dealt with.

The importance of contractors for the TIS is also based on their capability to scale up and validate innovations in real world project applications. Contractors can utilise their experience in the proven and traditional methods, to assess how alternative technologies score on performance indicators.

Suppliers/manufacturers

In an industrialised production system, the supplier or manufacturer plays a central role. Hence, in this TIS, the relevance of this actor group is undeniable. While this actor group is named to incorporate both suppliers and manufacturers, interviews showed that there are mostly suppliers who supply manufactured elements. Hence, this group will be referred to as suppliers in this subsection.

In the Dutch infrastructure context, a handful of suppliers were identified. For the most part, these suppliers filled their production capacity through exploitation of a singular discipline, being concrete, wood, steel, or alternative materials such as composite. In general, these suppliers provided asset components, to be used in on-site installation by contractors. However, there were examples of suppliers that extended their service to incorporate complete installations as well. The business activities of this actor group showed the most comparable characteristics with elements from industrialisation, such as off-site prefabrication in a controlled environment. Hence, if other factors are mitigated, this actor group would have the capability to further develop their current business approach and apply further concepts of industrialisation.

Engineering/architectural firms

Contracted by either asset owners or contractors, engineering and architectural organisations can be responsible for varying elements, such as preparatory data collection, project planning and project design. Perhaps even more so than contractors, engineering and architectural organisations have a high degree of knowledge and technical expertise. In the Dutch V&R context, this type of actor was partially responsible for life expectancy calculations, and furthering data collecting for bridge assets. In addition, interviews showed that this type of actor was closely involved with the development of standards and guidelines, which are applied throughout the sector.

Knowledge institutes & branch organisations

Knowledge institutes and branch organisations represent crucial parties in the TIS. In this wording branch organisations are used as an overarching terminology to include network and platform organisations as well. On the one hand, knowledge institutes are the main contributor to shared knowledge documents such as guidelines, standards, norms and recommendations, consequently shaping the way that construction activities are planned and executed. On the other hand, branch organisations serve as a connecting party, enabling the flow of information between different actor types, the alignment of ambitions, and harmonisation of future efforts. As an example, this research is predominantly facilitated by De Bouwcampus, which can be seen as a branch organisation.

Even though they serve the interest of the construction sector, knowledge institutes have the ability to stimulate or reduce the applicability of certain types of new technologies or innovations. Hence, the trajectories they pursue have a direct influence on which types of innovations or technologies are developed further and implemented in projects.

Technological startups

Given the importance of innovations and new technologies on the transitional process within the Dutch construction sector, technological startups are incorporated in the TIS as a relevant actor type. In this research context, this type of actor is defined as a party that attempts to enrich the set of alternative technologies that could challenge traditional processes. After assessing organisations that fall within this category, two different backgrounds for this type of actor were observed. First, there were startups that were created because of a knowledge or technology gap in traditional construction processes, with the intend to fill that gap. Second, there were companies that saw potential in other sectors and industries and had the ambition to apply comparable ideas in the Dutch construction context.

In general, technological startups introduce techniques that have the potential to either disrupt, complement or substitute traditional processes. Meaning, they may introduce new concepts that form the foundation of the main construction approach in ten years.

4.1.2 System institutions

The TIS functions within the constraints of its institutions. Both ‘hard’ institutions such as rules, laws and regulations, and ‘soft’ such as customs, habits, routines, traditions and norms (Wieczorek & Hekkert, 2012). Both types are presented in this subsection, along with their general effects on the TIS. The institutions are described in order of how binding they are to the value chain parties, starting with laws, followed by partially binding norms, and closing off with varying soft institutions.

The primary hard institutions ensure that the quality of bridge infrastructure is maintained above the minimal threshold. The primary hard institutions that are relevant for the V&R challenge context consist of the Environment & Planning Act (Omgevingswet) and the procurement law (Aanbestedingswet). The Environment & Planning Act is highly influential in many areas of construction projects, as it bundles 26 laws and a number of rules and guidelines concerning the built environment (Ministry of the Interior and Kingdom Relations, 2021). Consequently, it is difficult to identify which construction processes are most affected or defined by the effects of this act. For example, it encompasses rules that could either restrict or enable the reuse of components, through the decree on material bound sustainability profiles.

In turn, the procurement law defines how potential new projects are brought to the tendering stage in order to ensure that there is no discrimination, equal treatment, a transparent process, and proportionality in the procurement process (Ministerie van Economische Zaken, 2023). Public authorities such as RWS, provinces and municipalities are bound by this law, and the market parties organise their activities in a way that increases the likelihood of projects being awarded to them.

In the middle, different partially binding guidelines and norms exist, of which publications from knowledge institutes are the most influential. These knowledge institutes publish norms, guidelines, recommendations, handbooks, and knowledge documents that are formulated based on agreements between construction sector parties. If mutually agreed upon by project parties and thus integrated in project contracts, these publications can be binding. Out of all, CUR recommendations and NTA/NEN (Netherlands Technical Agreement) standards can be considered to be the most important for V&R challenge related activities.

The effects of these guidelines, recommendations and norms are ambiguous. For example, CUR-recommendation number 124 significantly increased the number of bridges that required renovation and replacement activities, considering their expected constructive safety (CROW-CUR, 2019). Thus, CUR-124 served as a catalyst for the V&R challenge. Alternatively, standards are being developed to facilitate new approaches in construction, such as NTA8085, NTA8086, and NTA8089. These three standards, developed by NEN, describe how IFD principles should be implemented in bridge construction projects (D7).

To close off, soft institutions in the TIS were evaluated. They posed a bigger challenge to assess, as many elements are implicit. Yet, it is evident that these soft institutions are highly influential. Interviewees mentioned that across the value chain, there is a general preference to rely on proven methods and traditional approaches (with the technological startups being the exception). This preference was mentioned to be on both technical and procedural elements of the construction activities. Interviewees were often preferred to conduct business as usual, exploiting the expertise that was built through repetition of established practices. There is a general perception that expectations are high concerning both quality and the ability to achieve ambitions in areas such as sustainability.

4.1.3 System interactions

This structural dimension requires insights in how actors interact within the TIS. In literature, interactions between actors are viewed from both the perspective of networks and individual contacts. Since the TIS is demarcated on the value chain and external parties that influence activities within it, system interactions relating to networks can be visualised through the production chain and the parties that can have influence on it. Hence, to assess these system interactions, an overview of the construction process is required.

Since the complete value chain serves as the unit of analysis for this report, it was concluded to be unfeasible to visualise the process using every activity, interaction, and responsibility for each actor type. To exemplify this argument, figure 12 shows the extensive list of responsibilities for asset owners, which is one out of six defined relevant actor types.

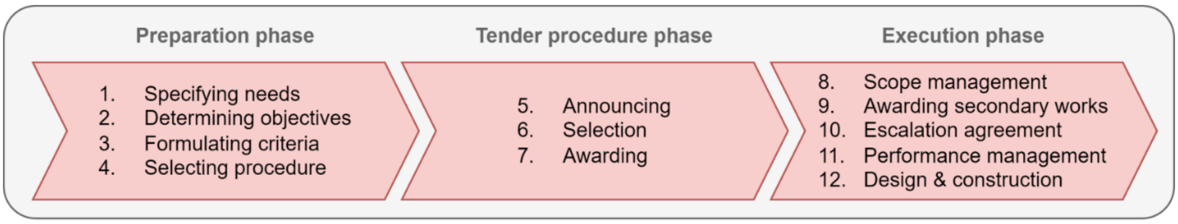


Figure 12: Asset owner responsibilities during project phases (PIANOo, 2023)

Hence, it was concluded to construct a construction process overview with a limited detail level, in order to elaborate on general actor interactions within the TIS. The process with a decreased level of detail is shown in figure 13, inspired by the process description of an asset owner in a V&R challenge project (Provincie Noord-Holland, 2022).

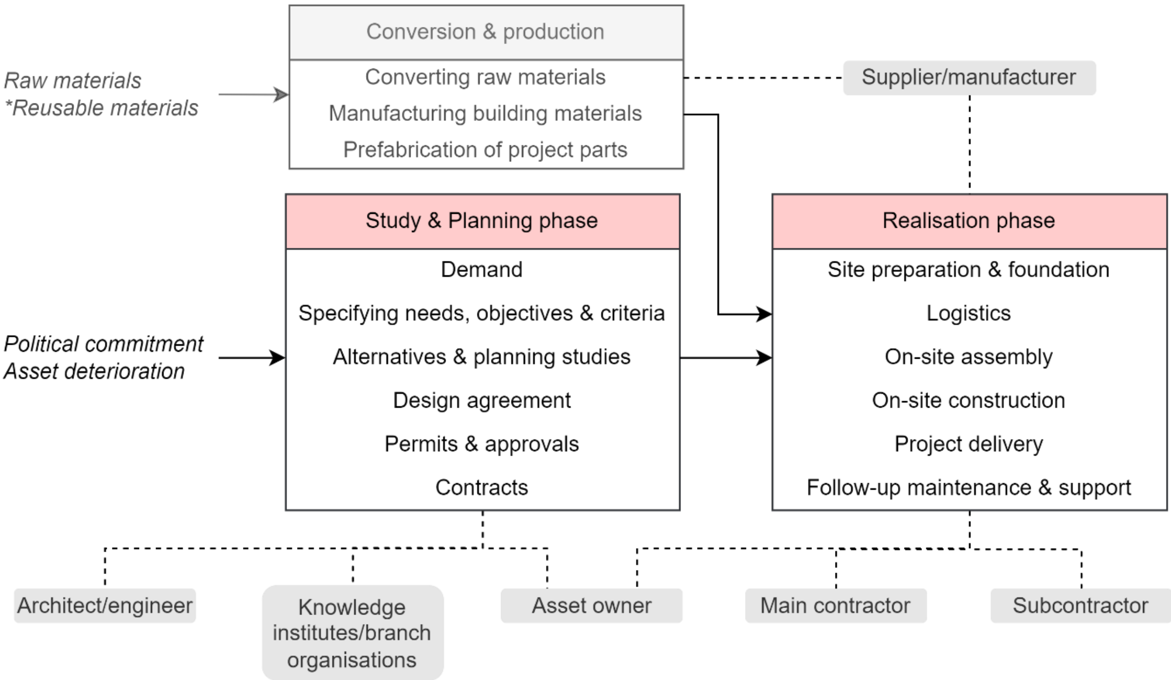


Figure 13: Generalised infrastructure construction process

Figure 13 requires a few clarifications. First, the conversion & production block is depicted separately, as this conversion is being done regardless of project confirmation. Naturally, the exception being the project specific components. Second, the actor group of technological startups is missing from the figure. Technological startups have the potential to add new forms of value addition in many different parts of the construction process. Hence, they are not depicted in a specific area. Third, the responsibilities of value chain parties can differ depending on which contract form is applied. For example, if an integrated contract is applied, the contractor will have an important role in the preparation and design phase (Voerman, 2023).

Within the phases, individual actors in the network have optimised their section of the value chain. Yet, when considered from the perspective of the complete value chain, the current form of interactions is suboptimal. This can be attributed to the high number of different project phases and differentiated responsibilities, and the fact that there often multiple sub tendering procedures in singular projects. In addition, partially caused by the often-fragmented project process, there are big moments of responsibility transfer. In those moments, the current form of interaction results in the loss of knowledge.

Interactions between actors on an individual level shows two main types. On the one hand, the TIS structure shows that there are organisations that have the ambition to form long-term collaborations or partnerships. On the other hand, it also shows that there are organisations that prioritise their independence and hence reject lasting interactions with the same organisations.

4.2 Results in regard to the IIC construct definition

Since the first interview segment covered the elements of the proposed IIC definition, this section evaluates all proposed constructs, and reviews whether the empirical findings require the IIC framework to be modified. Overall, all eight constructs were mentioned at least once. The initial coding process showed that in terms of frequency of observation, both the continuity & repetition by demand construct and the standardisation & norms construct were considered the most crucial by interviewees. From the same perspective, the constructs of continuous improvements and long-term relations were third and fourth most important. The subsections in this paragraph elaborate on those perceptions.

4.2.1 New IIC constructs

Continuity & repetition by demand
In general, without this construct, organisations within the construction chain that transition to a more industrialised form of business won't experience the benefits that such a system is supposed to bring.

If the urgency is high and represented in a high demand that is clustered and consistent, the possibilities for market parties to change their traditional ways increase, and therefore the potential to industrialise the production chain increases as well (D6; D8; D9). Currently, examples can be found of bundled demand by asset owners, where projects are offered in portfolios of 10-20 assets (D12). Consequently, repetition allows for development and improvement of production practices. In short, industrialisation thrives when bundled demand surges (D10). This applies for both replacing and renovating (D8). By consistently working with the same parties and people, the learning capacity is increased dramatically. In other words, while constantly doing new things creates a susceptibility for mistakes, "routine makes master" (D12). Nevertheless, in many cases, asset owners show little consideration for the comparable characteristics of their assets compared to assets from other asset owners, resulting in a perceived uniqueness that is not actually the case (D11). As a result, there is a lot of time, money, and material being lost if all asset owners approach their bridges in a unique way (D10).

To close off, continuity and repetition can be aided through framework contracts as described in the long-term relations section. However, there are examples of asset owners changing direction, even when framework contracts are in place and mutually agreed upon, resulting in uncertainty for market parties (D9).

Flexibility in design
This construct was conceived to fill gaps in the IHB framework regarding functional use and its change over time, changeability in both early project stages as well as the operational phase, and

dismantlability for repurposing – design for deconstruction. The interviews showed that there was little explicit consideration for flexibility in design. There was only one contractor that was actively prioritising reusability and dismantlability while avoiding complete uniformity (D10). It stood out that this was significantly more active in complete bridge replacement and the construction of new bridges instead of renovation or partial replacement. While flexibility was never mentioned explicitly, IFD was mentioned a lot. For the flexibility element, IFD is centred around expandability and changeability (NEN, 2021).

There is a contradiction to be found when combining the increased use of standardisation with the avoidance of completely uniform products. From a functional perspective, uniformity could be the optimal situation. Yet, the quality of the built environment and its effects on social security amongst other things should not be overlooked (D12). This argument is based on the visual aspect of bridge infrastructure, instead of the purely functional element that is often at the centre of the discussion. Likewise, the functional element was the main argument behind the formulation of this construct for the IIC framework.

Also, extensive processes in early project stages were emphasised by one interviewee, who argued that they result in decisions that prematurely shape the project, resulting in an inflexibility to make changes in later project stages (D1). This inflexibility was perceived as a restriction to optimise project results.

Standardisation & norms
This construct was mentioned extensively by nearly all interviewees, who are in agreement on the need for standardisation. Standardisation is seen as the key to increase the currently limited production capacity, in order to deal with the expected surge in demand that is expected given the V&R challenge characteristics (D4). Standardisation on both technical and process related elements is seen as the main instrument to move to an industrialised system (D2). The premise that assets within the V&R challenge lend themselves for standardisation is somewhat disputed. Some interviewees agree, whilst others emphasise the multi-disciplinary character of bridges, along with the effects of contextual factors. Nevertheless, if the differences between bridges turn out to be too much, standardisation can be achieved in the areas of process, contract, and components (D12). The use of standard platforms with a degree of customisability on the detail level is also already being done by some chain parties.

Mostly, the problems seen in end-of-life assets can be categorised into standard problems, which in turn require standardised solutions in terms of both technical approach and procedural (D11). However, there is a complexity in making the step from a generic standard or norm to an operational standard or norm that can directly be applied to projects. For example, contextual factors such as dyke height were found to be highly influential in a partial bridge replacement project (D8).

However, its definition in the IIC framework focused on general standardisation and norms which all parties comply with, which is how it was not always perceived by the interviewees. Nearly all participants who mentioned standardisation were speaking in term of standards on the level of their own organisation. In general, the concept of standardisation does not apply when all parties formulate their own standards, without aligning them with other parties that are active in the same field of work. If all contractors and manufacturers retain their own standards, which differ from each other, industrialisation is less applicable. Only standards by the NEN, the Dutch National Technical Agreements (NTA), serve as norms that exceed internal organisational standards. Yet, compliance is not mandatory.

Continuous improvements
In essence, this construct represents the same general idea in the IIC framework compared to the IHB framework, describing the need for systematic improvement on all processes and systems. In specific, this construct also incorporates the use of experience and performance measurements.

On the one hand, an industrialised system enables the process of continuously learning from previous work and developing construction methods based on those lessons to exploit potential positive factors (D3; D8; D9; D10; D12). Hence, this covers the use of experience that inherent to this construct. On the other hand, continuous improvements are vital to the development of an industrialised system that exploits the intended theoretical benefits (D10). It should be noted that there was no explicit mentioning of applying performance measurements.

In general, it was expected that no interviewee would argue with the importance of this construct. Its general definition results in a natural tendency to agree, as it is hard to argue against consistently improving something. Yet, its importance as a construct is derived from the understanding that it is very unlikely to successfully implement a new construction approach without requiring iterations of improvements.

4.2.2 Unchanged IHB constructs

Some constructs were unchanged from the IHB to the proposed IIC framework, excluding small construct name changes. However, a brief assessment regarding their relevance in the infrastructure setting can be found in this section.

Prefabrication of components
Whilst being defined as a core construct for IIC, prefabrication was only mentioned once during the first segment of the interviews. Yet, this is not a result of interviewees being unaware or in denial about its benefits. On the contrary, it shows that prefabrication is common practice already, maximised within constraints as size and complexity. Implementing a prefabricated method for construction wherever possible was implicitly given preference by all interviewees. In the case of smaller assets, such as pedestrian or bicycle bridges, complete prefabrication and one-on-one replacement is common practice. Overall, because of the abovementioned reasons, this construct does not require further elaboration.

Long-term relations
Nearly all interviewees were aligned in the ambition for long-term commitment, when asked about relations and collaborative efforts. Without long-term relations, the industrialisation process remains hindered as a result of the fragmented sector (D8). Besides, long-term commitment enables early investment, thus enabling a planned increase in effectiveness and efficiency (D11). Long-term relations are needed to ensure harmonisation across the production chain (D8).

As an answer to the question in what way interviewees maintained relations and collaboration, construction teams (bouwteams) were often mentioned. Yet, construction teams are mostly organised for a singular project, or a handful of projects. Meaning, the collaboration it entails is of limited term. To industrialise and prepare for the V&R challenge, the way of working together requires something other than construction teams (D11). Framework agreements and framework contracts (raamcontracten) were also frequently observed. In contrary to construction teams, framework contracts consist of a higher number of bundled projects over the span of multiple years. Overall, contracting is a critical element for long-term relations, in order to retain them when things are down (D4).

There were a few examples of parties that actively avoided consistent relations with other sector parties, to ensure their independent position in the market. The potential negative of depending on relations and collaboration to deliver projects was also mentioned. By doing most work individually, and reducing the number of parties involved, changes in the project can be made swiftly, and thus more flexible (D10). However, this argument depends on the project size, which show great variation within the set of V&R challenge projects.

Integrated logistics

Empirical evidence of the importance of integrating material flows with design, planning, manufacturing and on-site activities was not explicitly found in the interview results. However, parametric design was often mentioned. By adapting parametric design, preconditions from other areas of project expertise can be incorporated, ensuring that the final design is a viable option for all relevant project parties. Hence, parametric design can be seen as a way to incorporate information about materials and their flow in the construction process.

Furthermore, an important element for this construct was that suppliers and manufacturers are involved during the development process (Lessing, 2015). The interviews showed indicators that this is increasingly being done (D1; D4). The importance of designing and planning projects with the market and production capacities in mind was also emphasised by a few interviewees.

Use of ICT

The use of ICT as a core element for industrialisation was not observed explicitly during the interviews. However, digitalisation was mentioned frequently, and in some cases even argued to be at the core of developments (D9; D12). In addition, the focus on BIM is argued to represent the use of ICT. In contrast to the use of ICT, BIM was mentioned by multiple interviewees.

The lack of mentioning of ICT raises new questions, as it is expected to be a significant factor in industrialising, especially so given the current digitalisation of society. Hence, this construct will be discussed further in chapter five.

4.3 Classification of innovations

Creating an overview of potentially relevant innovations and emerging technologies was done by assessing both the V&R challenge value chain through interviews, and other sources such as sector magazines, reports, and other documents. Findings from both sources are kept separated in order to correctly represent initiatives in the V&R context, while also being able to see potential beneficiary initiatives from other sources. The complete overview of innovations can be found in appendix 1. Given the extensiveness of that list, innovations collected from other sources are only mentioned when there are indications that they fill a gap. Meaning, if they presented clear complementary characteristics, they were added to this analysis.

Table 9 shows the innovative efforts or technological directions that were observed during the interviews with V&R challenge related actors. It should be noted that a green cell does not necessarily represent that organisation corresponding to the interviewee number is actively stimulating or developing the innovation. While that could be the case, the green cell also represents a general positive attitude towards the innovation, or an ambition to work with it in the future. There is no way to ensure anonymity if table 9 were to only show the innovations that were being developed or stimulated by each interviewee.

Table 9: Innovations mentioned by interviewees

Innovation/technology	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13
IFD													
3D concrete printing													
Alternative material - Composite													
Building Information Modelling (BIM)													
MKI in RAW (climate cost indicator in procurement)													
Broad standardisation													
Database enhanced component reuse													
Prefabrication													
Platformisation within parameters													
Modulair steel bridges													
Alternative material - Cement substituted concrete													
Parametric design													
Online design visualisation software													
Digitalisation - Robotisation off-site													
Artificial intelligence													
Digitalisation - on site (E.g. GIS)													
Digitalisation - Innovative monitoring methods													
Asset life extending measures													
4D & 6D project planning													
3D composite printing													
3D cloud modelling													
Data driven asset management													

Table 9 shows that IFD was mentioned the most, followed by prefabrication, off-site robotisation, innovative monitoring methods, broad standardisation, and parametric design. Given the frequency of mentioning by interviewees, IFD is described briefly in section 4.3.1.

4.3.1 IFD

Representing the principles of Industrial, Flexible and Deconstruction, IFD has been developed as a new approach to bridge construction projects. Mainly focused on new projects and extensive renovation, it prescribes construction using standardised prefabricated components, implemented in an expandable and changeable configuration, combined with consideration for ease of deconstruction. (EIB, 2023). In general, interviewees showed a positive perception of the potential of IFD, which is operationalised through the NTA’s as mentioned in section 4.1.2. However, a few points of critique were also observed.

Currently, IFD is still too generic to implement without requiring extra work (D3). If IFD doesn’t define the details, its usability as a standardised solution is lost (D6). Also, IFD seems to be primarily focused on new constructions, or complete replacement. The applicability and potential benefits for IFD in renovation projects is smaller (D6). In addition, the future reusability of IFD bridge components is often mentioned as a major benefit. However, the shift in focus from complete replacement towards renovation and asset life extension is a development in the opposite direction (D9). In seven years of discussing IFD, only two projects have been attempted (D13). IFD is still used too little because asset owners fail to use it as a required approach (D8). Without an explicit requirement, the current state of IFD requires a higher initial investment (D8), thus rendering it uncompetitive compared to proven methods.

Nevertheless, IFD is by far the innovation that is the best fit to the IIC constructs, as it shows direct links multiple industrialisation constructs, such as standardisation & norms and flexibility in design, and indirectly references to continuity & repetition by demand.

4.3.2 Innovation facet categories

Table 10 shows the innovations and technologies that were mentioned during the interview, with their corresponding facet categories. For more detailed overview of the frequency of facet categories, including innovations from other sources, see appendix 2.

Table 10: Faceted classification of innovations mentioned by interviewees

Innovation/technology	Form	Location	Asset life cycle	Estimated maturity
IFD	Multiple	Multiple	Multiple	Medium
3D concrete printing	Multiple	Factory	Manufacturing	Low
Alternative material - Composite	Material	Factory	Manufacturing	Medium
Building Information Modelling (BIM)	Process	Digital collaboration	Multiple	Medium
MKI in RAW (climate cost indicator in procurement)	Process	Office	Design	Low
Broad standardisation	Process	Multi-site	Multiple	Low
Database enhanced component reuse	Service	On-site	Deconstruction	Low
Prefabrication	Multiple	Factory	Construction	High
Platformisation within parameters	Process	Multiple	Multiple	Medium
Modulair steel bridges	Product	Factory	Construction	Medium
Alternative material - Cement substituted concrete	Material	Multiple	Manufacturing	Low
Parametric design	Process	Digital collaboration	Design	Medium
Online design visualisation software	Service	Digital collaboration	Design	Low
Digitalisation - Robotisation off-site	Multiple	Factory	Multiple	Low
Artificial intelligence	Multiple	Digital collaboration	Multiple	Low
Digitalisation - on site (E.g. GIS)	Multiple	On-site	Multiple	Low
Digitalisation - Innovative monitoring methods	Multiple	Multiple	O&M	Medium
Asset life extending measures	Process	On-site	O&M	Medium
4D & 6D project planning	Process	Digital collaboration	Planning	Low
3D composite printing	Multiple	Factory	Manufacturing	Medium
3D cloud modelling	Service	Digital collaboration	Multiple	Low
Data driven asset management	Multiple	Digital collaboration	Multiple	Medium

The frequent placement of ‘multiple’ will be discussed in chapter five. Overall, the first facet shows an underrepresentation of innovations or technologies in the form of equipment. The same applies for innovations that are office-related for the location facet. For the third facet, both O&M and deconstruction received little explicit mentioning. The final facet shows that a lot of innovations and technologies are not yet perceived to be ready for broader implementation, with a lot of low and medium scores.

4.3.3 Complementary innovations for industrialisation

On some occasions, interviewee mentioned sequences of innovations or technologies that would constitute an industrialised value chain from their perspective. For example, gathering on-site data with tools such as 3D laser scanning. Then, compiling that data in parametric design software that also incorporates requirements and performance indicators as defined through hard institutions. If the requirements are met, the software delivers a model that is ready to be manufactured through means of 3D printing (D5). All of the mentioned innovations can also be found in table 10.

Likewise, parametric design can also be combined with IFD standards, resulting in the ability to order ‘modules’ to be constructed by contractors (D8). However, this would require IFD to be validated more in different projects by different parties.

3D printing of concrete was also mentioned by a few interviewees. Whilst not being perceived as a potential technology to aid market supply for the upcoming V&R challenge related workload, interviewees underlined its potential to optimise current processes. One interviewee saw 3D printing of concrete of an experiment in how to digitalise manufacturing processes (D11), while others stated its potential in complementing current prefabrication processes (D5). Current practice of prefabrication makes use of molds, which require contemporary material use. 3D concrete printing could substitute the current approach in making those molds, increasing customisability and enabling more convenient reuse of material that is used for molds (D5). In addition, 3D composite printing allows for material reuse as well (D13).

4.3.3 Importance of asset data collection

One interviewee placed emphasis on the collection of information prior to the project initiation phase. There is a degree of uncertainty regarding the current state of assets (D1), and "industrialising uncertainty is very difficult" (D8). Lack of knowledge on the state of assets partially causes a passive attitude for asset owners (D10). In current practice, data collection is often conducted via physical on-site inspection. Introducing more effective and precise methods of collecting asset data would help to provide overview of the asset specific urgency. In addition, by standardising asset information or asset data collection in early stages, efficient and effective planning tools can be used to improve planning and execution (D11). The availability of asset data enables proper decision making in regard to renovating, replacing, or doing nothing (D13). Hence, the use of innovative monitoring and data collection techniques seems like an important requirement, for which multiple options were observed, such as drone inspection, 3D laser scanning, and smart sensor technology.

4.4 TIS – functional analysis

So far, the structural dimensions of the TIS are defined in section 4.1, the conditions for the focal concept of industrialisation are assessed in 4.2, and observed innovations and technologies that may shape the practical implementation of industrialisation are classified in 4.3. In this subsection, a functional analysis of the seven TIS functions was conducted, as described in chapter three.

Before going into the results, it's crucial to clarify the usage and interpretation of the scores obtained. Given the qualitative nature of this research, these scores shouldn't be viewed as precise numerical measures or definitive conclusions. Instead, they serve to highlight the effectiveness or shortcomings of specific aspects within the system or its functionalities. The scores are primarily meant for comparative purposes, instead of seeing them as absolutes. Their significance is derived from the insights provided by the interviewees regarding the rationale behind each score. Therefore, throughout this section, a score will be introduced to offer a directional guide, followed by an exploration of the various viewpoints provided by the interviewees to provide context for that score. As explained in chapter three, participants scored questions using a five-point Likert scale, ranging from 1 (very weak) to 5 (very strong). Therefore, if a function scores above average, it is unlikely to be the source of a systemic barrier in the TIS. Nevertheless, a score between 3 (neither weak nor strong) and 4 (strong) does not necessarily mean that no developments are required for that function. More details on the scoring can be found in section 3.4.2.

Table 11: Likert scale interpretation for TIS function scores

Likert scale function scoring	
1.0	Very weak
2.0	Weak
3.0	Neither weak nor strong
4.0	Strong
5.0	Very strong

First, the TIS functions are assessed in the same sequence as they were presented in chapter three. This way, contradictions or curiosities within a system function can remain transparent. In the end, the section is concluded with a general overview of function scores.

4.4.1 F1 – Entrepreneurial experimentation

The overall score of this function was a 2.6. Hence, the functions are reviewed to see why entrepreneurial experimentation is lacking in the TIS. In general, no significant outliers were identified in the responses for this function. Interviewees generally perceive that while there are entrepreneurial experiments underway, they are inadequate in addressing both present and future challenges.

Table 12: Average actor group scores - function 1

Function 1 - Entrepreneurial experimentation **Diagnostic questions (Table 7)**	**Asset owners**	**Contractors**	**Engeneers & Archictects**	**Suppliers & Manufacturers**	**Knowledge & Branch**	**Technological statrtups**	**Total average**
F1.1 - Number & diversity of actors	2.7	2.8	3.5	3.0	4.0	3.0	3.2
F1.2 - Degree of innovation through supply or demand	2.5	2.0	2.0	2.5	2.0	4.0	2.5
F1.3 - Stimulation of innovation scale-up	2.0	2.3	2.0	3.0	3.0	2.0	2.4
F1.4 - Further development of experiments/living labs	2.7	2.8	2.5	2.0	2.0	3.0	2.5
Functionality score	2.5	2.4	2.5	2.6	2.8	3.0	**2.6**

In regard to question 1.1, there was a general consensus among interviewees that the number of actors that are actively pursuing or stimulating innovations through experimentation and pilots have to increase if infrastructure goals are to be achieved.

For question 1.2, there was an emphasis on the restricting effects caused by organisations within the asset owner category (D3; D6; D9), as little consideration is given to the alternative sources of value that innovations and new technologies bring. Yet, it was also mentioned that organisations from the supply side of the value chain are negatively influencing larger scale adaption of innovation, because of risks (D8) or passive attitude (D1). Within the asset owner actor category, larger clients are doing more to improve on this function compared to smaller clients (D2; D4)

There was frequent mention of a lack of scaling up of innovations in the answers for question 1.3, because of factors such as risks, budgets, and culture. Risk adverse behaviour in both the supply and demand sides of the value chain were seen as a significant factor (D5; D8; D13). In addition, there business models for innovations seem to fall short in their competitiveness (D4, D11).

The answers to question 1.4 showed that further development of existing experiments or living labs is also considered to be insufficient by many interviewees, given the arguments that are mentioned for question 1.3. It was said that validation through actual project implementation is critical to develop a new technology, which is difficult to achieve in the current system (D7; D8).

In general, many interviewees underline how current construction processes and demands restrict the compatibility of innovations or new techniques. The added value of these new developments is often not considered for tendering processes, as the basic criterium of project costs is still dominant in decision making (D6; D9; D10). Consequently, new developments are not given the chance to develop and improve in real project applications, thus restricting its potential to be adapted by a broader group. Even when project tenders are explicitly steered towards a specific (group) of innovations, alternative criteria regarding sustainability can be dropped as soon as it becomes apparent that the initial costs are higher compared to a proven method.

4.4.2 F2 – Knowledge development

The second function received a 3.5 score overall, almost reaching the 'strong' classification on the Likert scale. For question 2.3, scores were converted to ensure that positive reactions by interview participants are correctly represented in the scores.

Table 13: Average actor group scores - function 2

Function 2 - Knowledge development **Diagnostic questions (Table 7)**	**Asset owners**	**Contractors**	**Engeneers & Archictects**	**Suppliers & Manufacturers**	**Knowledge & Branch**	**Technological statrtups**	**Total average**
F2.1 - State of knowledge development for industrialisation	3.0	2.8	4.0	3.5	4.0	3.0	3.4
F2.2 - Quality of knowledge development for innovations	3.0	3.0	4.0	4.0	3.0	3.5	3.4
F2.3 - Knowledge development as a transition barrier	3.7	3.0	4.0	4.0	4.0	3.5	3.7
Functionality score	3.2	2.9	4.0	3.8	3.7	3.3	**3.5**

In general for question 2.1, the state of knowledge development in regard to innovations that contribute to industrialisation was not perceived to be a primary issue amongst interviewees. Many expressed confidence that the required technical knowledge would swiftly become available if other negative factors were mitigated. However, there was a differentiation for asset owners, for which the state of knowledge development is considered 'good' for larger asset owners (D1; D12), and poor for smaller asset owners (D2; D8; D10).

For question 2.2, the quality of developments was disputed, with the third and fourth actor category perceiving it as high, and other parties scoring it lower. However, clear arguments lacked from nearly all interviewees.

For the final question in this function, there was a wide agreement in all interviews that the function of knowledge development did not pose a significant barrier to transition. In addition, it was interesting that interviewees within the actor category of asset owners agree with other actor groups that the current knowledge development does not function as a transition barrier.

4.4.3 F3 – Knowledge exchange

The knowledge exchange function received the lowest overall score of all seven functions. In general, knowledge exchange between asset owners and contractors, and between contractors themselves were argued to be insufficient.

Table 14: Average actor group scores - function 3

Function 3 - Knowledge exchange **Diagnostic questions (Table 7)**	**Asset owners**	**Contractors**	**Engeneers & Archictects**	**Suppliers & Manufacturers**	**Knowledge & Branch**	**Technological statrtups**	**Total average**
F3.1 - Between actors within the defined actor group	3.3	2.3	2.5	3.0	2.0	3.0	2.7
F3.2 - Between research sector and value chain	2.3	3.0	2.5	2.0	2.0	2.0	2.3
F3.3 - Sharing of lessons learned with the value chain	2.0	2.5	2.5	2.0	2.0	1.0	2.0
F3.4 - Knowledge exchange as a transition barrier	2.7	2.3	3.0	2.5	2.0	2.0	2.4
Functionality score	2.6	2.5	2.6	2.4	2.0	2.3	**2.4**

Question 3.1 resulted in varying responses. Amongst themselves, asset owners engage in a degree of knowledge exchange (D1). While knowledge sharing among engineering firms was observed (D3; D8), it is still in a very early stage, and not common practice. However, limited knowledge exchange within the contractor group is observed, mainly due to the competitive nature of the market (D2; D8). The same applies for suppliers and manufacturers (D4).

Question 3.2 inquired about the exchange of knowledge between research organisations and the practical value chain. It was said that relevant elements can often be found in literature, yet little is actually tested in practice (D2). In addition, research subjects and activities lacked alignment with practical needs (D4) and are sometimes being conducted in a timeframe that renders them inconvenient for market parties (D6).

The third diagnostic question for function three scored the lowest, for which a variety of reasons were mentioned. One startup mentioned that relevant practical information can be hard to come by (D5). Another indication of shortcomings for this function was the observation that lessons learned are only shared when they are stories of success (D1). Even if lessons about failures are shared, the way it is received varies greatly. Some actors do share (D3), while some keep information that may portray them as vulnerable close to the chest (D4). In addition, pilots initiated by public parties have a higher degree of knowledge availability compared to pilots done by market actors (D1; D4).

In regard to knowledge exchange posing a barrier for the TIS to transition, the lack of knowledge exchange between asset owners and supply side actors such as suppliers and contractors was often mentioned. One contractor stated that asset owners regard them as mere project executers (D9). One interviewee elaborated on the concept of exchanging knowledge, by arguing that it requires both the sharing of knowledge, and the acceptance of knowledge, leading to practical implications. In the TIS, it was said that a lot of knowledge is only being shared, yet little knowledge that is actually exchanged (D3; D11). While the generalised level of knowledge exchange is insufficient, the reasons and significance are disputed amongst interviewees. It is either argued to be insignificant for the transition (D1), or something that will fix itself when the urgency has practical implications (D4), or explicitly emphasised to be crucial to make changes in the current value chain.

4.4.4 F4 – Guidance of the search

The fourth function, which describes whether there is a clear direction for the TIS to move forward in, was scored 2.5 overall by research participants. In varying ways of framing, the interviews showed that a better guidance in the form of either a shared vision or set of ambitions, or a collective and mutually agreed upon plan, would bring significant benefits in furthering the TIS.

"Differentiation as a result of the current fragmented approach, resulting in diversity, which opposes a structural and universal approach" (D8).

Table 15: Average actor group scores - function 4

Function 4 - Guidance of the search **Diagnostic questions (Table 7)**	**Asset owners**	**Contractors**	**Engeneers & Archictects**	**Suppliers & Manufacturers**	**Knowledge & Branch**	**Technological statrtups**	**Total average**
F4.1 - Clear vision of value chain industrialisation	2.7	2.8	3.0	2.0	2.0	2.5	2.5
F4.2 - Perception on validity of new tech./innovations	2.0	3.5	2.5	3.0	-	2.0	2.6
F4.3 - Clarity & consistency of policy ambitions and goals	3.0	2.0	3.0	2.0	4.0	2.0	2.7
F4.4 - Alignment of actors for industrialisation challenges	2.3	1.8	1.5	2.0	4.0	2.5	2.4
F4.5 - (Lack of) collective vision as a transition barrier	2.3	2.5	2.0	2.5	2.0	2.0	2.2
Functionality score	2.5	2.5	2.4	2.3	3.0	2.2	**2.5**

The responses to question 4.1 varied. On the one hand, a lack of vision was mentioned in over half the interviews. On the other, some interviewees regarded current developments in approaches such as IFD as evidence that that shared vision is being realised. The 'vision' was defined as a something for the complete value chain. However, there were examples where comparable elements were disputed within the organisational context itself (D4; D12).

The arguments that were given to question 4.2 indicated that the organisations have confidence in the positive effects that new technologies and niche innovations can bring to the value chain performance. However, it was frequently observed that the current system institutions restrict the development, and thus their validity. Reasons that were mentioned were the traditional culture within the TIS (D8), and how current norms restrict the implementation of new techniques (D11).

For question 4.3, scores show a discrepancy between contractors, suppliers and startups, compared to asset owners, engineering firms, and knowledge institutes. The first group experienced that policy ambitions and goals did not translate to practical implications for their business approach. The way project demand was presented remains very differentiated (D4; D6; D9), and the urgency of challenges related to the V&R challenge are not considered. In contrast, the second group saw the general policy ambitions clear and consistent.

The often observed, general consensus for question 4.4 was that the organisations within the TIS are unified in the challenges that the V&R of infrastructure brings, but there are still significant differences in ideas on how to deal with them. A unified and collective approach is missing. Also, the lack of integration between disciplines within the TIS were mentioned as a significant shortcoming.

Linking all four questions that were asked prior, question 4.5, the general perception was that the lack of a collective vision contributes to the TIS ability to transition. However, most interviewees emphasised on formulating a more concise plan, instead of an abstractly defined vision.

4.4.5 F5 – Market formation

The fifth function describes whether the market is perceived as a barrier to further develop and diffuse innovations. As mentioned in the first chapter, the V&R challenge is believed to provide an opportunity to innovate, because of the amount of work that it requires. The function received the overall highest score of 3.7.

Table 16: Average actor group scores - function 5

Function 5 - Market formation **Diagnostic questions (Table 7)**	**Asset owners**	**Contractors**	**Engeneers & Archictects**	**Suppliers & Manufacturers**	**Knowledge & Branch**	**Technological startups**	**Total average**
F5.1 - Current and expected demand market sufficient	2.5	3.5	3.5	4.0	4.0	3.5	3.5
F5.2 - (Insufficient) market size as a transition barrier	3.0	3.3	4.0	4.5	4.0	4.0	3.8
Functionality score	2.8	3.4	3.8	4.3	4.0	3.8	**3.7**

All participants were in agreement in regard to both question 5.1 and 5.2. The demand will allow innovations within the TIS to be developed and diffused further. Meaning, there will be no transition barrier that is caused by an insufficient market size.

Yet, a few considerations were mentioned, the biggest one being the fragmented way in which projects are brought to the market. If the demand for construction activities is not bundled or presented in a continuous, repetitive way, market parties lack the ability to prepare and optimise their methods (D4; D6; D9). This concern was mostly shared by contractors and suppliers.

4.4.6 F6 – Resource mobilisation

The sixth function assesses how the (in)availability of resources affects the TIS. This function received a score of 2.6.

Table 17: Average actor group scores - function 6

Function 6 - Resource mobilisation **Diagnostic questions (Table 7)**	**Asset owners**	**Contractors**	**Engeneers & Archictects**	**Suppliers & Manufacturers**	**Knowledge & Branch**	**Technological startups**	**Total average**
F6.1 - Human capital as a barrier for transition	3.0	3.3	2.0	2.5	2.0	3.0	2.6
F6.2 - Financial security as a barrier for transition	2.7	2.5	1.5	2.5	2.0	3.0	2.4
F6.3 - Physical resources as a barrier for transition	3.0	4.0	4.5	3.5	3.0	3.0	3.3
F6.4 - Current form of value chain as a barrier	2.0	2.5	2.5	1.5	3.0	1.0	2.1
Functionality score	2.7	3.1	2.6	2.5	2.5	2.5	**2.6**

Answers to question 6.1 showed both a shortage of human capital, and the lack of human capital with different backgrounds other than civil engineering (D1; D3; D9; D12). Yet, it was also mentioned as a driver for new approaches, as current approaches rely on the availability of human capital (D9; D10). Thus, alternative approaches that focus on automating and digitalising are in need.

Financial security, as inquired by question 6.2, scored low across all actor groups. It became evident in nearly all interview that the effects of limited funds are widespread. Alternative approaches initially cost more compared to the traditional, proven method. Hence, asset owners are reluctant in committing to alternative technologies, and supply side organisations are reluctant in investing in new technologies (D3; D7).

Indicated by a slightly higher score compared to other question for function six, the effects of the availability of physical resources as mentioned in question 6.3 were perceived as a driver for change, instead of barrier. The consensus amongst respondents is that shortages lead to impulses to adapt approaches that rely less on high use of new materials

To close off, question 6.4 assessed how participants perceived the current form of the value chain, in regard to its capacity to stimulate a transition using exploiting innovative techniques. Interviews showed a negative perception, because of various reasons. The negative effects of the focus on competition on collaboration and knowledge exchange was emphasised by one interviewee (D2), while others mentioned that the ability of suppliers and manufacturers were not considered enough (D1; D3). Another important characteristic of current practices is the lack of project exceeding strategy.

4.4.7 F7 – Counteract resistance to change/Legitimation

The final function deals with factors that could impede the development and diffusion of the concept of industrialisation in the TIS. It was scored with a 2.5, which should be interpreted as the TIS having a lack of legitimation.

Table 18: Average actor group scores - function 7

Function 7 - Counteract resistance to change/Legitimation **Diagnostic questions (Table 7)**	**Asset owners**	**Contractors**	**Engeneers & Archictects**	**Suppliers & Manufacturers**	**Knowledge & Branch**	**Technological statrtups**	**Total average**
F7.1 - Resistance to (collectively) implement innovations	2.3	2.8	1.5	2.0	4.0	3.0	2.6
F7.2 - General resistance to the concept of industrialisation	2.0	2.3	2.0	3.5	3.0	3.0	2.6
F7.3 - Institutions as barriers for transition	2.7	2.5	2.5	1.5	-	2.0	2.2
Functionality score	2.3	2.5	2.0	2.3	3.5	2.7	**2.5**

Regarding the resistance to implement innovations, question 7.1 found that it affects the TIS. The construction sector is conservative, so there will always be resistance or scepticism towards innovations (D1; D3; D4; D9). In addition, innovations inherently bring risks and extra costs, inherently require development, and thus always require a learning process. Hence, it is often faced with resistance (D8).

For question 7.2, many interviewees followed the same line of reasoning. Many interviews showed a general positive perception of industrialisation as a concept, but a resistance in what was required to actually change practical ways of conducting business.

For the final question, institutions were identified as a significant barrier for a transition, as their current form restricts the ability to implement innovative or alternative techniques. In addition, the current form often fails to value positive externalities or life cycle value that alternative approaches bring. Both in early project phases (D1), where institutions require extensive planning and agreements, and in design criteria for contractors, where norms favour traditional methods (D10).

4.4.8 Overview of function scores

Table 18 shows the general overview of function scores per actor group. As depicted, function two and five show relatively high scores, compared to the other functions. The other five functions with low scores only show marginal differences and are generally perceived to need improvement. Function score differences per actor group do not present clear inconsistencies, as the biggest score difference is slightly more than one point on the Likert scale.

Table 19: Overview of total average TIS function scores

Overview of function scores / **TIS functions**	**Asset owners**	**Contractors**	**Engeneers & Archictects**	**Suppliers & Manufacturers**	**Knowledge & Branch**	**Technological statrtups**	**Total average**
F1 - Entrepreneurial experimentation	2.5	2.4	2.5	2.6	2.8	3.0	**2.6**
F2 - Knowledge development	3.2	2.9	4.0	3.8	3.7	3.3	**3.5**
F3 - Knowledge exchange	2.6	2.5	2.6	2.4	2.0	2.3	**2.4**
F4 - Guidance of the search	2.5	2.5	2.4	2.3	3.0	2.2	**2.5**
F5 - Market formation	2.8	3.4	3.8	4.3	4.0	3.8	**3.7**
F6 - Resource mobilisation	2.7	3.1	2.6	2.5	2.5	2.5	**2.6**
F7 - Counteract resistance to change/Legitimation	2.3	2.5	2.0	2.3	3.5	2.7	**2.5**

4.5 Functional barriers

Low function scores indicate that the defined innovation system is not functioning well. The low scores are an (indirect) consequence of structural system dimensions providing less than optimal circumstances for the TIS to thrive. Hence, the system does not function well because of shortcomings in the structural dimensions. Section 4.1 assessed three structural dimensions, being system actors, institutions, and interactions. So, this section combines these dimensions as described in section 4.1 with the function scores and its arguments from the previous section, to formulate the functional barriers concerning the demarcated TIS. The most critical elements within those functional barriers are then translated to blocking mechanisms. For this section, function one, three, four, six and seven require further assessment, given their low scores (table 18). Naturally, if there are no observable problems relating to a structural dimension, that dimension is not mentioned.

4.5.1 Functional barrier 1 – Entrepreneurial experimentation

Given its low score, entrepreneurial experimentation was identified to be a functional barrier. Multiple problems were identified for both presence and capability factors concerning TIS actors.

Actors' problems

From the presence point of view, the number of actors that are actively pursuing or stimulating innovations is insufficient. As a result, traditional supply-side actors are able to adapt a passive attitude towards innovations and new technologies. From the perspective of actor capabilities, two causes were found to explain the low function score. First and foremost, asset owners are currently not successful in using their tools to stimulate market parties to give higher priority to innovations and new technologies to aid the TIS. Innovation specific project tenders are few, little continuity and repetitive opportunities are brought to market, and alternative ways of value creation by innovations are not sufficiently taken into consideration. Second, it seems that nearly all actors within the TIS have little room in their financing structures to consistently develop on pilots and living labs. Ambitions are high, yet the willingness and ability to finance the development they require is insufficient.

Institutional problems

Two presence related problems, and one capability related cause was identified in regard to TIS institutions. Both the lack of norms, and the slow development or changes of norms are restricting the ability to use new materials or processes. Also, the presence of traditional soft institutions has broad negative effects on the TIS development. While they are difficult to make explicit, the conservative culture within the sector was often mentioned, as were the effects of a shortage of people within the sector with backgrounds other than civil engineering. From a capability point of view, institutions that define the tendering process are restricting the further development of relevant innovations, as their alternative ways of value creation are often overshadowed by the basic selection criterium of costs.

4.5.2 Functional barrier 2 – Knowledge exchange

The second functional barrier is function three, knowledge exchange within the TIS. This function was often mentioned as a system function that requires improvement.

Actors' problems

Two main capability related problems were observed. There was a general acceptance of the observation that a lot of knowledge is being shared. However, the actual exchange of knowledge is lacking. The current way in which knowledge is shared either lacks focus on the most relevant lessons learned, or only focuses on the wins while leaving out the failures. Second, TIS actors are still reluctant to share knowledge on non-public pilot. Mostly argued to be a result of the competitive nature of the sector. Actors do not seem to be able to both retain competitiveness while participating in useful knowledge exchange processes.

Institutional problems

The actor problems are not mitigated by the TIS institutions. Instead, there is a lack of institutions that allow for a higher degree of knowledge exchange without potential sacrificing of competitive advantage. It seems that institutions fall short in their ability to allow the generation of benefits from knowledge exchange. The current form of institutions in the TIS lacks financial structures to stimulate knowledge exchange.

Interaction problems

Interaction is mostly lacking on the presence side. There are isolated areas of knowledge in the TIS, which are not sufficiently integrated across the value chain. In addition, interactions between actors that promote project level-exceeding knowledge exchange is scarce, as collaboration forms are often finite. The lack of interaction between disciplines in the TIS is also seen as a problem, as it results in a lack of collective approaches and understanding of other perspectives.

4.5.3 Functional barrier 3 – Guidance of the search

Function four represents the third functional barrier. There seems to be little guidance and roadmaps for TIS organisations to support the further development in a general direction.

Actors' problems

For the guidance of the search, there is a lack of presence of a leading party or an ambassador for change that can support smaller actors in doing their part. RWS is often mentioned as the only suitable party, yet currently not sufficient in their activities. From an actor capability perspective, there is a lack of determined direction at the front. Actors refer to each other to set the direction, which is not being done. Even though most actors seem to be unified in the challenge, there are inconsistent or contradictory views on how to approach the V&R challenge and the transition it requires within and between organisations. In addition, asset owners do not seem to be able to guarantee the continuity and repetitive work for other value chain members, through multiple reasons such as political agendas, budgets and risk adverse behaviour. Finally, there is a degree of fragmentation within and between asset owners, resulting in ambiguous demand which the market side is experiencing difficulty with.

Institutional problems

Regarding this function, institutions seem to fall short in translating general policy ambitions into practical applications for the market to prepare their business for.

Interaction problems

Smaller asset owners tend to have less knowledge in regard to the state of their assets, and how to deal with unforeseen circumstances regarding their infrastructure. Yet, there is little guidance for smaller asset owners, resulting in varying project requirements as a result, which in turn restricts industrialisation efforts.

4.5.4 Functional barrier 4 – Resource mobilisation

Concerning both financial, human and physical resources, the fourth functional barrier is represented by the sixth function, resource mobilisation.

Actors' problems

For this functional barrier, asset owners are found to still lack the capacity to tender their projects in a way that stimulates the TIS. Current ambiguous and diverse project requirements suit the traditional approach more. Even though a positive trend is emerging, there is still little bundling, little use of framework agreements, and often a project-to-project focus. In general, both the lack of skilled labour in a niche sector like infrastructure and the lack of people from backgrounds other than civil engineering was considered to be a problem. Also, the lack of resources to reallocate to increased constructive efforts required by the V&R challenge was noted to be relevant for smaller asset owners.

Institutional problems

The standard practices that are a consequence of the varying forms of institutions in the TIS seem to favour traditional approaches, resulting in little resource mobilisation for alternative methods. In addition, institutions lacked clear definitions in regard to which TIS actor carries what costs and responsibilities.

4.5.5 Functional barrier 5 – Counteract resistance to change/Legitimation

The final functional barrier is found in function seven, where it was observed that TIS actors lack general alignment in regard to the TIS.

Actors' problems

Two capability problems were identified in regard to actors and resistance for change. As mentioned before, the general conservative culture within the TIS results in adverse behaviour regarding innovation and other negative effects. Also, acquiring support or acknowledgement for new technologies is an extensive process, consistently requiring a lot of work. As a consequence, validating and maturing new technologies is complicated, as there is general scepticism for their (long-term) quality.

Institutional problems

There was one main presence related problem that was observed frequently, being the restricting effects of current hard institutions on alternative approaches. While some alternatives show great promise in achieving quick wins regarding general ambitions, the building codes and permit procedures are argued to complicate situations unnecessarily. Also, permits regarding local construction projects are awarded by local municipalities, resulting in suboptimal performance.

4.6 Conclusion on the third sub-question

Chapter four combined the findings from the second and third chapter with interview data, to assess the third research sub-question, which was:

What are the key conditions to industrialise V&R challenge bridge projects, what innovations or new technologies are currently being developed that could contribute, and which TIS elements represent blocking mechanisms for the transition towards an industrialised value chain?

4.6.1 Key conditions

The conditions for industrialisation based on perceptions from actors within the V&R challenge context are represented by the proposed IIC framework constructs. These eight constructs serve as conditions for a well-functioning industrialised value chain. Results are aligned in the confirmation of most IIC constructs, and no clear contradictions were observed that require immediate changes to the proposed IIC framework. Yet, chapter five will elaborate further on the validity and generalisability of the framework. Hence, the factors (or conditions) to industrialise V&R challenge related construction activities are continuity & repetition by demand, flexibility in design, standardisation & norms, prefabrication of components, long-term relations, integrated logistics, use of ICT, and continuous improvements.

Even though all constructs had some degree of relevance to the concept of industrialisation, there are constructs that are clearly perceived to be more important compared to others. So, since the third sub-question assesses the key conditions, it is concluded that for V&R challenge related industrialisation efforts, four constructs should be given priority. These are continuity & repetition by demand, standardisation & norms, long-term relations, and continuous improvement.

For the first, industrialisation inherently means making (impactful) changes to the traditional and proven methods that have been the norm for decades. Hence, it makes sense why supply side actors in the TIS see this construct as a direct condition to even consider transitioning their way of approaching projects. While this construct does not necessarily mean that all demand has to be uniform, it indicates the detrimental effects of uncertainty on the general support to collectively move to an industrialised system.

Second, the stimulation of standardisation and norms showed numerous advantages in the interviews, with little negative effects. In addition, development of standards and norms that decrease the degree of custom, one-off project elements and are readily implementable is a trend that is already happening in the research context. The challenge for this construct lies in ensuring that standards are aligned across the value chain, and not only on the level of individual organisations.

Third, like the other two constructs, long term relations are perceived to be crucial in collectively developing a new approach. Yet, the examples of these relations found in the interviews seldomly complied with the construct definition. In most cases, ambitions to acquire long-term relations were mentioned. Yet, those ambitions were seldomly materialised in actual partnerships or other forms of long-term commitment.

Fourth and final, continuous improvements were identified as highly important in regard to two perspectives. On the one hand, it was identified as a factor that had to be improved in order to develop more industrialised construction systems. On the other hand, perhaps more important, was the notion that an industrialised system enables the actors within it to improve their continuous learning capacity, to further optimise the system.

It should be noted that prefabrication is already a dominant strategy in current practices, so its importance as a construct doesn't require any further elaboration. In addition, the results showed a correlation between several constructs, which will be elaborated on in the next chapter.

4.6.2 Innovations for industrialisation

The interviews revealed a limited set of innovations with no clear major disruptors to the traditional system. Additionally, there were no indications contradicting the notion of industrialisation. Both the IIC framework and the original IHB framework allow for various forms of industrialisation, enabling innovations to contribute in different areas. Prefabrication is perhaps the most specific construct related to construction practices, and nothing observed contradicted its role as a main trajectory. The classification allowed for analysis of observed facets, which are visualised in the second appendix.

In terms of frequency, service-based innovations were most observed. In terms of location in the value chain process, digital collaboration showed most relevant innovations. The innovation asset life cycle was less clear in terms of frequency of observation, as many identified innovations and new technologies are intended to be applied in multiple phases. However, innovations regarding deconstruction were observed the least. The estimation of innovation maturity showed a low number of highly mature innovations.

The classified innovations and technologies suggest that the technical potential to increase automation through digitalisation is either already available or could become available shortly if urgency demands. Some complementary innovations were noted, such as the smart use of sensors and other forms of asset data collection. High-quality data availability can aid production capacity planning, which is further supported by parametric design with integrated standards like IFD. By adopting parametric design, the fragmented project chain can achieve integration, as its output can be manufactured without interventions. The off-site manufacturing process could then be optimised through innovations like robotisation. While sets of complementary innovations may lead to a functional industrialised production system, this potential is decreased more disciplines and complexities are introduced by larger scale assets.

4.6.3 Functional barriers

The final part of the third sub-question is formulated to identify what structural characteristics in the defined TIS result in systemic problems that negatively influence the systems' ability to develop and diffuse alternative approaches to transition away from the traditional approach. Through TIS function scores, five out of seven functions were identified to represent functional barriers, since they scored below neutral, depicted in figure 14.

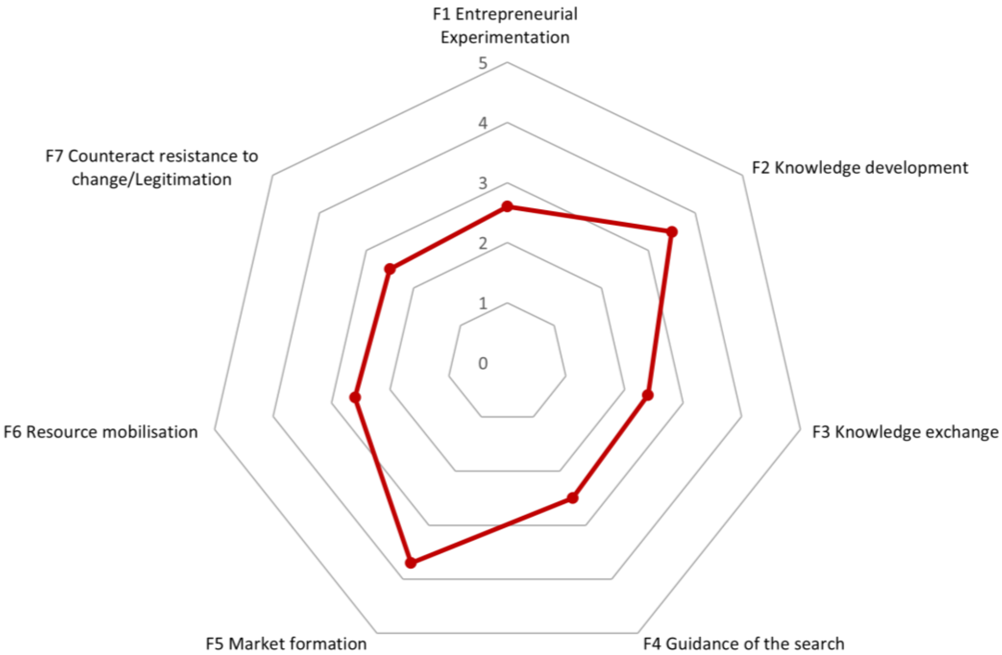


Figure 14: Spider diagram of TIS function scores

The shortcomings in the current system that caused these low scores were reviewed in section 4.5, by assessing how structural system elements contribute to their low scores. However, for this section, the conclusion on the third sub-question would be that barriers for TIS development were found in the current organisation of knowledge exchange, the guidance of the search, the mobilisation of resources, the resistance to change, and the degree and quality of entrepeunerial experimentation. Improvements in those functions would support further development of the TIS. The interpretation of key causes for these low scores is done in the next chapter, which synthesises all arguments from this chapter into formulating key blocking mechanisms. Also, the most important blocking mechanisms are translated into systemic problems, if they are a direct result of structural TIS dimensions.

CH5

Discussion

The previous chapter presented the analysis results. This chapter reflects on how the general findings relate to the existing literature. The study aimed to examine the transition to an industrialised Dutch infrastructure sector by the system of actors, institutions and interactions within V&R challenge projects. Now, in this discussion chapter, the findings are considered in relation to the literature discussed in the second chapter. However, these results should be interpreted with caution due to the research limitations, which will be addressed after the main conclusions in chapter six.

Section 5.1 starts with an interpretation of the results as presented in chapter four. After that, section 5.2 evaluates the scientific relevance of both the results and applied methodology through reflexive assessment on the conducted research. To conclude, the answer to sub-question four is formulated in section 5.3.

5.1 Interpretation of results

To start of this chapter, the results as presented in chapter four require further interpretation in order to conclude on the relevance of this research from both an academic and methodologic point of view. Both the IIC framework and results of the TIS analysis are reflected on in a specific subsection. The classified innovations and their relation to the results are discussed in 5.1.3.

5.1.1 Interpretation of results regarding the IIC framework

Through analysis of results, the four constructs that were argued to be of the highest importance are continuity & repetition by demand, standardisation & norms, long-term relations, and continuous improvement. Of those four, the first two are newly defined constructs for the IIC context, and the second two being unchanged constructs from the IHB framework. Their importance is clearly observed, and their perception is mostly aligned with the theoretical intend of the IIC framework. The exception being that standards were also considered advantageous on a singular organisation level, while the definition was meant to harmonise multiple value chain parties. Also, the long-term relations construct was seen as highly important. However, the definition of long-term relations that was observed in the interviews is not aligned with the definition and intent of long-term relations from theory. Interviewees spoke highly of their collaborative efforts, while their nature was explicitly finite due to being organised on the level of one project. In theory, long-term relations were defined to bring about benefits relating to long term commitment, which by definition exceeds the level of singular projects. Nevertheless, the general consensus in regard to the four abovementioned constructs was of significant importance. Therefore, they require little further reflecting in this section.

However, simply stating that these four are vital for industrialisation and the other constructs are negligible would be an oversimplification of the results. For example, the prefabrication of components construct was not frequently mentioned by interviewees, as the result of prefabrication already being the dominant practice in the current situation. In other words, constructs could be very important, but unmentioned for multiple reasons. Therefore, before conclusions can be made in regard to the interpretated importance of each construct, the reasons behind the lack of observation have to be reviewed. Again, the constructs are seen as conditions, for which a properly functioning industrialised system requires a sufficient 'score' on all.

Flexibility in design was introduced as a framework construct for infrastructure industrialisation to enable asset owners to conveniently change bridge functionalities as a result of practical implications of uncertainty. In addition, implementing flexibility in design has clear benefits, such as long-term reusability and customisability. However, the way this construct was observed in chapter four shows that this construct does not seem to be a hard requirement to achieve an industrialised system. If the V&R challenge were to become a challenge that is dominantly focused on complete replacement, this construct would arguably become more important. Flexibility in design becomes more significant when the same degree of flexibility is built in a high number of assets, or when future demands are uncertain. However, with the increased focus on renovation activities, this construct is seen more as a potential benefit rather than a necessity. The elements within its definition that do represent vital factors for proper industrialisation can be incorporated through the standardisation & norms construct. Alternatively, the concept of platformisation was observed in both theory and the collected data. By adapting platforms, standards can be maintained, while also incorporating flexibility in design in elements that had no prescribed approach in those standards.

The final two constructs, being integrated logistics and use of ICT, were copied from the IHB framework. Hence, they have been reviewed numerous times in the context of housing construction. Given their places in the IHB framework, they can be concluded to be important.

However, as chapter four mentioned, there was little explicit mentioning of both constructs in the research results. It remains unclear whether this is caused by the same reason as the prefabrication construct, caused by a perception of insignificance, or even because system actors fail to identify it as something that requires improvement. The definition by Lessing described the integrated logistics construct as "*The flow of materials and related information is integrated with design, production and building processes*" (Lessing, 2015). Despite the lack of explicit observations, there were indications of innovation trajectories that stimulated the integration of material and information flows, such as parametric design. In turn, the use of ICT construct was defined as *"ICT-tools and –systems support structuring and managing information throughout all processes and technical systems"* (Lessing, 2015). This definition results in a very abstract interpretation, which complicates its assessment. For example, it is unclear whether the use of ICT implies sensoring and collecting data. If not, data collection and data quality (through sensoring or other means) seemed vital for the market to industrialise. Data collection is also vital when the ambition is to increase reuse on both complete asset level and component level. Given the complicated analysis of this construct, section 5.2 will elaborate further on the complications regarding the IHB framework constructs.

In addition to the assessment of their general presence in the research context, the observed constructs also showed indications of interdependence and correlations. For one, continuity & repetition by demand is closely related to standardisation and norms. Even if there is an aggregated demand that would enable market parties to invest in an industrialised approach, that demand is meaningless if it requires completely unique construction approaches. For example, one asset owner bundles its bridge rehabilitation needs and requires the market parties to focus on composite bridges, while a neighbouring asset owner only awards tenders based on the use of reused concrete components. As a result, the market parties that are active in that area can't invest in one specific optimised production system.

There is also a link between continuity & repetition by demand and long-term relations. Real long-term relations that do not end at the completion of a singular project allow the continuity & repetition element to be more consistent and effective. The characteristics of framework agreements enable long-term commitment, as they are able to cover a high number of projects. Yet, there are examples of framework agreements failing, because of different reasons (more knowledge, decreased budgets, other policy directions).

Furthermore, there is a natural link between continuity & repetition and the ability to apply continuous improvement to the process. Continuity & repetition by demand results in an increased learning capacity, therefore positively affecting the system's ability to apply continuous improvements. In addition, standardisation & norms have an interesting dynamic with flexibility in design. There is a natural complexity in ensuring general standardisation to optimise productivity and generalisability while also incorporating the condition that products have to have a degree of customisability. Finally, the Integrated logistics constructs seems to depend greatly on the use of ICT. Without proper ICT systems, harmonisation of material and component logistics and their processes through the different project stages is a complicated task.

5.1.2 Interpretation of TIS results

The TIS results are concluded by the functional barriers and the mechanisms through which they are conceived. This section further interprets the results and formulates the most pressing systemic problems that require attention. This process ensures that a retraceable process is followed, and all elements that affect the TIS are taken into consideration.

The five functions that represent the functional barriers were assessed using the structural TIS dimensions. For the most part, blocking mechanisms relate to both actor and institution related characteristics. System interactions were not identified as a source as frequently compared to the other two structural dimensions. For both actors and institutions, problems were identified in both the presence and capability category. In general, blocking mechanisms that were identified in the current situation are summarised below. The reasoning behind each blocking mechanism can be found in section 4.5. Also, the blocking mechanisms are numbered for reference purposes, not to indicate absolute significance in the system.

Presence related blocking mechanisms

1. Not enough actors experimenting and innovating to further industrialisation
2. Absence of institutions that facilitate knowledge exchange without compromising on the competative element of the system
3. Absence of interdiscplinairy interactions
4. Lack of ambassador for change to guide and align smaller parties
5. Lack of continuity and long-term plan
6. Lack of project level exceeding strategies (in regard to resource mobilisation for activities other than the main construction activities)

Capability related blocking mechanisms

7. Asset owners not able to stimulate the TIS through the institutional tools at their disposal
8. Limited availability of financing structures for innovations, current practices disfavour alternative approaches
9. Limited knowledge exchange through system competition
10. Suboptimal exploitation of knowledge exchange
11. Fragmented, differentiated demand by asset owners
12. General conservative culture in the TIS

For number one, it should be noted that this describes both the lack of experimenting and innovating of current TIS actors, and the general lack of organisations developing niche concepts into implementable techniques. This first blocking mechanisms was also indicated by the classification, which estimated many of the identified innovations and new technologies to be of low or medium maturity. For the second presence related blocking mechanism, the institutions refer to the way that defines the current practice across the value chain. Currently, there is a lack of procedures, agreements or routines that enable sector actors to engage in more extensive knowledge exchange. Retaining competitive advantages is still a high priority. Hence, the absence of those institutions that stimulate knowledge exchange through means such as financial benefits have a wide effect on the required knowledge exchange for industrialisation. Like mechanism two, the absence of interdisciplinary interactions also is concluded to have broad effects. The expected workload that the V&R challenge brings is at the key of this research, meaning that the supply side of the TIS has to increase combined productivity. In that sense, using different disciplines in a complementary way instead of the current competing way is essential to increase general productivity. The current TIS has subsystems of actors that are differentiated by which material (concrete, steel, wood, composite) they focus on, which only very rarely seem to interact. This lack of interaction was even observed within singular organisations, where different departments were misaligned.

The fact that the V&R challenge will bring about a lot of projects is undisputed in the TIS. However, a key characteristic to the V&R challenge is the vast number of asset owners with decision making authority on all assets. Since a high percentage of assets is in ownership of relatively small municipalities, there is a need to have a leading party to ensure alignment within the asset owner group. Hence, the fourth presence related blocking mechanism mentions the lack of ambassador for change. This party would have to have technological knowledge, and authority to formulate directives which the sector can adhere to. Therefore, RWS is perhaps the only suitable party. However, RWS is currently not at the required level to support all smaller asset owners and sector organisations in dealing with localised effects of V&R related projects.

Partially caused by the previous mechanism, the fifth mechanism listed mentions the lack of continuity and long-term plans. After considering all perspectives, it is argued that asset owners can't expect the supply side of the sector to be able to transform without some form of consistency or certainty from them. Also, the translation from problem perceptions, ambitions and visions towards concrete practical plans is also lacking in the TIS. As a result, most TIS actors lack a clear priority for project-exceeding innovations because the current state of the TIS means that those efforts are very costly and seldomly rewarded.

Despite developments to change, asset owners are not able to adapt the institutions they are bound by to stimulate the TIS, as described by mechanism seven. In many cases, new and alternative approaches are not valued on all relevant aspects, which results in them being completely uncompetitive, and thus not considered for project execution. In addition, as described in number eight, there are limited financing structures for innovations. The ninth mechanism is very similar to the second, but framed from the perspective of supply side actors, excluding the emphasis on institutions. Supply side actors are currently incapable of either organising a mutually beneficial form of knowledge exchange or do so very in a very constrained way. In general, the current way of knowledge exchange does not result in exploitation of lessons learned across the value chain.

As stated, the V&R challenge contains a vast number of asset owners. This characteristic affects both presence and capability related TIS elements. Number 11 describes the fragmented, differentiated demand having a strong negative effect on the TIS development. Finally, the last blocking mechanism mentions the general conservative culture within the TIS. For this mechanism, a lot of causes can be identified, and a lot of effects can be described. However, for this TIS study, the key takeaway is that this mechanism has a broad effect on the conversion of innovation ambitions to actual long-term commitment in practice.

For further use, referring to all twelve mechanisms hinders the communication and overview. Hence, the twelve blocking mechanisms can be summarised in four systemic problems (SP), being:

SP1 Lack of upfront coordination & long-term planning

SP2 Insufficient support for innovation & knowledge exchange

SP3 Conservative culture in a competitive sector

SP4 Insufficient interdisciplinary collaboration

It should be noted that the positive TIS score on knowledge development could indicate that the degree of viable technological alternatives that support an industrialised approach may not be the main bottleneck. In turn, this translates to the interpretation of the classified innovations, raising the point that developments of institutions and interactions require more emphasis compared to technological development.

5.1.3 General interpretation

The synthesis of results as discussed in the previous subsections and in section 4.6 indicates that two sets of factors that are important for the general transition to an industrialised system were identified. First, a list of eight conditions (of varying importance) concerning the definition of industrialisation were identified. Then, the TIS analysis provided five functional barriers, which were formulated as four systemic problems in the previous section. While both the set of conditions and systemic problems differ greatly in their area of influence, it is argued that efforts that stimulate compliance to those conditions and that mitigate systemic problems are in need. These efforts can come in many forms, such as policy directives, and are partially represented by the innovations and new technologies that were identified using the faceted classification approach. Hence, this section attempts to combine the results of all analysis steps, to assess whether clear connections can be observed that would help the defined TIS to develop and diffuse further.

As the faceted classification framework depicted, innovations differ in form, area of application, project phase of application, and estimated maturity. Chapter four results indicate that the best perceived innovations that were identified within the TIS were IFD, prefabrication, off-site robotisation, innovative monitoring methods, broad standardisation, and parametric design. All of these approaches are complementary. Yet, their application remains very project specific. Framework agreements are not mentioned as an innovation but show a lot of potential if applied for long-terms, and do not change as a result of contextual changes. Of all identified innovations within the TIS, only two could present an alternative approach that is not complementary with the industrialisation concept, being component reuse through database and asset life extending measures. As stated before, industrialisation has bigger potential for bigger renovation and replacement activities.

It is unfeasible to assess all potential combinations of all identified innovations. If combinations presented big and exploitable opportunities, the expectation is that the market would have capitalised on them already. In addition, it could also be that innovations and new approaches with high potential were unmentioned by interviewees given the culture and competitiveness. Hence, the scope of innovation contributions to an industrialised system is through the direct positives, and quick wins. Not through a complete disruption of the old practice to move to the new practice. The fact that knowledge development scores high indicates that technical ability in the system is not regarded as the bottleneck for the transition. Therefore, it can be argued that technical innovations will not make or break the transition to an industrialised system. Furthermore, after assessment of the classified innovations, there is not one uniform industrialised value chain that can be broadly implemented. This was to be expected, given the diversity of V&R challenge related projects.

A few conclusions can be made in regard to the identified systemic problems (SP). First, SP1 can be aided through an improvement in the availability and quality of asset data. By further implementing innovations regarding sensoring and monitoring methods and methods for on-site parameter scanning, a degree of uncertainty can be removed from the research context. The benefits are often mentioned in the description of data driven asset management practices. Industrialising uncertainty is difficult, so by improving on data aspects, improvements can be made on the ability to plan for longer-term.

SP2 can’t be aided through innovations and new technologies, as it concerns a structural dimension that is bound by current institutions. Knowledge exchange affects the success of innovation integration efforts. On a positive note, it seems that policy makers and asset owners with authority are working on improving on this systemic problem. In regard to SP3, it should be said that the competitive nature also has benefits. However, in the context of collectively developing a new system, the untransparent consequences of competition restrict harmonisation and alignment of actors. Also, the conservative culture requires leading by example. Stories of success are needed to accelerate the innovations that contribute to industrialisation. SP4 depends greatly on the practical urgency of the situation. In the current situation. Interdisciplinary collaboration has significant benefits. Yet, the current situation does not result in drivers to accelerate its exploitation.

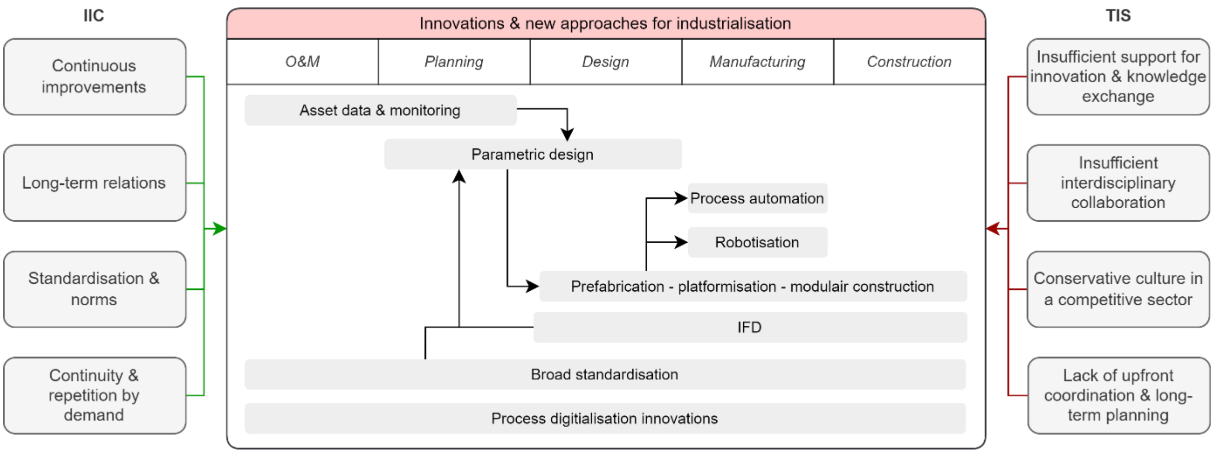


Figure 15: Overview of result interactions

Figure 15 visualises an overview of the interpretated results. It is important to note that O&M is placed at the front of the value chain, since this figure is based on the rehabilitation context. In new construction projects, O&M would be the second to last phase, only followed by deconstruction. Since no innovations were identified for deconstruction, this value chain phase is left out of the figure. Figure 15 shows the general negative effects of the systemic problems on the right side, and the general positive effects on the left side. In the middle, a potential future outlook on a construction system that meets IIC framework conditions is provided. This outlook is based on the observed innovations or innovation types with the highest perceived potential. It should be noted that this process is not to be interpreted as the only potential approach.

5.2 Scientific & academic relevance

The previous section described the general interpretation of the combined results and analysis. It mainly shows practical implications for this research context, by addressing concrete systemic problems and elements that may help to mitigate them. In this section, the assessment perspective is one layer higher, referring back to the theory behind all conducted research activities, to see how the findings and applied methodology can contribute to the current supply of scientific and academic knowledge regarding the research subject. For the most part, it does so by following the structure and methodological sequences as conducted in the previous chapters.

5.2.1 Broad implications of findings

To assess the theoretical implications of the findings on the academic field, is contributions are argued through three main elements. Firstly, this research adds to the definition of industrialisation in a sector where an established definition is lacking, but the concept is used relatively frequently. The research also adapted the faceted classification framework, for which a few implications can be described. Third and final, the TIS methodology was applied to study the transition from current construction practices to an industrialised construction system. Therefore, something can be said about the (in)applicability and research fit of a TIS study for system transitions. In addition, the TIS study was done with the focus on an abstractly defined technology, which requires discussing.

IIC in relation to IHB

First, a reflection from the adapted IIC framework to the theoretically embedded IHB framework by Lessing (2015). The IHB framework is an established and proven framework. Therefore, the changes that were made to adapt it to the infrastructure context must be founded by strong arguments. This poses the question whether the new constructs are valid, and whether the original IHB constructs are equally relevant in the infrastructure context.

In section 5.1, the flexibility in design construct was argued to be something that is ambitioned and wanted by some system actors, but not a hard condition for industrialised infrastructure construction. Its intentions can be deferred to be added to standardisation and norms. Overall, the choice was made to remove it as a construct.

The question also rose regarding the undeniable importance given to continuity & repetition by demand framework in this research, compared to the lack of mentioning in the work by Lessing. The reason behind this can be attributed to the public versus private orientation of the sector of infrastructure versus housing. In chapter two, the differences between housing and infrastructure construction were evaluated. The biggest difference was found in the public nature of infrastructure, compared to the mostly private nature in housing construction. Infrastructure construction is characterised by public asset owners, requires public commissioning, and often has a public finance structure.

The importance of standardisation & norms as a construct was already partially acknowledged by Lessing (2015), who presented it as an implicit characteristic of both his planning & control of processes and developed technical systems constructs. Framing it as an explicit construct in the infrastructure context seemed correct, considering the emphasis put on it by research participants.

Further underlining the findings in regard to the definition of industrialisation in the infrastructure context is found in the research by Larsson et al. (2014). Through independent analysis, without applying the IHB framework, they conceive seven core elements of industrialised infrastructure construction, being process, standardisation, repetitiveness, cooperation, prefabrication, continuous improvement, and experience feedback. Clearly, these elements align with the findings in this research. Since Larsson et al. (2014) identified prefabrication, cooperation and continuous improvement as key elements, their presence in the IIC framework can be argued to be correct.

That leaves the constructs of use of ICT and integrated logistics as undiscussed. Despite lack of presence in the results, use of ICT is a natural condition considering the general trend of digitalisation across all sectors. In addition, the form facet of the classified innovations showed the highest frequency for digital collaboration, also hinting at use of ICT. How the construct is defined is highly influential in its score. Hence, while lacking explicit mentioning, use of ICT is considered a vital condition for industrialisation. The implications of the integrated logistics construct are also difficult to assess, due to two main reasons. First, it has a broad definition, leaving a lot of room for interpretation. Also, it seems to be a condition that is more influential when industrialisation is increasingly brought to practical implementations. When efficient and effective off-site manufacturing is realised, there will be a logical requirement for integrated logistics. Hence, for the logistics construct, more review is required.

Another thing to note is that the original IHB framework was defined for application and scoring in a single organisation. The proposed IIC framework was defined to apply on the complete value chain, since that was the unit of analysis for this research. Even though the IHB framework was intended to be applied to singular organisations, the principle behind an industrialised system was that combining the construct scores of each organisation had to result in an overall sufficient 'score' on the framework. Following that logic, it is argued that applying the basic framework on the complete value chain assesses the same principle, in a different way.

To close of implications regarding the definition of industrialisation, it is important to remember the fundamental long-term idea behind its concept. The V&R challenge provides an opportunity for change. However, the sector should be careful not to consider implementing industrialisation as a sort of emergency solution, only to address the short-term spike in demand. Industrialisation should also (or even primarily) be considered from the perspective of long-term sustainable development, instead of only enabling short-lived exploitation. This is also emphasised by Eriksson et al. (2014), who asses how both short-term and long-term benefits of industrialisation can be ensured. Results in this research show small indications that the continuously conservative culture might be emphasising the short-term exploitation and quick wins, without realising the potential benefits if they account for room to change and innovate within new construction systems. If long-term exploration and development is not incorporated, it could be that we will be discussing the conservative construction culture in thirty years, with the only difference being an industrialised production system instead of a project-based construction system.

Identified innovations and the faceted classification framework

The five-faceted classification method for innovation in the construction sector by Delarue et al. (2022) was applied to maintain an overview of any innovation or new technology that may be relevant for this research context. In chapter two, the decision was made to change the facets to better suit the context of this research. This was done by removing the business function and discipline facets, and adding the estimated maturity facet. The business function facet was removed since it focused on departments within singular organisations, and the discipline was found to largely provide the same information as the asset life cycle. Adding the estimated maturity facet was a practical consideration, to be able to assess whether innovations were perceived to be ready for scale-up, or in requirement of more R&D. Naturally, adding a new facet requires verification and validation, which was not done explicitly. Hence, it was approached with caution, resulting in many innovations outside the TIS being categorised as being of unknown maturity. Nevertheless, innovations mentioned by TIS actors were often explained in a way that gave clear indications on their readiness.

It was evident that some innovations represent bundles of innovations, such as digitalisation, prefabrication, or broad standardisation. Each of those three has multiple innovations that form the overarching term, or contribute to it. These broadly defined innovations affect multiple types within each facet, resulting in facets often displaying ‘multiple’. Hence, they are difficult to classify. In addition, by stating facet scores as multiple, the classification approach loses its core intention to provide overview. However, as seen in figure 15, visualisation tools can help to address that lack of overview on some occasions. Nevertheless, figure 15 only depicts a handful of innovations, which is often less than the classification method is designed to provide overview for. Overall, the added value of the classification methodology was considered limited.

TIS

The TIS was concluded by the formulation of four main systemic problems. These were constructed by combining the presence and capability related blocking mechanisms for each function. In turn, the blocking mechanisms were found by analysing the functions with insufficient function scores, as depicted in section 4.5.

SP1 Lack of upfront coordination & long-term planning

SP2 Insufficient support for innovation & knowledge exchange

SP3 Conservative culture in a competitive sector

SP4 Insufficient interdisciplinary collaboration

The conducted TIS analysis was done without incorporating the structural dimension of infrastructure, as its applicability as a structural dimension was debated within TIS literature. For this research case, the other three structural dimensions are argued to have been able to incorporate relevant structural elements through rephrasing. For example, if a function scored low because of lack of knowledge, that was contributed to insufficient actor capability instead of a knowledge infrastructure shortcoming.

Hall et al. (2019) also assessed systemic innovation in a construction context, and constructed figure 16. It can be observed that the systemic problems show similarities with both the resulting risk & industry structure, and effects on innovation diffusion. All effects as seen in the third column were in observed in the TIS in some shape or form. To deal with these structural issues, Hall et al. (2019) argue for a redefinition of the system architecture through new forms of integration and the emergence of platforms.

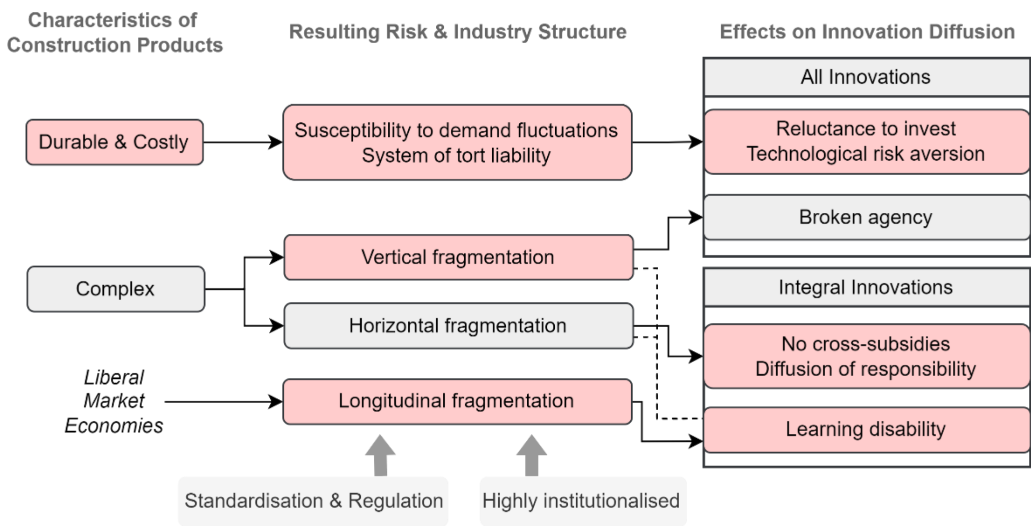


Figure 16: Structural barriers to innovation in construction, by Hall et al. (2019)

As mentioned in the methodology chapter, the relevance of the TIS study for this research context is argued to end at the third TIS analysis phase, of which the output are the four systemic problems. The next phase for the TIS would be to determine policy goals and instruments to mitigate the systemic problems. That way, the TIS can be developed further, and be scaled up in the market.

5.2.2 Methodological reflection on the TIS analysis

In the early stage of this research, TIS was selected out of a large set of innovation-driven transition frameworks. Then, the main reason to select TIS over other approaches was its ability to gain insights in the key bottlenecks for innovation development and diffusion through its combined structural-functional analysis. In addition, a clear guide for analysts could be found regarding the TIS approach, which was not always true for others. Besides practical arguments, the TIS approach allowed for more in depth analysis of actor roles, strategies, interactions, and capabilities.

Literature and critics on transition frameworks such as MLP, MIS, TIS and others show a lot of discussion between the factors that determine the applicability of each framework. For example, the Mission-oriented Innovation System (MIS) would have arguably been a good fit for this, but a clear mission statement was lacking in this research context. On the other hand, TIS studies are argued to be less suitable for a large variety of solutions. Yet, if the focal technology is defined as industrialisation, the question presents itself whether that counts as one solution or a large variety of solutions. For this research, industrialisation was seen as one solution, which can appear in many different forms, for which the key principle is the same (as formulated by the IIC framework definition). Hence, the decision for adapting TIS as the methodological framework can be justified following that line of reasoning. In addition, many transitional frameworks have a tendency to have highly abstract and conceptual results. Given the current urgency of the V&R

challenge, an approach with results that could directly be used to formulate policy goals and instruments was argued to be beneficial.

Given the ambiguous perception of industrialisation in an infrastructure context, Adapting the TIS approach meant that in order to analyse the defined TIS, industrialisation had to be argued as the focal technology. In the manual that was consistently used to conduct the TIS research, defining the focal technology was not a defined TIS analysis phase. Hence, the IIC framework and its empirical review were a necessary addition to the TIS analysis, in order to perform the analysis as intended. Consequently, the innovations and technologies that could form the operationalisation of industrialisation in the defined research context had to be assessed as well, for which the classification of innovations was conducted.

In regard to the conducted TIS analysis, the use of diagnostic questions to formulate function scores resulted in extensive checks for bias and interpretation errors. As prescribed in TIS manuals, diagnostic questions are used to score TIS functions using Likert scales. Through consulting both examples of TIS research and the manuals themselves, it was interpretated that each diagnostic question should be scored by the research participant themselves, after which a combined function score can be calculated. However, diagnostic questions were formulated in a way unsuited to the use of Likert scales, such as “What are the products” for the construct of entrepreneurial experimentation (Wieczorek & Hekkert, 2012). In hindsight, scoring each diagnostic question could have been a misinterpretation of the TIS analysis steps. Nevertheless, the experience of using Likert scales for multifaceted diagnostic questions resulted in a complicated data analysis process.

To conclude, it is argued that despite restrictions and critics, the TIS allowed for a structured analysis that resulted in relevant insights concerning the main research questions.

5.2.3 Research reliability and validity

To reflect on the quality of the conducted research and its findings, the reliability and validity are reviewed. Leung (2015) provides the means to analyse these elements for qualitative research.

Reliability

The general definition for research reliability refers to the replicability of processes and results (Leung, 2015). Contributing to internal reliability are general consistency of processes, the implementation of verification methods and refutational analysis. In general, the consistency of processes is considered sufficient due to the thesis structure consistently using the output of each chapter as input for the next. In terms of verification methods, constant data comparison was applied to ensure that the influence of contextual factors was minimised. No explicit refutational analysis was applied. However, alternative explanations for findings were consistently evaluated. In addition, statements made by individual participants would not be used in general conclusions unless underlined by other participants. As stated before, the TIS analysis scores were amended through interviewee-provided context. That way, discrepancies in data due to faulty interpretations of interview questions were assessed and resolved. In general, exact replication of qualitative research is always difficult due to the informal circumstances.

Validity
The validity of research is mainly characterised by the appropriateness of tools, processes, and data (Leung, 2015). The testing of validity starts at reviewing the appropriateness of the research question, followed by an assessment of the choice of methodology, the appropriateness of sampling and data, and a check whether results and conclusions can be made in regard to the sample and context. Overall, constant iterative and reflexive processes were applied during all research stages.

For the appropriateness of the research question, the findings from chapter one have to be assessed. Clear indicators were found that the main research question should focus on the V&R challenge given its unique characteristics. In addition, the focus of industrialisation as a research direction was both widely hinted by sector leaders and supported by theory. Describing the required changes as a 'transition' is deemed valid as well, as research background showed a general acceptance of the need to change, and transition is used to describe both gradual and drastic changes. The choice of methodology was argued in chapter two, after consideration of multiple alternatives. By deciding on the TIS framework, an increased emphasis had to be put on properly defining the focal technology of industrialisation.

In terms of sampling and data related activities, minimising suggestive bias was explicitly considered to be high priority. Therefore, a conservative approach was applied in regard to reviewing the proposed IIC framework. In addition, the TIS methodology with seven functions and correlating diagnostic questions has been adapted numerous times, and can thus be considered to be sufficiently validated. Also, an experienced mentor was consulted to discuss the interview protocol, in order to ensure optimised data collection.

As per the results and conclusions, direct results of the applied methodology (chapter four) were separated from the interpretations of the results (section 5.1). This was done to ensure that research results are as objective as they can be, given the inherent subjectivity of qualitative research. Chapter four only presents what was described in actual interviews. Naturally, the interpretation of these results is affected by a higher degree of subjectivity.

The validity of this research could have been improved by a few activities. First, explicit review of alternative explanations could have been more extensively. However, given the high number of functional barriers and industrialisation elements, writing a section on these alternative explanations was considered out of scope. For the structural TIS analysis, more expert consultations in early research stages may have been beneficial in ensuring the research focus is on the exact area required. Lastly, having a second round of consults with sector parties could perhaps have allowed for a deeper understanding of both systemic problems and the perception of industrialisation, by testing the first-round results to the sector. This will be discussed further in the end of chapter six.

5.3 Conclusion on the fourth sub-question

The fourth and final research sub-question was:

What insights does the TIS analysis in the context of the V&R challenge provide for innovation driven transitions towards industrialised infrastructure construction?

In regard to this question, three main sets of insights can be described. These three sets can be seen as insights regarding industrialisation itself, insights regarding the innovations that contribute to industrialisation and the innovation driven transition, and TIS insights themselves. For the transition to an industrialised construction system for the infrastructure sector, the revised IIC framework is depicted in figure 17. There are two implicitly important conditions, being prefabrication and use of ICT. Next, there are four explicitly observed conditions, being continuity & repetition by demand, standardisation & norms, long-term relations and continuous improvements. One construct was removed, being flexibility in design. This construct was removed as it is considered less significant for the basic conditions of industrialisation.

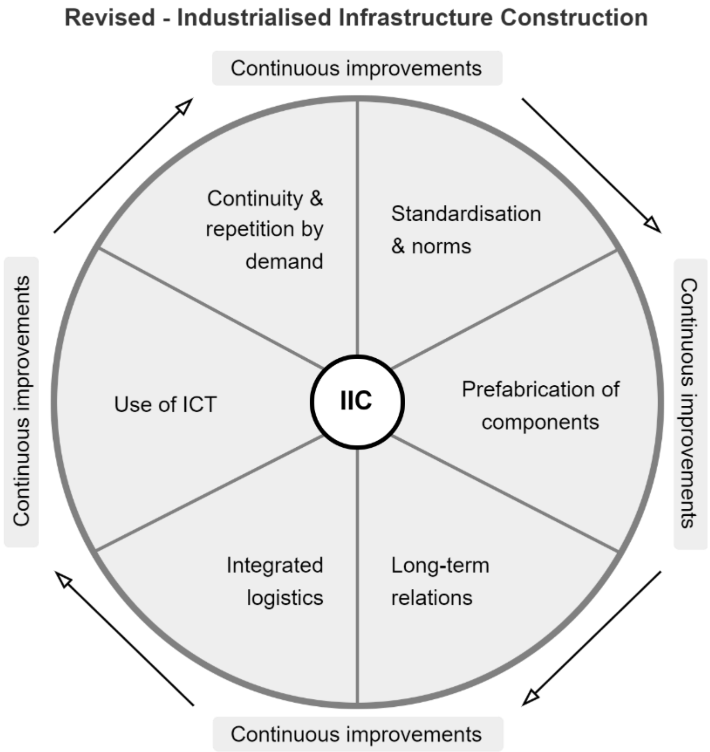


Figure 17: Revised IIC framework

All seven construct are concluded to require more empirical testing, which is especially true for the integrated logistics constructs. Nevertheless, the construct in the current form and in this research context are summarised in table 20. The original description of the IHB framework was consulted for the description of constructs that were unchanged (Lessing, 2015).

Table 20: Proposed IIC constructs explained

Industrialised Infrastructure Construction - proposed constructs	
Continuity & repetition by demand	- Bundled, unfragmented demand allows for project level exceeding investments and process prioritisation - Continuity decreases uncertainty, allows for long-term resource planning - Enables both effective long-term relations instead of project based collaboration and continuous improvements
Standardisation & norms	- Binding standards to create a repeatable and uniform construction approach, customisability on detail level - Defined, documented, and communicated processes for all project phases, and alignment of actors - Standardised, tested, and structured technical subsystems, available in platforms to fit contextual requirements
Prefabrication of components	- Components are manufactured in off-site facilities suitable for effective production - Optimised and stable production processes unhindered by interference from activities by other parties - Complete asset prefabrication in smaller asset size projects
Long-term relations	- Value chain participants are engaged on a long-term basis, exceeding the level of singular projects - Enabling of joint development through long-term relations, increasing the learning capacity and retaining knowledge - Achievable through multiple means (framework agreements, partnerships, collaborative licensing, relational contracts)
Integrated logistics	- Integration of material and information flow with design, planning, manufacturing, and site work - Coordination of transports throughout the supply chain - Involvement of material, component, and element suppliers in development processes
Use of ICT	- ICT tools to support industrial processes with accurate digital information management and communication - ICT tools handle digital materials and structure technical data - ICT manages performance and knowledge sharing, integrating digital information into manufacturing
Continuous improvements	- Continuous improvements are executed in all sub-areas to continuously develop the production system - Systematic re-use of experiences and application of lessons learned to ensure best practice - Improvements establish new levels of standards

For the innovation-driven element in the sub-question, analysis provides three main insights. As per the list of identified innovations and technologies, almost all have the potential to complement efforts to industrialise. One main set indicating the highest potential, as shown in figure 15. Third, innovations should be considered from their overarching type, and then selected on the fit to the specific requirements.

The TIS analysis showed that there are systemic problems that need to be mitigated in order to stimulate a system transition. For the TIS insights, four main systemic problems were derived from identified blocking mechanisms. These are lack of upfront coordination & long-term planning, insufficient support for innovation & knowledge exchange, conservative culture in a competitive sector and insufficient in interdisciplinary collaboration.

It should be noted that in addition to the four systemic problems derived from the TIS analysis, there is an additional structural problem with broad negative effects on the TIS. While findings from both theory and interview data aided in shaping the definition of infrastructure construction industrialisation, many of the participants showed a limited view on what industrialisation is and what it requires. The revised IIC framework depicts a definition that is constructed by combining all findings. Yet, if industrialisation had been defined by each individual interview, it would show little understanding for key conditions for a properly functioning industrialised value chain. Meaning, any current use of the term industrialisation (or industrialised) is up for varied interpretation by people and organisations active in the infrastructure sector. In practice, it was observed that interviewees often use the term industrialisation when they actually mean optimalisation of current processes. This structural problem was not a result of any function score in the TIS analysis, as the TIS approach does not account for abstractly defined innovations such as industrialisation.

For all insights, there is a degree of generalisability to other efforts related to assets other than bridges. The first set of insights presents no clear contradictions when compared to other asset types, the second set allows specific interpretations through the use of overarching typologies of innovation, and the third can be argued to be sector wide. Hence, while more validation processes are required, the findings from this research are argued to be usable in other infrastructure construction related contexts.

This research was conducted to fill the identified theoretical knowledge gaps, as stated in section 1.2.1. The knowledge gap can be summarised in 3 components. First, literature showed that the concept of industrialisation in housing construction was more mature compared to the infrastructure, were it was underrepresented. To contribute to its development, this research formulated the IIC framework. Another identified lack in theory were research papers with a focus on either the complete project asset life cycle, or the complete value chain. This research contributed to the latter, by assessing the complete value chain for Dutch bridge rehabilitation. The third and final knowledge was identified as a lack of knowledge in regard to integrating individual innovations efforts to achieve systemic innovations required for transitions. This research contributed by combining the TIS analysis with a classification of individual innovations, combined with an assessment of complementarity and contradictory elements.

CH6

Conclusion

To conclude this thesis, all key takeaways from the previous chapters are used to answer the main research question. After that, important limitations are stated to understand how the conclusions should be interpretated. Finally, those limitations are translated into recommendations. The recommendations are explained for both the academic and practical context.

6.1 Answer to the main research question

The main research question was constructed to address three main aspects that contribute to the sector problems. There is a general need for the construction sector and its clients to change its ways, in order to sustain and thrive through current and future challenges. Consequently, the practical challenge to ensure that the infrastructure construction sector has the means and organisation to fulfil short-term demand surges and create a long-term sustainable construction system had to be addressed. One last contributing aspect were the specific requirements and opportunities in regard to the V&R challenge in the Dutch infrastructure sector, which serves as both a threat to the current construction approach and a window of opportunity to exploit new and innovative forms of construction activities.

In order to deal with the abovementioned aspects, the concept of industrialising infrastructure construction has gotten more attention over the last years. However, definitions for industrialisation, its requirements, supporting elements, and barriers to adapt it were inadequate. Hence, the research design was formulated to address those elements, resulting in the main research question as stated below. This section answers the main research question by combining the conclusions on the four research sub-questions, which can be found in the final section of the previous chapters.

What (combinations of) innovations or technologies contribute to the transition towards an industrialised value chain for Dutch bridge rehabilitation, and what systemic barriers affect their development and diffusion in the market?

The transition towards an industrialised value chain is at the centre of the main research question. As depicted in figure 18, analysis of this transition was done through the application of three interrelated research activities, being the definition of industrialisation, the evaluation of (complementary) innovations and the TIS analysis for systemic barriers. Combined, these assessments enable the formation of conclusions on the general transition. The three questions shown in figure 18 do not represent the research sub-questions, as the answer to sub-question two was of a methodological nature, and the answer to sub-question four was intended for the discussion in chapter five.

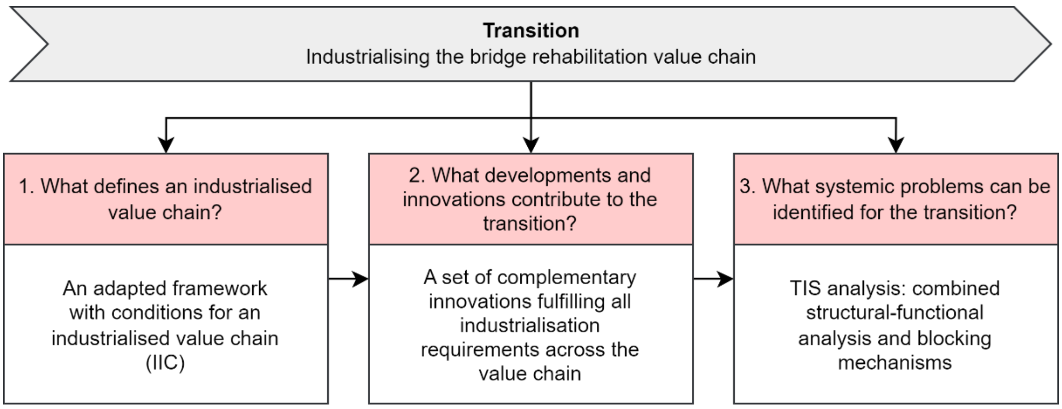


Figure 18: Conducted analysis steps to assess the transition to an industrialised system

Evaluating the main research question, in can be concluded that it is *unfeasible to attempt to apply a universal approach* to achieve the transition to an industrialised infrastructure construction system. Nevertheless, analysis of the demarcated system showed that there is a *general positive contribution of current innovations and emerging technologies to industrialisation*. However, conclusions in that area are restricted by the *limited understanding of the definition and requirements of industrialisation in the sector*, as current conclusions are based on the conditions from an unvalidated definition framework (the proposed IIC framework). Besides, the development and diffusion of innovations and technologies with complementary characteristics are constrained by *four identified structural problems*, which have to be mitigated in order to stimulate the transition.

Unfeasibility of universal approach to industrialisation

First of all, the research identified that there is no universal, singular form that constitutes an industrialised value chain. While bridge assets are often considered basic, contextual factors and relevant discipline specific knowledge is required for assets with varying functionalities and sizes. In addition, there will always be differences due to the number of actors, and their way of conducting business. Also, difference in priority perspectives and different future expectations by actors are influential. By extension, the inability to describe one integrated approach as a directive for the whole sector to adhere to means that industrialisation has to be made fit for purpose for its contextual application. In addition, both theory and the data collected for each research participant have made it evident that the definition of industrialisation for the infrastructure context is inadequate.

For this reason, the adapted and revised IIC framework describes the general conditions for the infrastructure sector unlock the potential of the industrialisation concept. By combining all individual perceptions by research participants with established literature, seven key conditions were formulated to represent the definition of industrialised infrastructure construction. The first six being continuity & repetition by demand, standardisation & norms, prefabrication of components, long-term relations, integrated logistics, use of ICT. The final construct of continuous improvement relates to all others.

General positive contribution of innovations to industrialisation

The IIC constructs are translated for the assessment of innovations and technologies for this research subject. Whereas the initial intend was to find a universally applicable complementary set of specific innovations, practical implications quickly showed that the diversity of V&R challenge related assets rendered that intend unfeasible. This was emphasised through the conducted classification activities, which showed that most innovations and new directions of both technological and procedural development are aligned with the contextual definition of industrialisation. Hence, a general conclusion to this section of the main question would be that nearly all identified innovations and new technologies have the potential to contribute to an industrialised construction system.

Even though no clear set of specific innovations was identified, a more generalised set of overarching innovation types was observed to have high potential. These types show complementary characteristics across the traditional project life cycle phases, connected through digitalisation innovations. In short, the combination of asset data innovations provide input for parametric design practices, which can in turn be aligned with broad standardisation and IFD standards, ensuring a manufacturing plan for the prefabrication of components. The latter can be further optimised through manufacturing and constructing innovations, such as robotisation and other automated processes. Consequently, this combination of complementary efforts requires further specification for the asset data innovations, broad standardisation, manufacturing automation and robotisation, and overall innovations regarding digitalisation. These five elements can be seen as overarching typologies, consisting of a wide array of specific innovations that can be categorised within them. In addition to the conclusion in the previous paragraph, it is found that there general overarching typologies that provide the biggest contribution to industrialisation, being defined by the five abovementioned types.

Limited understanding of the definition of industrialisation

Combined, interviews with participants across the bridge construction value chain assisted in shaping the definition of industrialisation in the defined research context. However, on an individual level, results showed that research participants only rarely perceived the concept of industrialisation as something that requires alignment on various different fields, as underlined by the IHB framework by Lessing (2015). In most cases, data showed that industrialisation was either perceived as increased prefabrication and intensifying off-site practices, or used interchangeably with process optimisation practices, both on and off-site. An important example was found in the requirement of long-term relations, which nearly all research participants regarded as crucial. Yet, few participants had relations that complied with the definition and intend of long-term relations as implied in established industrialisation frameworks.

The key takeaway from this observation is that the varying perceptions of industrialisation have a restricting effect on its development in the sector. Furthermore, lack of aligned interpretation of industrialisation efforts hinders how sector parties can make effective long-term plans and create effective means of knowledge exchange.

Four systemic problems for development and diffusion

The final segment of the main research question assessed the systemic barriers for the development and diffusion of the innovations and technologies that contribute to the transition to an industrialised construction system. The initiation phase of this analysis was conducted with the IIC framework, as its conditions clarify the requirements that structural sector elements need to fulfil. These structural elements are represented by the actors relevant to infrastructure construction, institutions governing infrastructure related processes, and interactions between infrastructure sector organisations.

The TIS methodology allowed for structural assessment of these structural system dimensions, and combined them with the established functions for innovation development and diffusion. The initial expectation for this research was that the results would show a set of specific innovations for which restricting factors concerning their development and diffusion could be identified. However, in line with the unfeasibility of a universal approach to industrialisation, analysis showed that overarching types of innovations were observed most. Meaning, the systemic barriers as a result of the functional TIS analysis are relevant to those overarching types as well. Out of the seven system functionalities, five were identified as functional barriers, which were in turn reviewed for their underlying blocking mechanisms. These five are knowledge exchange, the guidance of the search, the mobilisation of resources, the resistance to change, and the degree and quality of entrepeunerial experimentation. Review of the arguments and perception of sector actors, four key systemic problems were formulated to adress the root cause of these functional barriers. These four are lack of upfront coordination & long-term planning, insufficient support for innovation & knowledge exchange, conservative culture in a competitive sector, and insufficient interdisciplinary collaboration. The key elements are explained in the description of each systemic problem.

1. *Lack of upfront coordination & long-term planning*

This systemic problem implies five main factors. First, lack of upfront coordination leads to unstructured workloads through differentiated and unique project tenders. Fragmented and differentiated demand restricts the potential for industrialised construction efforts. Second, there is limited guidance and directly implementable knowledge development for actors with limited knowledge and influence. The lack of long-term planning synthesis the lack of project-level exceeding efforts. In turn, lack of those efforts results in a lack of resource mobilisation for activities that are not within the main set of construction activities. Lastly, there is little continuity for sector parties, resulting in uncertainty.

2. *Insufficient support for innovation & knowledge exchange*

For the second systemic problem, four generalised causes can be named. First, there is an absence of institutions that facilitate knowledge exchange without compromising on the competative element of the system. Second, like the first systemic problem, a lack of ambassador for change or leading party to guide and align parties in their transition to alternative approaches hinders collective innovation development and diffusion. Third, the current system of institutions and interactions lack the ability to stimulate and value alternative approaches consisting of new technologies. In addition, the limited availability of financing structures for innovations, and long-term commitment to innovation development is considered a cause.

3. *Conservative culture in a competitive sector*

Broad effects of culture and competition were identified. In regard to the culture, its negative effects on technical development and innovations in procedural elements are implicit. On all sides of the sector, it was observed that commitment to change is not common. In addition, decisions to fall back on proven and traditional methods are made without critical causes. Innovations and new technologies require extensive validation processes, which are complicated due to their lack of practical applications. There is general emphasis on proven methods, and adverse behaviour in regard to unvalidated technologies. In addition, not enough actors are actively seeking to adapt to future challenges by experimenting and innovating. Competition in the sector was observed to restrict proper knowledge exchange, and therefore leading to a suboptimal exploitation of effective learning capacity and application of best practice. Even though the infrastructure sector has a limited number of actors per main category, the current system is highly demand-driven, and the margins for supply-side actors are narrow.

4. *Insufficient interdisciplinary collaboration*

The final systemic problem affects the ability to collectively improve and transform the construction system. It describes a general shortage of collaboration between technological disciplines, departments within organisation and the internal alignment of system actors, and between actor groups relating to specific materials. This systemic problem can be partially attributed to vertical, horizontal, and longitudinal fragmentation. The shortage of collaboration results in suboptimal exploitation of opportunities and a disregard for potential for potential complementary elements. To improve the sector and achieve the collective capacity needed to deal with future challenges, more interdisciplinary collaboration is required.

Concluding remarks
Overall, the potential for industrialisation is high, and mitigation strategies for the transition to an industrialised system can be designed. This research does not prescribe the use of a (set of) concise innovations for industrialisation. The specific choice of technology is not critical for enabling industrialisation, but ensuring that those technologies and approaches are adhering to standards is. Yet, despite the choice, developments of new technologies are of all time, thus requiring asset owners to keep stimulating the market. The findings of this research argue that necessary developments required to industrialise can be stimulated by asset owners through two approaches. Either through increased consideration of alternative value creation by innovation through institutions and interactions and increased stimulation of innovation development in practice, or by providing certainty of high demand.

6.2 Research limitations

Conclusions from this research require a description of the relevant research limitations to bring nuance and put them in perspective. Hence, to assess the soundness of conclusions from the previous section, research limitations have to be reviewed.

6.1.1 Limitations induced by focus on industrialisation

The focus on industrialisation has a few complications that are worth mentioning. The concept of industrialisation represents many elements, and has numerous different applications in other industries and areas of expertise. Hence, the decision to make industrialisation as a whole the focal technology of this research, resulted in the need for a broad analysis. Therefore, the research used a relatively high number of different frameworks for different elements within the research context. The original intend for this research was to conduct a broad and explorative study of industrialisation in the infrastructure context, as constructed by the combined efforts of the TU Delft, De Bouwcampus and TNO. Naturally, narrowing down the scope would have allowed for more and deeper interpretations on more concisely specified theoretical elements. Yet, the research would have lacked the overview wanted by research initiators.

6.2.2 Methodological limitations

Because of the broad scope, numerous methodological decisions were made regarding how the frameworks were to be adapted. Of those, the most influential were the adaption of the IIC framework based on the IHB framework, the changes in applied facets for the faceted classification method, and the decision not to assess the infrastructure dimension in the TIS methodology. In addition, the categorisation of actors in six categories neglected overlap and actors that fulfil multiple roles. The theoretical implications of these choices are described in chapter five. Yet, limitations regarding the methodologies require more attention.

For the IIC framework, it is clear that the validity and generalisability to different types of infrastructure contexts requires more work. Even though constructs in the IIC framework showed similarities with findings from research in other countries, other constructs lacked that external confirmation. Hence, especially the integrated logistics framework requires more empirical review. Furthermore, indications of interrelations and interdependencies between framework constructs were found, but not explicitly assessed. By doing so, the definition of the IIC framework could be sharpened even more. In general, the IIC framework requires extensive efforts in order to gather empirical justification, for which a second round of validation with sector experts would have been beneficial for this research. While this was originally part of the research plan, other parts of this thesis also demanded time investments, resulting in an infeasibility to gather the data that was required for a second round of external validation. Consequently, calling the IIC definition as found in this thesis a framework can be contested. In the end, the decision was made to retain calling it the IIC framework for convenience and readability, while emphasising that its content was both merely proposed, unvalidated, and to be regarded more as a tool for this research context instead of a universal framework.

For the TIS analysis, three main sources of research limitations were identified. First, the TIS method has different guides for analysts, which tend to have small differences that complicated the execution of the TIS study. Second, different interpretations of the focal TIS during the interviews was hard to manage, and may have affected the results. In a way, some interviewees interpreted the diagnostic TIS questions from the perspective of development and diffusion of innovations in general. Third and final, a second round of validation for the interpretated results and systemic problems could have increased the validity of the findings. However, time and resource constraints made this unfeasible.

6.2.3 Limitations induced by research scope

Besides the methodological limitations, scoping the research on the V&R challenge as a whole constituted to limitations as well. While argued to fit both the exploratory nature of the research and the decision to utilise the value chain as unit of analysis, the differences within the complete V&R challenge may have been too big to construct a general assessment. The V&R challenge requires varying strategies depending on the chosen perspective. Meaning, a more concise scope definition within the V&R challenge cases could have aided the soundness of the conclusions made in the previous section.

6.2.4 Participants and selection process related limitations

Limitations induced by the research participants and selection process represent the final category. In general, the number of interviews could have been higher. To state that the value chain is applied as the unit of analysis, at least two or three actors per actor group should have been interviewed. For the knowledge and branch actor group, only one organisation was interviewed. In addition, each organisation was represented by the single interviewee. Hence, his/her opinion could misrepresent the opinion of the organisation.

Regarding the selection process, the choice was made to conduct interviews with participants that are active within V&R challenge related efforts, because they were perceived to have more knowledge. While this was the case, it may misrepresent the opinion of the actors that are not active within the research context yet. Nevertheless, data can only be gathered from actors that understand what is being asked, which requires a degree of prior knowledge.

6.3 Recommendations

In this section, recommendations have been formulated based on the discussion, conclusions, and limitations. The recommendations are categorised to either be relevant for academic purposes, or practical implications of this research. First, academic recommendations describe potential areas for further research, based on the theoretical findings of this thesis. Then, the practical recommendations are provided, giving parties directions to apply the findings from this research in practice.

6.3.1 Academic recommendations

Chapter five described a few areas where this thesis attempts to contribute to the body of knowledge regarding innovation driven system transitions and industrialisation efforts in construction. Three main elements were identified, in regard to the proposed IIC framework, application of the TIS methodology, and the implementation of the faceted classification method. This study introduced a proposal for a framework to define the requirements for industrialisation in the infrastructure context, which was lacking in literature. The TIS methodology was implemented using a abstractly defined focal technology, while the common practice shows that TIS studies are often conducted with a concisely defined singular technology. Hence, a methodological addition to the body of knowledge would be that a transition study can be conducted with an extra defining step in early analysis stages. In addition, the faceted classification method was applied. However, no mitigating strategy was found for previously identified shortcomings, such as the excess of facets being scored with ‘multiple’.

As per the recommendations for the future, six proposed research directions were identified based on the findings and limitations of this study. Since the proposed and revised IIC framework is currently only partially validated by a small number of construction sector parties, Further testing and developing is required. Hence, conducting similar research for other infrastructure asset typologies could be beneficial. Also, the integrated logistics construct requires further defining and testing. Second, this research can be continued by assessing the dynamics between both IIC framework constructs and infrastructure context-induced correlations between the seven TIS functions and identified blocking mechanisms.

The effects of cultural elements on industrialisation efforts requires more research as well. Its abstract forms and widespread effects could be made explicit by conducting research with assessing culture as its primary focus.

Given the importance of understanding the V&R challenge urgency and its future practical implications, the methods behind standardised asset data collection and its consequential possibilities in longer-term planning integration may constitute an interesting research direction.

Finally, assessing finance and risk structures regarding innovations and alternative approaches in infrastructure applications would provide valuable insights. By analysing this from both the supply and demand perspective, new organisational and institutional structures may be developed, further stimulating the transition towards a sustainable construction practice.

6.3.2 Practical recommendations

For the practical recommendations, five main elements were identified through analysis of the systemic problems and the blocking mechanisms they are based on.

Proper and efficient knowledge exchange is vital. Yet, currently insufficient. Even though overarching branch organisations such as De Bouwcampus have a big positive effect, the dependence of market organisations on general project demand is highly influential. As a practical recommendation, organisations should look into alternative forms of finding value or profit. Currently, all individual parties are motivated by their individual interests. If a way can be designed in which collaborative efforts are valued through licensing or other forms of mutual benefit, uniformity and alignment within the sector could be increased, enabling the transition to an industrialised value chain. There is no need to completely remove the competitive element, yet ensure collaboration on the shaping decisions in early phases, to create a level playing field. In addition, it would be recommended to review current forms of knowledge exchange, as it is evident that the effect of its current form does not result in the expected learning capacity. Knowledge exchange should be conducted in a format that enables external parties to adapt without extra input.

Furthermore, there are currently not enough actors that are actively experimenting and innovating to stimulate a transition to industrialisation. This is caused by numerous factors, amongst the fact that innovations and new technologies tend to initially be more expensive and risky, as they develop through real-world applications. In addition, most asset owners currently have little resources to innovate themselves, and depend on market parties to develop innovative solutions. The exception being the bigger asset owners and RWS. The lack of rewards, combined with the costs and risks paired with investing in experimentation and innovation, has a negative effect. Hence, asset owners are recommended to find ways to value innovative and sustainable approaches, and reward organisations for placing tender bids outside the traditional proven methods and materials. It is recommended to increase ways of appreciating alternative forms of value, such as life cycle material costs, reusability, modularity, footprint, etc. Currently, time and costs are often the only key project performance indicators, indicating a persistent focus on short-term effects. In addition, they should allow these approaches to be tested in non-pilot projects, to accelerate the learning process.

Also, there is a need to increase and improve interdisciplinary interactions and collaborative activities on various levels. This need has been consistently mentioned to be a restricting factor in construction practice. However, the V&R challenge will create an even bigger urgency to aggregate supply, in order to deal with the scope of work. Currently, this requirement is not evident, as the sense of urgency regarding the challenge itself is still limited to a few organisations at the forefront. The recommendation would be to stimulate interdisciplinary interactions and collaboration with other disciplines and align activities regarding V&R challenge within the same discipline or organisations. For example, increasing the detail levels for the IFD related NTA's by collaborating on its requirements.

To address the V&R challenge and transition to a new construction approach, the analysis showed that there is a lack of continuity, a lack of a long-term plan, and a lack of ambassador for change, or transition leader. Reviewing the organisations in the infrastructure sector, RWS is the only party that can have a significant effect on the way the V&R challenge is approached nationwide. While RWS is not capable of 'leading' the transition as of right now, investments are made that will enable them in the future. For the V&R challenge, it is crucial that RWS sets the precedents and effectively communicates to smaller asset owners how and what innovative approach should be applied. That way, market parties are better able to plan their long-term approaches, and continuity is improved.

Hence, the recommendation for asset owners would be to look for ways to provide certainty to market parties. This could be in the form of framework agreements, project portfolios, commitment to new standards, financial benefits for alternative approaches, taxes on negative construction outputs. By decreasing the level of fragmentation and individual project demand, traditional and reluctant market behaviour can perhaps be mitigated. Increased use of these long-term plans can then also lead to more consideration of project level exceeding strategies.

To conclude the practical recommendations, it can be argued that there are two main trajectories to stimulate sector organisations to change and improve their approach. On the one hand, asset owners should collectively force market parties to change through alternative tendering institutions and value assessments, which will inevitably cost asset owners more compared to the traditional approach and requires knowledge on their side. Currently, ambitious project tenders that prescribe alternative approaches often fall through when negative developments are experienced, resulting in uncertainty for supply side actors, which in turn leads to risk-adverse behaviour and favouring of traditional approaches.

On the other hand, asset owners should prioritise to offer a bundled workload to market parties. By doing so, they enable market parties to invest in the necessary changes through an improved business case, as they can manage their resources under a decreased level of uncertainty. In short, continuity and repetition by demand enables a wide array of benefits. To achieve that, priority should be given to activities that stimulate effective bundling of V&R challenge related assets. That could be done through intensifying collaboration between asset owners, and gathering more and better quality data in regard to asset state and urgency

References

Aanbestedingsprocedures. (2023). PIANOo - Expertisecentrum Aanbesteden. https://www.pianoo.nl/nl/inkoopproces/aanbestedingsprocedures

Adams, W. T. (2015). Conducting Semi-Structured Interviews. Handbook of Practical Program Evaluation, 492–505. https://doi.org/10.1002/9781119171386.ch19

Al-Aidrous, A. M. H., Shafiq, N., Rahmawati, Y., Mohammed, B. S., Al-Ashmori, Y. Y., Baarimah, A. O., & Alawag, A. M. (2023). Major blocking factors affecting the application of industrialized building system. Ain Shams Engineering Journal, 14(10), 102151. https://doi.org/10.1016/j.asej.2023.102151

Aldersey-Williams, J., Strachan, P. A., & Broadbent, I. D. (2020). Validating the “Seven Functions” Model of Technological Innovations Systems Theory with Industry Stakeholders—A Review from UK Offshore Renewables. Energies, 13(24), 6673. https://doi.org/10.3390/en13246673

Allam, A. S., & Nik-Bakht, M. (2023). From demolition to deconstruction of the built environment: A synthesis of the literature. Journal of Building Engineering, 64, 105679. https://doi.org/10.1016/j.jobe.2022.105679

Almeida, F., Faria, D & Queirós, A. (2017). Strengths and Limitations of Qualitative and Quantitative Research Methods. European Journal of Education Studies. 3. 369-387. https://doi.org/10.5281/ zenodo.887089

Attouri, E., Lafhaj, Z., Ducoulombier, L., & Linéatte, B. (2022). The current use of industrialized construction techniques in France: Benefits, limits and future expectations. Cleaner Engineering and Technology, 7, 100436. https://doi.org/10.1016/j.clet.2022.100436

Ayinla, K. O., F. Cheung, and A. R. Tawil. (2019). “Demystifying the concept of offsite manufacturing method: Towards a robust definition and classification system.” Constr. Innovation 20 (2): 223–246. https://doi.org/10.1108/CI-07-2019-0064

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analysing the functional dynamics of technological innovation systems: A scheme of analysis. Research Policy, 37(3), 407–429. https://doi.org/10.1016/j.respol.2007.12.003

Bergelson, I., Tracy, C. R., & Takacs, E. B. (2022). Best practices for reducing bias in the interview process. Current Urology Reports, 23(11), 319–325. https://doi.org/10.1007/s11934-022-01116-7

Bingham, A. J. (2023). From Data Management to Actionable Findings: a Five-Phase process of qualitative data analysis. International Journal of Qualitative Methods, 22. https://doi.org/10.1177/16094069231183620

BPIE (Buildings Performance Institute Europe). (2021). Driving transformational change in the construction value chain > BPIE - Buildings Performance Institute Europe. https://www.bpie.eu/publication/construction-value-chain/

Braun, Dr.-I. A., Hall, D. M., & Mueller, B. (2021). Business Innovation Framework for Industrialized Construction.

Buildings Performance Institute Europe (BPIE). (2021). Driving transformational change in the construction value chain. BPIE - Buildings Performance Institute Europe. BPIE - Buildings Performance Institute Europe. https://www.bpie.eu/publication/construction-value-chain/

Cândido, L. F., Da Silva Filho, J. C. L., De Freitas E Silva, A. O., & De Paula Barros Neto, J. (2023). Sustainability Transitions in the construction Sector: A bibliometric review. Sustainability, 15(17), 12814. https://doi.org/10.3390/su151712814

Coenen, L., & Lopez, F. D. (2010). Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities. Journal of Cleaner Production, 18(12), 1149–1160. https://doi.org/10.1016/j.jclepro.2010.04.003

Costa, S., Carvalho, M. S., Pimentel, C., & Duarte, C. (2023). A systematic literature review and Conceptual framework of construction Industrialization. Journal of the Construction Division and Management, 149(2). https://doi.org/10.1061/(asce)co.1943-7862.0002410

CROW-CUR. (2019). CROW-CUR Aanbeveling 124:2019: Constructieve veiligheid bestaande bruggen en viaducten van decentrale overheden. CUR-aanbevelingen.nl. Retrieved May 13, 2024, from https://www.cur-aanbevelingen.nl/cur-aanbeveling-124

Cuartas, G. V., Goyeneche, O. Y. R., Berjawi, A. E. H., Bergek, A., & Haddad, C. R. (2022). Evaluating Transformative Innovation Policy Outcomes as Unfolding Processes Of Change In Socio-Technical Configurations. In Transformative Metrics (pp. 63–105). *https://doi.org/10.17533/978-628-7592-15-5*

De Bouwcampus. (2021). Samenwerken aan vervanging en renovatie infrastructuur - kansen en belemmeringen. In De Bouwcampus.nl. *https://debouwcampus.nl/bestanden/transitietrajecten/Open_Leeromgeving_Seriematige_Aanpak_VR/Samenwerken-aan-vervanging-en-renovatie-infrastructuur.pdf*

DeJonckheere, M., & Vaughn, L. M. (2019). Semistructured interviewing in primary care research: a balance of relationship and rigour. Family Medicine and Community Health, 7(2), e000057. https://doi.org/10.1136/fmch-2018-000057

Delarue, C., Poirier, É. A., & Forgues, D. (2022). A faceted classification system for innovation in the construction industry. In Lecture notes in civil engineering (pp. 17–30). https://doi.org/10.1007/978-981-19-0968-9_2

Demirkesen, S. & Tezel, A. (2022). "Investigating major challenges for industry 4.0 adoption among construction companies", Engineering, Construction and Architectural Management, Vol. 29 No. 3, pp. 1470-1503. https://doi.org/10.1108/ECAM-12-2020-1059

Dingelstad, D. (2021). Management of opportunities in the construction sector: A comparison of theory and practice. *https://repository.tudelft.nl/islandora/object/uuid:670dfb4b-753f-4879-8d6d-a264b0d15aab?collection=education*

Edquist, C. (2006). Systems of Innovation: Perspectives and challenges. In Oxford University Press eBooks. https://doi.org/10.1093/oxfordhb/9780199286805.003.0007

EIB - Economisch Instituut voor de Bouw. (2023). Eindrapport IFD in de infrastructuur: Potentie, effecten en acties. EIB. Retrieved January 11, 2024, from https://www.eib.nl/wp-content/uploads/2023/01/EIB-Eindrapport-IFD-in-de-infrastructuur-web.pdf

Eriksson, P. E., Olander, S., Szentes, H., & Widén, K. (2014). Managing short-term efficiency and long-term development through industrialized construction. Construction Management and Economics, 32(1–2), 97–108. *https://doi.org/10.1080/01446193.2013.814920*

Eurostat. (March 15, 2023). Number of employees in the construction industry in the European Union (EU-27) from 2011 to 2020, by segment (in millions) [Graph]. In Statista. Retrieved April 24, 2024, from *https://www.statista.com/statistics/763219/total-employed-persons-in-building-construction-industry-eu/*

Fathi, S., Mirasa, A. K., & Abedi, M. (2012). Construction industry experience of IBS in Malaysia. 9th International Congress on Civil Engineering (9ICCE) 2012. https://www.researchgate.net/publication/307932416_Construction_Industry_Experience_of_Industralised_Building_System_in_Malaysia

Lessing, J., Stehn, L., & Ekholm, A. (2005). Industrialised housing: definition and categorization of the concept. In Annual conference of the International Group for Lean Construction: 18/07/2005-21/07/2005 (pp. 471-480). International group for lean construction.

Feng, J., Ma, L., Broyd, T., & Chen, K. (2021). Digital Twin and its implementations in the civil engineering sector. Automation in Construction, 130, 103838. *https://doi.org/10.1016/j.autcon.2021.103838*

Finn, V. (2022). A qualitative assessment of QCA: method stretching in large-N studies and temporality. Quality & Quantity, 56(5), 3815–3830. *https://doi.org/10.1007/s11135-021-01278-5*

Galdas, P. (2017). Revisiting bias in qualitative research. International Journal of Qualitative Methods, 16(1), 160940691774899. https://doi.org/10.1177/1609406917748992

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems. Research Policy, 33(6–7), 897–920. https://doi.org/10.1016/j.respol.2004.01.015

Gerding, D. P., Wamelink, H., & Leclercq, E. M. (2021). Implementing circularity in the construction process: a case study examining the reorganization of multi-actor environment and the decision-making process. Construction Management and Economics, 39(7), 617–635. *https://doi.org/10.1080/01446193.2021.1934885*

Goh, E. H., & Loosemore, M. (2016). The impacts of industrialization on construction subcontractors: a resource based view. Construction Management and Economics, 35(5), 288–304. https://doi.org/10.1080/01446193.2016.1253856

Gopal, K., Groenemeijer, L., van Leeuwen, G., Omtzigt, D., & Stuart-Fox, M. (2021). Primos 2021. ABF Research.

Grimmon, M. (2024, April 17). Pekela gooit het roer om: nagenoeg alle bruggen moeten blijven. RTV Noord. *https://www.rtvnoord.nl/verkeer/1153423/pekela-gooit-het-roer-om-nagenoeg-alle-bruggen-moeten-blijven*

Hall, D., Whyte, J., & Lessing, J. (2019). eaking strategies to enable digital manufacturing in Silicon Valley construction Firms: a comparative case study. Construction Management and Economics, 38(4), 322–339. https://doi.org/10.1080/01446193.2019.1656814

Hekkert, M. P., & Negro, S. O. (2009). Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. Technological Forecasting and Social Change, 76(4), 584–594. https://doi.org/10.1016/j.techfore.2008.04.013

Hekkert, M. P., Janssen, M. J., Wesseling, J., & Negro, S. O. (2020). Mission-oriented innovation systems. Environmental Innovation and Societal Transitions, 34, 76–79. https://doi.org/10.1016/j.eist.2019.11.011

Hekkert, M. P., Suurs, R., Negro, S. O., Kuhlmann, S., & Smits, R. (2007). Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting & Social Change/Technological Forecasting and Social Change, 74(4), 413–432. https://doi.org/10.1016/j.techfore.2006.03.002

Hekkert, M., Negro, S., Heimeriks, G., & Harmsen, R. (2011). Technological Innovation System Analysis: A manual for analysts (tech. rep.)

Hilbolling, S., Deken, F., Berends, H., & Tuertscher, P. (2022). Process-based temporal coordination in multiparty collaboration for societal challenges. Strategic Organization, 20(1), 135-163. *https://doi.org/10.1177/1476127021992705*

Jain, N. (2021). Survey versus Interviews: Comparing data collection Tools for Exploratory research. The Qualitative Report. *https://doi.org/10.46743/2160-3715/2021.4492*

Ji, Y., Zhu, F., Li, H. X., & Al-Hussein, M. (2017). Construction industrialization in China: current profile and the prediction. Applied sciences, 7(2), 180. *https://doi.org/10.3390/app7020180*

Jin, R., S. Gao, A. Cheshmehzangi, and E. Aboagye-Nimo. (2018). “A holistic review of off-site construction literature published between 2008 and 2018.” J. Cleaner Prod. 202 (Nov): 1202–1219. https://doi.org/10.1016/j.jclepro.2018.08.195.

Joshi, A., Kale, S., Chandel, S., & Pal, D. K. (2015). Likert scale: explored and explained. British Journal of Applied Science and Technology, 7(4), 396–403. *https://doi.org/10.9734/bjast/2015/14975*

Kamar, M., Anuar, K., Zuhairi, H & Azman, M., Azhari, N., Ahamad, S & Sanusi, M. (2011). Industrialized Building System (IBS): Revisiting Issues of Definition and Classification. International Journal of Emerging Sciences - IJES. 1.

Katila, R., Levitt, R. E., & Sheffer, D. A. (2018). Systemic innovation of complex one-off products: the case of green buildings. In Advances in strategic management (pp. 299–328). https://doi.org/10.1108/s0742-332220180000040011

Kern, F. (2014). What future for the technological innovation systems approach in analysing sustainability transition. Sussex Energy Group at SPRU. https://blogs.sussex.ac.uk/sussexenergygroup/2014/09/22/what-future-for-the-technological-innovation-systems-approach-in-analysing-sustainability-transition/

King, A. A., & Baatartogtokh, B. (2015). How useful is the theory of disruptive innovation? MIT Sloan management review, 57(1), 77.

Lachman, D. A. (2013). A survey and review of approaches to study transitions. Energy Policy, 58, 269–276. https://doi.org/10.1016/j.enpol.2013.03.013

Larsson, J., Eriksson, P., Olofsson, T., & Simonsson, P. (2014). Industrialized construction in the Swedish infrastructure sector: core elements and barriers. Construction Management and Economics, 32(1–2), 83–96. https://doi.org/10.1080/01446193.2013.833666

Lessing, J. (2015). Industrialised House-Building - Conceptual orientation and strategic perspectives. Lund University Publications. https://lup.lub.lu.se/search/publication/8145659

Leung, L. (2015). Validity, reliability, and generalizability in qualitative research. Journal Of Family Medicine And Primary Care, 4(3), 324. https://doi.org/10.4103/2249-4863.161306

Li, L., Li, Z., Li, X., Zhang, S., & Luo, X. (2020). A new framework of industrialized construction in China: Towards on-site industrialization. Journal of Cleaner Production, 244, 118469. https://doi.org/10.1016/j.jclepro.2019.118469

Liao, Longhui & Yang, Chuan & Quan, Lirong. (2022). Construction supply chain management: A systematic literature review and future development. Journal of Cleaner Production. 382. 135230. *https://doi.org/10.1016/j.jclepro.2022.135230*

Luo, L., Jin, X., Shen, G. Q., Wang, Y., Liang, X., Li, X., & Li, C. Z. (2021). Supply chain management for prefabricated building projects in Hong Kong. Journal of Management in Engineering, 36(2). *https://doi.org/10.1061/(asce)me.1943-5479.0000739*

Malik, A & Aditi, M. (2018) Construction Industry Value Chain: How Companies are Using Carbon Pricing to Address Climate Risk and Find New Opportunities. No. 132770. The World Bank, 2018.

Markard, J. (2020). The life cycle of technological innovation systems. Technological Forecasting and Social Change, 153, 119407. https://doi.org/10.1016/j.techfore.2018.07.045

Markard, J., Hekkert, M. P., & Jacobsson, S. (2015). The technological innovation systems framework: Response to six criticisms. Environmental Innovation and Societal Transitions, 16, 76–86. https://doi.org/10.1016/j.eist.2015.07.006

Mckinsey & Company - Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., Bertram, N., & Brown, S. (2017). Reinventing Construction: A Route to Higher Productivity. McKinsey & Company

McKinsey & Company - Blanco, J. L., Mullin, A., Pandya, K., Parsons, M., & Ribeirinho, M. J. (2018). Seizing opportunity in today's construction technology ecosystem. McKinsey & Company. *https://www.mckinsey.com/capabilities/operations/our-insights/seizing-opportunity-in-todays-construction-technology-ecosystem*

Meelen, T., & Farla, J. (2013). Towards an integrated framework for analysing sustainable innovation policy. Technology Analysis & Strategic Management, 25(8), 957–970. https://doi.org/10.1080/09537325.2013.823146

Ministerie van Economische Zaken (2023, September 28). Regels voor aanbesteden door de overheid. Aanbesteden | Rijksoverheid.nl. https://www.rijksoverheid.nl/onderwerpen/aanbesteden/aanbestedingsregels

Ministerie van Infrastructuur en Waterstaat. (2023, September 28). Bruggen. https://www.rijkswaterstaat.nl/wegen/wegbeheer/bruggen

Ministry of the Interior and Kingdom Relations. (2021). The Environment Buildings Decree of the Netherlands. Informatiepunt Leefomgeving. Retrieved May 13, 2024, from https://iplo.nl/publish/pages/195436/the-environment-buildings-decree-bbl-2020.pdf

Nadim, W. & Goulding, J.S. (2011), "Offsite production: a model for building down barriers: A European construction industry perspective", Engineering, Construction and Architectural Management, Vol. 18 No. 1, pp. 82-101. https://doi.org/10.1108/09699981111098702

Nawi, M., Hanifa, F., Kamar, K., Lee, A., & Azman, M. (2014). Modern method of construction: an experience from UK construction industry. Australian journal of basic and applied sciences, 8(5), 527-532

NEN. (2021). NTA - Nederlands Technische Afspraak: IFD-bouw vaste bruggen en viaducten (ICS 93.040). *https://www.nen.nl/nta-8085-2021-nl-284893*

Nicmanis, M. (2024). Reflexive Content Analysis: An Approach to Qualitative Data Analysis, Reduction, and Description. International Journal of Qualitative Methods. 23. *https://doi.org/10.1177/16094069241236603*

Oti-Sarpong, K., Pärn, E.A., Burgess, G. and Zaki, M. (2022), Transforming the construction sector: an institutional complexity perspective, Construction Innovation, Vol. 22 No. 2, pp. 361-387. *https://doi.org/10.1108/CI-04-2021-0071*

Provincie Noord-Holland. (2022). Integraal meerjarenprogramma infrastructuur 2023-2030.

Rathnayake, A., & Middleton, C. (2023). Systematic Review of the Literature on Construction Productivity. Journal of Construction Engineering and Management, 149(6). *https://doi.org/10.1061/JCEMD4.COENG-13045*

Redactie Nationale Bouwgids. (2021). Tekort aan vakkrachten bouw: tijd voor een andere zienswijze? Nationale Bouwgids. https://www.nationalebouwgids.nl/woningbouw/nieuws/10190-tekort-aan-vakkrachten-bouw-tijd-voor-een-andere-zienswijze

Rose, T & Manley, K. (2012). Adoption of innovative products on Australian road infrastructure projects. Construction Management and Economics. 30. 277-298. 10.1080/01446193.2012.665173.

RWS. (2016). Grote Projecten en Onderhoud. Sloopoorzaken bruggen en viaducten in en over rijkswegen. Sloopoorzaken 2.0. 30-11-2016

Sepasgozar, S. M., Loosemore, M., & Davis, S. R. (2016). Conceptualising information and equipment technology adoption in construction: A critical review of existing research. Engineering, Construction and Architectural Management, 23(2), 158-176. DOI:10.1108/ECAM-05-2015-0083

Shove, E., & Walker, G. (2007). Caution! Transitions Ahead: Politics, practice, and sustainable transition management. Environment and Planning A: Economy and Space, 39(4), 763–770. https://doi.org/10.1068/a39310

Steen, M., Bach, H., Bjørgum, Ø., Hansen, T., Kenzhegaliyeva, A. (2019). Greening the fleet: A technological innovation system (TIS) analysis of hydrogen, battery electric, liquefied biogas, and biodiesel in the maritime sector. 10.13140/RG.2.2.24651.54568.

Taylor, J.E. and Levitt, R. E. (2004). Understanding and managing systemic innovation in project-based industries. Innovations project management research. Newton Square, PA: Project Management Institute.

Tidd, J. (2010). Gaining momentum: Managing the Diffusion of Innovations. In Series on technology Management. https://doi.org/10.1142/p625

TNO. (2023). Rapport Vernieuwingsopgave infrastructuur | Landelijk prognoserapport 2023. *https://publications.tno.nl/publication/34641584/8AVcEq/rasker-2023-vernieuwingsopgave.pdf*

TNO. (2024). TNO Nitrogen Approach a blueprint for all sustainability challenges. *https://www.tno.nl/en/search/?zoeken_term=TNO+nitrogen+approach+a+blueprint+for+all+sustainability+challenges*

Twomey, P., & Gaziulusoy, A. I. (2016). Review of system innovation and transition theories. https://apo.org.au/node/70179

Van den Broek, F. (2020). Circular Industrialized Construction: The current situation and its potential for expansion in Switzerland.

Van Rijt, J., Hompes, M., & Santema, S. (2010). The Dutch Construction Industry: An Overview and its use of performance information. Journal for the Advancement of Performance Information and Value, 2(1), 33. https://doi.org/10.37265/japiv.v2i1.117

Voerman, W. (2023). Wat is UAV-GC en wanneer wordt dit ingezet? - Tenderteam. Tenderteam. https://www.tenderteam.nl/blog/wat-is-uav-gc/

Wang, G., H. Liu, H. Li, X. Luo, and J. Liu. (2020). "A building project-based industrialized construction maturity model involving organizational enablers: A multi-case study in China." Sustainability 12 (10):4029. https://doi.org/10.3390/su12104029.

Wieczorek, A., & Hekkert, M. P. (2012). Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. Science and Public Policy, 39(1), 74–87. *https://doi.org/10.1093/scipol/scr008*

Williamson, K., Given, L. M., & Scifleet, P. (2018). Qualitative data analysis. In Elsevier eBooks (pp. 453–476). *https://doi.org/10.1016/b978-0-08-102220-7.00019-4*

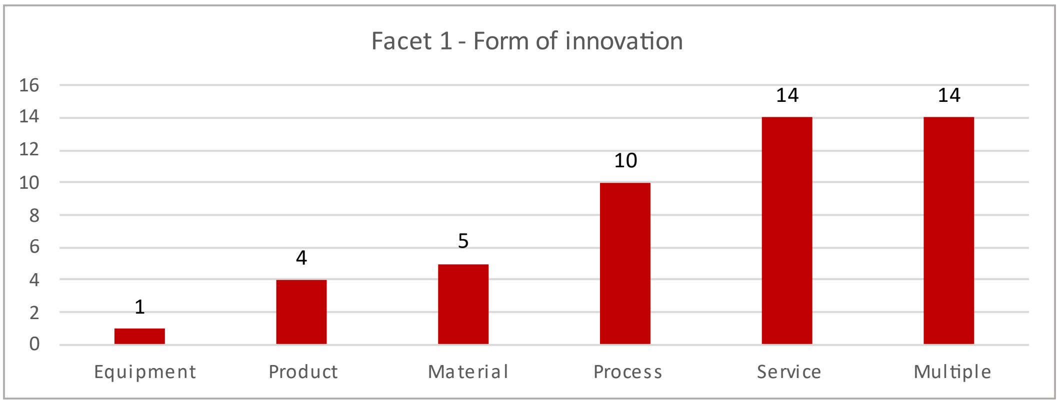
Wuni, I. Y., and G. Q. Shen. (2020). "Barriers to the adoption of modular integrated construction: Systematic review and meta-analysis, integrated conceptual framework, and strategies." J. Cleaner Prod. 249 (Mar):119347. https://doi.org/10.1016/j.jclepro.2019.119347

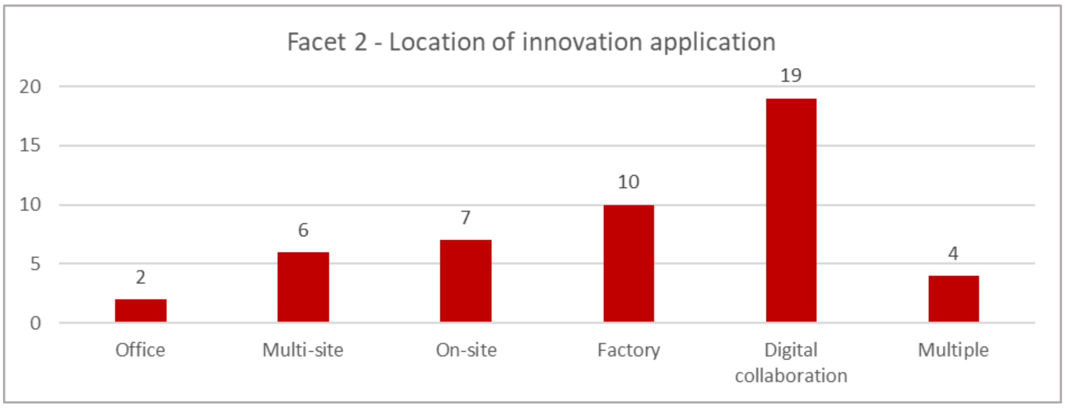
Appendices

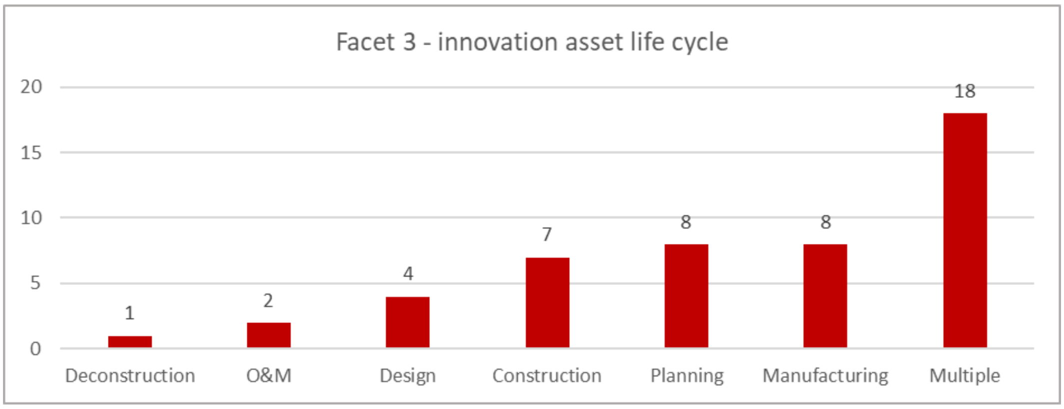
Appendix 1 – Complete innovation overview

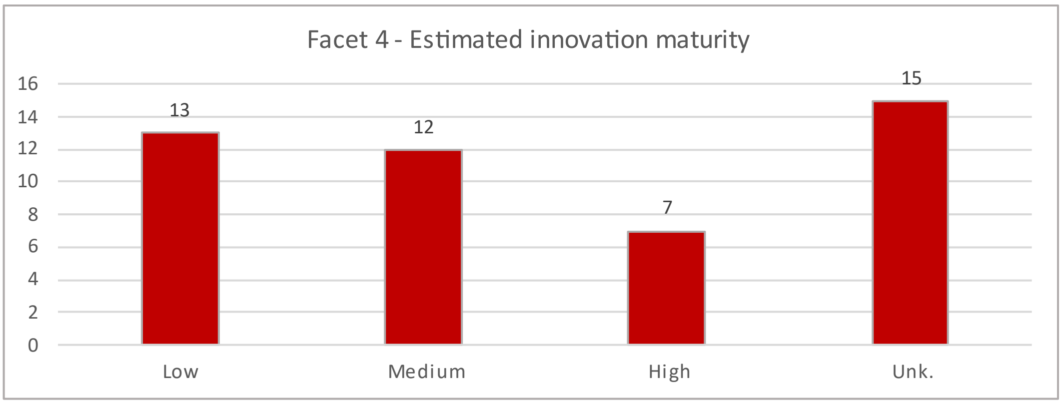
Innovation / technology	Form	Location	Asset life cycle	Estimated maturity
IFD (Industrieel, Flexibel, Demontabel)	Multiple	Multiple	Multiple	Medium
3D concrete printing	Multiple	Factory	Manufacturing	Low
Alternative material - Composite	Material	Factory	Manufacturing	Medium
Building Information Modelling (BIM)	Process	Digital collaboration	Multiple	Medium
MKI in RAW (climate cost indicator in tendering)	Process	Office	Design	Low
Broad standardisation	Process	Multi-site	Multiple	Low
Component reuse through database	Service	On-site	Deconstruction	Low
Prefabrication	Multiple	Factory	Construction	High
Platformisation within parameters	Process	Multiple	Multiple	Medium
Modulair steel bridges	Product	Factory	Construction	Medium
Alternative material - Cement substituted concrete	Material	Multi-site	Manufacturing	Low
Parametric design	Process	Digital collaboration	Design	Medium
Online design visualisation software	Service	Digital collaboration	Design	Low
Digitalisation - Robotisation off-site	Multiple	Factory	Multiple	Low
Artificial Intelligence & machine learning	Multiple	Digital collaboration	Multiple	Very low
Digitalisation - on site (GIS)	Multiple	On-site	Multiple	Low
Digitalisation - Innovative monitoring methods	Multiple	Multiple	O&M	Medium
Asset life extending measures	Process	On-site	O&M	Medium
4D & 6D Project planning	Multiple	Digital collaboration	Planning	Low
(Material) Passports	Service	Digital collaboration	Multiple	Medium
3D Composite printing	Multiple	Factory	Manufacturing	Low
RAMAC geopolymeerbeton	Material	Multi-site	Multiple	High
SQAPE geopolymeerbeton	Material	Multi-site	Multiple	High
InfraCore modular composite bridge components	Product	Factory	Manufacturing	High
Data driven asset management	Multiple	Digital collaboration	Planning	Medium
Innovative sensoring	Service	On-site	Planning	High
Biobased composite	Material	Factory	Manufacturing	Medium
Composite bridges	Product	Factory	Manufacturing	High
Circularity measuring tools	Service	Digital collaboration	Design	Medium
Digital twin technologies	Service	Digital collaboration	Multiple	Low
(IoT) material passports	Service	Digital collaboration	Multiple	Low
Contractual Portfolio Approach (CPA)	Process	Office	Planning	Unk.
Performance tracking tools/technologies	Service	Digital collaboration	Multiple	Unk.
IPM (Integral Project Management)	Process	Multiple	Multiple	Unk.
GPS technologies	Service	Digital collaboration	Construction	Unk.
Drones for asset inspection	Product	On-site	Planning	High
Self-healing concrete	Product	Multi-site	Construction	Unk.
Enterprise Resource Planning (ERP)	Process	Digital collaboration	Planning	Unk.
Equipment tracking tools	Service	Digital collaboration	Construction	Unk.
Job site data collection integration tools	Service	Digital collaboration	Construction	Unk.
Laser/3D scanning	Multiple	On-site	Planning	Unk.
Construction Quality Management software	Service	Digital collaboration	Multiple	Unk.
Construction site monitoring software	Service	On-site	Construction	Unk.
Digital Asset Information Management (AIM) platforms	Service	Digital collaboration	Multiple	Unk.
360° and 3D camera ground survey	Process	Digital collaboration	Planning	Unk.
Bridges of Laminated Timber (BoLT)	Multiple	Factory	Manufacturing	Unk.
Mixed material bridges	Multiple	Multi-site	Multiple	Unk.
Cloud computing	Multiple	Digital collaboration	Multiple	Low

Appendix 2 – Classification of innovations: facet scores









Appendix 3 – Interview protocol and themes

Segment 1 - Primary & follow-up interview questions & corresponding arguments
The interviews will be conducted in Dutch. Hence, the questions are presented in Dutch as well.

Vraag 1: Wat is de hoofdbezigheid van de organisatie die je representeert (client, aannemer, ingenieur of architect, leverancier of fabrikant, kennisinstituut of brancheorganisatie, technische startup), of spelen jullie meerdere infrastructuur gerelateerde rollen?

Vraag 2: Wat is jullie houding betreft de vervanging –en renovatie opgave in de Nederlandse (brug)infrastructuur?

Vraag*: Wat versta je onder industrialisatie, en wat denk je dat daarvoor nodig is in de keten?

Vraag 3: Denken jullie dat de huidige werkwijze en ontwikkelingen omtrent bruginfrastructuur toekomstbestendig is? (Toekomstbestendig dan minimaal gedefinieerd als het instandhouden van de infrastructuur op het huidige niveau)

Vraag 4: *Innovaties 1* - Zijn jullie zelf bezig met innovaties of ontwikkelen van nieuwe technieken, of stimuleren jullie innovaties of ontwikkelingen? Zo ja, welke, en waarom? Zo niet, waarom niet?

Follow-ups per genoemde techniek/innovatie:

- Staat het volledig op zich, of is het een mix van verschillende technieken?
- *Als onduidelijk* - Op welk vlak (onderdeel, proces, dienst)
- Concurreert het met andere innovaties?
- Is het/zijn ze complementair aan iets?

Vraag 5: *(N.V.T. indien 'Nee' op vorige vraag) Innovaties 2* - Wordt deze innovatie al opgeschaald? Zo niet, hangt dat af van de techniek zelf, de markt, of iets anders?

Follow-ups

- Is het stadium van ontwikkeling ver genoeg gevorderd?
  - Is er een toereikende en constante vraag?
  - Waarom is de techniek er niet klaar voor? (Afhankelijk van iets?)

Vraag 6: *Innovaties 3* – Hoe zien jullie de toekomst van infrastructuur bouw – en rehabilitatie qua innovaties en dominante technieken?

Follow-ups

- Wat is opkomend?
- Welke stimuleren jullie? / Wat denken jullie dat groot gaat worden?
- Hebben jullie zelf ambities wat betreft innovatie in de toekomst?
- Over welke ontwikkelingen/innovaties zijn jullie kritisch, en waarom?
-

Vraag 7: Hebben jullie in het verleden innovatierichtingen gestimuleerd of nagestreefd die nu geen deel meer uitmaken van de discussie? Zo ja, Waarom?

Follow-up

- Hebben standaarden en normen ooit effect gehad op jullie initiatieven in innovatie?

Vraag 8: *Samenwerking & relaties 1* - Werken jullie samen met andere partijen met betrekking tot activiteiten omtrent bruginfrastructuur renovatie en vervanging?

Follow-ups

- Met welke intentie/ambitie zijn jullie deze samenwerking(en) aangegaan?
- Wat voor voordelen halen jullie daaruit
- Werken jullie vooral samen met andere soorten actoren? Of met ‘concurrenten’?
- *Indien nee:* Hebben jullie de ambitie om samen te gaan werken?

Vraag 9: *(N.V.T. indien ‘Nee’ op vorige vraag) Samenwerking & relaties 2* - Hebben jullie ambities om deze samenwerking(en) op lange termijn te houden?

Vraag 10: Wordt er in jouw ervaring genoeg moeite gedaan om de gebruikelijke gang van zaken en technieken te verbeteren door het toepassen van vorige ervaringen?

Segment 1 interview protocol in English

Question 1: What is the primary activity of the organization you represent (client, contractor, engineer or architect, supplier or manufacturer, knowledge institution or industry organization, technical startup), or do you play multiple infrastructure-related roles?

Question 2: What is your attitude towards the replacement and renovation challenge in the Dutch (bridge) infrastructure?

Adapted question: How would you define industrialisation in a bridge infrastructure context, and what do you think is required to move towards an industrialised system?

Question 3: Do you think the current approach and developments regarding bridge infrastructure are future-proof? (Future-proof then minimally defined as maintaining the infrastructure at its current level).

Question 4: *Innovations 1* - Are you involved in innovations or developing new techniques yourselves, or do you encourage innovations or developments? If yes, which ones, and why? If not, why not?

Follow-ups per mentioned technique/innovation:

- Does it stand entirely on its own, or is it a mix of different techniques?
- If unclear - In what area (part, process, service)?
- Does it compete with other innovations?
- Is it/are they complementary to anything?

Question 5: (N/A if 'No' to the previous question) *Innovations 2* - Is this innovation already being scaled up? If not, does that depend on the technique itself, the market, or something else?

Follow-ups:

- Is the stage of development advanced enough?
- Is there sufficient and continuous demand?
- Why isn't the technique ready? (Dependent on something?)

Question 6: *Innovations 3* – How do you envision the future of infrastructure construction and rehabilitation in terms of innovations and dominant techniques?

Follow-ups:

- What is emerging?
- Which ones do you encourage? / What do you think will become significant?
- Do you have any ambitions regarding innovation in the future?
- On which developments/innovations are you critical, and why?

Question 7: Have you in the past stimulated or pursued innovation directions that are no longer part of the discussion? If yes, why?

Follow-up:

- Have standards and norms ever affected your innovation initiatives?

Question 8: *Collaboration & relationships 1* - Do you collaborate with other parties regarding activities related to bridge infrastructure renovation and replacement?

Follow-ups:

- With what intention/ambition did you enter into these collaboration(s)?
- What benefits do you derive from them?
- Do you mainly collaborate with other types of actors? Or with 'competitors'?
- If no: Do you have the ambition to collaborate?

Question 9: (N/A if 'No' to the previous question) *Collaboration & relationships 2* - Do you have ambitions to maintain these collaboration(s) in the long term?

Question 10: In your experience, is enough effort made to improve the usual practices and techniques by applying previous experiences?

Segment 2 diagnostic questions in Dutch

Key innovation functions and indicative questions	
F1 Entrepreneurial experimentation	1.1 Zijn er genoeg diverse actoren binnen de bruginfra keten die innoveren en expirementeren? 1.2 Wordt er binnen de keten voldoende geinnoveerd door partijen die op grote schaal kunnen uitvragen of aanbieden? 1.3 Wordt er voldoende gedaan om schaalvergroting van bestaande innovaties te stimuleren? 1.4 Hoe staat het met de doorontwikkeling van innovatieve experimenten/Living Labs?
F2 Knowledge development	2.1 Wordt er genoeg kennis ontwikkeld om industrialisatie te stimuleren? 2.2 Is de kwaliteit van de ontwikkelingen in kennis met betrekking tot innovaties voldoende? 2.3 Vormt de huidige staat van kennisontwikkeling een barriere voor een transitie naar een geindustrialiseerde keten?
F3 Knowledge exchange	3.1 Wat is de mate van kennisuitwisseling tussen actoren binnen dezelfde groep? (Clienten/aannemers/leveranciers) 3.2 Wat is de mate van kennisuitwisseling tussen wetenschap en de keten? 3.3 Worden de geleerde lessen van oude projecten/initiatieven met andere partijen in de keten gedeeld? 3.4 Hoe verhoudt de manier van kennisuitwisseling zich tot barrieres voor collectieve innovatie in de keten?
F4 Guidance of the search	4.1 Is er een duidelijk beeld op welke manieren industrialisatie zich moet ontwikkelen in de sector? 4.2 Wat is je perceptie van de huidige implementeerbaarheid van nieuwe technieken en innovaties? 4.3 Zijn er duidelijke en stabiele beleidsdoelen wat betreft collectieve syteeminnovatie in de sector? 4.4 Zijn actoren eensgezind ten opzichte van uitdaging en de vereiste veranderingen voor industrialisatie? 4.5 Hoe verhoudt (het missen van) een collectieve visie zich tot barrieres voor collectieve innovatie in de keten?
F5 Market formation	5.1 Is de huidige en verwachte marktgrootte in Nederland toereikend voor een geindustrialiseerd productie systeem? 5.2 Hoe verhoudt (ontoereikende) marktgrootte zich tot barrieres voor collectieve innovatie in de keten?
F6 Resource mobilisation	6.1 Vormt menselijk kapitaal een barriere om collectief te innoveren in producten en processen? 6.2 Vormt financiele zekerheid een barriere om collectief te innoveren in producten en processen? 6.3 Vormen fysieke middelen (grondstoffen/infrastructuur) barrieres om collectief te innoveren? 6.4 Is de huidige vorm van de keten genoeg ontwikkeld om innovaties achter industrialisatie te implementeren?
F7 Counteract resistance to change (legitimation)	7.1 Is er weerstand voor het (collectief) implementeren van innovatieve technieken in delen van de keten? 7.2 Is er weerstand voor het industrialiseren van de bruginfrastructuur keten? 7.3 Zijn er vanuit vergunningen en regelgeving barrieres voor collectieve initatieven in innovaties?

Appendix 4 – Informed consent form

Informed consent form – Industrialising Dutch Bridge Construction

You are being invited to participate in a research study titled '*Industrialising Dutch Bridge Construction - Mapping vulnerabilities and capabilities for achieving system innovations in the value chain'*. This study is being done by MSc student Tom Brouwer from the TU Delft, supervised by Daan Schraven, Martijn Leijten & Daniel Hall (TU Delft), Alexander Bletsis (TNO) & Thijs Mackus (De Bouwcampus). Internship location is provided by De Bouwcampus.

The purpose of this research study is to assess the current state of innovative efforts within the bridge construction value chain, and gain insights in barriers and opportunities for broader implementation of innovation by interviewing parties within the value chain. This is done through the principles of industrialised construction and will take you approximately 60 minutes to complete. The data will be used for constructing a master thesis, which consequently can be used for practical discussion in later stages.

In general, we will be asking you to provide insights in your organisations' perspective on innovation within the value chain, the barriers your organisation identifies regarding the adaptation of industrialised construction concepts, and any ideas your organisation has regarding the transformative effort needed to tackle future challenges. The resulting master thesis will be published, except confidential data, on the educational repository of the TU Delft, which is accessible by TU Delft students and employees. The information you provide can be used for argumentation and for providing examples. Your input (views, perspectives, responses to questions) can be used in research outputs in an anonymous manner. In addition, it is possible that the data this research gather will be used to support scientific publication. If that is the case, all mitigations to ensure anonymity and data safety will be taken, including all other terms mentioned in this and other forms.

The interview or consultation will be captured in audio format and subsequently transcribed. The transcription will be anonymized. All audio recordings, transcriptions, and personal data will be stored within the protected digital infrastructure of TU Delft. As part of the verification process, data regarding professional roles will be gathered; however, these details will be generalized to prevent the identification of specific individuals. As with any (online) activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by deleting the gathered data two years after the research is completed.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. Summarised interview transcripts will be sent to the interviewee prior to anonymising, to ensure that the gathered data is correct and cleared for further use. If participants do not agree with the gathered data, the gathered data will be removed within 48 hours.

To conclude, we wish to thank you for your participation in this research. If you have any questions, these can be addressed at any time by contacting T.Brouwer-1@student.tudelft.nl (+31614438362) or the responsible researcher Daan Schraven at D.F.J.Schraven@tudelft.nl. If you've had a chance to read and understand all information and your questions have been answered, you can sign here:

Name of participant	Signature	Date

I, as researcher, have read the informed consent form closely to the potential participant and ascertained to the best of my ability that the participant understands what is voluntarily agreed to.

Researcher name	Signature	Date
Tom Brouwer		*November 13th, 2023*