IDENTIFYING AND SUBDUCTING THE KEY BARRIERS OF REUSING PRECAST GIRDERS IN DUTCH OVERPASSES

Provisional Version

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PREFACE

This research report is the result of an eight-month graduation internship at Royal HaskoningDHV. The graduation internship is the completion of the master Construction Management & Engineering given at TU Delft.
I would like to thank my graduation committee who guided my in the process towards the report that lies before you. Secondly, I would like to thank Royal HaskoningDHV for the opportunity to be part of the organization and all the aspects that they offered me to improve this thesis. Special thanks to Rob Vergoossen, Rien Bakker and Gert-Jan van Eck who supported and helped me with guidance and connections. I am also grateful for all the individuals who helped me collecting data in the inventory interviews and semi-structured interviews. This research could not have been performed without input from experts.

Enjoy your reading.

Jonathan Donker

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SUMMARY

The Netherlands is now working nationally to reduce emissions by 49%. Furthermore the goal is set to emit 95% less CO2 emissions in 2050 compared to 1990 (Rijksoverheid, 2020). The Concrete Agreement was introduced and signed by private companies, local social organisations, governments, and knowledge institutes. The overarching problem is that the goal is set but the elaboration of the action plan is not yet practiced in the Dutch infrastructure sector (Dijcker, 2018). The circularity can be taken to a higher level when construction elements are reused in new constructions instead of recycled (CB23, 2018). Whereas several large-scale circular building projects have been realised in the Netherlands, large-scale circular infrastructure projects are yet to be completed. Adams et al. (2017) state that there is a significant body of literature on the drivers and benefits of circular economy in general; however, little research or wide- scale application has been undertaken within a construction context. To bridge the gap between theory and practice the barriers and drivers of a specific case will be investigated. The researcher will execute a real time case study looking at the barriers and drivers of reusing precast overpass girders in the Dutch infrastructure sector. When the specific drivers and barriers are known for reusing concrete girders of Dutch overpasses, the gap between the theory and practice can be bridged.

Diminishing the barriers and enhancing the drivers is the most efficient to become one step closer to circularity of construction elements. There is however no notable consensus between stakeholder parties of the Dutch infrastructure about the most important drivers and barriers of reusing prefab girders. The overall most important barriers are nominated as important by less than 50% of the interviewees. The most important drivers are nominated by less than 60% of the interviewees.

The main reasons why girders are never reused in the main road network of Rijkswaterstaat are displayed in red in the table below.

Table 1 Barriers mentioned during the semi-structured interviews

Mentioning of barrier		Importance		Sample n=29	
		Occurrence	Importance	Average	Rank
Cultural	Ignorance	38%	10%	24%	6
	Mindset	38%	17%	28%	4
Market	Disassembling	3%	7%	5%	11
	Financial	45%	28%	36%	3
Institutional	Law & Regulations	41%	41%	41%	1
	Certification	10%	17%	14%	10
Technical	Safety of the construction	24%	3%	14%	10
	Missing information (History & Design)	24%	21%	22%	7
	Disassembling technical	14%	14%	14%	10
	Residual life	34%	45%	40%	2
	Application	31%	7%	19%	8
Organisational	Supply & Demand	24%	31%	28%	4
	Contract/responsibility	21%	31%	26%	5
	Planning	17%	17%	17%	9

These barriers are felt by a group of experts in the sector. However, the SBIR project of the consortium Liggers 2.0 subducted a couple of the mentioned barriers. According to the consortium Liggers 2.0, reusing overpass girders is economically feasible, has a positive impact on the environment and can be executed with if the required knowledge is present. In the process of dismantling an overpass and recalculating the strength of the dismantled girders, the conclusion is that a couple of felt barriers are not present according to the consortium Liggers 2.0. The laws & regulations are sufficiently clear and the existing girders meet the required demands. The

residual life is determined and found adequate for additional decades of usage. The financial barrier is not present if only direct costs are measured. When indirect costs such as vehicle lost hours (voertuigverliesuren) are take into account, the financial barrier is significantly present.
The cultural barriers point out that the main barriers are psychological. Culture barriers such as mindset of the clients and market parties, is mainly active risk aversion. The conservative attitude of the infrasector hampers innovation such as reuse of structural components. Ignorance is the passive cultural barrier which is a combination of all factors that are unknown. Mentioned ignorance barriers are, the unknowing what is possible with new techniques and not really understand the laws & regulations. The culture barriers which are mentioned by the experts amplify the contradicted results resulting from the case study and the interviews.

The common factor which stands out is the uncertainty about materials, residual life, processes, costs, impact etc. Therefore, the integral solution for the mentioned barriers can be summarized in one word: Insight. The solution to diminish the felt barriers is to create insight in the process and the results of the pilot project. Insight is necessary in the total process, environmental impact, financial impact, supply and demand, and dismantling the structural components. The SBIR/ pilot project can be used as overarching experience to test the separately mentioned solutions concerning the insight of the process and impact.

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LIST OF ABBREVIATIONS

CE:	Circular Economy
CO2:	Carbon dioxide
LCA:	Environmental lifecycle assessment
MKI:	Milieu Kosten Indicator (Environmental Costs Indicator)
RHDHV:	Royal HaskoningDHV
RWS:	Rijkswaterstaat
SBIR:	Small/strategic business innovation research

DEFINITION OF TERMS

Term	Definition
Durability	The quality of being able to last a long time without becoming damaged.
Sustainability	The idea that goods and services should be produced in ways that do not use resources that cannot be replaced and that do not damage the environment for future generations.
Circularity	Developing, using and reusing buildings, areas and infrastructure, without unnecessarily depleting natural resources, polluting the living environment and affecting ecosystems. Building in a way that is economically and ecologically sound and that contributes to the well-being of humans and animals. Here and there, now and later (Nelissen, 2018).
Barriers	Factors that impede or hinder change. Other commonly used terms for barriers are: challenges, obstacles, hindrances (J. Kirchherr, et al. , 2018).
Drivers	Factors which cause a particular phenomenon to happen or develop (Oxford Dictionary, 2019a) Another commonly used term in literature is enablers.
Recycling	Involves the collection of products for separation into their base materials, which can then be re-used as a resource to replace raw materials in the production process.
Remanufacturing	Involves the product being returned to the place of manufacture to be disassembled into its base components which, if still serviceable, are then re-used in the manufacture of new products.
Disassembling	To take apart. When used in this research, disassembling means the dismantling of an overpass whereby all components are neatly discarded from the structure for future reuse.
Maintenance	Involves the repair and servicing of a product to extend its initial service life.
Reuse	Using the same material in construction more than once, including using the material again for the same function (e.g. formwork in construction) and new-life reuse for a new function.
SBIR	Strategic/Small Business Innovation Research. An innovative contest used by the government to challenge entrepreneurs to come up with innovative products and services to solve social issues. In this way, innovations emerging from the SBIR competitions help society move forward.
MKI	The environmental cost indicator (also known as the MKI) is a single-score indicator expressed in euros. It aggregates all relevant environmental impacts into a single environmental cost score, showing the environmental shadow price of a product or project.
Liggers 2.0	(English: Girders 2.0) The SBIR consortium consisting of Royal HaskoningDHV, Dura Vermeer, Haitsma, Vlasman and SGS Intron

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Introduction

Circularity is both in the construction sector and beyond one of today's most important social themes (CB23, 2020). The environmental impact is becoming an increasingly important factor when looking at producing or purchasing a product in The Netherlands and the circular economy is a widely shared goal. To give a voice to this goal, the Paris Agreement was signed and endorsed by 190 of the 197 nations in 2015. The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. In order to achieve the set goals, EU member states have an arrangement which state that the EU must emit at least 40% less CO2 in 2030 (Knopf, 2015).

The Netherlands responded to the international agreement with a national programme in 2016: Circular economy in The Netherlands in 2050 (Dijksma, 2016). As part of the programme, the Natural Resources Agreement was set up. This is an initiative of the Dutch government to set up the circular economy in The Netherlands. The agreement states that only reusable materials could be used in 2050 in the Dutch economy. The Netherlands is now working nationally to reduce emissions by 49%. Furthermore the goal is set to emit 95% less CO2 emissions in 2050 compared to 1990 (Rijksoverheid, 2020). The document called the Concrete Agreement, was signed by the various social partners in the Dutch building environment; private companies, local social organisations, governments, and knowledge institutes.

Benefits of the circular economy are significant. Environmental quality of life is better in a circular economy than a linear one (Wijkman, 2015). The same goes for the security of supplying essential natural resources. It also promotes the development of new knowledge and skills, triggers innovation and creates new businesses and jobs. A recent study on the circular economy's impacts on the labour market estimates a 0.5% increase in the EU's GDP by 2030, thereby creating around 700,000 new jobs (Cambridge Econometrics, 2018). For individual companies, the circular economy can lead to new market opportunities, cost savings — for example, because of increased resource productivity — and more competitiveness. As producers remain responsible for their products throughout their whole life cycles, consumers can buy high-quality circular products and services which are apt for reuse and high-value recycling. If a circular economy is so promising, why not put it into practice? Unfortunately, significant barriers still stand in the way of a transition (Cramer, 2020) .

1.1 CIRCULAR ECONOMY IN THE DUTCH CONSTRUCTION SECTOR

The goals of the Paris Climate Agreement are clear but not fully embedded in the construction industry and the society as a whole (Cramer, 2020). What specific goals are set in The Netherlands and what needs to be done to reach the set goals? This question can only be answered if the current situation is known. In the following paragraphs, the current situation, the policy and the set goals are explained.

1.1.1 POLICY

The Netherlands is a member of the EU, and many regulatory and economic measures concerning the circular economy are formulated at the EU decision-making level. Member states are expected to adopt the circular economy policies laid out by the EU. Since the turn of the century, concerns have grown in the EU about the overconsumption of resources and its environmental impacts. Yet since 2015, Europe has been giving circularity issues attention, exponentially so (Cramer, 2020). The Dutch government supports the Concrete Agreement where goals are set to reduce the CO_2 emissions with 49% and to reuse all used concrete in 2030. Al government tenders must be circular from 2030 (BetonAkkoord, 2020). In the Concrete Agreement of 2018, private and public parties agreed to make the entire concrete chain more sustainable.

"Open innovation and knowledge exchange should lead to solutions that are feasible, affordable and practicable. Achieving the objectives requires intensive cooperation between government, industry and knowledge institutions" (BTIC, 2020).
The concrete sector must take steps to adhere to the objectives of the Concrete Agreement. (Van der Vooren, 2015). This requires a change in our current systems, which are currently based on a linear economy. For the construction sector this means, among other things: more and higher quality reuse of materials, products and elements and a different approach in producing, commissioning, designing and executing construction projects (CB23, 2020). The main goals of the implementation of CE in the Dutch construction sector have been described in the Transition Agenda Circular Construction-Economy (Nelissen, 2018).

1.1.2 GOALS

The ultimate goal is to be fully circular in the concrete sector. The main objectives of the Concrete Agreement are (CB23, 2018):

- A CO_2 reduction of at least 30% though with an intended 55% compared to 1990 in 2030;
- 100% circular concrete, which was in line with the Circular Construction Economy transition agenda and the policy goal to make material passports of buildings and constructions obligatory in 2030;
- A net positive value of natural capital, meaning that after extracting sand and gravel, in particular, the natural environment is left with higher biodiversity than before;
- Increased social capital in the form of improving and sharing knowledge, innovation and education.

To reach the goals, less materials must be used and less CO2 must be emitted. According to CB23 this can be done with circular entrepreneurship. Structures needs to be circularly designed and current infrastructure needs to be used in a smart sustainable way.
A circular construction is a construction that,

1) Has been designed and executed in accordance with circular design principles;
2) Has been realized with circular products, elements and materials

The above stated goals can only be met if the linear consumption pattern changes. The linear consumption pattern is characterized with the waste of finite resources at the end of their lifetime. The current situation of extracting finite resources and raw materials and convert those into products is unsustainable. The products made of finite resources are fulfilling a certain purpose during their life cycle, but the products are disposed at the end of their lifetime. The (Foundation, 2013) defines this as the *"take, make and dispose principle"*.
Over the last years, a transition is being proposed to move from the current linear economy towards a Circular Economy (CE). Mentink (2014), has defined CE as *"an economic system with closed material loops"*. In a study by (J. Kirchherr, Reike, D., & Hekkert, M. , 2017), 114 definitions of the CE were analysed. The main aim of the implementation of CE is to realise economic prosperity, followed by environmental quality. The impact on social equity and future generations is barely mentioned. Based on the 114 definitions, the authors have developed their own, all-encompassing definition for CE:

"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and be-yond), with the aim to accomplish sustainable development, which

implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations."(J. Kirchherr, Reike, D., & Hekkert, M. , 2017)

1.1.3 CURRENT SITUATION

Each year, the Dutch concrete sector produces 15 million m3 concrete, which generates about 3.7 megatons (1.7%) of the national CO_2 emissions (GMB, 2019). Cement accounts for about 80% of concrete production's CO_2 emissions. Due to the high volumes of concrete used worldwide, the cement industry is responsible for 5 to 7% of anthropogenic CO_2 emissions worldwide. Moreover, the annual aggregate concrete production and its water consumption lead to depletion of natural resources. To reduce this impact, decreased use, reusing and recycling should become matters of course. In the Netherlands, 90% of demolished concrete now ends up as pavement under roads. More high-value recycling and reuse are possible, but not yet commonly applied. It should be noted, however, that more new buildings are constructed than demolished in the Netherlands, meaning that only about 20% of concrete used in new buildings can come from recycled materials. Sand and gravel availability are not yet a problem. But extra efforts should be made to guarantee that excavation does not lead to biodiversity losses (Cramer, 2020).

The Dutch construction sector is responsible for 36% of the national CO_2 emissions, contributes to 50% of the national material usage and accounts for 40% of the total energy consumption (CEDelft, 2013). The building industry is a major consumer of materials that are not all recycled or reused at the end of their service life. Often, parts of buildings and used materials cannot be adapted during their lifecycle because most construction projects have not yet been designed or implemented in a circular manner (Bijleveld, 2013). Reusing construction materials is therefore difficult and raw material efficiency is still low. Considering the large amounts of CO_2 emitted by the Dutch construction sector and the vast amount of (raw) materials that are used, adopting the circular economy (CE) may significantly lower the Netherlands' climatological impact. Adopting CE in the Dutch infrastructure sector can be done with reusing construction elements, such as prefab overpass girders.

The Dutch construction industry consist of two sectors, the infrastructure sector and the building sector. The building sector is ahead of the infrastructure sector when looking at realizing circular projects in The Netherlands. There are a couple of examples for the implementation of the circular economy in the building sector, but only one project is circularly realized in the infrastructure sector (Rijkswaterstaat, 2019). The realized circular project in the infrastructure is the circular overpass in Kampen, The Netherlands. This implies that for some reasons there is a difference in implementing circular projects in both sectors.

The current civil concrete structures of Rijkswaterstaat that are not fulfilling their task technically, functionally, legally or economically are being demolished, crushed, sorted and for 90% reused as road foundation (Rense, 2011). This is a waste of good materials considering that the overpasses in the Netherlands are currently most of the time removed for functional reasons. The structures are technically capable to keep performing for multiple decades (Nooij, 2016).

1.2 PROBLEM STATEMENT

Limited progress has been made on the implementation of CE in the Dutch construction sector (Rijksvastgoedbedrijf, 2018). In order to reach a sustainable environment, the construction industry and the Dutch government presume the circular economy as an important instrument to limit climate change globally. It is clear that the circular economy gets more attention, but the implementation is still in the early stages. According to Ghisellini (2016) the focus is mainly on recycling rather than re-using construction materials. Also according to Schut (2016), the circular economy is not fully embedded in the Dutch construction sector (E. Schut, Crielaard, M., & Mesman, M. , 2016). The importance and potential of implementing a Circular Economy in the Dutch construction sector has been acknowledged by a large number of public and private parties (Dijksma, 2016). However, as of today, implementation of the CE in specifically the Dutch infrastructure sector is still in its infancy (Dijcker, 2018). While the Netherlands is considered by some as a pioneer in circularity it too is still far away from reaching a circular economy (Dijksma, 2016). For the required national CO_2 reduction goals to be achieved, the Dutch infrastructure sector should rapidly transition towards a circular economy.

The overarching problem is that the goal is set but the elaboration of the action plan is not yet practiced in the Dutch infrastructure sector (Dijcker, 2018). The circularity can be taken to a higher level when construction elements are reused in new constructions instead of recycled (CB23, 2018). The current building cycle is far from circular and not reaching its full potential. The question arises what the reason is why construction elements are not reused in practiced. There is currently no specific information about the practical barriers and drivers of reusing construction elements in Dutch infrastructure projects. There is a lot of academic literature about drivers and barriers of the circular economy, but these are too broad or not always applicable in The Netherlands.

1. Too broad, because the mentioned barriers are not explicated, the reasoning is superficial and cannot be applied on specific products or projects.
2. Not applicable in the Netherlands, because the literature is created with different starting points and specific boundary conditions. Those boundary conditions are not always applicable in The Netherlands. An example is the relatively high percentage of prefabricated construction elements Dutch infrastructure. In other countries most of the structures are made with in situ concrete. A reason of the high percentage in comparison to other countries are the strong roads and innovative transport sector (Quartel, 2021).

1.3 SCOPE OF THE RESEARCH

To bridge the gap between theory and practice the barriers and drivers of a specific case will be investigated. When the specific drivers and barriers are known for reusing concrete girders of Dutch overpasses, the gap between the theory and practice can be bridged. Royal HaskoningDHV believes that reusing precast concrete girders is technically possible, economically feasible and sustainable. However, there is no proof that reuse of overpass girders will result in a lower CO2-equivalent and/or lower costs for the client. Overpass girders have never reused in the main roads of Rijkswaterstaat before. The specific reasons why are unknown. The drivers and barriers of reusing construction elements need to be identified. After that solutions can be proposed to reuse girders.

The research is aimed on the existing Dutch overpasses and all the surrounding processes and stakeholders. Only the girders of the overpasses of Rijkswaterstaat will be investigated. This choice is made because most of the statistics of the girders is present and most of the Dutch overpasses are in management of RWS. If the reuse of girders of Rijkswaterstaat prove to be economical and environmental, other parts of overpasses, and girders of other owners, will be next to be researched. To make the research specific, only the prefab rail girders of Rijkswaterstaat will be researched. This type of girder is most common and frequently applied in the sixties and seventies of the last century. Other types of girders may be easier to deconstruct but the rail girders are most common in areal of Rijkswaterstaat.

This thesis is conducted in cooperation with Royal HaskoningDHV, which is one of the largest engineering and consultancy firms in The Netherlands. Royal HaskoningDHV participates in a strategic business innovation research project (SBIR) of Rijkswaterstaat. In the SBIR a circular viaduct is asked and multiple companies came up with innovative ideas. To get to the last three of 32 parties of the tender, a feasibility study must be made. For an integral solution there are multiple aspects to take into account when identifying the barriers. In this research not only the technical aspects will be investigated, also the cultural, financial, organisational, institutional and environmental aspects are involved in the research.

1.4 AIMS & OBJECTIVES

The main aim of the research is to increase the circularity in the Dutch building industry, this is done with the specific case of reusing rail girders from overpasses in the Netherlands.

This shall lead to the following objectives:

1. Analyse the current barriers and drivers of the circular economy based on scientific literature
2. Identifying the barriers and drivers of reusing precast concrete girders with the input of relevant stakeholders from practice.
3. Experience the process of reusing precast girders with a real Dutch infrastructure project as real time case study.
4. Compare the current methods of demolishing and rebuild with disassembling and reuse of precast girders based on the real time case study
5. Develop a design to subduct the main barriers and to enhance the key drivers.
6. Verify and validate the design based on the real time case study

By enhancing the drivers and diminishing the barriers of reusing concrete girders out of current overpasses, the gained knowledge can be applied on other infrastructure projects. The broader implication of the findings is mentioned in the final chapter of this report.

1.5 RESEARCH QUESTIONS

The problem statement compells to get answer to the research question:

RQ	How can the barriers of reusing precast girders in Dutch overpasses be diminished?

The answer of this research question will fill the gap that is currently present. The research question will be answered with the help of the following sub questions:

SQ 1	What is the theory of circular entrepreneurship and what hampers this ideology in the Dutch infrastructure sector?
SQ 2	How can the specific barriers and drivers concerning reuse of construction elements be mapped out?
SQ 3	Is there an integral solution to tackle the main barriers and to enhance the key drivers?
SQ 4	What is the significance of the design for the construction industry?

1.6 RELEVANCE OF THE RESEARCH

The knowledge of circularity and sustainability in the concrete sector has grown over the last decade. The center point of all the knowledge in the construction industry is around circularity for the building sector and specific on houses or public buildings (Kanters, 2020).The infrastructure sector is underrepresented in literature and is behind on new innovations and application of circularity. The theory is clear but the conclusions of the academic literature are too broad to apply in real projects. It is known that reusing constructions or construction elements is more circular than recycling the raw materials, but in practice 90% of all concrete is used once and then used outside the cycle as round foundation. The infrastructure sector cannot act on the broad barriers, drivers and solutions. This research can provide specific barriers, drivers and solutions which can be generalized for some other projects or innovations.

1.6.1 SCIENTIFIC RELEVANCE

The scientific literature about the circular economy is over the last years grown rapidly (Reike, 2018). The progress that has been made focused mainly on the building sector. In the Dutch infrastructure sector, CE is still in its infancy (Dijcker, 2018). The gap seems to remain present between the implementation in practice and the theoretical concept of the circular economy. When looking at literature focusing on barriers and drivers of the construction industry, only limited scientific papers are available (Adams, 2017). However, research is found which covers the economic feasibility of reusing structural building components and the impact of reused construction materials. Furthermore, a thesis about the drivers and barriers of reusing structural components in the Dutch infrastructure is found. In that thesis a broad assessment of the barriers and drivers are mentioned for the infrasector as a whole. These researches will be used as background information and as starting point for this research. According to Adams (2017) more research is necessary to specify the current barriers and drivers in the Dutch infrastructure. Whereas several large-scale circular building projects have been realised in the Netherlands, large-scale circular infrastructure projects are yet to be completed. Adams et al. (2017) state that

"there is a significant body of literature on the drivers and benefits of circular economy [in general]; however, little research or wide- scale application has been undertaken within a construction context"

The key barriers of reusing current concrete girders in Dutch overpasses are never specifically quantified before. This is unfortunate when take into account that in the coming years dozens of overpasses are demolished and rebuilt. In this research the literature on specific drivers and barriers in the Dutch infrastructure environment will be extended. While some progress on the implementation of the circular economy in the buildings sector has been made, both in practice and academia, the implementation of circularity in Dutch infrastructure projects is yet a relatively unexplored territory (Van der Sande, 2020). This study aims to shed light on the relatively unexposed yet important topic of implementing circularity of concrete in Dutch infrastructure projects.

1.6.2 PRACTICAL RELEVANCE

The implementation of CE in the construction sector has gained increasing attention over the last year (Nelissen, 2018). Rijkswaterstaat, one of the biggest clients in The Netherlands, is asking for circular pilot projects. One of those projects is the so-called Strategic Business Innovation Research (SBIR) project "Het Circulaire Viaduct" (The Circular Overpass). Over 30 consortia participated in this SBIR project and came up with innovative solutions to build a circular overpass. The idea of reusing prefab girders from existing viaducts is chosen as one of the ten consortia to continue in the SBIR tender. Consortium Liggers 2.0 has come up with the idea of reusing the construction elements and is doing a feasibility study over the technological innovation. The consortium is interested in the key barriers why this idea is never executed before. Also they are looking at the solution how to overcome these barriers. The research process is motivated by a problem observed in practice, as well as the gap in literature on the application of service aspects in the construction industry. By sharing of the attained knowledge regarding the drivers of, and barriers to the implementation of the circular economy in Dutch infrastructure projects from a practice-based perspective, this research makes an important, yet modest contribution to the transition of the Dutch infrastructure sector towards a circular economy.

1.7 AUDIENCE

The audience of this research are the structural engineers, contractors, and clients in the infrastructure sector of The Netherlands. The possibilities of circularity are shown to the clients and the constructors and the potential of reusing is shown. The audience will be contacted before, while and after this research. The main parties involved in the real-time case study are Rijkswaterstaat, demolishing contractor Vlasman, contractor Dura Vermeer, girder supplier Haitsma, certificating company SGS Intron and engineering consultancy Royal HaskoningDHV. Another type of audience are other researchers investigating this problem. This methodology and example of a research can help to better understand the current problems and solutions in the Dutch infrastructure sector.

1.8 STRUCTURE OF THE RESEARCH

This research consists of 5 chapters. The Introduction, Background, Methodology, Results & Analysis and Conclusion & Discussion. In the chapter 2, the theory of circular entrepreneurship will be explained and the current knowledge of the barriers and drivers is elaborated upon based on literature research. In the methodology chapter, the central methodology is explicated with all corresponding methods used in this research. In the results & analysis chapter, the main methodology will be performed and the most important results will be analysed in detail. In the last chapter the main research question will be answered in the conclusion and the discussion will be outlined.

2

Reusing construction elements, the background

What is the theory of the circular economy and what hampers this ideology in the Dutch infrasector?

This question will be answered in the following chapter. In the first paragraph the theory of the circular economy and how circularity can be measured is explained. In the second part of this chapter, a literature study is performed to map the barriers and drivers of the circular economy.

2.1 THE THEORY, AVAILABLE METHODS AND THE TECHNICAL READINESS LEVELS

In this paragraph the theory of circularity, the available methods to measure circularity and the technical readiness levels are discussed.

2.1.1 THEORY OF CIRCULARITY

Circularity can be achieved with multiple strategies named in the 10-R method. The 10-R model is designed by Prof. Dr. J. Cramer and is a detailed version of Lansinks Ladder (CB23, 2018). The 10-R method contains a list of ten strategies that all begin with the letter R and are hierarchical categorized. The first R has the most impact, and the tenth R has the lowest impact. Recycling is a strategy that is low rated in the 10-R method because the concrete can be reused higher in the building cycle (Bijleveld, 2013).

The elements that are covered in the 10 R method are displayed in figure 1.

Nr.	10-R method	Explanation
10	Refuse	Preventing the use of raw materials
9	Reduce	Reduction of raw materials
8	Rethink	The redesign of a product with circularity as a starting point
7	Re-use	Product reuse (secondhand)
6	Repair	Maintenance and repair
5	Refurbish	Product refurbishment
4	Remanufacture	Making a new product from the parts of the original.
3	Re-purpose	Product reuse for other purposes
2	Recycling	Processing and reuse of materials
1	Recover	Energy recovery from materials

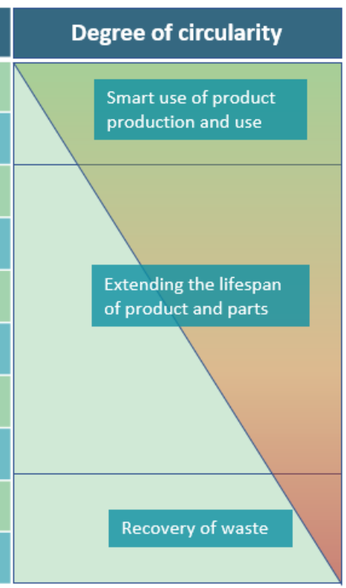


Figure 1 The 10-R Model (CB23,2019)

As a rule of thumb, circularity strategies that are higher up the ladder (Figure) require fewer materials, avoiding the environmental impact of resource usage. Within each strategy, companies, governments and knowledge institutes are already developing innovations, both nationally and internationally. The Dutch ministry of Infrastructure & Water management has circular design principles to become more circular in the future, see figure 2.

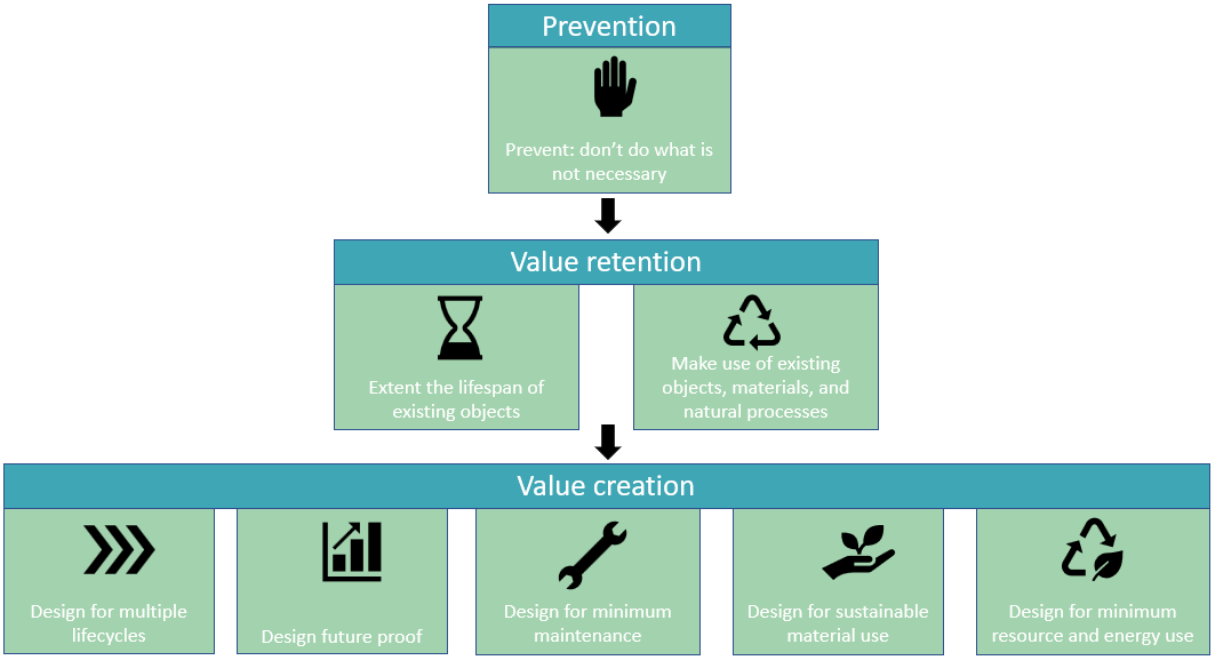


Figure 2 Circular design principles for the built environment (Ministry of Infrastructure and the Environment, 2016)

The accent of circular constructions is on making new products in such a way that the materials can be reused in the future and by circular in the next generation of constructions. The emphasis of this research is the use of the current constructions to be circular in this generation.
Within the circular economy, reusing objects and elements is preferable to recycling. To achieve this in a safe and economical way, reliable information about the residual life of existing structures is essential (Ghisellini, 2016). To improve the circularity of Dutch infrastructure more reuse of constructions, construction elements and materials is desirable (CB23, 2018). The deconstruction and dismantling of buildings instead of their demolition helps to increase the number of components to be reused or materials to be recycled. This requires close collaboration with partners who also pursue a circular economy in their products. The increased attention for circular economy in the construction industry stresses the (growing) need for applying other business models, since currently the focus of linear business models is not in line with the principles of a circular economy.

2.1.2 LIFE CYCLE ANALYSIS (LCA) AND THE DUBOCALC METHOD

In practice it is difficult to make good agreements on sustainability or circularity between investors, clients, designers, builders, consultants and users about sustainable (re)construction. This is why a determination method has been developed with which professionals can measure the environmental performance of a building. This determination method is based on life cycle analysis (LCA). An LCA describes the environmental impact of a building material, product, composite building component, or an entire structure throughout its entire cycle: from extraction of the raw materials, production and transport, to usage, demolition and waste processing. The LCA is summarized in eleven environmental impacts on a so-called MRPI sheet for the building material, product or element in question. The environmental effects listed on the MRPI sheet can be converted into a single entity: the environmental cost indicator (MKI). This is a hypothetical amount of money that would be needed to prevent or compensate for the environmental impacts. The higher the amount, the more harmful the chosen solution for the environment.

Calculating the environmental impact can be done with various calculation tools. Rijkswaterstaat uses the DuBoCalc method (Sustainable Construction Calculation Method) but also accepts other methods that show how high the environmental impact is. DuBoCalc calculates the environmental impact of a material, a construction work or a construction method. DuBoCalc then converts these environmental impacts into a single figure using the so-called 'shadow pricing method': The Environmental Cost Indicator value (MKI value). A lower MKI value often means a relative CO_2 reduction and a contribution to the objectives of the Circular Economy (Rijkswaterstaat, 2020b).

Knowledge production involves different types of actors with different roles; universities, companies, and governments. This Triple Helix model assumes the traditional forms of institutional differentiation among universities, industries, and government as its starting point. The model thus takes account of the expanding role of knowledge in relation to the political and economic infrastructure of the larger society (Etzkowitz, 2000). The triple helix can also be seen in the innovations of new technologies in the Technical Readiness Levels (TRL).

2.1.3 TECHNICAL READINESS LEVELS

New technologies can contribute to the sustainability and circularity of concrete. Technical Readiness Levels (TRL) is a method to score the maturity of a new technology. TRL 1 is the lowest level of development; an idea based on fundamental scientifically proven principles. TRL 9 is the highest level of development; a system whose operation in an operational environment has been proven over a long period of time. An explanation per level is shown in figure 3. When a technology is further developed, and therefore has a higher TRL, there is also more certainty about the CO2-eq reduction potential and the costs of the technology (de Blois, 2018). Reusing girders in has a TRL level of 3 and a feasibility study is performed by Dutch engineering & consultancy firm Royal HaskoningDHV. With the feasibility study and the pilot project an attempt is made to achieve TRL 7.

Universities
Research institutes
Companies

TRL	Explanation
1	Basic principles of the idea are explored
2	Technological concept and its practical application is formulated
3	Applicability of concept is investigated on an experimental basis. Hypotheses are tested and validated
4	The operation of the technological concept is tested on a laboratory scale
5	The operation of the technological concept is tested in the relevant environment
6	The demonstration of the concept will be further tested with a prototype. The concept provides insight into the operation of different components together
7	Demonstration of the concept in a user environment
8	The concept is technically and commercially ready
9	The product is a common product in the Dutch market and falls within current legislation and regulations.

Figure 3 TRL-level explanation

2.1.4 EXPERIENCES IN OTHER COUNTRIES

In Germany and France several research projects have proven that dismantling of buildings also helps to reduce the environmental burden of recycled construction materials by encouraging the production of recycling materials containing less harmful substances. Furthermore, it can be shown, that environment-friendly dismantling and recycling strategies can even be advantageous from an economic point of view. In order to encourage cost efficiency as well as the fulfilment of environmental requirements such as high-grade recycling, sophisticated planning approaches have to be applied (F. R. Schultmann, O., 2000).

It seems to be particularly significant to reuse precast elements, reinforced concrete and prestressed (pre-tensioned) concrete prefabricates alike. Such elements are relatively easy to dismantle and to take away for next use (Ajdukiewicz, 2013). Based on the performed prestressed beams and floor slabs tests, despite their former long service period (ca. 40 and 45 years) it has been stated that they could still be used in other structures instead of being crushed. This procedure is reasonable from ecological and economical points of view. Therefore, future reuse should be considered at design today (Ajdukiewicz, 2013).

2.3 IN LITERATURE FOUND BARRIERS AND DRIVERS OF THE CIRCULAR ECONOMY

If a circular economy is so promising, why not put it into practice? Unfortunately, significant barriers still stand in the way of a transition. Reuse although a higher-level treatment method, is rarely adopted. It is limited to the reuse of products such as doors, windows and interior installations. Existing demolition methods do not allow for product recovery as it a costlier and time-consuming process (Jabeen, 2019). Barriers and drivers of circularity are often researched, and many academic literatures is found of this subject. This paragraph contains a literature study of the barriers of the circularity of concrete in the infrastructure sector. The information that can be found in academic literature is mainly broad viewed about the circular economy. The focus of the desk study is the reusability of concrete construction elements in the infrastructure sector of the Netherlands.

2.3.1 BARRIER & DRIVER CATEGORIES

During the whole process of deconstructing and reconstructing a lot of barriers are found in literature. The barriers are commonly categorized in broad categories such as technical, financial and cultural. Table 2 shows which key literature is used as background for this research. Not all literature is illustrated but the categories mentioned are included in this literature study.

Table 2 key literature about barriers and drivers

Author	Year	Region
De Jesus & Mendonca	2018	World
Ghisellini, Ripa, et al.	2018	World
Hart et al.	2019	World
Williams	2019	World
Diaz Lopez et al.	2019	World
Araujo Galvão et al.	2018	World
Ritzén & Sandström	2017	World
Kirchherr et al.	2018	Europe
Gálvez-Martos et al.	2018	Europe
Nußholz et al.	2019	Scandinavia
Sigrid Nordby	2019	Norway
Tura et al.	2019	Finland
Eberhardt et al.	2019	Denmark
Velenturf & Jopson	2019	United Kingdom
Densley Tingley et al.	2017	United Kingdom
Adams et al.	2017	United Kingdom
Nasir et al.	2017	United Kingdom
Van der Sande	2019	The Netherlands

During the literature study a lot of categories of barriers and drivers where found. The categorized barriers and drivers are noted and grouped in table 3.

Table 3 barrier categories found in literature

Technological	Governmental	Environmental
Regulatory	Information	Operational
Financial	Structural	Attitudinal
Definitions	Legislative	Institutional
Customer	Supply chain	Social
Performance indicators	Organisational	Economic
Political	Managerial	Cultural

In the barrier categories that are named in the key literature can be regrouped because of the similarities in categories. For example, the categories, regulatory, political, governmental, legislative, institutional can be put in one main category. Al these types of barriers are listed under a denominator and the most important ones are shown in table 4. The categories of barriers and drivers are distinguished by a lot of authors, including Van der Sande (2019). The barrier types that are most common in literature are displayed below.

Table 4 Categories of barriers and drivers

Barrier type	Definition	Examples
Institutional	Barriers cased by institutions framing the " rules of the game"	Regulations and laws, fiscal measures, conditions for investment
Market	Market conditions, economic climate, and value network conditions	Monopolies, lack of information, subsidies, supplier leverage, relative cost of labor, materials and energy, etc.
Organisational/ behavioural	Firms as social systems influenced by goals, routines, organizational structures, Individual values and attitudes within companies	Company strategy or focus, lack of funds, lack of management systems etc. Lack of attention, lack of perceived control, lack of information, risk averse nature of existing market actors, etc.
Technological/information	Availability or lack of knowledge, technical artifacts or know-how	Lack of equipment or other tools, undeveloped technology from the market, cost of technology, unable to support technology, etc.

De Jesus & Mendonca (2018) investigated the barriers and drivers for eco innovations in the world. The results of the study on the circular economy in the world can also be used as background for this research. Jesus & Mendonca distinguished also four similar main barrier categories. The distinguished categories and the proportions of each category can be seen in Figure 5.

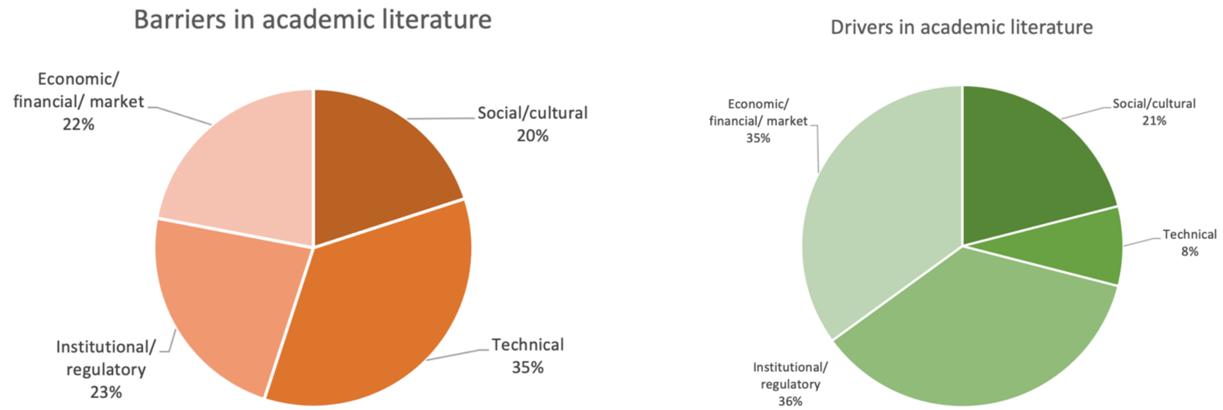


Table 5 Barriers and drivers mentioned in academic literature (De Jesus, 2018)

Kirchherr (2018) investigated the barriers and drivers with focus on the EU since the European Commission adopted a variety of ambitious CE policies. An example of such a policy is the 'Circular Economy Package'. The focus of the policy was on closing the loop of project lifecycles through greater re-use and recycling. Despite the adoption of these policy measures, most EU Member States are said to have seen limited CE implementation so far (McDowall, 2017; Stahel, 2014). This was the motivation for the first large-N-study on CE barriers, the research was conducted by Kirchherr et al. They conducted 47 interviews with CE experts, supplemented by a survey with 208 stakeholders from businesses and governments in the EU. The results of Kirchherr's research will are shown in the table 6. In the table the barriers are categorized, shortly mentioned and ranked by percentage. The most important barriers are highlighted in green.

Table 6 mentioned barriers research Kirchherr (2018)

Mentioning of barrier		Full sample n =208	Rank
Cultural	Lacking consumer interest and awareness	47%	1
	Hesitant company culture	46%	2
	Operating in a linear system	44%	4
	Limited willingness to collaborate in the value chain	38%	7
Market	Low virgin material prices	45%	3
	High upfront investment costs	40%	5
	Limited funding for circular business models	24%	10
	Limited standardisation	13%	11
Regulatory	Obstructing laws and regulations	37%	6
	Lack of global consensus	25%	9
	Limited circulare procurement	24%	10
Technological	Limited circular design	29%	8
	Too few large-scale demonstration projects	24%	10
	Lack of data e.g. on impacts	21%	12
	Ability to deliver high quality remanufactured products	11%	13

Interesting is that Kirchherr (2018) distinguished businesses (n=153) and policymakers (n=55). The differences between those two types of stakeholders are displayed in table 7 (J. Kirchherr, et al. , 2018).

Table 7 Distinguished barriers from clients and markets perspective (J. Kirchherr, et al. , 2018)

Mentioning of barrier		Stakeholder perspective: Businesses n = 153	Rank	policy-makers n = 55	Rank
Cultural	Lacking consumer interest and awareness	44%	2	53%	2
	Hesitant company culture	48%	1	40%	7
	Operating in a linear system	42%	3	47%	4
	Limited willingness to collaborate in the value chain	36%	6	42%	5
Market	Low virgin material prices	39%	4	62%	1
	High upfront investment costs	37%	5	49%	3
	Limited funding for circular business models	25%	11	18%	10
	Limited standardisation	14%	14	11%	15
Regulatory	Obstructing laws and regulations	35%	7	42%	5
	Lack of global consensus	29%	8	15%	14
	Limited circulare procurement	25%	11	24%	9
Technological	Limited circular design	28%	9	33%	8
	Too few large-scale demonstration projects	27%	10	16%	11
	Lack of data e.g. on impacts	23%	13	16%	11
	Ability to deliver high quality remanufactured products	8%	15	16%	11

In the technical category there is stated that a barrier is the lack of data. The question that needs to be answered is: What type of data is lacking? Also 'lacking consumer interest and awareness' is identified as a barrier. What is exactly lacking and in what way can this be dealt with? When knowing the specific barriers and reason why this barrier is mentioned, a solution can take shape. The method to find the specific barriers will be explicated in chapter 3.

Diaz Lopez et al. (2019) state that there is only a limited amount of literature available that links business models to circularity, explaining why so few of the 143 studied case were on CE (Diaz Lopez, 2019). Velenturf & Jopson (2019) conducted a study which focussed on the business case for resource recovery. Data was gathered during the *Resource Recovery from Waste* conference in the United Kingdom, in 2017 (which was attended by 68 experts from a variety of backgrounds). The authors identified 37 themes for the resource recovery business case, the most important themes covering the *Economic, Social, Environmental* and *Technical* value of resources and *Regulatory* change. Velenturf & Jopson (2019) state that *"focusing business cases on these is likely to deliver positive impacts regarding all identified themes"* (p. 1031). An overview of detailed barriers and drivers for companies to adopt circular practices is presented in the article.

Barriers mentioned by Dutch infrastructure stakeholders are given by Van der Sande (2019) as a result of study consisting of interviews with multiple stakeholders (n = 15). The most important barriers and driver categories are displayed in figures 4 and 5.

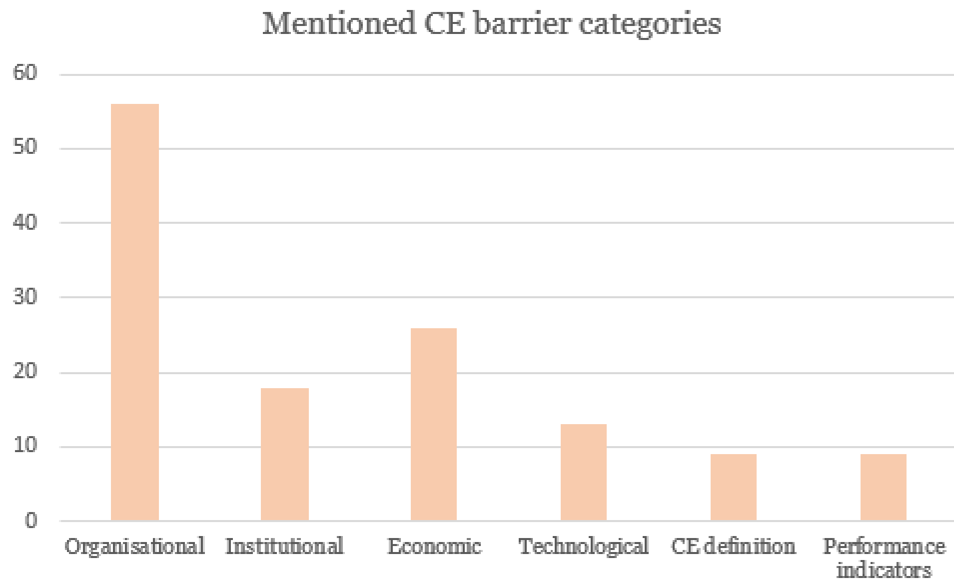


Figure 4 Mentioned CE barriers in the research of Van der Sande (2019)

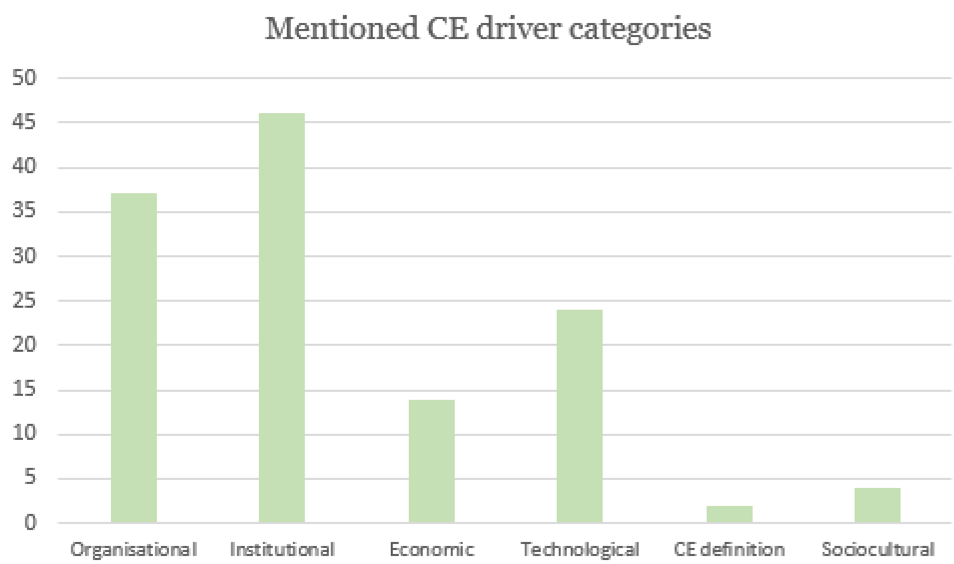


Figure 5 Mentioned drivers in the research of Van der Sande (2019)

2.3.2 MENTIONED BARRIERS

In addition to the main categories presented in Table 8. There were found a couple of more specific barriers in literature. For example, by Crowther and Hobbs, who mention the degree of disassembly of structural components in the infrasector.

"One of the major hindrances to successful deconstruction, for the reuse of building materials and components, is the difficulty in recovering items in good condition. Modern construction methods are very dependent on permanent fixing methods that allow for little else but destructive demolition." (P. Crowther, 2001)

"Modern construction methods are very dependent on permanent fixing methods that allow for little else but destructive demolition. Pre-cast beams are often pre- or post-tensioned and can be very hazardous to demolish and therefore require special care." (Hobbs, 2001)

Other more specific barriers for the circular economy as a whole are mentioned by Van der Sande (2019). The results of his research are displayed in table 8.

Table 8 Distinguished barriers by Van der Sande (2020)

Category	Description of identified barriers
Organizational	Circularity or the implementation of CE is a requirement in only a limited number of infrastructure
	In the tenders that are labelled as 'circular', awarding of the tender is still often largely based on lowest price and minimization of traffic hindrance, not on circularity.
	The implementation of CE in Dutch infrastructure projects requires different forms of collaboration between organizations
	Clients are hesitant to adopt circular innovations or solutions in their projects and prefer to stick to the conventional, 'known' way of working. Whereas the Dutch infrastructure sector is often labelled as being conservative, this can more likely be ascribed to the aversion of risks.
	In several tenders in which circularity should be incorporated, the specifications requirements are formulated so specific that it is impossible for contractors to implement circular solutions
	Specifications of materials are deliberately not provided, as providing incorrect information in the past has led to contractors suing the client. This impedes the high-grade reuse of materials and therefore circularity
	The 'production chains' for construction materials are primarily designed for use with virgin materials
	Organizations are unable to adopt circularity due to the unavailability of the resources time and money, or because other departments within the organization are unwilling to cooperate as they need to change the way they work
Technological	Demolition: the existing infrastructure has not been 'designed for demolition' or 'designed for re-use', which impedes high-grade reuse of materials and therefore circularity
	Due to weathering and erosion, materials can only be high-grade re-used once or twice
	There is uncertainty on the lifespan of circular materials
Economic	Due to the additional costs for transportation and possible processing of secondary materials, along with the lack of economies of scale for secondary materials, the costs for the use of secondary materials are often higher than for 'primary' or virgin materials.
	For most infrastructure assets there is no information about the materials' specifications, preventing high-grade re-use of materials
	Whereas in many other sectors, scarcity of materials drives up the price of primary materials and thus acts as an incentive to use secondary materials, primary materials required for the realization of Dutch infrastructure projects are abundantly available
Institutional	The lack of legislation and regulation that obligates the use and application of circular materials in Dutch infrastructure projects is considered a barrier, as there currently is no incentive to realize circular projects
	Standards and guidelines, such as the Eurocode and the 'Standaard RAW bepalingen 2015' have been mentioned to obstruct or prevent the use of circular or secondary materials.

The barriers mentioned in this chapter show that transitioning towards a circular economy is a complex process. It implies radical transformation of our current consumption and production patterns, in which new circular businesses are developed and linear ones are broken down. Such innovations are still in their infancies, though need to be nurtured and developed (Cramer, 2020). The innovations such as reusing structure components can be stimulated according the mentioned drivers in literature. The categories of drivers are already mentioned in paragraph 2.3.1. In the next paragraph the mentioned drivers are more specified for the circular economy in the infrastructure sector of the Netherlands.

2.3.3 MENTIONED DRIVERS

In a research conducted by Bouw Circulair (2020) a survey was distributed, and 271 participants responded. The participants consist of 126 market parties and 145 clients. Table 9 displays which parties were included in the research.

Table 9 Included parties in survey Bouw Circulair (2020)

Market		Clients	
Respondents	126	Respondents	126
Type of company		Type of organisation	
Contractor GWW	39%	Municipality	78%
Supplier end products	35%	Province	16%
Engineering & consultancy	18%	Water authority	5%
Recycling	17%	Other	1%
Demolishing contractor	13%		
Contractor B&U	4%		
Other	2%		

The participants were asked to fill in the survey were drivers of the circular economy were presented. Courage and decisiveness of clients is a must for both groups as can be seen in table 10. Also more (chain)cooperation and adaptation of legislation and regulations score high. The three tables cover three subjects, how can the circularity goals be reached? What actions are most important to perform? And what are the most important conditions for innovation? The tables below show the questions and the corresponding answers of the clients and market companies.

Table 10 Questions and answers about drivers of CE (BouwCirculair, 2020)

How can be achieve 100% circularity in 2050?		
Top 4 of market companies	No.	Top 4 of Clients
Courage and decisiveness of clients (64%)	1	Courage and decisiveness of clients (63%)
Prescribe circularity in contract (35%)	2	More cooperation (of chain) (41%)
More cooperation (of chain) (32%)	3	Adaptation of laws and regulations (32%)
Adaptation of laws and regulations (32%)	4	Policy support (31%)

What are the most important conditions for innovation?		
Top 4 of market companies	No.	Top 4 of Clients
Collaboration between supply chain parties (58%)	1	Ambitions from clients (57%)
Ambitions from clients (49%)	2	Collaboration between chain parties (43%)
Support from clients (43%)	3	Money from clients (40%)
Money from clients (31%)	4	Support from clients (36%)

Which actions are most important to perform?		
Top 4 of market companies	No.	Top 4 of Clients
Circular innovations (68%)	1	Experiences share sustainable projects (56%)
Experiences share sustainable projects (53%)	2	Monitoring results in relation to objectives (56%)
Deepen knowledge circ. Procurement (49%)	3	Circular innovations (51%)
Monitoring results in relation to objectives (41%)	4	Deepen knowledge circ. Procurement (46%)

It is interesting to see that the top four of each subject is shared with both clients and market parties but in a different ranking order.
In the research the questions were asked: What role do innovations play in the realization of the circular economy? Most of the market parties and clients (69% and 64% respectively) opt for the proposition:

> *Innovations play an essential role in the realization of the circular economy. At the moment there is insufficient investment and attention for this (Bouw Circulair, 2020)*

2.4 CHAPTER CONCLUSION

According to the theory of the 10-R-method, reusing construction elements is more circular than the current demolition process. The reasons why construction elements are not reused can be distinguished into 4 main categories: Technical, Organisational, Financial and Institutional. The most specific barriers and drivers for reusing construction elements in the construction sector are displayed below. The main barriers found in literature are summarized below:

- Organizations are unable to adopt circularity due to the unavailability of the resources time and money, or because other departments within the organization are unwilling to cooperate as they need to change the way they work
- Clients are hesitant to adopt circular innovations or solutions in their projects and prefer to stick to the conventional, 'known' way of working. Whereas the Dutch infrastructure sector is often labelled as being conservative, this can more likely be ascribed to the aversion of risks.
- Due to the additional costs for transportation and possible processing of secondary materials, along with the lack of economies of scale for secondary materials, the costs for the use of secondary materials are often higher than for 'primary' or virgin materials.
- The lack of legislation and regulation that obligates the use and application of circular materials in Dutch infrastructure projects is considered a barrier, as there currently is no incentive to realize circular projects
- One of the major hindrances to successful deconstruction, for the reuse of building materials and components, is the difficulty in recovering items in good condition. Modern construction methods are very dependent on permanent fixing methods that allow for little else but destructive demolition (P. Crowther, 2001).
- Insufficient investment and attention for innovations that realize the circular economy. (Bouw Circulair, 2020)

The drivers of the circular economy in the Netherlands are summarized below:

- Courage and decisiveness of clients
- Collaboration between supply chain parties
- Ambitions from clients
- Experiences share sustainable projects

3

The Double Diamond methodology

Double diamond is the name of the methodology that is used to find the answer to the main research question. The reason why this methodology is chosen and how it is used, is explained in the following paragraphs. The first paragraph is about the nature of the research, the following paragraphs explain the different stages of the Double Diamond methodology. In the last paragraph the implementation of the methodology in the research will be explained.
This chapter aims to answer the second sub-question:

How can the solution regarding the circularity in the infrastructure sector be found?

3.1 RESEARCH DESIGN / DESIGN RESEARCH

The research design refers to the overall strategy that is chosen to integrate the different components of the study in a coherent and logical way. The chosen research design is the design research. Design research means that the research is specifically undertaken to support the strategic design and development of products, services, and programs. Design research can contribute to more practical relevance and relates to scientific ambitions.
With help of the design-method the gap between theory and practice can be reduced. This is done using theory to design the needed interventions and to develop these for the application. Design based research is defined as follows:

"design-based research is a research methodology aimed to improve educational practices through systematic, flexible and iterative review, analysis, design development and implementation, based upon collaboration among researchers and practitioners in real-world settings, and leading to design principles or theories" (Collective, 2002)

A methodology is the foundation of the research approach and the lens through which the analysis is conducted. In other words, a methodology describes the "general research strategy that describes the way in which research should be undertaken" (Howell, 2013). The methodology should influence which method for a research effort are selected in order to generate the compelling data
A method is a research technique or tool that will be used to conduct the research. A method is simply the tool that is used to answer the research questions.

3.2 THE DOUBLE DIAMOND METHODOLOGY

The main method that is used during this research is called the Double Diamond method. The main feature of this method is its emphasis on the "divergent" and "convergent thinking", where first many ideas are created, before refining and narrowing down to the best idea. This is happening twice in this model, once to confirm the problem definition and once to create the solution. Although there are various methods, the double diamond methodology is the most complete one for this research, as it includes all the perspectives; financial, cultural, technical, organisational etc. (Tschimmel, 2012). The methodology takes two important aspects in consideration, 'designing the thing right' and 'designing the right thing'. This implies that the problem must be fully understood before a solution can be proposed. The method does not solely focus on designing solutions or interventions as an output, but it gets more into the actual problem definition prior to developing the solution as an output (Design Council, 2007).
The double diamond model can be described as an overview of the design and research process, which is divided into four distinct stages: the discover stage, the define stage, the develop stage and the deliver stage (Council, 2007). An important aspect of the double diamond method is to take the problem as the central focus in the design process, and not the preliminary research. This will support the development of a solution, because it keeps the problem open to new insights. According to the Design Council (2007), every design process starts with a divergent phase of discovering new ideas, followed by going through a convergent phase of analysis, as well as synthesis, to find diverse areas of opportunity. The application of the four phases of this methodology are explained in the following sections. The theory and background of the Double Diamond method is stated in Appendix D.

3.3 APPLICATION OF DOUBLE DIAMOND

The application of the Double Diamond methodology is divided in three layers: the phase of the methodology, the completion of that phase, and the method used in the completion of the phase. An overview of these layers can be seen in figure 6.

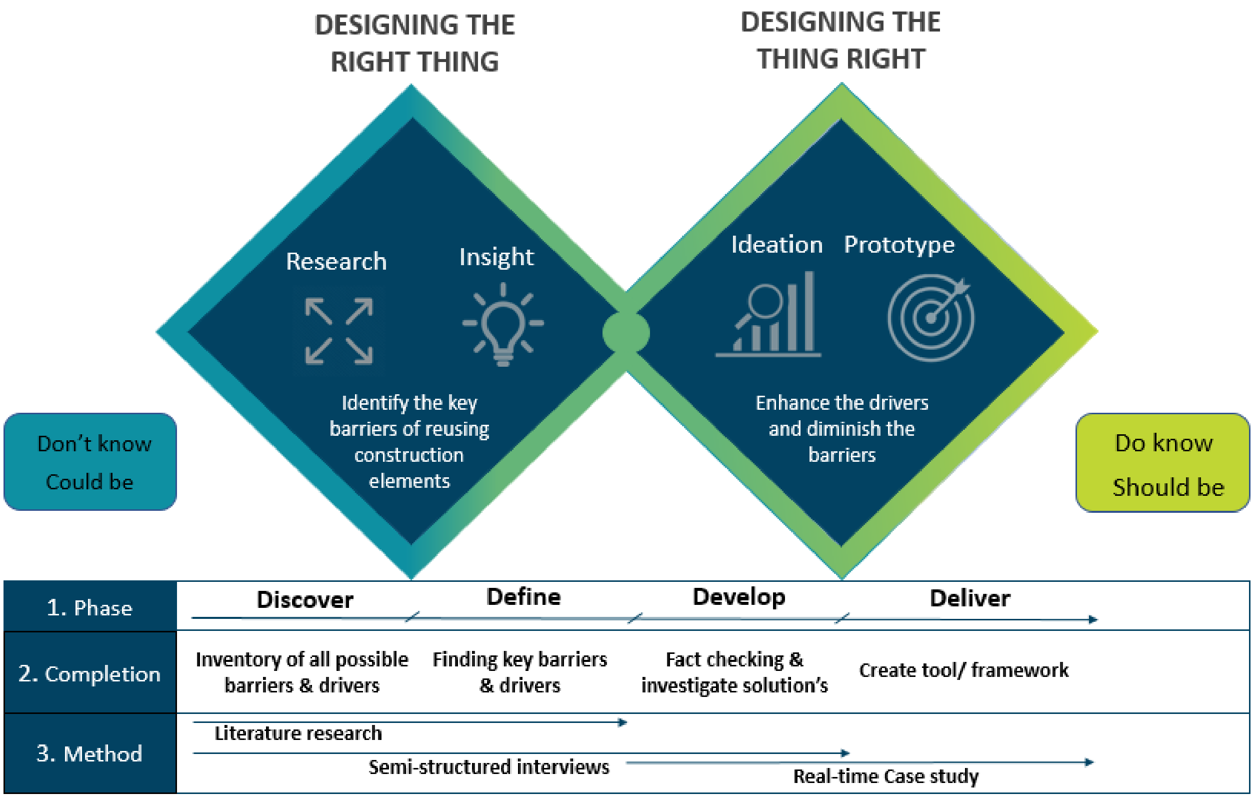


Figure 6 Application of the double diamond method

The first part of the research is covered by the first diamond. In the discover and the define phase, the barriers and drivers of reusing overpass girders will be investigated. To find the proper method, literature is viewed to see what the most common methods are to find barriers and drivers. The most common methods were literature research, interviews and case studies. These methods will also be applied in this research. The overview of used methods by authors researching barriers and drivers is stated in Appendix A.

The application of the different phases of the Double Diamond methodology will be discussed in the following sections. Research regarding the first diamond will deliver an overview of the most important barriers and drivers. The second diamond focusses on the solution to enhance the drivers and diminish the barriers.

3.4 STEP 1: THE DISCOVER PHASE

In the first phase of the Double Diamond methodology, multiple methods are used; literature research, observation and semi-structured interviews. These methods are explained in the following sections.

3.4.1 LITERATURE RESEARCH

Chapter 2 of this research consists of a literature research, this research is used in the double diamond method. The part of chapter 2 that is used is the broad range of barrier and driver categories that are mentioned in literature. It is important to know what is already named in literature to compare the self-found results. This self-found results come from interviews with experts of the Dutch infrastructure sector.

3.4.2 SEMI-STRUCTURED INTERVIEWS

Additional to the literature research, semi-structured interviews will be conducted. In this interview form, a structure is applied by establishing a predetermined list of topics that must be discussed during the interviews. The order of the topics, the formulation of the questions and the formulation of answers are not fixed. To secure the reliability of the data all interviews will be audiotaped and fully transcribed. Afterwards, a full transcript of the conversation will be sent to the participants to confirm the content. The interviews will each last approximately one hour. For the specific case and research, the right participants must be selected. A longlist will be made in the discover phase. This is done with help of consultancy & engineering firm Royal HaskoningDHV and assessment of authors of the Dutch literature. Also contacts from comparable research are included in the longlist. The longlist will be converted in a shortlist of 30 interview participants in the define phase.

The interview starts with an introduction about the background of the interviewer and interviewee. In addition, the theory of the circular economy in the Dutch infrastructure will shortly be introduced to ensure that there is a mutual understanding of the topic. The interviews will be divided into three parts. The first set of questions in the research guide are broad questions that put the interviewee at ease and encourage them to give you their perspective. The middle section is where the ideas are pursued in more depth and where the answers to the specific research questions are obtained. In the concluding section of the interview, the participants are asked to name the barriers most present in their opinion. Also a possible solution for the specific problem is asked for, and clarification for anything that is still unclear is searched for. The solutions mentioned in the interview will be used in the develop phase of the interview. The interview protocol is shown in Appendix F.

To fulfil the criterium of all involved stakeholders represented in the interviewees or in other words the entire 'chain' connected to the girders. The stakeholders that are interviewed in this research are summed up in table 11.

Table 11 Stakeholder parties and their description

Stakeholder type	Description
Public clients	Governmental organisations that give the order to commission a project
Engineering & consultancy firms	Organisations that provide consultancy and guidance for the design and realisation of technical projects
Contractors	Organisations that take responsibility for the realization and coordination of construction activities; a contractor provides, for a price specified in the contract and within an agreed period, the delivery of a fully completed structure. The demolition contractor is specialized in safely and efficiently tearing down buildings and other man-made structures
Girder Suppliers	Suppliers that are specialized in producing and transporting prefab girders for bridges and viaducts
Knowledge institutions	Organisations with acquiring and discovering new knowledge as core business. Examples are technical universities and Dutch Organization for applied scientific research (TNO)

3.5 STEP 2: THE DEFINE PHASE

Processing the results of the semi-structured interviews mentioned in the previous section is the method to converge in this step. The main barriers and drivers are extracted from the made transcripts of the interviews. This is done with the help of coding the interview transcripts. The interviews will be coded in a systematic manner following the three steps of the Grounded Theory (Corbin, 1990). Open coding, Axial coding and selected coding. The explanation of the Gounded Theory and the different coding steps can be seen in Appendix E. The codes can be extracted from the Atlas TI program to an Excel document and read out. The most important barriers and drivers will emerge from the result analysis. The results of the different stakeholder parties will also be evaluated.

3.3.3 STEP 3: THE DEVELOP PHASE

The develop phase consist of three parts, validation, ideation and evaluation. The three parts together form the diverging phase where ideation is approached with an open mind. In the first part of the develop phase the results from define phase are validated. This is done by means of reflection of the case study and with the validation by experts in in the industry. The validation by case study is further explained in the next section. After validation the ideation phase starts. Every solution count and there are no good or bad solutions, the solutions will not be judged on feasibility or impact yet. The solutions will party be extracted from the interviews, where the interviewees are asked for potential solutions. Other solutions will come from brainstorm sessions with the earlier defined experts. The list of solutions will be evaluated with an impact-feasibility matrix. This matrix is formed with acquired knowledge of the interviews, the real-life case study and observation from practice.

3.5.1 REAL LIFE CASE STUDY

After the literature research and interviews, a real-time case study is an additional method to validate the barriers, drivers and a design solution. This real-time case study is in cooperation with Royal HaskoningDHV, an international consultancy engineering firm. The reason Royal HaskoningDHV is investigating the reuse possibilities of prefab girders of Dutch overpasses is the SBIR (Small Business Innovation Research) set up by Rijkswaterstaat. The core of the SBIR is the method by which the government uses an innovation competition to challenge entrepreneurs to come up with innovative products and services to solve social issues. In this way, innovations emerging from the SBIR competitions help society move forward. Royal HaskoningDHV believes that the circularity of the Dutch infrastructure could be brought to a higher level. From current situation of recycling the concrete to reusing the concrete of girder overpasses. RHDHV is doing a feasibility study with the author and wants to understand why this innovation is not practiced before. Therefore, it is chosen to take this SBIR as real-life case study to collect data and apply the knowledge in the research. In the case study multiple aspects of reuse overpass girders will be investigated. The barriers resulting from the real time case study will be reflected to the found barriers and drivers in literature and the interviews. This will be the validation of the findings so far and solutions resulting from the case study will be documented in the deliver phase.

3.6 STEP 4: THE DELIVER PHASE

In the fourth stage the most feasible integral solution with the highest impact will be worked out and validated, this is called the deliver stage. The integral solution will result from the found barriers and drivers in the first diamond and the evaluation step of the develop phase of the second diamond. After the solution is formed, it can be validated with the real time case study.

3.7 Reliability and Viability

The solution model can be validated with the help of participating stakeholders of the SBIR project. Not only the validity of the research is tested also the reliability and viability are addressed. Construct validity is concerned with the extent to which your research measures what it claims to measure. External validity is concerned whether a study's research findings can be generalized to other relevant settings or groups.

Reliability refers to whether the data collection techniques and analytic procedures would reproduce consistent findings if they were repeated on another occasion or if they were replicated by another researcher.
Threats to reliability:

- Participant error. Any factor which adversely alters the way in which a participant performs
- Participant bias. Any factor which produces a false response.
- Researcher error. Any factor which alters the researcher's interpretation.
- Researcher bias. Any factor which induces bias in the researchers' recording of responses.

As part of the team of Royal HaskoningDHV in the SBIR project, the objectivity of the author can be questioned. The influence of the author must be limited and may never affect the data. It is therefore important to distinguish the data and the interpretation of the data. The data results from the interviews and the information is the interpretation of that data.
In the real-life case study, the influence of the author is present because the author can propose ideas with knowledge of the interviews or contribute to the completion of a process.
The data is all the interview material and found scientific papers in the literature research. The results of the interviews are the bundled data and is called information. With the information conclusions can be drawn and with those conclusions a solution can be formed. The researcher can have influence on the information, knowledge and wisdom but is challenged by the TU Delft graduation committee, the experts who validate the results of the interviews and the SBIR participants who validate the design. The influence of the author will be mentioned when the results are affected because of the influence. In the discussion the influence of the author will be explained in more detail.

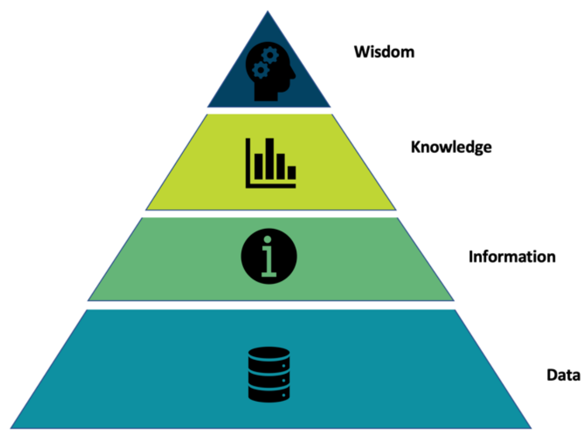


Figure 7 Data, information, knowledge and wisdom

4

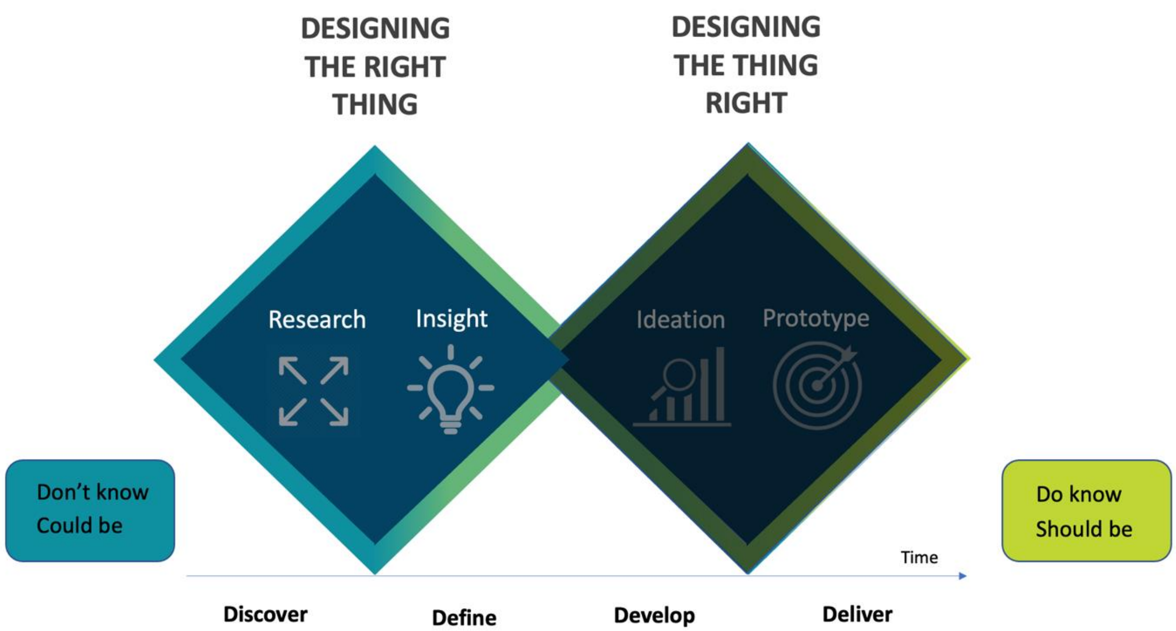
Results & Analysis

In this chapter the results of the research are displayed. The four phases of the double diamond are walked through and this is explicated in the following paragraphs. In the first two paragraphs the focus is on the first diamond where the main focus is to design the right thing. In the final two paragraphs the focus is on the second diamond and the focus shifts to designing the thing right.

Is there an integral solution to tackle the main barriers?

4.1 PHASE 1: DISCOVER

The discover phase consists of a literature research and semi-structured interviews. The results of the literature research from chapter 2 are the starting point of the diverging scope. The initial proposal and the initial research question are challenged in this step. Every part of the research proposal is critically reviewed, and the fields of interests are evaluated. A list with all elements that can be found as a barrier or driver is made. This is done with the results of the literature study, the inventory meeting with experts and the real-life case study experiences. Furthermore, all relevant parties and people are explored. A list of 97 potential interview candidates is composed. Finally the literature study is used to explore the barriers and drivers of the circular economy in the infrastructure sector. This resulted in over ninety specific barriers and drivers of the circularity in the Dutch infrastructure. The people, potential challenges, potential solutions are clustered into categories. The list of potential interview candidates and the list of barriers and drivers from the discover phase are stated in Appendix B. In the next step these findings will be used to narrow down and converge the scope.



4.2 PHASE 2: DIVINE

"Finding problems, worth solving"

The focus of this step is to find problems worth solving. After carefully look at each interviewee from the longlist of potential interview participants, a short list is made with the help of the experience and knowledge of Royal HaskoningDHV. The shortlist consists of 29 specialists, working at 18 companies. The anonymized shortlist is displayed in Appendix B. The interviews were transcribed and coded following the three coding steps explained in chapter 3. First open coding, then axial coding and thirdly selected coding. The full process of coding can be found in appendix E. After the coding process the barriers and drivers where selected into categories and subcategories. The clustered barriers and drivers are stated in table 12 and 13. In these tables, the subject is explained and a number is given to the barriers and drivers.

Table 12 Remaining barriers after coding and clustering

Barrier Category	No.	Barriers	Explanation
Technical	1	Safety of the structure	The safety of the constuction cannot be guaranteed because of the missing shear force reinforcement in old girders
	2	Missing information	Technical specifications are not properly archived and are digitally and physically stored at multiple places, therefore it is difficult to determine the construction safety, The history of the trafficload and the potential damage/repairs is not known, therefore it is difficult to determine if the girders are still strong enough
	3	Disassembling technical	It is a challenge to disassemble the girders due to the connections with the rest of the excisting overpass
	4	Residual life	The residual life of the girders cannot be guaranteed for the required amount of years, therefore the clients are hesitant to purchase reused girders
	5	Application	The girders cannot be adjusted and are designed for a unique project. The current length, height and intersectionangle of the girders ensure that the girders cannot be used in a new unique design.
Financial	6	Disassembling	The disassembling of an overpass is more expansive than the traditional way of demolishing a girderoverpass
	7	Financial	Due to the extra activities; transportation, certification, testing and storage, it is more expansive to reuse girders in comparison with the traditional way of demolishing and constructing an overpass
Institutional	8	Law & Regulations	The girdersoverpasses built before 1980 are likely not satisfying the current building laws and concrete regulations, therefore they can not be applied in new overpasses
	9	Certification	It is difficult to determine when a girder is certified to reuse, there is no test where the strength can be measured after which the girders can be used again in an overpass.
Organisational	10	Supply & Demand	It is not known where girders can be gained and where girders can be stored.
	11	Contract/responsibility	It is not clear who has responsibility of the harvested girders
	12	Planning	The planning of infrastructure projects is tight and everything needs to be done as fast as possible, lost vehicle hours is an example of a planning barrier
Cultural	13	Ignorance	The culture of todays infrastructure sector is calibrated on the linear economy, the opportunities of circularity are not known and are not thought of
	14	Mindset	Because of the positive business cases of the linear economy, some sector parties deliberately do not want to change

Table 13 Remaining drivers after coding and clustering

Driver Category	No.	Drivers	Explanation
Technical	15	Safety of the structure	The old constructions are over dimensioned in the past, the used girders can easily fulfill the constructive task in a second life
	16	Residual life	When looking at the materialproperties and the condition of the girders, they can be placed in a construction for decades
	17	Disassabling technical	There are methods to disassamble the girders in one piece, e.g. hydro demolition.
	18	Application	The girders can be adjusted in limited proportions. Also, the new overpass can be designed taking into account the dimensions of the girders
Financial	19	Financial	Financial compensation for circular building, to bridge the financial gap between the traditional way of demolishing and the circular way of deconstructing
Institutional	20	Law & Regulations	New building laws and concrete regulations can provide the possibility to reuse construction elements
	21	Certification	Certifying girders will stimulate the confidence of clients
Organisational	22	Pilot project	Experience is necessary to overcome some uncertaintainties
	23	EMVI/ Contract	The circularity demand/request in the contract is a stimulans for reusing concrete girders
	24	Supply & Demand	It must be know what the supply of girders is. A physical and virtual database of girders
	25	Planning	The girders do not have to be manufactured anymore, they are ready to use on the storage yard
Environment	26	Circular ideology	The circular ideology and the trend that the preservation of the environment is becoming more important

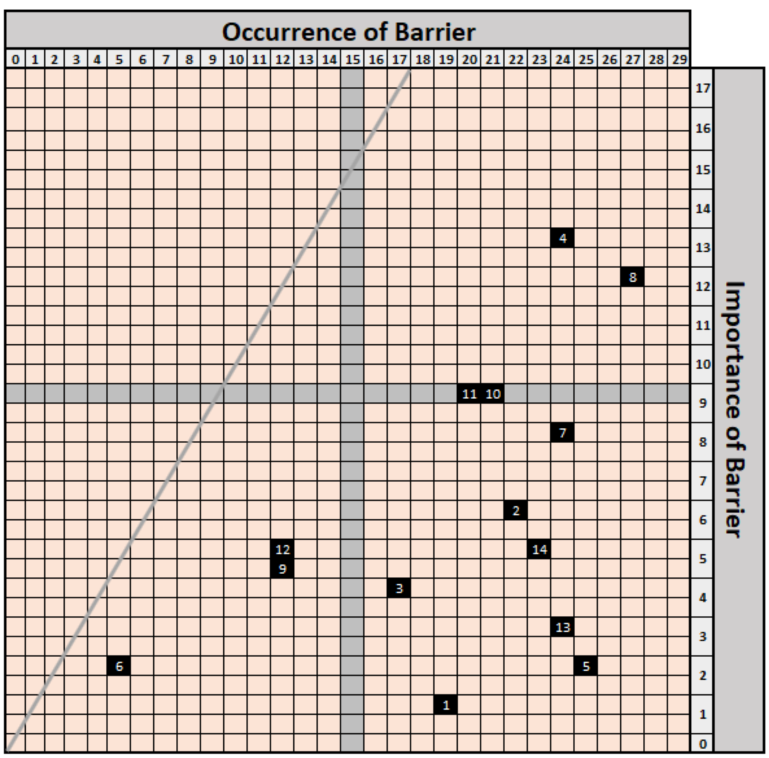
The interviewees where asked questions about the barriers and drivers of reusing overpass girders. The results are categorized in occurrence and in degree of importance. These definitions need some clarification for better understanding.

Occurrence: If a barrier of driver is coded at least once in the interview. The barrier or driver will be counted as one. The sum of all subcategories named in the interviews is called, occurrence. The reason why occurrence is measured in this way is because of the large range of total codes per interview. The least amount of codes per interview is 28, and the most codes per interview is 83. The degree of occurrence with this method is insensitive for the difference in total codes per interview. This method of counting occurrence ensures that no interviewee is dominant in their proclamation of barriers or drivers. The data of the quantity of codes is not lost, this will be further explained in paragraph 4.2.2.
For example: Interviewee A mentions barrier "disassembling technical" three times, the occurrence of the interview is counted as one.

Importance: In phase III of the interview the interviewees are asked what the most important drivers and barriers are in their opinion. The sum of the answers to this question are group coded as importance.

4.2.1 BARRIERS

Figure 8 displays the results of the barriers resulting from the interviews. The numbers correspond to the subcategories named in table aside.



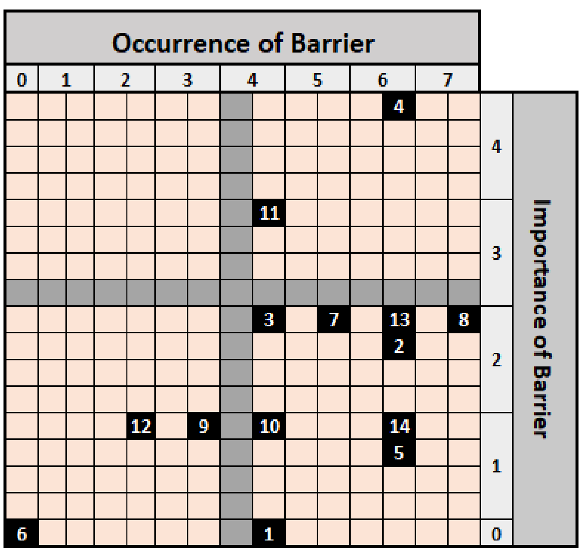
No.	Barriers	Barrier Category
1	Safety of the construction	Technical
2	Missing information (History & Design)	
3	Disassembling technical	
4	Residual life	
5	Application	
6	Disassembling	Market
7	Financial	
8	Law & Regulations	Institutional
9	Certification	
10	Supply & Demand	Organisational
11	Contract/responsibility	
12	Planning	
13	Ignorance	Culture
14	Mindset	

Figure 8 Results of barriers mentioned in the interviews

In the result graphs there are a few aspects that stand out. These deviant results will be explicated in the next paragraphs. First, the barriers and drivers in the top-right quadrant will be viewed in more detail. The results of both graphs are explained in the following sections.

When looking at the barrier graph there are a few outstanding barriers in the top right quadrant and but most of the barriers are in the bottom part of the graph. Another aspect is that the scale of the axes is not the same. The occurrence is as large as the total amount of interviewees. The scale of the importance is about half the size of the occurrence axis. For the barriers this implies that there is no barrier is called most important by more than 45% of the interviewees.

The results in the top-right quadrant of the graph are seen as most important barriers which are named in the interviews. However there cannot directly be concluded that these barriers are of most hindrance for the circularity of prefab girders. The graph points out that most interviewees see residual life and law & regulation as most important barriers. This can be felt as the most important barrier, but rules & regulation is for example challenged by a group of interviewers.
There can be a group interviewees distinguished who are involved in the norm commissions of concrete structures. This is a group of 7 individuals who are working in different stakeholder companies. Their opinion is that rules and regulation is not the most important barrier and some of the interviewers explicitly mention that law & regulation is not the biggest barrier. Only 28,6% of the interviewees mentions Law & regulations as important barrier. The data of the results from interviewees in norm commissions can be seen in figure 9.



No.	Barriers	Barrier Category
1	Safety of the construction	Technical
2	Missing information (History & Design)	
3	Disassembling technical	
4	Residual life	
5	Application	
6	Disassembling	Market
7	Financial	
8	Law & Regulations	Institutional
9	Certification	
10	Supply & Demand	Organisational
11	Contract/responsibility	
12	Planning	
13	Ignorance	Culture
14	Mindset	

Figure 9 Barriers mentioned by interviewees of norm commissions

Other outstanding results from the interviews are barriers 7, 10 and 11. These barriers will be shortly discussed.

7: Financial

The financial barrier is in 86% of the interviews and is the barrier arranged as fifth most important barrier. This is mostly because of the extra activities that are necessary to reuse the girder. This is however a barrier that is contradicted by a few interviewees who are mentioning that reusing concrete girders is cheaper than the traditional way of working and designing.

10: Supply & demand	Supply & Demand is the third barrier that is felt to be important by the interviewees. The deal breaker is the ignorance where girders can be stored and where they can be handed in. There is no physical storage available and there is no database where can be seen which reusable girders are on the market.
11: Contract/responsibility	As can be seen in figure 8, this barrier is in the top 5 of most important barriers according to the interviewees. The question; who is responsible for the girders after they are disassembled from the overpass? Is called a barrier because every party avoids responsibility.

Remaining outstanding results are the ignorance category where ignorance and mindset play a significant role the reusability of overpass girders. 80% of the interviewees mentions ignorance and mindset as a barrier. The barriers are also named several times as most important barrier. An interviewer mentioned quoted the following:

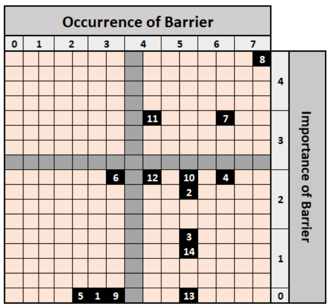
"If I do not know what the weather is going to be like, I will bring my umbrella, suntan lotion, rain suit and hat. All measures because I do not know. When I know my business, I know it is going to rain and I leave my sunscreen at home. It is just a lack of knowledge of people who invent all those barriers "

The overall conclusion that can be made is that there is a disagreement which barriers most hinder the reusability of the concrete girders. At most 13 interviewees rated a subcategory most important, while 29 experts are interviewed. The most important barriers according to the interviewees are:

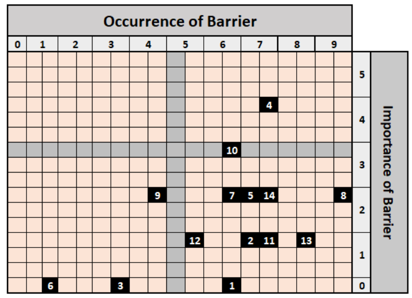
1. The residual life of the reused components
2. The current laws & regulation
3. Supply & demand
4. Contract Responsibility
5. Finance

4.2.2 DIFFERENCES STAKEHOLDERS PERSPECTIVES

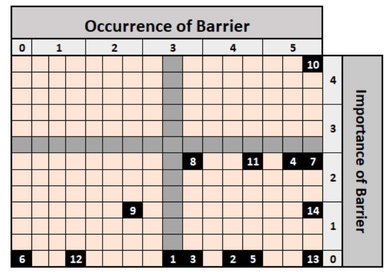
Differences between the different stakeholder parties can be seen in the figures below. The most outstanding differences will be pointed out in the following section. There are no differences in drivers which are significantly standing out. The analysis of the different drivers per group is explicated in Appendix C. The barriers that differentiate the most are barriers 2,4,5,7,8,10,13.



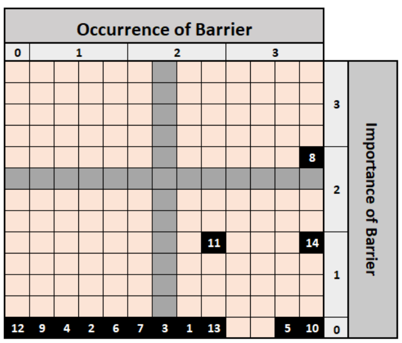
Contractors



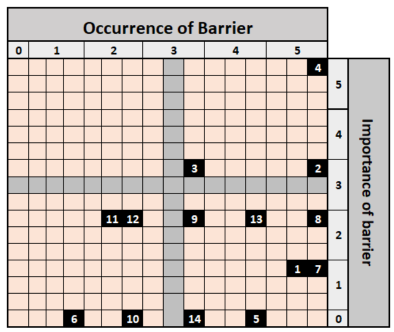
Clients



Consultancy & Engineering



Girder suppliers



Knowlegde institutions

No.	Barriers	Barrier Category
1	Safety of the construction	Technical
2	Missing information (History & Design)	
3	Disassembling technical	
4	Residual life	
5	Application	
6	Disassembling	Market
7	Financial	
8	Law & Regulations	Institutional
9	Certification	
10	Supply & Demand	Organisational
11	Contract/responsibility	
12	Planning	
13	Ignorance	Culture
14	Mindset	

2: Missing information
Missing information is the second most important barrier for knowledge institutes but is not once as important barrier by consultancy & engineering and girder suppliers

4: Residual life
Residual life is the most important barrier for knowlegdge institutes and clients. It is the second important barrier for consultancy & engineering firms. Contractors and girder suppliers do not see residual life as one of the biggest barriers.

5: Application
The barrier of application is only by the clients seen as important. All other parties did not mentioned application once as important.

7: Financial
Contractors and clients see financial barriers in the top 3. Other parties do not see the financial barrier as most important. On the other hand, this barrier is most often named by girder suppliers and knowlede intitutes.

8: Law & Regulation Law and regulation is seen as top barrier by girder suppliers and contractors. All other parties do not see law and regulation as one of the three most important barriers.

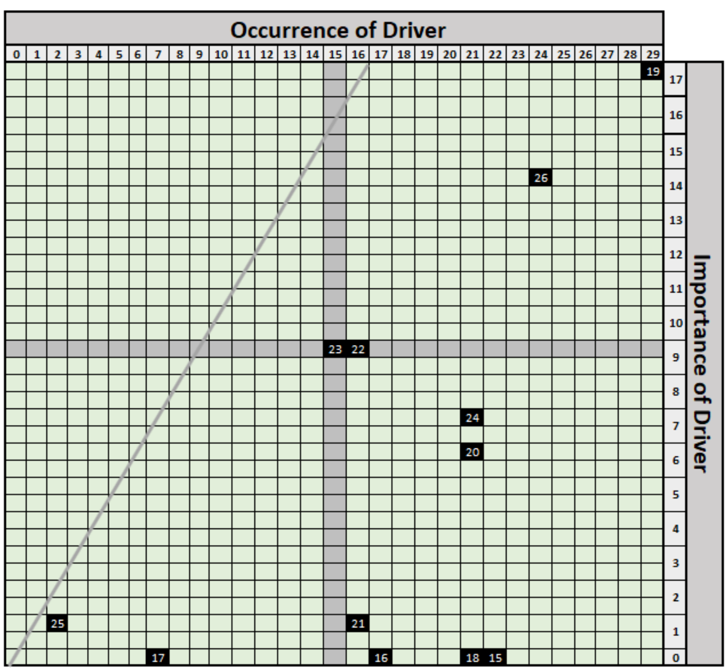
10: Supply & Demand Supply and demand is seen as most important barrier by consultancy & engineering firms. Also clients and contractors see this as important barrier. Girder suppliers and knowledge institutes do not share this opinion.

13: Ignorance Ignorance is not as outstanding in the graphs as the barriers mentioned above. However this is the most inconsistent barrier. Law and regulation is the same for every party but ignorance is different. Girder suppliers see ignorance as the limited knowledge of clients regarding residual life of the product. Engineering & consultancy see ignorance as the limited knowledge of demand and supply and the idea of reusing girders. Clients see ignorance of the application of the laws and regulations. A client mentioned that there is not enough knowledge present at other companies to really understand the rules, laws and norms. Therefore other parties think that the law is to strict.

4.2.3 DRIVERS

The most important drivers mentioned in the interviews are also in the top right quadrant of the graph in figure 10. The most mentioned driver is the financial incentive. Interviewees indicate that there need to be a business case for reused girders. The interview participants mention that a reward of the client is the fastest way to a circular economy.

The second driver is the overall circular ideology of The Netherlands. This has to do with the goals of Rijkswaterstaat mentioned in Chapter 1. The drivers that complement the most important drivers are numbers 20,22,23 and 24. These drivers will be shortly discussed.



No.	Drivers	Driver Category
15	Safety of the construction	Technical
16	Residual life	
17	Dismantling technical	
18	Application	
19	Financial	Market
20	Law & Regulations	Institutional
21	Certification	
22	Pilot project/ experience	Organizational
23	EMVI/contract	
24	Supply & Demand	
25	Planning	
26	Circular ideology	Environment

Figure 10 Drivers mentioned in the interviews

20: Law and regulation	Law and regulation is named as a driver because something is missing in the current available norms, according to the interviewees. There are 4 types of rules & regulations in the Netherlands. Rules for Existing structures, Newly built structures, Rejection level and usage level. It is not clear which rules apply for reused structures. Therefore, new regulation is necessary.
22: Pilot project/experience	Learning by doing is a much-pronounced sentence during the interviews. The interviewees arrange the experience on the area of reusing structural components highly as can be seen in figure 10.
23: EMVI/contract	The EMVI is equally important as the supply and demand, according to the interviewees. This implies that the parties are stimulated when circularity or sustainability is asked in the request contract of the tendering client.
24: Supply & Demand	The supply & demand ensures that there are girders available for the ones how want to reuse girders in their projects. A physical storage yard and a digital database is necessary according to the interviewees.

Another outstanding result of the drivers can be seen when looking at the bottom of the graph. There are four drivers on the bottom of the graph. These drivers are named various times in the interviews but are not once named as important. When analyzing these results, it was clear that two types of drivers can be distinguished, namely: Passive and active drivers.

Structural drivers are situated on the bottom of the driver graph. These drivers stimulate the reuse of concrete overpass girders, but these drivers are not enhanced by an action. The structural drivers that can be distinguished are: Residual life, safety of the construction, dismantling technical and application. These are characteristics of the current overpasses and can therefore not be triggered by taking some form of action. The structural drivers cannot be stimulated by an action and the fluid ones need an action to be driver. This is insight is taken to the next phase of the Double Diamond methodology.

Fluid drivers stimulate the reuse of concrete overpass girders and they need a change, an action to make it happen.
An example of an active driver is the subcategory “supply and demand”. It is currently not known where the used girders can be stored and gained. Therefore, there need to come a platform online where people can find which girders are available and there need to be physical storage yard where the used girders will be stored.

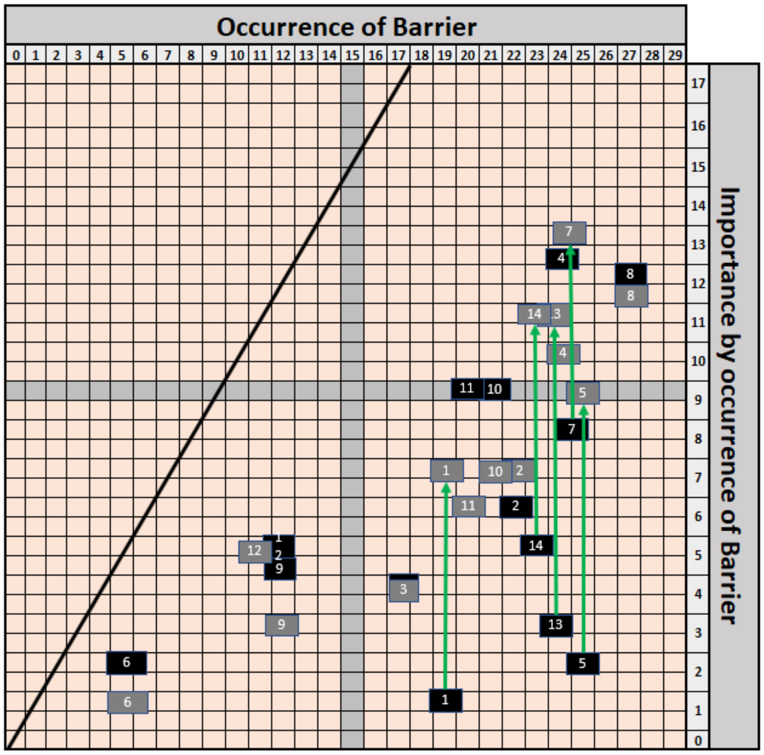
The overall conclusion of the drivers is that the financial driver is mentioned in every interview. It implies that money is one way of the other, always a driver. The most important drivers according to the interviewees are:

1. Finance
2. Circular ideology
3. Pilot case/ experience
4. EMVI/ contract
5. Supply & Demand

6. New/adjusted Laws & regulations

4.2.2 OCCURRENCE BY IMPORTANCE

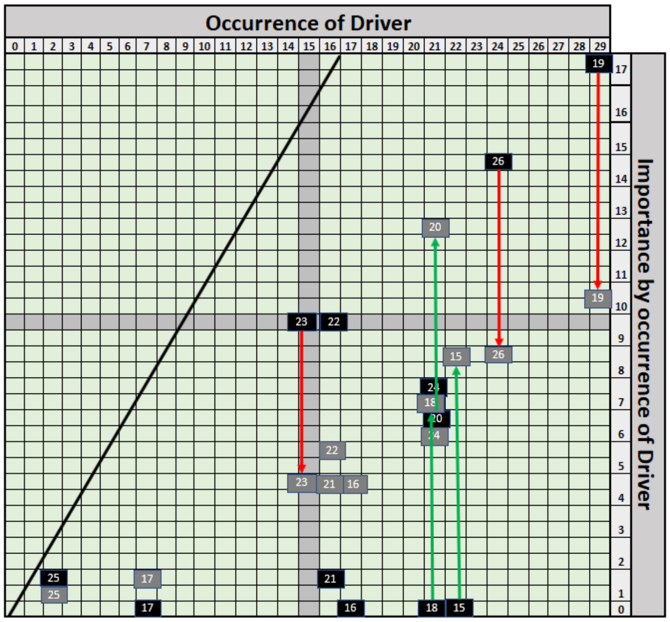
In several research there is no interview question about the importance of the barriers and drivers.



No.	Barriers	Barrier Category
1	Safety of the construction	Technical
2	Missing information (History & Design)	
3	Disassembling technical	
4	Residual life	
5	Application	
6	Disassembling	Market
7	Financial	
8	Law & Regulations	Institutional
9	Certification	
10	Supply & Demand	Organisational
11	Contract/responsibility	
12	Planning	
13	Ignorance	Culture
14	Mindset	

Figure 11 Barriers mentioned occurrence vs. importance by occurrence

In these researchers the importance is inferred by occurrence. How many times a interviewee mentions a barrier or driver indicates that this is an important aspect. In other words, the verbal implicit determination of importance. To compare the results of the previous paragraphs with this method, occurrence by importance is introduced. The horizontal axe has the same meaning as before, the vertical axe changes from importance to importance by occurrence. In every single interview the subcategories are counted and divided by the total amount of mentioned codes. The result implies what subcategory is relatively more mentioned in comparison to other codes. The importance by occurrence is summed up for all interviewees and is shown in grey in figure 11 and 12. The black boxes show the results mentioned in the previous sections. The arrows indicate the biggest differences between the two results.



No.	Drivers	Driver Category
15	Safety of the construction	Technical
16	Residual life	
17	Dismantling technical	
18	Application	
19	Financial	Market
20	Law & Regulations	Institutional
21	Certification	
22	Pilot project/ experience	Organizational
23	EMVI/contract	
24	Supply & Demand	
25	Planning	
26	Circular ideology	Environment

Figure 12 Drivers mentioned occurrence vs. importance by occurrence

What stands out is that barriers 1, 3, 5, 7 and 14 are ranked significantly more important than is mentioned in the last part of in the interview, where the arrangement of barriers is asked. The biggest changes relatively to the ranking by importance are displayed with the green and red arrows.

When analysing the drivers, it stands out that there are green arrows and red arrows. The green arrow indicates that a driver is classified as more important than declared in the arrangement phase of the interview. The red arrow indicates that the driver is classified as less important than declared in the arrangement phase of the interview.

4.2.3 CONCLUSION OF THE DEFINE PHASE

The most important barriers mentioned by the interviewees are current laws & regulations, the residual life, supply & demand, extra costs to reuse girders, contract/responsibility, mindset and disassembling technical. A solution for these barriers is the most efficient to become one step closer to circularity of construction elements. There is however no notable consensus between stakeholder parties of the Dutch infrastructure about the most important drivers and barriers of reusing prefab girders. The overall most important barriers are nominated as important by less than 50% of the interviewees. The most important drivers are nominated by less than 60% of the interviewees. The girder suppliers did not once mention the residual life as an important barrier. The interviewees of the norm commissions do not see law & regulation as much as a barrier as the rest of the interviewees. Disassembling the girders technically is seen as one of the most important barriers mentioned by knowledge institutes. The demolishing contractors however explicitly mention that the girders can be disassembled in good state.

When arranging the most important barriers according to the results of the occurrence by importance, the differences are clearly visible in table 14.

Table 14 Ranked barriers

Mentioning of barrier		Importance		Sample n=29	
		Occurrence	Importance	Average	Rank
Cultural	Ignorance	38%	10%	24%	6
	Mindset	38%	17%	28%	4
Market	Disassembling	3%	7%	5%	11
	Financial	45%	28%	36%	3
Institutional	Law & Regulations	41%	41%	41%	1
	Certification	10%	17%	14%	10
Technical	Safety of the construction	24%	3%	14%	10
	Missing information (History & Design)	24%	21%	22%	7
	Disassembling technical	14%	14%	14%	10
	Residual life	34%	45%	40%	2
	Application	31%	7%	19%	8
Organisational	Supply & Demand	24%	31%	28%	4
	Contract/responsibility	21%	31%	26%	5
	Planning	17%	17%	17%	9

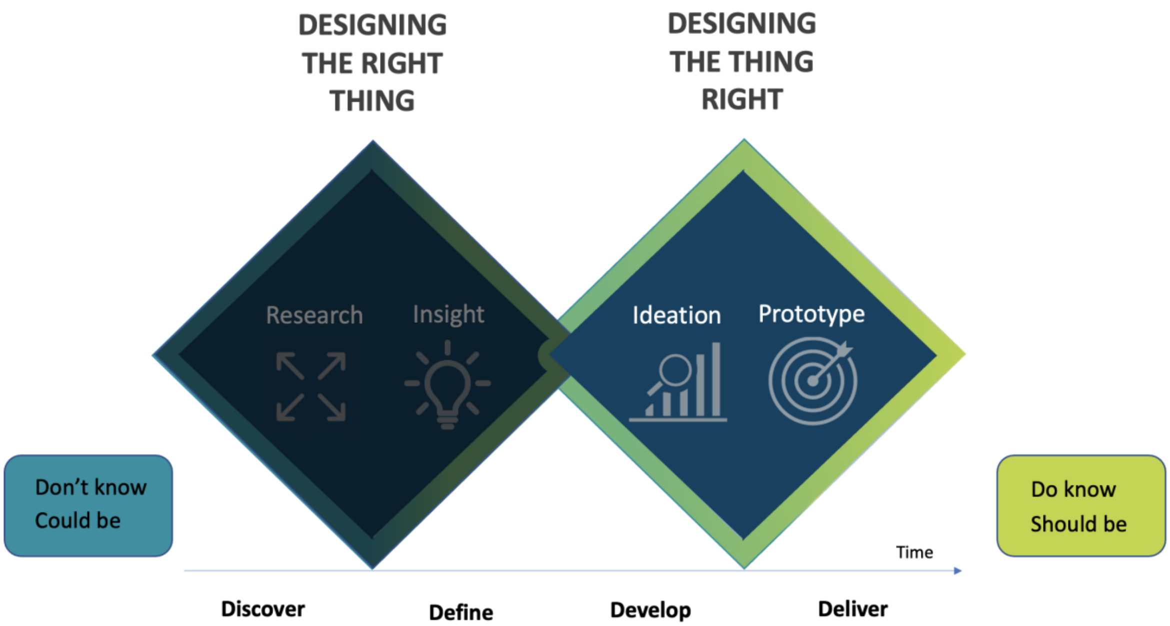
The most important drivers are mentioned in table 15. These drivers must be enhanced as much as possible in the solution.

Table 15 Ranked drivers

Mentioning of Driver		Importance by		Sample n=29	
		Occurrence	Importance	Average	Rank
Environmental	Circular ideology	34%	48%	41%	2
Market	Financial	48%	59%	53%	1
Institutional	Law & Regulations	52%	21%	36%	3
	Certification	17%	3%	10%	8
Technical	Safety of the construction	38%	0%	19%	4
	Disassembling technical	17%	0%	9%	9
	Residual life	7%	0%	3%	10
	Application	31%	0%	16%	7
Organisational	Pilot/experience	21%	31%	26%	4
	Supply & Demand	17%	31%	24%	5
	Contract/responsibility	24%	24%	24%	5
	Planning	3%	3%	3%	11

4.3 Develop stage

Now that the first diamond is has been completed, the processes of the second diamond can be started. The second diamond starts with the develop phase. The develop phase consist of three parts, validation, ideation and evaluation. The three parts together form the diverging phase where ideation is approached with an open mind. Every solution count, there will be no judging of solutions until the evaluation.



4.3.1 VALIDATION

The validation of the found barriers and drivers is an important step in the design methodology. The process of the research and the analysis of the results is validated in two different ways.

1. Validation by experts of the infrastructure sector
   The definition of expert is given in paragraph 3.3. There are five experts asked to validate the process of the research and the analysis of the results. Two of the experts who validated the results are earlier interviewed in this research, the other three experts were not interviewed.
2. Validation by real time case study
   The validation by real-time case study is executed by looking at barriers in case study and validate if those barriers are mentioned. Also barriers from literature and interviews can be tested with the real-time case study.

Validation by experts

Five experts validated the process from interviewing towards the analysis of the results. After presenting the process the experts had one hour to give feedback and ask questions about the made choices. The experts all mentioned that the results where interesting and asked for a copy of the results. This implies that something new is found or something is researched that proves what the experts already knew. This analysis is validated by the experts. In the validation some subjects where recurring; mindset, ignorance, circular ideology and finance. Also the descriptions of barriers and drivers was not always clear, this is adjusted after validation sessions. The important validation topics are discussed below.

Culture
The culture category (mindset and ignorance) was mentioned most often. The experts mentioned that these barriers are experienced higher in practice.

Finance
An expert mentioned that finance is the overall barrier, every subcategory can be linked to finance.

Validation by real-time case study
The process of the SBIR case, which is described in chapter 3, is followed during this phase of the research. When following the process, the barriers and drivers which were mentioned in literature and the interviews could also be validated via the real time experienced barriers and drivers. The validation of the results gained in the first diamond will be discussed below. There are 4 themes that will be highlighted.

1. Laws & regulations
2. Dismantling
3. Measuring circularity
4. Culture

1. Laws & regulations

The results from the interviews and literature study indicates that the current laws & regulations is a barrier for the reuse of construction elements. This barrier is not shared with the SBIR team Liggers 2.0. In the Netherlands there is a concrete regulation set up by Rijkswaterstaat which provides guidance to the recalculation of existing structures. The consortium Liggers 2.0 claims that the rules for existing structures (RBK) is also applicable to reuse of existing construction elements.

2. Dismantling

Dismantling the girders is good condition is a mentioned barrier in literature and in the interviews. The consortium Liggers 2.0 does not share this opinion and do not see the dismantling as a barrier. Dismantling girders from an overpass is done dozens of times but not with reuse in mind. Usually a girder overpass is dismantled if this overpass is located above a rail track. Also in interviews the ability of dismantling of overpasses is contradicted by most contractors and demolition contractors.

3. Measuring circularity

In the case the circularity is measured with the methods described in chapter 2, DuBoCalc and MKI calculation. The sustainability experts of Royal HaskoningDHV and Dura Vermeer indicated that reuse of structural components is not properly included in the calculation tools. The main question of the calculation was: What do you set as initial value and what is the end value of the calculation. Is a reused beam free in terms of environmental impact? When a girder is not reused, it is crushed and the material is used as road foundation.

4. Culture

Mindset and ignorance are subcategories which were frequently mentioned as important barriers in literature and in the interviews. These barriers are shared with the consortium Liggers 2.0. There is a lot of ignorance in the infrasector and this hampers the innovations such as the reuse of overpass girders. One example is given.

A girder overpass is built up with among other things girders, columns, foundation and endcarriers (einddwarsdragers). These endcarriers are applied in each girder overpass in the past and still applied in the overpasses of the present. In the SBIR project the build-up of the overpass is revisited. The endcarriers are found redundant by the consortium Liggers 2.0. They have no significant function according to leading professional of existing structures Rob Vergoossen.
This is an example of ignorance and mindset. The infrasector continues to do what works, and what is always has worked.

4.3.2 IDEATION

The solutions are gathered from the interviews. The interviews are coded again with a new purpose. This time the interviews are coded with a new code, namely: '*Solutions*'. This new code is implemented 183 times in the 29 interviews. The solutions clustered by similarity and the remaining 69 solutions are shown in table 16 on the next page. The solutions are ranked on impact and feasibility by experts (n=3) from practice. There are a couple of solutions who are marked as passive. These potential solutions do not require an active measure to improve the current situation. The chain of evidence of finding the solutions is included in Appendix H.

4.3.3 EVALUATION

The solutions cannot all be executed; this is not efficient and is therefore an evaluation is necessary.

"Applying all solutions to the specific problem is like taking all available medicines and hope that one will work"

The evaluation of the develop phase is executed with an Impact – Feasibility matrix. Where impact and feasibility are defined as indicated below.

Impact: The effect that the solution has on the mentioned barriers. The impact of the solution is higher if the solution diminishes an important barrier.

Feasibility: The possibility that the solution can be executed, made or achieved by the Dutch infrastructure sector.

As a result, the author ought to end up with one or a small number of ideas which can be prototyped and tested in the deliver phase of the Double Diamond methodology in order to find the best answer or solution to the initial problem. The solutions in de top right quadrant have most potential and the solutions in the down left quadrant can be discarded in this phase of the innovation.

Table 16 Impact-Feasibility table of potential solutions mentioned in the interviews

Sector					
Category	No.	Solution	Passive or active	Impact	Feasiblity
Technical	1	Over-dimensioning in design	Passive	-	-
	2	Test method non-destructive	Active	2	9
	3	Drilling cores	Active	3	7
	4	Monitoring	Active	2	3
	5	Supplementing knowledge level on shearforce	Active	8	2,5
	6	Over-dimensioning with safety factor	Active	6	3,5
	7	Practical tests	Active	4,5	4,5
	8	Disassemble and reconstruct	Active	9	9
	9	Calculate with tools of the past	Active	4	8
	10	Residual life assumption	Active	7	0
	11	Material properties become stronger in time	Passive	-	-
	12	Adapt new design to current elements	Active	8,5	9
	13	reinforce the girders with reused girders	Active	3	2
	14	statisch onbepaald constructies, statisch bepaald toepassen	Active	9	10
	15	Disassemble current girders can be done	Active	7	2
	16	Calculate until you satisfy the underlying norms	Active	9	9
	17	Determine the residual life	Active	7	2
Financial	18	Assign value to current girders	Active	0	10
	19	Make girders more expensive	Active	8,5	3
	20	Business case for material recycling	Active	2	7
	21	Innovate to maintain the business	Active	5	7
	22	Be willing to pay for circularity	Active	5	9
	23	understanding of the (extra) costs	Active	8,5	8
	24	Voertuigverliesuren cadeau	Active	8,5	6
Institutional	25	Certificering the girders	Active	9	5
	26	Reuse law and regulation	Active	2	2
	27	Adjustment Current law & regulation	Active	7	6,5
	28	Other application than highway network of Rijkswaterstaat	Active	10	10
	29	Accept renovation level regulation	Active	10	9
	30	Translation table which point out what is possible	Active	7,5	7
	31	Call the older concrete alternative concrete.	Passive	-	-
	32	Not all bridges must fulfil the highest safety demands	Active	9,5	9,5
	33	Current girders have proven technology	Passive	-	-
	34	Preservation of transport regulation	Active	9	1
	35	Current laws & regulation are sufficient	Passive	-	-
	36	Client contract, granulate fine	Active	8	6
Organisational	37	Collect all data of prefab overpasses	Active	9	2,5
	38	Gewicht meten in kraan waardoor onzekerheid kleiner wordt	Active	2	8
	39	Insight in process	Active	8	8
	40	project Overarching MKI (CO2 ladder)	Active	6,5	2
	41	Standaardisation	Active	0	4
	42	SBIR / pilot projects	Active	8,5	8
	43	project overarching thinking	Active	8	2
	44	Material passport	Active	9	5,5
	45	mapping bottlenecks	Active	8	9
	46	Take time for adaptation in the market	Passive	-	-
	47	Product as a service	Active	9,5	1
	48	Supply & Demand tool	Active	9	7,5
	49	Gemeentelevering	Active	10	1,5
	50	Awareness of the barriers, drivers and solutions	Active	6	6
	51	Pysical storageyard	Active	10	9
	52	Digitize and automate	Active	5,5	4,5
	53	Standardization in processes	Active	4	2,5
	54	Precursors who	Passive	-	-
	55	mulitparametric design	Active	3	8
	56	Sharing knowledge	Active	8,5	7
	57	See what the right method is for each situation	Passive	-	-
Environmental	58	CO2 Tax	Active	4	6
	59	Understanding of the environmental impact	Active	8	8
	60	MKI methode die echt doet aan hergebruik	Active	8	5
	61	scarcity of materials	Passive	-	-
	62	Abiotic depletion taks	Active	7	6

Resulting from the table on the previous page, the results of the evaluation are plotted in a diagram. In this diagram the most promising results can be seen in the top right quadrant. The numbers correspond to the numbers in figure 13.

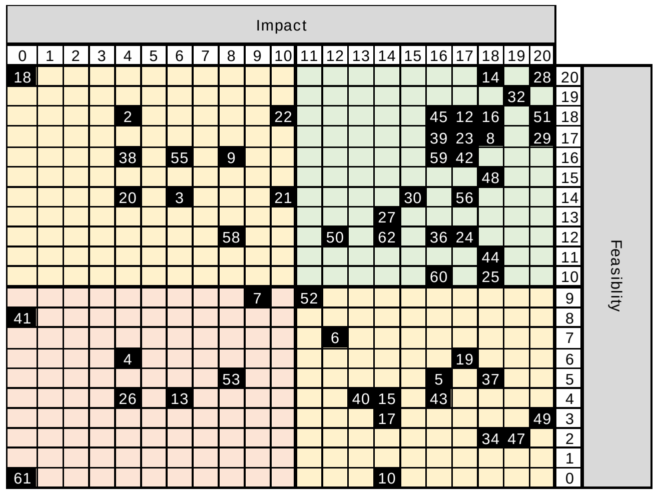


Figure 13 Impact feasibility matrix for market parties

Also, an Impact-Feasibility matrix is made where feasibility has another definition. In this matrix the feasibility is defined as the possibility that a solution can be executed, made or achieved by the author. In figure 14 can be seen that a couple of solutions reduce in feasibility, these solutions cannot be worked out by the author. However, the solutions which are feasible for the market are described in Appendix I to provide guidance to experts who can work out the solutions.

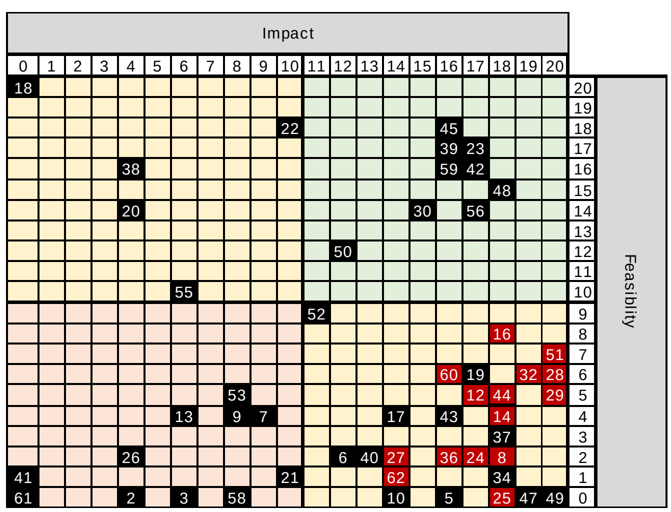


Figure 14 Impact feasibility matrix for author

The remaining solutions in the top-right quadrant will be worked out in an integrated solution in the deliver phase of this research design. These solutions are displayed in table 17. Some solutions cannot be designed by the author because they already exist e.g. material passports. These solutions can be integrated in the integral solution in their current state.

Table 17 Feasible solutions with highest impact

No.	Solutions	Nature	Impact	Feasibility
45	Mapping bottlenecks	Active	16	18
39	Insight in process	Active	16	17
59	Understanding of the environmental impact	Active	16	16
23	understanding of the (extra) costs	Active	17	17
42	SBIR / pilot projects	Active	17	16
48	Supply & Demand tool	Active	18	15
56	Sharing knowledge	Active	17	14
30	Translation table which point out what is possible	Active	15	14
50	Awareness of the drivers and solutions	Active	12	12

Some solutions are already performed during this research, these solutions are:

- **45: Mapping bottlenecks of reusing precast girders**
    - This solution is performed in the first diamond
- **50: Awareness of the drivers and solutions**
    - This solution is performed within this research

Experience is an important driver according to the interview results, the underlying argument is the insight in some processes, impact, barriers and solutions will become known. The solutions below all relate to the process and the insight in the results from the innovation.

- **56: Sharing knowledge**
  The knowledge from the research and gained from the real time case study is send to all interested parties of the construction industry.
- **39: Insight in the process**
  The process of reusing precast girders will be explicated during the SBIR. This process will be compared with the traditional process of demolishing and rebuilding an overpass consisting of new elements.
- **59: Understanding of the environmental impact**
  In the SBIR project an MKI sum will be performed to see what the environmental impact of the process and materials are in comparison with the traditional materials and processes.
- **23: Understanding the (extra) costs**
  In the SBIR project a calculation will be made of the costs with the methods explained in chapter 2.
- **48: Supply & Demand tool**
  To clarify where the girders can be stored and gained, a platform for reused girders can be a solution.

4.4 THE DELIVER PHASE

The remaining and already existing solutions resulting from the previous phase will be worked out in the deliver phase in one integral solution. Before the solution and the process towards that solution is explained, a definition of integral solution is given.

An integral solution is a solution consisting or composed of parts that together constitute a whole, considering multiple perspectives e.g. technical, financial, organisational, culture, institutional and environmental.

The integral solution will be validated based on the real time case study with consortium Liggers 2.0. The SBIR/ pilot project solution that is suggested can be used as overarching experience to test the separately mentioned solutions stated below. The common factor which stands out is the uncertainty about materials, residual life, processes, costs, impact etc. Therefore, the integral solution for the mentioned barriers can be summarized in one word: **Insight.**

The barrier "ignorance" directly concludes that insight of the reuse possibilities is missing. In the analysis of other outcomes of the interviews can be concluded that there is no consensus about the main barriers. This implies that the possibilities and feasibility of reusing precast girders is (partly) unknown. The feasibility of reusing components from the infrastructure will be documented by a real-time case study.

There are a lot of unknowns when it comes to the process of the dismantling of the girders, the machinery that is used, how the storage will be organized and if the existing girders can be redesigned for new application as overpass girder. All those aspects are performed by Liggers 2.0 and the black box can be lifted when the processes are documented and made transparent. The key processes that are mentioned are, availability dismantling and impact.

4.4.1 AVAILABILITY

Precast girder overpasses are common in the Dutch infrastructure. In figure 15 can be seen that most overpasses are made with precast concrete in recent years.

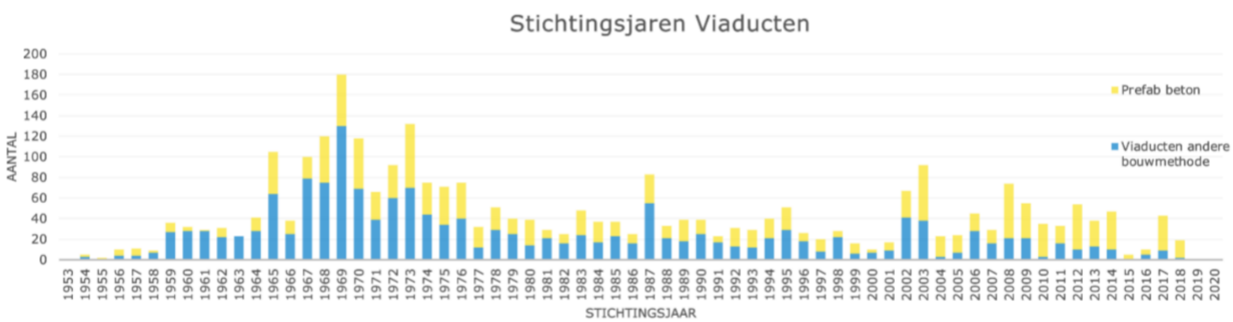


Figure 15 foundation years overpasses from Rijkswaterstaat in The Netherlands

After construction, the overpasses will be used until they are depreciated. The design lifespan is usually 50 to 100 years. In practice an overpass rarely hits the design lifespan. The operation lifespan of an overpass can be categorized in four different types:

1. Technical lifespan
2. Functional lifespan
3. Commercial lifespan
4. Compliance lifespan

The lifespan of a civil construction is often considered as the technical lifespan. With this type of aging there is often a deterioration of structural parts. As a result, the technical requirements that have been determined in advance, are no longer met. Economic obsolescence refers to the gradual increase in the operating costs of assets, with decreasing profit margins as a result. Hereby, the maintenance costs no longer outweigh the costs of replacing a structure. The functional lifespan means that the asset no longer meets the primary function requirements, the products produced, or the services to be provided. If a construction can no longer meet the applicable legal requirements, this is referred to as the compliance lifespan. As a result, the risks, the incidents and calamities that occur increase and are no longer acceptable (Dongen, 2011). In civil structures like overpasses, the functional lifespan is often the reason for replacement (Dongen, 2011). The overpasses are fulfilling their task technically but due to the following reasons a girder is demolished:

- Extra car lanes under the existing overpass
- Extra car lanes in the overpass
- A new zoning plan

An example of the functional lifespan of an overpass is the widening of the A2 in the province Limburg. The highway becomes broader as a result of the plans to add two extra car lanes. Figure 16 shows the overpasses in this trajectory.

According to the DISK database of Rijkswaterstaat, 10 overpasses are demolished each year. Most of these overpasses contain girders that are demolished for functional reasons (Dongen, 2011).

Figure 16 Overview overpasses in the A2

4.4.2 DISMANTLING

The dismantling of an overpass is seen as barrier in the literature and in the interviews. The consortium Liggers 2.0 disassembled the girders of an overpass in the A9. The case study if further described in Appendix G. The contractor, demolishing contractor and consultancy firm had a couple of meetings where the dismantling of the overpass was the main topic. Together they made a plan to remove the girders within 24 hours in good condition. The endbarrier is drilled with holes side by side. The rest of the girders are sawn throw between the barriers. In Appendix K the disassemble process is described in more detail.

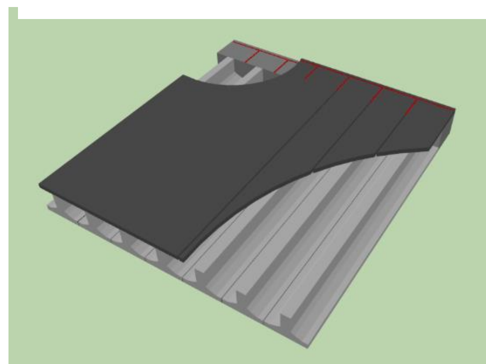


Figure 17 process of dismantling girders in one figure

4.4.3 IMPACT

The impact of reusing the girders are calculated in environmental impact and financial impact. The environmental impact is measured in MKI and this is calculated with the tool DuBoCalc. For this calculation, all the different components of the overpass must be mapped out. The quantities of each material are the input for this method which resulted in an Excel with all the different components and corresponding material type and quantity. The quantities are used in DuBoCalc and the DuBoCalc tool calculates the processes of cranes, fuel and other emissions resulting from the estimated work. A table of MKI calculation is added in Appendix L. The results from the calculations is given in table 18.

Table 18 MKI savings resulting from reusing overpass girders

Besparing o.b.v. case	Hergebruik heel viaduct	Hergebruik bovenbouw	Hergebruik ligger+druklaag	Hergebruik ligger alleen	Per viaduct	Per jaar (10 viaducten)
MKI-besparing	40%	49%	61%	73%	€29.460	€294.600
CO2-besparing	45%	57%	72%	87%	331 ton	3310 ton
Abiotische grondstoffen besparing	48%	58%	73%	93%	0,3 kg	3 kg

The direct financial impact of the innovation is measured with the quantities of materials and the production costs that is saved with reusing existing building components. All processes are included in the calculation. The storage time of the girders is estimated on 6 months. With all the savings of production and materials and the extra costs of storage and the more complicated dismantling process. There can be concluded that reusing girders is more financial than the traditional way of working. The indirect costs are largely determined by the vehicle lost hours (voertuigverliesuren). These indirect costs are not visible in the financials of a project but is a cost to society. Lost vehicle hours refer to the total number of extra hours that is spend when suffered from congestion on the road. This can be a traffic jam, but also a diversion due to road works. The vehicle lost hours in the Netherlands are extremely high and therefore a significant financial barrier if these costs is calculated in the project costs.

5

CONCLUSION & DISCUSSION

5.1 CONCLUSION

Reusing overpass girders is economically feasible, has a positive impact on the environment and can be executed with if the required knowledge is present. The main reasons why girders are never reused in the main road network of Rijkswaterstaat are displayed in red in the table below.

Table 19 Barriers mentioned in semi-structured interviews

Mentioning of barrier		Importance		Sample n=29	
		Occurrence	Importance	Average	Rank
Cultural	Ignorance	38%	10%	24%	6
	Mindset	38%	17%	28%	4
Market	Disassembling	3%	7%	5%	11
	Financial	45%	28%	36%	3
Institutional	Law & Regulations	41%	41%	41%	1
	Certification	10%	17%	14%	10
Technical	Safety of the construction	24%	3%	14%	10
	Missing information (History & Design)	24%	21%	22%	7
	Disassembling technical	14%	14%	14%	10
	Residual life	34%	45%	40%	2
	Application	31%	7%	19%	8
Organisational	Supply & Demand	24%	31%	28%	4
	Contract/responsibility	21%	31%	26%	5
	Planning	17%	17%	17%	9

These barriers are felt by a group of experts in the sector. However, the SBIR project of the consortium Liggers 2.0 subducted a couple of barriers. In the process of dismantling an overpass and recalculating the strength of the dismantled girders, the conclusion is that a couple of felt barriers are not present according to the consortium Liggers 2.0. The laws & regulations are clear and the existing girders meet the required demands. The residual life is determined and found adequate for decades of usage. The financial barrier is not present if only direct costs are measured. When indirect costs such as vehicle lost hours (voertuigverliesuren) are take into account, the financial barrier is still present.
The cultural barriers point out that the main barriers are psychological. Culture barriers such as mindset of the clients and market parties, is mainly active risk aversion. The conservative attitude of the infrasector hampers innovation such as reuse of structural components. Ignorance is the passive cultural barrier which is a combination of all factors that are unknown. Mentioned ignorance barriers are, the unknowing what is possible with new techniques and not really understand the laws & regulations. The culture barriers which are mentioned by the experts amplify the contradicted results resulting from the case study and the interviews.

The solution to diminish the felt barriers is to create insight in the process and the results of the pilot project. Insight is necessary in the total process, environmental impact, financial impact, supply and demand, and dismantling the structural components.

5.2 DISCUSSION

The research is performed in cooperation with Royal HaskoningDHV. This company is participating in the SBIR project and the feasibility study was mainly to convince the client (Rijkswaterstaat) that this innovation is feasible. The author can be influenced by this environment and the opinions of the people in the consortium.
Despite the fact the interviewees selected with consideration, the interviewees have a predominantly technical view on the subject. This can cause that the technical aspects are given more attention than the financial, organizational or cultural aspects.

APPENDIX A: USED METHODS TO FIND BARRIERS AND DRIVERS IN LITERATURE

Title	Authors	Methods used
Exploring institutional drivers and barriers of the circular economy: A crossregional comparison of China, the US, and Europe	Valtteri Rantaa,⁎, Leena Aarikka-Stenroosa, Paavo Ritalab, Saku J. Mäkinena	Case study,
Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy	Ana de Jesusa,⁎, Sandro Mendonçab,c,d	Desk study, literature research
Barriers and drivers in a circular economy: the case of the built environment	Jim Hart, Katherine Adams, Jannik Giesekam, Danielle Densley Tingley	Literature research
Drivers and barriers to circular economy implementation	Martin Agyemang, Simonov Kusi-Sarpong	Survey instrument and interviews
Unlocking circular business: A framework of barriers and drivers	Nina Tura, Jyri Hanski, Tuomas Ahola, Matias Stahle	Case study & semi structured interviews
A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective	Kannan Govindan & Mia Hasanagic	Literature research
Barriers to the Circular Economy – integration of perspectives and domains	Sofia Ritzéna*, Gunilla Ölundh Sandströma	Semi-structured interviews
Barriers and drivers for sustainable building	Tarja Hakkinen and Kaisa Belloni	Case Study, interviews
Understanding and overcoming the barriers to structural steel reuse, a UK perspective	Danielle Densley Tingley, Simone Cooper, Jonathan Cullen	Semi-structured interviews
Project management in circular building projects, Developing a framework supporting the re-use of components	Lotte Meijers	Case Study, interviews
Economic Feasibility of Reusing Structural Components	Ilma Jabeen	Interviews, survey, case study
Overcoming barriers to the reuse of construction waste material in Australia: a review of the literature	Jungha Park & Richard Tucker	Literature research
In search of the barriers and drivers for the implementation of a Circular Economy in Dutch infrastructure projects	Lennard van der Sande	Interviews

APPENDIX B: SELECTED INTERVIEW PARTICIPANTS (ANONYMIZED)

RESPONDENT SELECTION

The key to good results of the semi-structured interviews is selecting the right people to interview and a well thought out interview protocol. The interviewees must fulfill a couple of requirements to be defined an expert. The requirements to select an expert is given in table 20.

Table 20 Requirements for the interviewees individually and collective

Nr.	Type of requirement	Interview requirements
1.	General	On average more than 10-year work experience in the infrastrucure sector
2.		All relevant stakeholder parties represented in the interviews with a minimum of three interviewees
3.		Multiple companies per stakeholder party, minimum of two companies
4.	Individual / Expert	Experience or extensive knowledge in or of the Dutch infrastructure
5.		Knowledge of the technical aspects of concrete Dutch girder overpasses OR knowledge of the transition towards circularity of the Dutch infrastructure.
6		Acquaintance with the building process and prescribed building laws and regulation

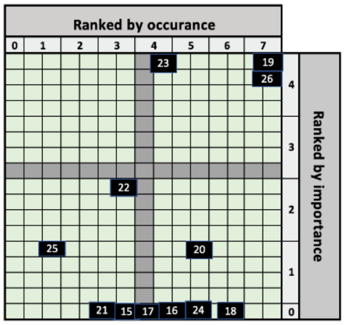
These requirements are set to acquire results that relate to the specific case of reusing prefab girders.

Table 21 Selected interview participants and corresponding company

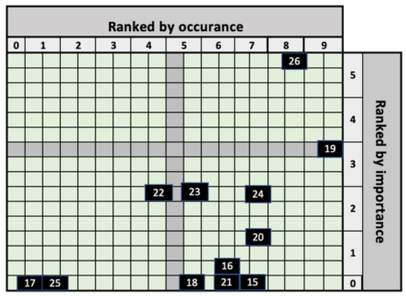
Nr.	Stakeholder	Function	Company
1	Client	Top adviseur	Rijkswaterstaat
2		Senior Consultant, beheerder ROK	
3		Senior advisor	
4		Advisor Bridges and overpasses	
5		Advisor Bridges and overpasses	
6		Manager sustainability	Provincie Noord Holland
7		Chef of the engineering firm	
8		Teamleider bevoegd gezag gemeente Rotterdam	Bevoegd gezag
9		Ministerie van Infrastructuur en Waterstaat	Ministerie van Infrastructuur en Waterstaat
10	Contractor	Head work planning	Besix
11		Senior Constructeur, Floriade	Dura Vermeer
12		PhD / Dura vermeer	Volker Wessels
13		Manager markt en strategie met constructieve achtergrond	Dura Vermeer
14		Ervaring demonteren liggerviaducten	Insert / Sloopaannemer
15		Strategisch specialist	VolkerWessels Infra Competence Centre
16		Manager demolition infrastructure structures	Vlasman
17	Girder supplier	Technical manager of prefab girder production	SpanBeton/Rijkswaterstaat
18		manager sales, marketing and estimating	Romein beton circulariteit, nu eigen bedrijf
19		Technical manager prefab girders	Haitsma
20	Consultancy & Engineering	Project manager	RHDHV
21		Innovation manager	
22		Senior project manager	IV-Infra
23		Duurzaamheids specialist	RHDHV
24		Director	SGS Intron
25	Knowlegdge institution	Constructive safety consultant	TNO
26		Senior Scientist Building Materials	
27		Senior Scientist Integrator	
28		PhD, overpass girders in current infrastructure	TU Delft
29		TU Delft Betonconstructies	

APPENDIX C: DIFFERENCES IN MENTIONED DRIVERS BY INTERVIEWED STAKEHOLDER PARTIES

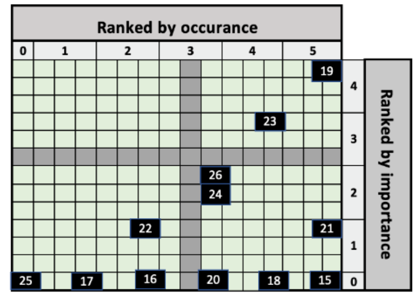
Differences between the different stakeholder parties can be seen in the figures below. The most outstanding differences will be pointed out in the following section. The drivers that differentiate the most are drivers 19,21,23,24,26.



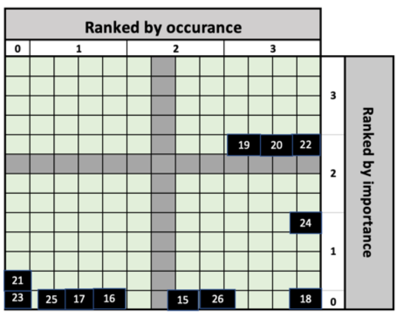
Contractors



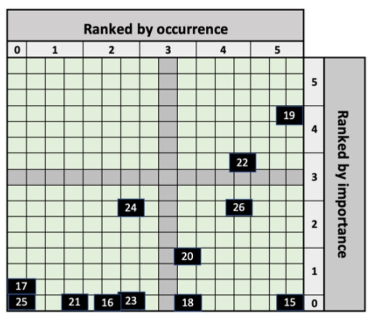
Clients



Consultancy & Engineering



Girder suppliers



Knowlegde institutions

No.	Drivers	Driver Category
15	Safety of the construction	Technical
16	Residual life	
17	Dismantling technical	
18	Application	
19	Financial	Financial
20	Law & Regulations	Institutional
21	Certification	
22	Pilot project/ experience	Organizational
23	EMVI/contract	
24	Supply & Demand	
25	Planning	
26	Circular ideology	Environment

19: Financial The financial driver is most mentioned as important; it is striking that 33% of the clients sees this as most important driver. In other parties this ratio is at least 57% of the interviewed.

21: Certification Certification is by most parties in the down left quadrant, this implies that this is not important. All interviewed at Consultancy & engineering firms see certification as a driver and 20% sees this as important driver.

23: EMVI/Contract EMVI/ contract drivers are not once mentioned by girder suppliers. In comparison with the contractors this is a big difference, which named this driver in the overall top 3 drivers. An explanation for this is that the girder suppliers seldom have a contract directly with the client and therefore do not profit from this driver.

26: Circular ideology Circular ideology is mentioned second in occurrence when looking at the combined results of every party. It therefore stands out that the girder suppliers do not mention this driver as most important.

APPENDIX D: THE THEORY OF THE DOUBLE DIAMOND METHOD

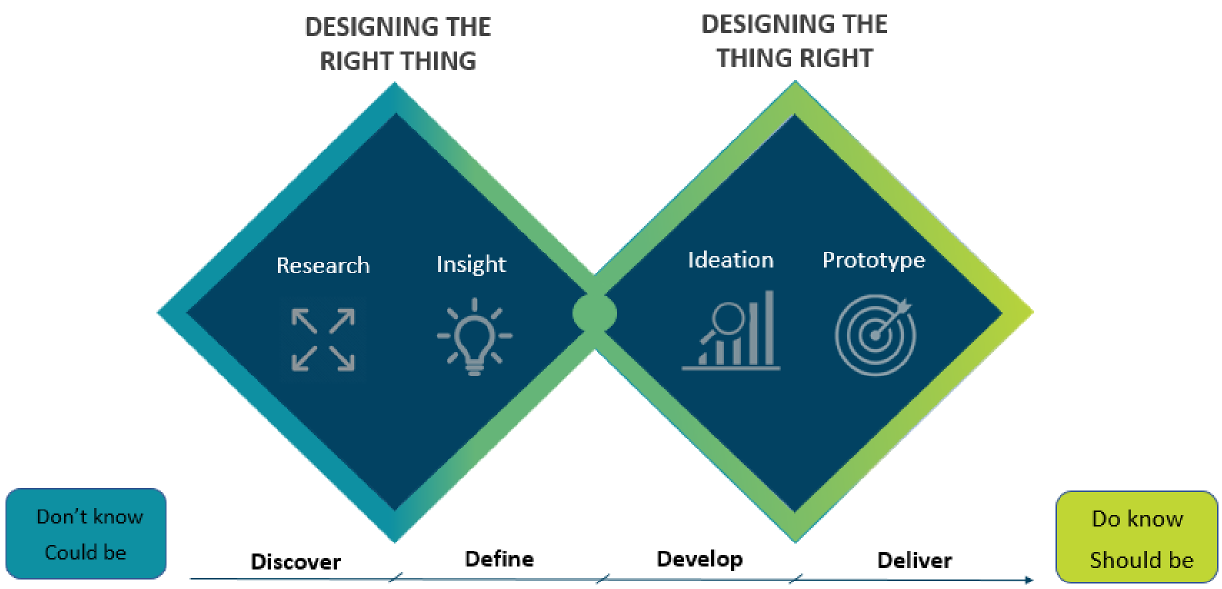


Figure 18 Double diamond method (made by author)

3.2.1 THE DISCOVER AND DEFINE PHASE

In the first part of the research the scope will diverge. The goal of this stage is to acquire more knowledge through literature and short interviews with relevant stakeholders, such as practitioners and academics. Diverse research methods will be used to collect data and analyse data, which will be further explored in paragraph XXX. The problem analysis starts with the selection of key people to identify which perspectives have to be included. The discover phase asks for methods to retain the perspectives of research and practitioners open for ideas to the problem. The following perspectives in relation to the subject of this thesis are identified as most relevant for the infrastructure sector: the contractors' perspective, the clients' perspective, and the suppliers' perspective.

To get insight in the practical problem, literature research is combined with the practitioners' perspective. The background knowledge of the circular economy barriers and drivers in infrastructure projects is investigated during the discover phase. Additionally, the results of semi-structured interviews with experts will be included to give insight of the specific barriers and drivers on reuse construction elements in the Dutch infrastructure. The requirements to be called an expert in this research are defined in paragraph XXX.

In the define phase the perspective of the most important stakeholders will be identified by conducting semi-structured interviews with experts for practice. In paragraph XXX the semi-structured interview is further discussed.

3.2.2 THE DEVELOP AND DELIVER PHASE

The third stage is called the develop stage. In this part of the research all possible solutions are investigated. The scope of the research widens again and every possible solution is stated. All the solutions are clustered and reviewed with the impact-feasibility matrix.

After identifying the barriers and drivers, all possible solutions are viewed in a divergent stage of the develop phase. The best or integral solution can be formed in the fourth and final phase of the Double Diamond methodology. In the deliver phase the solution will take shape and can be validated.

APPENDIX E: CODING OF THE INTERVIEWS

Every transcription is fully coded but not all mentioned arguments are included in the main results. To make a fair comparison every subcategory is counted once if the interviewee mentions the subcategory. This ensures that a frequently mentioned barrier or driver in one single interview does not affect the overall results of the interviews combined.

1. Open coding - Open coding is a common first step in the analysis of qualitative research and is often used as the initial coding pass in Grounded Theory. With open coding, the date is broken into discrete parts and create "codes" to label them. As its name would imply, open coding is meant to open up to new theoretical possibilities, as this is the first engagement with the qualitative data. The purpose of breaking up the data and labelling them with codes is to enable the researcher to continuously compare and contrast similar events in the data. This process forces the researcher out of preconceived notions and biases about your own research.
2. Axial coding - Axial coding in grounded theory is the second step of coding that follows open coding. With axial coding the researcher begins to draw connections between codes. With axial coding, the researcher organizes the codes which are developed in open coding. With axial coding in qualitative research, the researcher reads over the codes and the underlying data to find how the codes can be grouped into categories. A category could be created based on an existing code, or a new more abstract category can be developed that encompasses a number of different codes. After conducting axial coding there will be a number of categories that are supported by a cleaned-up set of supporting codes. These categories are the "axes" around which its supporting codes revolve.
3. Selected coding Selective coding is the last step in Grounded Theory, where the researcher connects all categories together around one core category. In doing so you define one unified theory around your research. Selective coding occurs later on in your research and connects categories you have developed from your qualitative data in previous coding cycles, such as axial coding. The core category that is developed in selective coding may come from elevating one of the categories from the axial coding stage or may be a new category that you derive based on your other categories. The core category ultimately represents the central thesis of the research.

The categories from the literature were clearly visible in the answers. This is also because the categories were used to set up the interview protocol. From the literature four categories were explicated, these categories were the starting point.

- Technical/Information
- Financial
- Institutional
- Organizational

The categories of the literature were not specific enough and in the first phase of coding it became clear that more subcategories were necessary. The literature categories are therefore divided into subcategories as is displayed in figure 11.

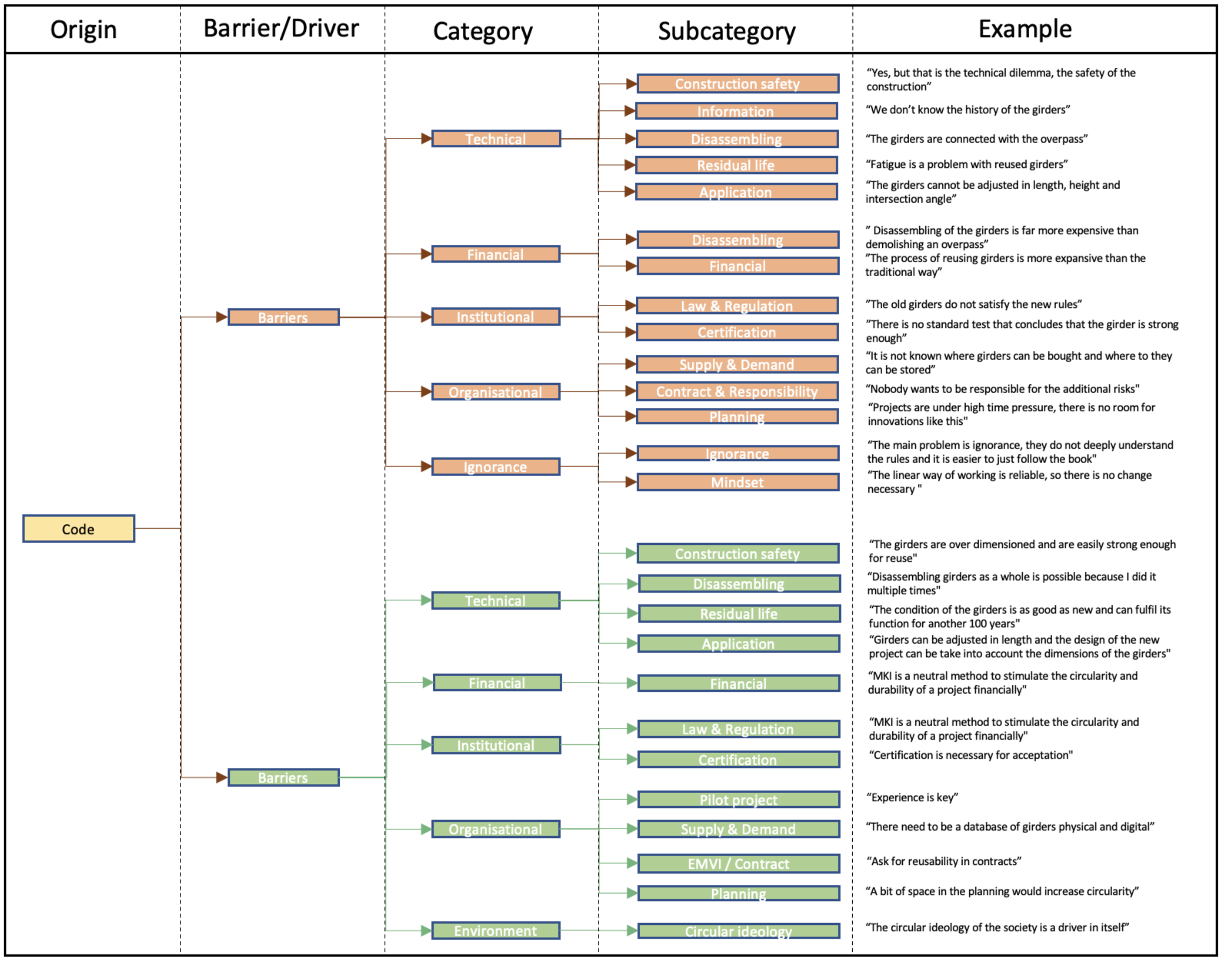


Figure 19 Overview coding categories and subcategories

Two types of coding

The reason to code a part of the transcription can be split into two, direct coding and indirect coding. The coding types are explained in the following 2 sections.

Direct coding

The first reason to code a part of the transcription is because a word triggered the thought of a subcategory. An example of this type is set out below.

"It is very hard to disassemble an overpass because the girders became part of the whole construction. They are connected and are not easily detached."

The word that triggered the subcategory was disassemble. This part of the transcription is added in the subcategory, disassembling technical.

There are a lot of terms that induced a certain subcategory. The trigger words are displayed in Dutch in the tables below.

Table 22 Direct coding trigger words per subcategory

Barrier category	No.	Barriers	Terms and corresponding variations
Technical	1	Safety of the construction	"dwarskracht", "veiligheid", "veiligheidsfactor", "constructieve veiligheid",
	2	Missing information	"Informatie", "data", "gegevens", "Geschiedings", "historie", "vorige leven", "vroeger"
	3	Disassembling technical	"Einddwarsdrager", "druklaag", "natte knoop", "verbinding", "monoliet verbonden", "natte verbinding"
	4	Residual life	"Staat", "beoordelen", "tweede leven", "carbonatatie", "chloride", "vermoeiing",
	5	Application	"Toepassen", "inpassen","aanpassen", "toepassing", "inkorten", "verlengen",
Financial	6	Disassembling	"onderdeel van totale constructie", "demonteren", "druklaag", einddwarsdragers", "voertuigverliesuren",
	7	Financial	"Economische wijze", "Economisch haalbaar", "financieel", "financiële", "kosten"
Institutional	8	Law & Regulations	"Regelgeving", "aantonen", "ROK", "RBK", "CUR", "CROW", "bouwbesluit", "Eurocode", "NEN", "toepassingsnorm", "voldoen", "wettelijke afspraak", "betonregelgeving"
	9	Certification	"Meten", "Metingen", "controle", "controleren", "verifiëren", "KOMO keurmerk" , "KOMO-Keur",
Organizational	10	Supply & Demand	"Vraag en aanbod", "opslagterrein", "opslag",
	11	Contract/Resposibility	"contract", "verantwoordelijkheid", "risicodrager", "garanderen", "garantie",
	12	Planning	"duurt langer", "kost meer tijd", "tijdrovend", "tijdsintensief",
Ignorance	13	Ignorance	"onwetendheid", "niet weten", "niet begrijpen",
	14	Mindset	"mindset", "niet willen", "tegenwerking", "geen aandacht"

Table 23 Direct coding trigger words per subcategory

Driver Category	No.	Drivers	Terms and corresponding variations
Technical	15	Safety of the construction	"Risico", "veiligheid", "veiligheidsfactor", "constructieve veiligheid",
	16	Residual life	"Staat", "beoordelen", "tweede leven", "carbonatatie", "chloride", "vermoeiing", "garanderen", "garantie",
	17	Dismantling technical	"onderdeel van totale constructie", "demonteren", "druklaag", einddwarsdragers", "voertuigverliesuren",
	18	Application	"Toepassen", "inpassen","aanpassen", "toepassing", "inkorten", "verlengen",
Financial	19	Financial	"Economische wijze", "Economisch haalbaar", "financieel", "financiële", "kosten", "materiaalkosten"
Institutional	20	Law & Regulations	"Regelgeving", "aantonen", "ROK", "RBK", "CUR", "CROW", "bouwbesluit", "versoepeling", "Eurocode", "NEN", "toepassingsnorm", "voldoen", "wettelijke afspraak", "betonregelgeving", "NTA", "Parijsakkoord"
	21	Certification	"Meten", "Metingen", "controle", "controleren", "verifiëren", "KOMO keurmerk" , "KOMO-Keur"
Organisational	22	Pilot project	"SBIR", "pilot", "onderzoeksproject", "ervaring", "van Hattum en Blankevoort",
	23	EMVI	"Gewaardeerd", "uitvraag",
	24	Supply & Demand	"Vraag en aanbod", "opslagterrein", "opslag",
	25	Planning	"extra tijd", "meer ruimte", "minder druk"
Environment	26	Circular ideology	"circulair", "circulaire gedachtegoed", "gedachtegoed" ,

Indirect coding

The second reason to code a part of the transcription is because there is an indirect link between the subcategory and the transcription part. An example in the form of a citation is given below.

"The time when you could say: it is a durable structure because of a couple of solar panels on the roof, has passed. We now have to go a step further. "

This is an example of an indirect code for the driver subcategory circular ideology.

Appendix F: INTERVIEW PROTOCOL IN DUTCH

Allereerst bedankt voor het vrijmaken van tijd om bij te dragen aan dit onderzoek. Voordat we beginnen met het interview zou ik willen vragen of het mogelijk is om dit gesprek op te nemen. Met behulp van de opname kan ik het interview later transcriberen en dit zal ik naar u opsturen ter verificatie van ons gesprek vandaag. Alle resultaten en citaten afkomstig uit dit interview zullen geanonimiseerd worden.

VOORSTELLEN

- Master Construction Management & Engineering aan de TU Delft
- Bachelor Civiele techniek gedaan, onderzoek naar betonstromen en samenstelling van beton in stage bij Mobilis.
- Nu afstudeerder bij Royal HaskoningDHV, onderzoek naar belemmeringen van het hergebruik van constructie elementen

De uitvoering van dit onderzoek in samenwerking met Royal HaskoningDHV – SBIR Het circulaire viaduct. De SBIR staat voor Strategisch Business Innovation Researchproject, en deze is uitgevraagd door Rijkswaterstaat. De vraag is om een circulair viaduct te maken. Hiervoor hebben zich meer dan 30 bedrijven ingeschreven en zijn er 10 doorgegaan naar de tweede ronde. We doen nu een haalbaarheidsstudie en proberen bij de derde en laatste ronde te komen waar een pilotproject van het idee wordt gebouwd.

Doel interview

Het doel van mijn onderzoek is om te onderzoeken waarom er nog nooit liggers van viaducten zijn hergebruikt in een nieuw viaduct van Rijkswaterstaat. Ik wil de kansen en belemmeringen onderzoeken en kijken of er oplossingen zijn om die belemmeringen op te heffen en circulair viaducten te bouwen binnen deze generatie. Mijn onderzoek bestaat uit een literatuuronderzoek en interviews zoals deze om data te verzamelen over de mogelijke kansen en belemmeringen. Om inzicht te krijgen in de verschillende perspectieven van opdrachtgevers, ingenieursbureaus, aannemers en leveranciers is gekozen om semigestructureerde interviews af te nemen met verschillende partijen.
Het doel van het gesprek is om inzicht te krijgen in de belemmeringen en kansen die stakeholders van de infrastructuursector zien.

Structuur

Het interview bestaat uit drie delen. Het eerste deel zal ik brede vragen stellen over uw ervaringen met circulariteit en hergebruik van prefab liggers van viaducten. In het tweede deel zal ik ingaan op antwoorden die u gegeven heeft in het eerste deel. Bij de afsluiting van het interview en wil ik u nog een laatste vraag stellen over de genoemde kansen en belemmeringen. (Rangschikken van belemmeringen).

PART I – Intro en Barriers & Drivers

Intro

- Wat is uw functie binnen uw organisatie en hoelang bent u hier al werkzaam?
- Wat verstaat u onder circulariteit in de infra sector?
- Wat zijn uw ervaringen met circulariteit en hergebruik?
- In hoeverre bent u actief bezig met de mogelijkheden van hergebruik van viaductliggers/constructie elementen?
    - Ervaart u hierbij moeilijkheden?

Barriers & Drivers

1. Wat weerhoudt u ervan om effectief liggers uit viaducten her te gebruiken?
2. Wat stimuleert juist om liggers uit viaducten her te gebruiken?

Gelijk doorvragen op genoemde kansen en belemmeringen.
Ander niveau: Aan de hand van scenario's kunnen meer kansen en belemmeringen genoemd worden door de geïnterviewde.
In de volgende scenario's gaan we uit van viaductliggers van 40-60 jaar oud. (Dit zijn momenteel de meest voorkomende viaducten met liggers die gesloopt worden)

Scenario's

1. Gedemonteerde liggers kunnen niet gelijk in een volgend project toegepast worden, deze moet eerst voor onbekende tijd opgeslagen worden op een opslagterrein.
2. Gedemonteerde liggers kunnen gelijk in een volgende viaduct toegepast worden, maar dit viaduct heeft een andere kruisingshoek dan het originele viaduct.
3. Gedemonteerde liggers kunnen gelijk in een volgend viaduct toegepast worden, maar de liggers zijn iets (0-2m) te lang.
4. Gedemonteerde liggers kunnen gelijk in een volgend viaduct toegepast worden met dezelfde kruisingshoek

Als er niks bedacht kan worden kan het lijstje met categorieën worden genoemd voor inspiratie.
Een vraag wordt dan bijvoorbeeld:
Uit de literatuurstudie is gebleken dat er veel organisatorische kansen/belemmeringen zijn die te maken hebben met de samenwerking van bedrijven.

- Wat zijn volgens u belemmeringen in deze categorie?
- Wat zijn volgens u kansen in deze categorie?

Technisch/informatie	**Financieel**
Technisch niet haalbaar	Extra kosten door andere processen
Geen informatie over beschikbare liggers?	Financiële risico's
Geen informatie van een te slopen viaduct.	Levenscyclus van projecten
Rest levensduur moeilijk te bepalen	Processen en interne organisatie
Institutional	**Organisatorisch**
Aanbesteding / specificeren van projecten	Wordt niet gevraagd in tenders/projecten
Huidige contractvormen	Samenwerking bedrijven
Contractuele afspraken	Beton keten niet ingericht voor hergebruik
Nieuwbouw normen	

3. Wat is uw toekomstperspectief ten aanzien van de toepassing van hergebruikte liggers in viaducten in de infrastructuur sector?
    a. Hoe wegen de belemmeringen af in relatie tot de kansen?

PART II – SPECIFIC BARRIERS AND DRIVERS

Doorvragen op Part II van het interview.

- Voorbeelden vragen
- Concrete feiten waarop men zich baseert
- Steeds met andere voeding op dezelfde vraag terugkomen

Part III - Rangschikken

Ik wil u als laatste graag vragen om de belemmeringen en stimulansen te rangschikken,

- Wat zijn volgens u de grootste belemmeringen voor het hergebruik van prefab liggers uit viaducten?
    - Alle genoemde belemmeringen uit Part I & II opnoemen
- Wat zijn de grootste stimulansen voor het hergebruik van prefab liggers uit viaducten?
    - Alle genoemde stimulansen opnoemen.

AFSLUITING

Bedankt voor uw tijd en deelname. Ik zal het interview transcriberen en vervolgens naar u toesturen ter beoordeling. Uiteraard zal u bij afronding van het onderzoek een kopie ontvangen.

APPENDIX G: REAL TIME CASE STUDY EXPLANATION

A girder overpass in the trace Badhoevedorp–Diemen will be removed because this trace is under construction. The A9 is a highway near Amsterdam of approximately five kilometers in length. The plan is to make a tunnel to restrain the traffic noise between the Bijlmer district and the district Holendrecht. An additional benefit is the area development above the tunnel and the connection between both districts. The subject of this case is to investigate the processes of deconstructing the girders of the A9 and finding a match for the free girders originating from the demolished overpass. The effect in terms of money and environmental impact is measured and mapped out with help of demolition contractor Vlasman.

An overview of the case location is displayed in figure X. The yellow circle points out the location of the overpass that is being demolished.

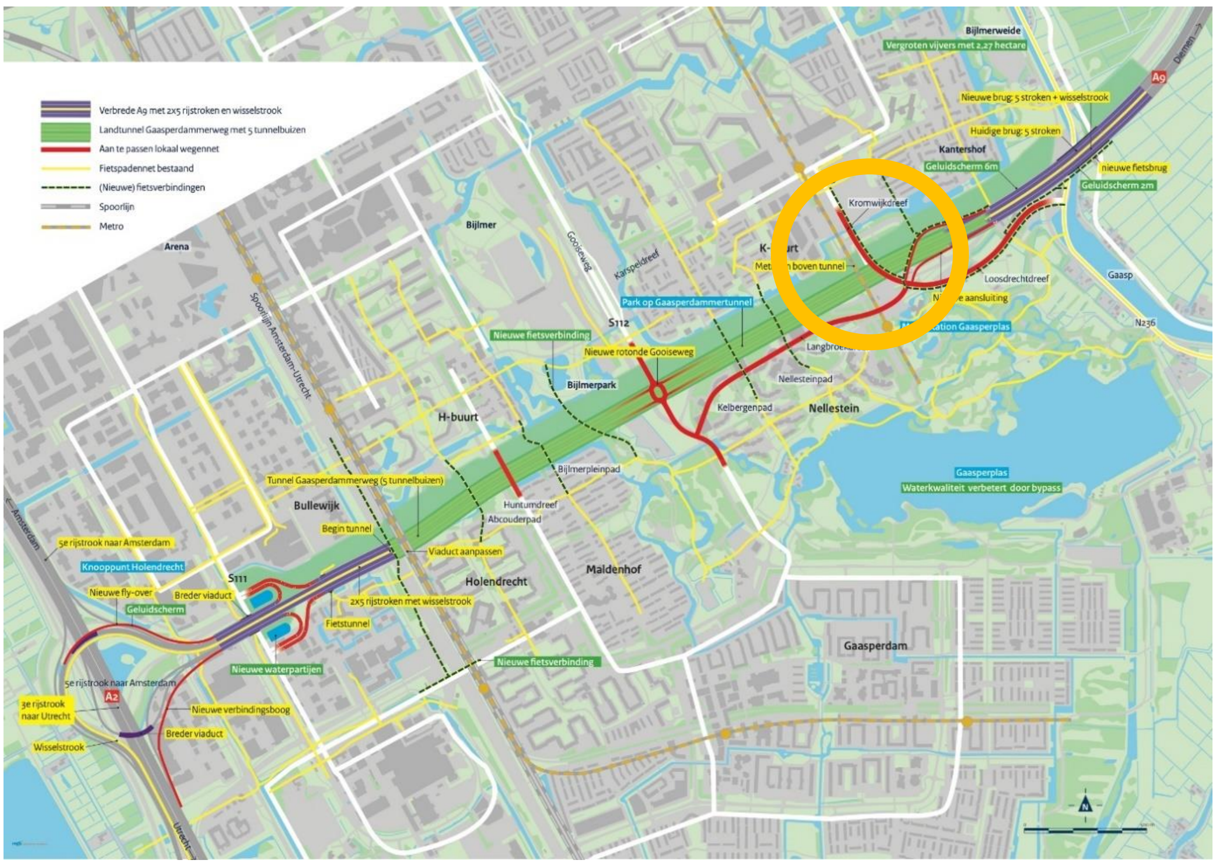


Figure 20 Girder viaduct in the A9 Holendrecht-Diemen

The overpass is February of 2021 disassembled. The girders were stored in a storage yard in Almere where the girders can be certified and repaired if necessary.

APPENDIX H: CHAIN OF EVIDENCE DESIGN PHASE

In the design phase the interviews are used to collect all possible solutions to enhance the main drivers and to diminish the key barriers. This is done with the code, 'solution'. In Appendix E is explained when this code is applied and what is the trigger to code the section of the interview. In paragraph 4.3.2 is stated which solutions are provided by the interviewees. In this appendix the solutions provided by the interviewees are described, grouped and analysed.

APPENDIX I: DESCRIPTION OF SOLUTIONS FEASIBLE FOR MARKET

In the develop phase of the double diamond method, an evaluation of the proposed solutions took place. The potential solutions that could not be executed by the author are not forgotten but explained in this appendix.

8	Disassemble and reconstruct	Active	18	17
12	Adapt new design to current elements	Active	17	18
14	statisch onbepaald constructies, statisch bepaald toepassen	Active	18	20
16	Calculate until you satisfy the underlying norms	Active	18	18
24	Voertuigverliesuren cadeau	Active	17	12
25	Certificering the girders	Active	18	10
27	Adjustment Current law & regulation	Active	14	13
28	Other application than highway network of Rijkswaterstaat	Active	20	20
29	Accept renovation level regulation	Active	20	17
32	Not all bridges must fulfil the highest safety demands	Active	19	19
33	Client contract, granulate fine	Active	16	12
44	Material passport	Active	18	11
51	Pysical storageyard	Active	20	18
60	MKI methode die echt doet aan hergebruik	Active	16	10
62	Abiotic depletion taks	Active	14	12

APPENDIX J – DIFFERENT TYPES OF GIRDERS APPLIED IN DUTCH INFRASTRUCTURE

The manufacturers of precast bridge girders in the Netherlands each have a package of standard girders that is broadly universal. The exact profile cross-sections differ from each other, but the principle of the solutions is broadly similar. First, the standard girders are treated for their specific field of application with the corresponding spans.

Plate Girder

This type of bridge is often used for lower load classes, Class 45 and Class 30. Plate girder bridges consist of prestressed plates with an in-situ reinforced compression layer. The plates are prestressed in the longitudinal direction. In the transverse direction a reinforcement of FeB 500 is applied. After the prefab slabs have been placed on the abutments, a transverse reinforcement is applied over the slabs. This reinforcement consists of a double net to absorb both negative and positive moments and transverse forces. The compression layer can be poured without further support of the slabs. The thickness of the compressive layer is usually 150 to 200 mm, which amounts to a mass of 3.75 to 5.0 kN/m2 . The pouring of the compression layer is therefore an important loading stage for the slabs. The stresses due to this loading remain throughout the life of the bridge. In this way, a deck structure with different stiffnesses is created in the span direction and the transverse direction. In longitudinal direction, the deck is uncracked due to the prestress in the factory phase. In the transverse direction the deck is reinforced, so that a lower, cracked, stiffness has to be taken into account. Plate girder bridges are used up to a span of approximately 8.0 m. The deck can be applied either statically determined or statically undetermined. In a statically indeterminate design, a joint of approximately 100 mm is maintained at the point of support between the plates. This joint is poured together with the compression layer. This creates a continuous construction in which negative moments can be absorbed by applying support point reinforcement.

Safety beams

The various manufacturers each have their own profiles, which do not differ too much in shape. The system corresponds broadly to the plate girder bridges. The difference lies in the capacity of the girder to carry the bulk weight even with a larger span without taking away a large part of the bearing capacity of the bridge. The profile consists of an inverted T-beam. The beams are laid side by side. The lower reinforcement is inserted through notches in the ribs. The top reinforcement is placed over the girders. Then the space between the ribs of the T's is filled up to about 80 mm above the girder. This creates a monolithic plate bridge. The properties of the plate are different in the span direction and in the transverse direction. In the longitudinal direction the bridge behaves like a prestressed plate. In the transverse direction a reinforced plate is created with a construction height that is equal to the total plate thickness minus approximately 120 mm. This is the thickness of the bottom flange of the girders. The joint between the bottom flanges of the beams is not filled. Composite beams can be used up to a span of about 16.0 m. They can be either statically determined or fabricated. They can be used either statically determined or statically undetermined, see Appendix I, page 19.

T-Girders

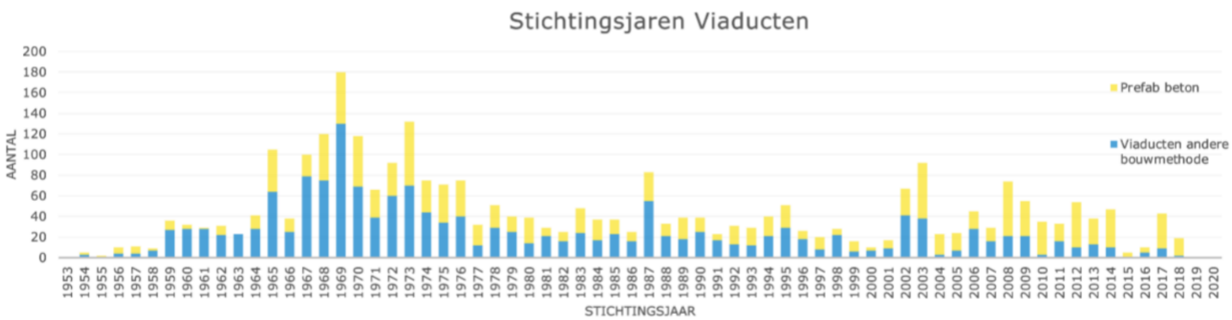
The T-girders are placed next to each other and given a compression layer at work. This creates a deck construction. In general, T-Joists are used for bridges with a lower traffic class and where the available construction height is large. They are also used as edge - beams at a T girder deck. T-girder decks are not suitable for statically indeterminate construction. At the bearing location, the beams are often connected by an in-situ transverse beam. In the construction phase and during the pouring of the compression layer, the stability of the beams must be ensured. Because the beams are set on the relatively narrow underside, they are susceptible to overturning. T-Joists are not very suitable for carrying collision loads. According to the Concrete Bridge Regulations (VBB) [13.1], bridges and viaducts passing over a road should be checked for the special load case of collision. For freeways, a collision load of 2000 kN with a load factor of = 1.0 should be considered. Because the lower flanges of T-girder bridges are not interconnected, the collision load must be transferred to the upper flange by one girder body. This is virtually impossible for this large load or involves very heavy bracing reinforcement in the web of the girders. The application is therefore suitable for locations where there is no danger of collision.

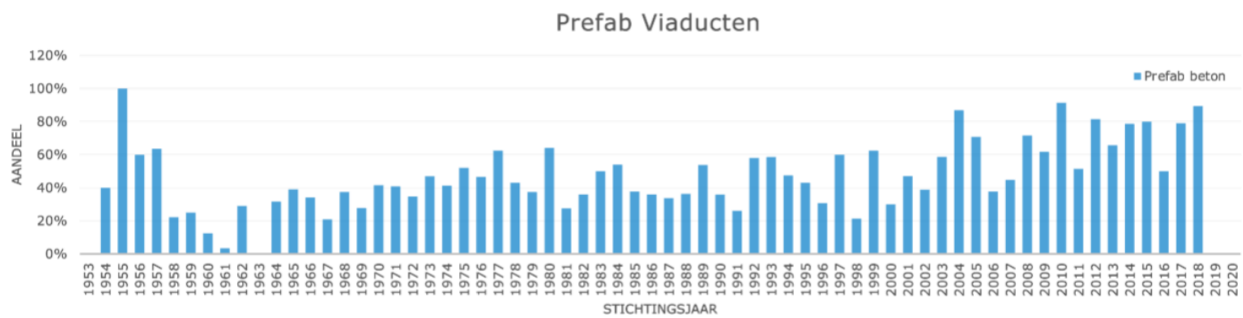
Reversed T-Girders
Reversed T-Joists are laid and pressure-coated in the same way as T-Joists. The difference is that a formwork has to be placed between the girder plates. Where the underside of the deck is closed, permanent timber formwork is usually used. For girder spacing greater than the gap width of the beams, a concrete formwork slab is used whose reinforcement is also utilized at the final stage. This type of girder is the most economical solution for bridge decks with spans between 16.0 and 35.0 m with sufficient construction height. The available construction height is determined by the client. In many cases a bridge or even more often a viaduct has to be provided with raised ramps to allow a free crossing. The height of the ramps is limited as much as possible in order to obtain an economically optimal design. This may lead to the abandonment of the most economical choice for deck construction where inverted T's are replaced by box girders, with their lower construction height. This type of girder can easily be made suitable for accommodating impact loads. The joints between the bottom flanges of the girders are filled with mortar to form a complete disc over the entire surface of the bridge. This disc can distribute the impact loads acting on the center of the girders over all the bearing blocks. At the location of the bearings, the inverted T-beams are provided with cross girders. Through the cross girders a reinforcement is placed which can serve as a suspension reinforcement to distribute the horizontal impact force over the bearing blocks (see Fig. 13.001). Because the construction of the bridge deck takes place in two phases, this should be included in the calculation. Age and concrete strength class differences between the girders and the subsequently poured deck also lead to internal stresses due to shrinkage and creep.

Box girders
Box girders form a complete precast concrete deck on site. The beams therefore do not need to bear the pouring load of a compression layer in the construction phase. As a result, the full capacity of the beams can be used to carry the variable load. This results in a small construction height. The hollow space in the girder is obtained either by using a polystyrene core or by casting the girder in two stages. In the latter case, a U-shaped section is produced first. As soon as this has hardened sufficiently (after about 3 hours) the deck is poured on a lost formwork. The end of the box girders is solid over a length of approximately 1.0 m. Two types of cross bracing are used to assemble the girders into a deck:

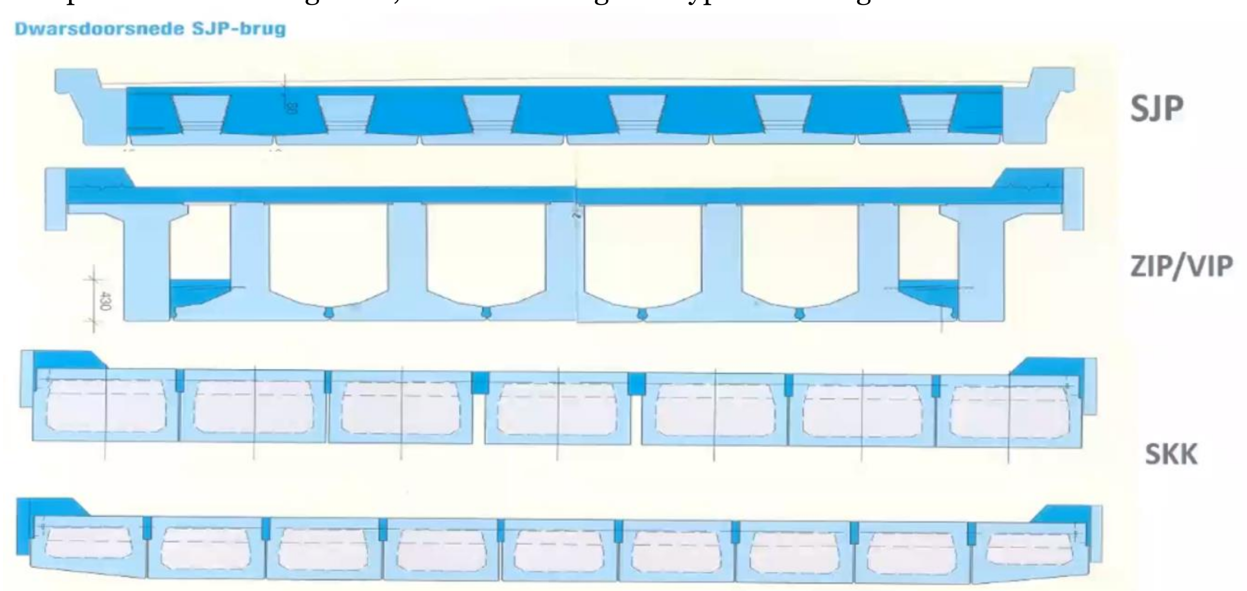
- Sleeves with reinforced joint Here, the beams are provided with laterally projecting reinforcement from the top flange. The beams are placed side by side and the joint is cast in situ.
- Transverse prestressing The transverse connection of the beams here consists of prestressing. The prestressing is carried out through slots in the deck of the girder. The joint between the beams is cast with a low shrinkage mortar.

Precast girders in the Netherlands over time can be seen in the figures below.





Different types of precast girders are displayed in the figure below. The top two girders are examples of reversed T-girders, the lower two girder types are box girders.



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