1 Introduction

This chapter provides an introduction to the research. The research topic and the research aspects are briefly introduced. The changing role of the architect in the field of bridge design is analysed in an historical context. The role of the commissioning authorities is introduced. The problem of segregation of knowledge is introduced. The objectives and research questions are stated, a hypothesis is formulated and the methodology is discussed. Furthermore, an outline of the dissertation is provided.

The basis of this chapter was laid in 2009 when parts of it were published as a chapter in the book: Bruggen 1950-2000. Techniek in ontwikkeling (Zutphen: Walburg Pers, 2009, 267 (1), 366 + dvd (2) blz., ISBN 978 90 5730 631 0 (1), ISBN 978 90 5730 632 7 (2)).

§ 1.1 Bridges for growth

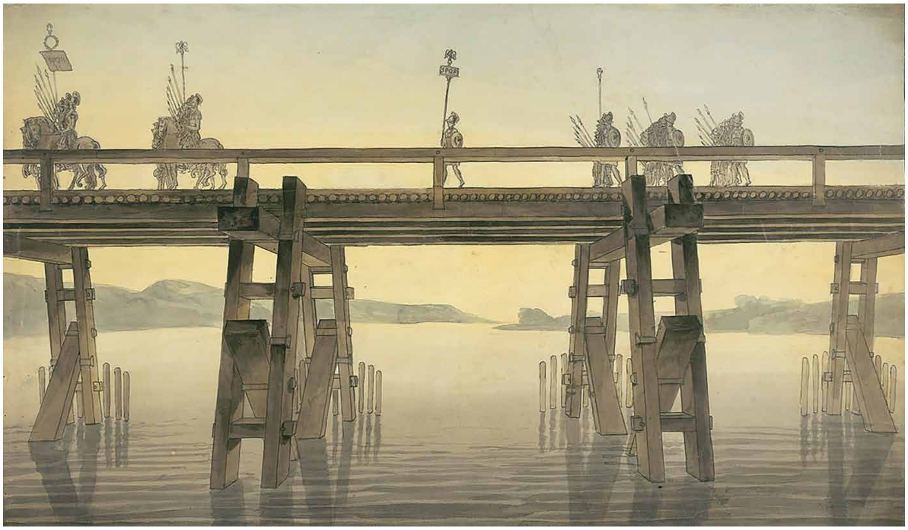

FIGURE 1.1 Artisit impression of Julius Caesar's Rhine Bridge, by John Soane (1814)

It is hard to imagine a world without bridges. Bridges lie at the very heart of our civilization bringing growth and prosperity to our society. It is by virtue of bridges that communities were able to physically connect to new people and to new places that were previously disconnected. However, bridges are more than mere functional assets. A well designed bridge reflects mankind's creativity and ingenuity. One could even state that the way bridges are designed tells us something about our identity [1].

The first bridges to be built by humans lie beyond historical records. In the early days of mankind one of our ancestors might have stumbled on a tree trunk fallen across a stream, or decided to lay flagstones across a wild ford to access new hunting grounds. Much later, when people began to organize themselves in permanent settlements and started to develop culture and trade, roads and bridges became quintessential for growth. All great civilizations in history thrived by means of a dependable infrastructural network that enabled swift mobility of goods and people. The ancient Romans knew this all too well. When Gaius Julius Caesar had submitted all of Gaul in 51 B.C. he had done so by means of efficient Roman highways that enabled his legions to travel great distances and to strike fast. The military bridges of those days were functional wooden structures that could be erected by skilled forces in little time.

Famous are the two wooden bridges that Caesar built in 55 and 53 B.C. to engage the Germanic tribes across the Rhine (figure 1.1). It took his soldiers and craftsman only ten days to build these multiple span bridges, and less to destroy them on their retreat. Directly in the wake of the conquest of Gaul came trading, civil servants and civilians, allowing Roman settlements to thrive in new territories. Roman roads were a marvel of technology, they were paved in stone, cambered, and flanked by footpaths, bridleways and drainage ditches. They were laid-out according to accurately surveyed alignments, cutting through hills, with permanent bridges and viaducts carrying them over rivers and ravines. These bridges and aqueducts were true works of art, skilfully crafted with highly precise and mortarless stone arches many of which still stand today.

From Antiquity all through to the late Middle Ages, the task of designing a bridge would typically be that of one person, usually referred to as the master builder. There was no distinction between technique and aesthetic design, the master builder was architect and engineer at once [2]. It wasn't until the late 18th century that the métier of the architect and that of the engineer went separate ways. When in 1794 the 'école *polytechnique*' was founded in Paris, followed by the 'école *des beaux art*', the division between the arts and technology became a fact. Two stand-alone educations for architects and engineers arose and other universities in Europe soon followed this example. The schism between architects and engineers remains the current practise until today and forms the premise of this dissertation.

§ 1.2 The architects role; from cosmetic advisor to design integrator

In the last two decades we have seen that bridges have become a trend-setting factor in the public realm. The time that bridges were designed as mere functional objects is past. Politicians and policymakers want to make good cheer with beautiful bridges. Whether it is as a part of a new building location, a historical city centre or out in the open landscape, bridges are seen more and more as symbols of culture and heritage. A noticeable trend in bridge design is the growing attention for the urban context or the landscape context. The beauty of the bridge design is taken beyond the architecture of the structure itself; society calls for bridges that are carefully integrated in the landscape or the urban fabric. The design can be subtle, it can be a beacon on the horizon and it can even be an iconic statement. What now is the role of the architect in the design process? In order for us to understand the current position of the architect in bridge design we must first go back in time to the antiquity.

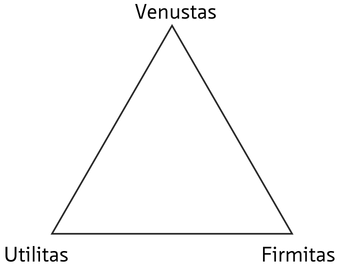

FIGURE 1.2 The Vitruvian adage.

More than 2000 years ago the influential Roman architect/engineer Vitruvius (80-25 BC), wrote his book "*de architectura*" [3]. From his book comes a famous adage that many today believe to be his greatest legacy to contribute to the education of architects. Vitruvius' adage states that in order for a structure to be of lasting value for society, there needs to be a balance between the three powers named *utilitas*, *venustas* and *firmitas* (functionality, aesthetics, firmness) (figure 1.2).

No other author has captured the essence of good design in such clarity. This adage defines the basis of all good design and is still very valid today. Vitruvius meant his adage to be valid for all manmade structures, not bridges in particular, although one can see how this trinity applies to bridge design as well. In the design process of a bridge the three powers are represented by the role of the commissioning authorities, the architect and the engineer. This delicate balance of power has shifted notably over the past 150 years.

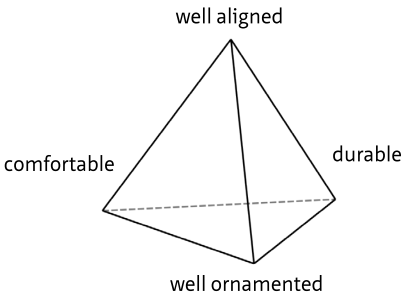

FIGURE 1.3 Palladio's values illustrated.

According to H. Gautier, A. Palladio (1508-1580) is the one exception of an author that writes at some length about bridges in his influential work *Quattro Libri dell' Architettura* (1570) [4]. In this work, Palladio acknowledges that bridges are the main parts of a road, that it is surprising to see that they actually form a path on the water, and that bridges should be; 1st well aligned, 2nd comfortable, 3rd durable and 4th well ornamented (figure 1.3). As we can see Palladio adds the criterium of being well aligned to Vitruvius triangle of Venustas, Utilitas and Firmitas. Being well aligned according to Palladio means that a bridge should cross a stream at an oblique angle and that it should do so without a slope. As for beauty, this Palladio reduces this feature of the design merely to the ornamentation of the bridge. Perhaps Palladio was of the opinion that a bridge that is well aligned and designed according to the forces that act on it is already intrinsically beautiful.

§ 1.2.1 The engineer's era

The separation between the métier of the architect and that of the engineer is not that old and can be dated as precisely as the end of the Middle Ages. The latter, as we have all learned in school, ended in 1492 when Christopher Columbus discovered the Americas. An event of a slightly lesser magnitude ended the era of the Master Builder, who was architect and engineer at once. In 1794 the 'école *polytechnique*' was founded in Paris, followed by the 'école *des beaux art*'. From that date on the formal division between the arts and technology became a fact. Two stand-alone educations for architects and engineers emerged and other universities in Europe followed this example. For instance, in 1842 the forerunner of the present Delft University of Technology was founded after the example of the École Polytechnique in Paris. The school was founded by Antoine Lipkens, an engineer who himself studied at the école polytechnique in Paris. At this school lessons were given in a strict way, often by military staff.

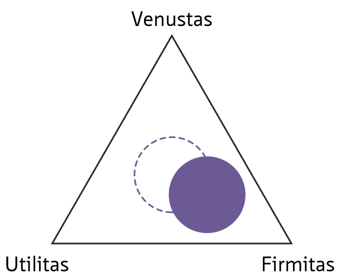

FIGURE 1.4 An engineering approach.

At the start of the industrial revolution in the *fin de siècle*, it was the engineer who ruled the field of bridge design. Technological discoveries, new insights on structural behaviour and new materials as steel and reinforced concrete were his playground (figure 1.4).

Some of these engineers were able to step beyond the boundaries of their discipline and turned out to be true craftsmen with a fine sense of aesthetics. Engineers such as Gustave Eiffel, Robert Maillart and Pier Luigi Nervi designed state of the art bridges. They let themselves be guided by the forces at play in the material and sometimes literally shaped those forces. The Salginatobelbrücke in Switzerland from the Swiss engineer Robert Maillart is a fine example of the elegant plasticity that concrete makes possible (figure 1.5).

FIGURE 1.5 Salginatobelbrücke in Zwitserland (Robert Maillart, 1872- 1940). Photo from https://grandtour.myswitzerland.com. visited on 25/02/2019.

Still the vast majority of engineers weren't endowed with such a fine sense of aesthetics [5]. Sometimes this called for the contribution of an architect, whose role was usually limited to the cosmetic upgrading of the final design by means of parapets and the use of colour. Needless to say that the relationship between the engineer and the architect wasn't always obvious and that there was a fair part of suspicion between the two.

An exception to this rule is found in the larger metropolitan cities. Dutch cities such as Amsterdam employed a town planner whom was usually an architect by profession. Such was the case with the Amsterdam town planner Piet Kramer. He built over 300 bridges in the period 1915-1940, the time of the influential *'Amsterdam School'*. Many of his bridges combined architecture with sculpture, such as the famous sculptor Hildo Krop (figure 1.6). H.P. Berlage was another famous town planner. His bridges were foremost objects in the urban fabric, including residential areas, benches and richly ornamented parapets and lampposts. The structure of his bridges was usually in service of the architectonic expression.

FIGURE 1.6 Boerenwetering Bridge in Amsterdam with sculptures from Hildo Krop. Photo from http://adambeeldenva1900.blogspot.com visited on 25/02/2019.

§ 1.2.2 The great wars era

In the era of the great wars and in the first post-war decades, the field of bridge design was dominated by two aspects, a shortage of resources and base materials. With only a few positive exceptions it was the engineer's task to bridge the gap from A to B in the most efficient and in the cheapest way (figure 1.7). Aesthetical aspects hardly mattered and the role of the architect was virtually non-existent. Due to the poor quality of materials at hand the durability of such bridges was quit inferior, not many examples from this era now remain to be seen and those that still stand are often in bad need of replacement or thorough refurbishment.

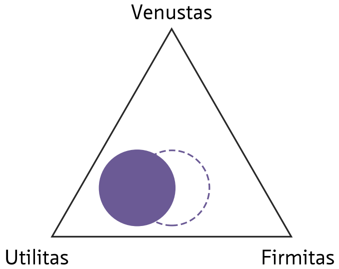

FIGURE 1.7 Shift to efficient and cheap.

The Star Architect's era

A turning point in the unilateral approach to bridge design came to us in the early 90's of the previous century [6]. In the Netherlands, commissioners of infrastructural projects and bridges in particular became culturally aware and were encouraged to do so by the Dutch government. The Spanish architect Santiago de Calatrava had just built his Alamillo bridge in Sevilla. In the Netherlands his former pupil Ben van Berkel completed the design of the Erasmus Bridge in Rotterdam in 1996. Even though the 75 million euro building costs exceeded the costs for a straight forward cable stayed bridge by far, the Erasmus Bridge has become the ultimate icon for the city of Rotterdam and the essential link to the new city expansion on the south shore of the Maas.

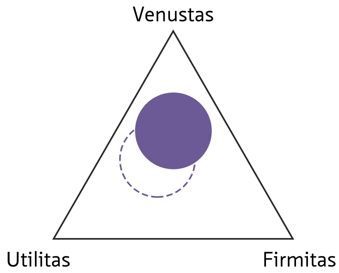

FIGURE 1.8 Architecture as a guiding principle.

All of a sudden it seemed as if architecture and bridge design had rediscovered each other. Al over Europe a huge increase in architectonic bridge design immersed. As if wanting to make up for the lost years when architects were only allowed to operate in the margins of bridge design. This probably explains the overenthusiastic attitude some of these architects manifest when it comes to the structural logic of the design. The shift of power had taken place and it was now the engineer's job to make sure that all the merry creations that architects came up with would not collapse at first sight. The bridge designs that these 'star architects' came up with had to be judged as sheer masterpieces of fine art, with a capital A (figure 1.8). This approach often resulted in structurally absurd bridge designs with an overkill of stay-cables for relatively small spans, arches burdened with point loads or bended compression rods. These are just a few examples of the inability of engineers and architects to speak the same language.

§ 1.3 Commissioning authorities and good procurement

The role of the commissioning authorities in the design process has always been an important one. To put it in terms of Vitruvius, the authorities represent the aspect "Utilitas" that lies at the basis of every bridge design. Until the end of the 20th century it was still common practice for the commissioning authorities to play an active and participating role in the design process. Authorities involved in bridge development were in the lead of the process. Public authorities that wanted a bridge were most of the time not only looking for the cheapest way to get from A to B but were equally culturally engaged to the point of sometimes acting as a patron of arts by instigating fine architecture. Basically the bridge building business was a three-party market economy; the client would commission an independent architectural office and an engineering office to make the design for, and with, the client. At the same time the architect and engineer would play a vital role in contracting, guiding and controlling the building contractor. Although this kind of design approach is still practised at times, Belgian authorities for example still use the three-party market system if they want to stay in the lead of the design, such a practice is unfortunately become more and more rare.

At the beginning of the 21st century the market for infrastructural projects has undergone drastic changes, triggered largely by to the economic recession. Public authorities were forced to downsize their organizations and focus on their core business; initiating infrastructural projects and securing an affordable result. Thus the authorities retreated from their participating role to make way for the market economy. Basically the 20th centuries three-party market had changed into a two-party market; on the one hand there is a public authority in the role of the commissioner of the bridge and on the other hand there is the contractor or commissionee (figure 1.9).

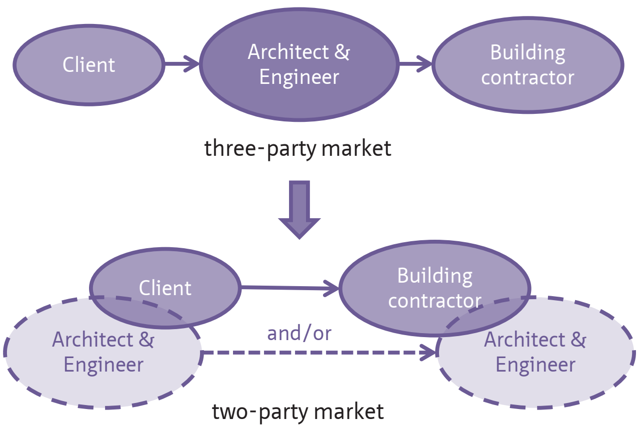

FIGURE 1.9 The transition from a three-party market to a two-party market.

The authorities had changed from an active partner in the design process into the initiator and facilitator of a process. Authorities no longer assume the responsibility for the design process.

In the Netherlands the former Director General Bert Keijts of Rijkswaterstaat (Ministry of Infrastructure) introduced the adage 'market, unless' between 2003 and 2010, pleading for maximum of freedom for the contractors to develop the most efficient and cheapest solutions. His successor Jan Hendrik Dronkers then turned back 'market, unless' and put the emphasis back on 'working together with the market'. Dronkers still found the introduction of integrated contracts a good idea, in which the roles have changed and the market has been given much more room for manoeuvre, "*Nobody is going to turn that back.*" according to Dronkers. To date, Rijkswaterstaat still works as a standard with D&C contracts. And as always, lesser authorities like provinces and municipalities follow the path led by Rijkswaterstaat.

When it comes to the role of aesthetics in integrated contracts we can see that the authorities are still searching for the best place to secure good design in the process, as much as they are searching for their own role and responsibility. In the early years of D&C contracts we have seen some very badly designed infrastructural projects in the Netherlands. The High speed railway line HSL near Zoetermeer-Bleiswijk (2000-2009) is such an example (figure 1.10). Here we see that aesthetics were clearly left out of the equation. The railway fly-over does not respect the laws of rhythm and symmetry and displays a haphazardous sequence of pillars and prefabricated beam in various depths with no attempt to bring harmony or to integrate it into the landscape. The unfortunate conclusion of the 'market unless' approach was that by taking a step back and leaving the design process to the market the authorities are no longer in control of the design.

FIGURE 1.10 HSL railway line near Zoetermeer-Bleiswijk, 2000-2009. Photo from https://mapio.net/images-p/85420570.jpg visited on 25/02/2019.

In later examples of D&C contracts authorities have tried allocating fictional price reductions by introducing EMVI scores for aesthetics. This strategy obliged the contractors to hire an architect in order to secure the price reduction. The problem with this scheme is that authorities had to indicate to what criteria a tender design will be judged. For this reason vaguely formulated sentences as '*we are looking for unity in diversity*' were part of the tender specifications for the new A50 bridge across the Waal at Ewijck-Valburg (2010-2013) that was to be built adjacent to the old cable stayed bridge (figure 1.11).

FIGURE 1.11 A50 bridge at Ewijk - Valburg, photo by Thea van den Heuvel/DAPh 2014.

The steering mechanism of the architectural design consisted of the introduction of the so called 'pro-competitive dialogue' with the contractor and their architect. However, from first-hand experience of the author of this dissertation, these dialogues are better described as monologues were the contractors' architect presents a proposed design whilst the authorities are shy to comment, for fear of legal repercussions if too much steering would have given the competition legal arguments to contest the outcome. The result of this kind of 'pro-competitive dialogue' is that contractor and architect are left pretty much in the dark when it comes to assessing what the client would like to see. The disappointing configuration of the winning design proved that what the client was looking for was something almost, but not quite, the same as the original bridge. The result does not convince as the composition of the original two steel pylons, solitary and slender, is not complemented nor enhanced by the addition of twice as many and slightly heavier concrete pylons with twice the amount of cable stays.

After the first child sicknesses of D&C contracts had been cured, authorities took back some degree of control over the aesthetical design by taking the drafting of the basic architectural requirements back in their own hands. In the Netherlands these documents are known by the generic term 'Beeldkwaliteitplan' (Plan for the quality of the appearance), or more recently the term 'aesthetical requirements' (AR). These AR documents, while at the beginning vague and multi-interpretable, became more on more concrete over the past years. The recent example of the N31 Traverse in Harlingen (2012-2018) shows that the authorities, in this case an alliance of Rijkswaterstaat, Province of Fryslân and the municipality of Harlingen, commissioned an architectural specification document, drafted by the author of this thesis (figures 1.12, 1.13).

In previous years one might have called such a document an architectural preliminary design. One difference is that these new kind of AR documents that are part of the tendering specifications cannot be specific about the type of construction methods used. The argument is that the benefits of a free market would be lost if the bridge design were to be defined in advance. Architecture is now reduced to the purely cosmetic description of the outer appearance. In AR documents the challenge for the architect and his client is that even though the construction cannot be shown, it still must be explored as the feasibility in terms of finance and constructability must be assessed before the publication of it.

We must now consider what the change to a two-party market means for the role of the bridge designers in the design process, architects and engineers alike. The former position of the bridge designer in the leading role between the authorities and the contractors no longer applies. It seems that nowadays Bridge designers have two choices. Either they supply manpower, knowledge and expertise to the organization of the authorities, thus acting on their behalf by drafting the tender documents, reference designs and in the best of cases including aesthetic requirements. The other choice that bridge designers have is to provide their services as a sub-consultants to building contractors. In this last case the architect and the engineer no longer answers directly to the responsible authorities but rather to the building contractor who in his turn is the commissioner to the architect and engineer. In both cases the architects and engineers are no longer leading in the design process. And in both cases the architects and engineers must make a clear choice on which side to opperate as they can not legally do both.

FIGURE 1.12 Animation from the Architectural Requirements document N31 Harlingen, Royal HaskoningDHV, Joris Smits et al. (2016).

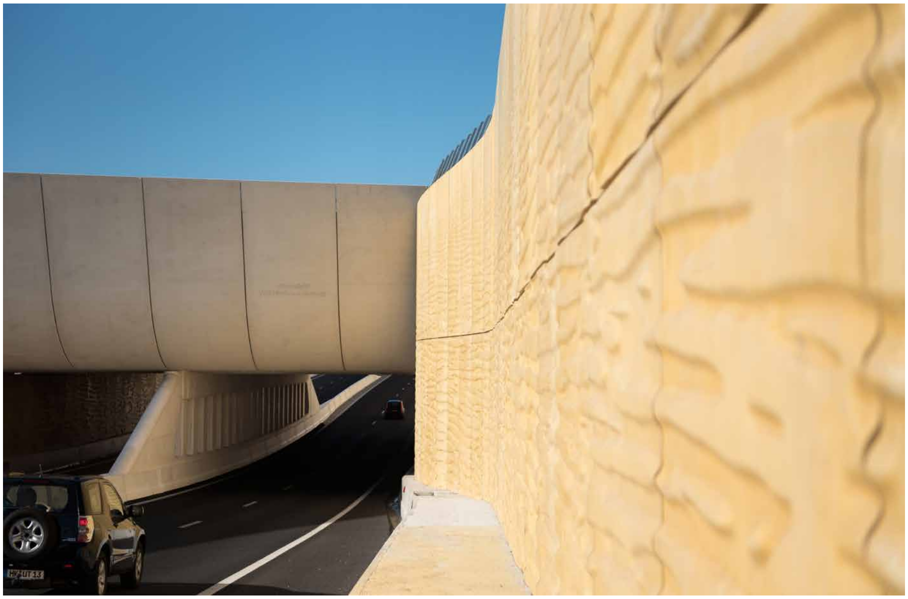

FIGURE 1.13 Traverse N31 Harlingen after realisation. Royal HaskoningDHV, Joris Smits et al. Photo by Jane van Raaphorst 2018.

These developments raise the question of how best to secure good design when commissioning a bridge. In the case that the architect works directly for the authorities, their job is restricted to formulating the requirements for aesthetical quality rather than making an integral bridge design. This kind of conceptual design is per definition limited to the description of the outward appearance of the project, for fear that the benefits of a free market would be lost if the bridge design were to be defined in advance. On the other hand architects working for the contractor within the tender team are usually restricted to the making of the tender design. Once the contract is awarded and the contractor starts on the detailed design and the building phase, there is no good way of controlling the aesthetics of the final product. In the detail engineering phase the winning contractor will mainly be driven by costs and will have little interest in going the extra mile for good design.

So the question that needs answering is how best to ensure design quality in our future infrastructure projects? How can we achieve well integrated bridges and infrastructure that works for the people in the communities, that are valued for their design and aesthetically appearance and at the same time allow the market economy to work? The key to the answer lies in the procurement process were the design quality needs to be secured. One way to achieve that is to claim back the 'D' in Design & Construct contracts, thus transforming them into E&C (Engineer & Construct) contracts. This would be a natural response to the loss of control that authorities experience when they leave everything up to the market, including the design. A next step would be to also claim back the preliminary engineering and cost estimate, thus leaving the detailed design to the market. The opposite approach to reclaiming the design would be to truly leave every aspect of the design process to the market. This can deliver good value if design can be turned into a key assessment for procuring the assignment. This approach resembles architectural competitions, the difference being that all competition entries will be accompanied by a price tag from the building contractors that minimizes the risks of overspending at a later stage.

A good friend of mine and renowned bridge designer from London, Martin Knight, puts it this way: "*Bad procurement is the biggest threat to design quality... The key to good design and procurement is to tie them together contractually, either through the construction contract or, better still, through the planning permission, so that there is an obligation on the contractor, the designer and the client to maintain design quality even as cost and time pressures increase.*" Another great bridge designer from the United Kingdom, the structural engineer Ian Firth, says in his TED talk of June 2018: "*We need to start talking to those who procure our bridges. Procurement is key. Bad procurement is prejudicated against good design.*" [1]

§ 1.4 Problem statement; the segregation of knowledge

After the schism of 1794 (page 6) when bridge engineers and architects went their own ways, bridge technology and material science developed at a fast pace. These developments resulted in a technological field too vast for one person to master. A typical bridge design project nowadays comprises specialists from many different disciplines such as (urban) planners, landscape architects, traffic designers, architects, structural engineers, mechanical engineers and material specialists. All these content experts work alongside the various managers that control the process such as project managers, permit managers, stakeholder managers, procurement managers, tender managers, contract managers and supervisors.

Ideally the design of a bridge is made through an integrated approach that addresses all relevant technological angles and stakeholders. In reality, many different people from many different disciplines work on the design during different phases of the project. The consequences are that the cohesion between the different design aspects often gets lost and that a symbiotic working relation between the different disciplines is missing.

Furthermore, it is noted that under the authority of the commissioning authorities the current practice in the procurement of our bridges does not promote an integrated approach either. In the past two decades we have seen how fragmentation in the design process has further increased due to an equally fragmented procurement approach, reminiscent of the 'divide and rule' policy of colonial times. It is no exception nowadays to commission the drafting of the landscape planning to one party, the writing of the brief of architectural requirements (Beeldkwaliteitplan in Dutch) to the another party, to occasionally commission a reference design to yet another party and to have the final bridge design being made by the architects and engineers that work for the contractor. It goes without saying that such a fragmented approach to procurement is incompatible with good design. And that in turn bad design makes for lowly valued bridges and a decline in public support for new infrastructure.

This leads to the following problem statement: the segregation of knowledge into discipline-specific fields, and the fragmented approach to bridge procurement, have resulted in a general lack of cohesion in bridge design. Furthermore, it is noted that the field of bridge design lacks critical investigation into how to pursue good integrated design.

§ 1.5 Hypothesis; introducing a design integrator for better bridges

The working hypothesis of this research is the assumption that the introduction of a design integrator will lead to better bridges and will increase public support for new infrastructure. If one person could oversee the design process in its entirety by fulfilling the role of design integrator and by defending the design in the public debate, the design process would greatly benefit. The design integrator should not be the omniscient master builder of old, but would instead act as the conscience of the design, the expert who directs and coordinates all design aspects of a bridge.

§ 1.6 Objective

The objective of the research is:

To identify a design approach, through all scales of the design, that leads to bridges that are well-integrated, integrally-designed and that are valued by society.

§ 1.7 Research questions

Accordingly, the objective can be met by answering the principal research question of the dissertation:

How can we identify a design approach, through all scales of the design, that leads to bridges that are well-integrated, integrally-designed and that are valued by society?

The research questions associated with the principal research question are:

1. **What design considerations can be identified for bridges at the scale level of the landscape or of the urban texture, and how can bridges fulfil social, cultural and regional requirements and strengthening regional identity?**

This question is answered in chapter 2.

2. **What design considerations can be identified for the design of a bridge at the scale of the object itself, and how can architectural and structural symbiosis in the design be achieved?**

This question are answered in chapter 3.

3. **What design considerations can be identified for the design of a bridge at the scale of the detail and that of the materialization?**

By taking the example of an innovative material in bridge design, Fibre Reinforced Polymers (FRP), a sub-question can be asked:

What design considerations can be identified to the use of FRP, both as a structural and as a non-structural application, in bridge design?

These questions are answered in chapter 4.

4 **What design considerations can be identified for the design of a bridge at the scale of the chosen materials and of the material properties that constitute a bridge?**

By taking the example of bio-composite, a natural fibre reinforced bio-polymer, a sub-question can be asked:

Can a fully bio-composite footbridge be produced form natural fibres and bio-resins?

These questions are answered in chapter 5.

5 **What design considerations can be identified to achieve a higher standard of durability and sustainability for bridges?**

The answer to this question is discussed in chapter 6.

6 **Will the transformation of the role of the architect as the aesthetical advisor, to the role of the design integrator, lead to well-integrated, integrally-designed and socially-valued bridges?**

The answer to this question is discussed in chapter 6.

7 **How can the commissioning authorities secure the design quality of our future bridges and infrastructural projects?**

The answer to this question is discussed in chapter 6.

§ 1.8 Research method; a project review through lenses and scales

The methodology through which the research questions are answered and the hypothesis is proven is that of a review of projects from my own bridge design practice. The choice to review my own projects is based on the fact that I have been fortunate to work on hundreds of integral bridge projects over the past 22 years, projects that have taken me through all phases of the design; from the initiative phase and the conceptual design at the start, to the detailed design and on site supervision at the end of every project.

The choice to review my own working practice was born out of practical considerations. First of all, the integral design of bridges is an important aspect of my dissertation and there are only two integral bridge design practices in the Netherlands that incorporate every aspect of the design. Of course, there are several architectural practices in the Netherlands that design bridges, just as there are several engineering practices and landscape architectural practices. These practices work in changing constellations on various bridge projects. However, it would have proven to be very arduous and time consuming to interview all these different parties involved in the design of a bridge. The second practical consideration was that I wanted to be able to review in length and detail all the challenges, problems and opportunities that a designer faces within every integral design process during the course of a project. The best way to achieve this was to write about it from the perspective of someone who has been involved in every aspect of the process from first-hand experience. Having said that, it is important from an academic point of view to maintain a critical and unbiased attitude toward the reviews of one's own work. There are in my opinion two factors that are able to create distance and can guarantee an unbiased view: time and knowledge. On the former, I have chosen to review mostly older work from my portfolio, with the exception of the bridges in Fibre Reinforced Polymers for obvious reasons. Being able to look back at my own work from a time induced distance has proven to be a good way to obtain critical and open-minded observations on my own working methods. On the latter, I have found from personal experience that the more you know about a certain art or discipline, the more critical you become to your own performance in this field, and the less likely you become to turn a blind eye on your deficiencies.

The chosen methodology has explicitly not resulted in a comprehensive manual that discusses all the involved disciplines, all bridge typologies and every possible material available to the engineer or architect. Rather, through the method of reviewing my own work, I have aimed to give an insight in bridge design as an integrating discipline. One that is practised across several technical disciplines, seen through various lenses and applied through a multitude of scale levels. For this reason the framework of this dissertation is broad, and focusses on the integration of the various disciplines that are involved in the design of a bridge. Each discipline typically looks at bridge design through its own lens and at its own preferred scale.

The mechanism through which the projects are reviewed and evaluated is based on three Vitruvian lenses and on four scale levels of design. The choice of the various lenses and scales is based on my own experience in the bridge design practice accumulated over a period of 22 years.

The three lenses are derived from the classical Vitruvian values; Utilitas, Venustas and Firmitas (functionality, aesthetics, firmness). In turn, each lens is represented by one or two of the most important actors in terms of content; the architect, the structural engineer, the builder and the client. The client operates from the perspective of Utilitas, asking for a certain functionality to serve the goal within planning and budget. The architects is the keeper of the value Venustas; he or she is in charge of the aesthetics of the bridge and responsible for making a design that is meaningful to the people who use it and contextually aware. The engineer and the builder both serve the purpose of Firmitas; the responsibility for structural integrity and durability lies with them.

The four scale levels are derived from the typical scales through which urbanists, architects, engineers and material experts bring their skills top practice at different phases of the design. In the planning phase of a project, planners, urbanists and architects practise their skills at the scale level of the city and that of the landscape (scale 1:1000). In the preliminary design phase of a bridge, the perspective of the architect is mostly directed at the scale of the bridge itself and that of its direct surroundings, while the engineer operates at the scale of the object itself (scale 1:100). In the detail design phase the architectural and engineering perspective typically zooms in at the structure itself and the forces at play within the structure (scale 1:10). The mechanical engineer and the material expert look at individual components and materials that compose the structure at the level of the mechanical and material properties (scale 1:1).

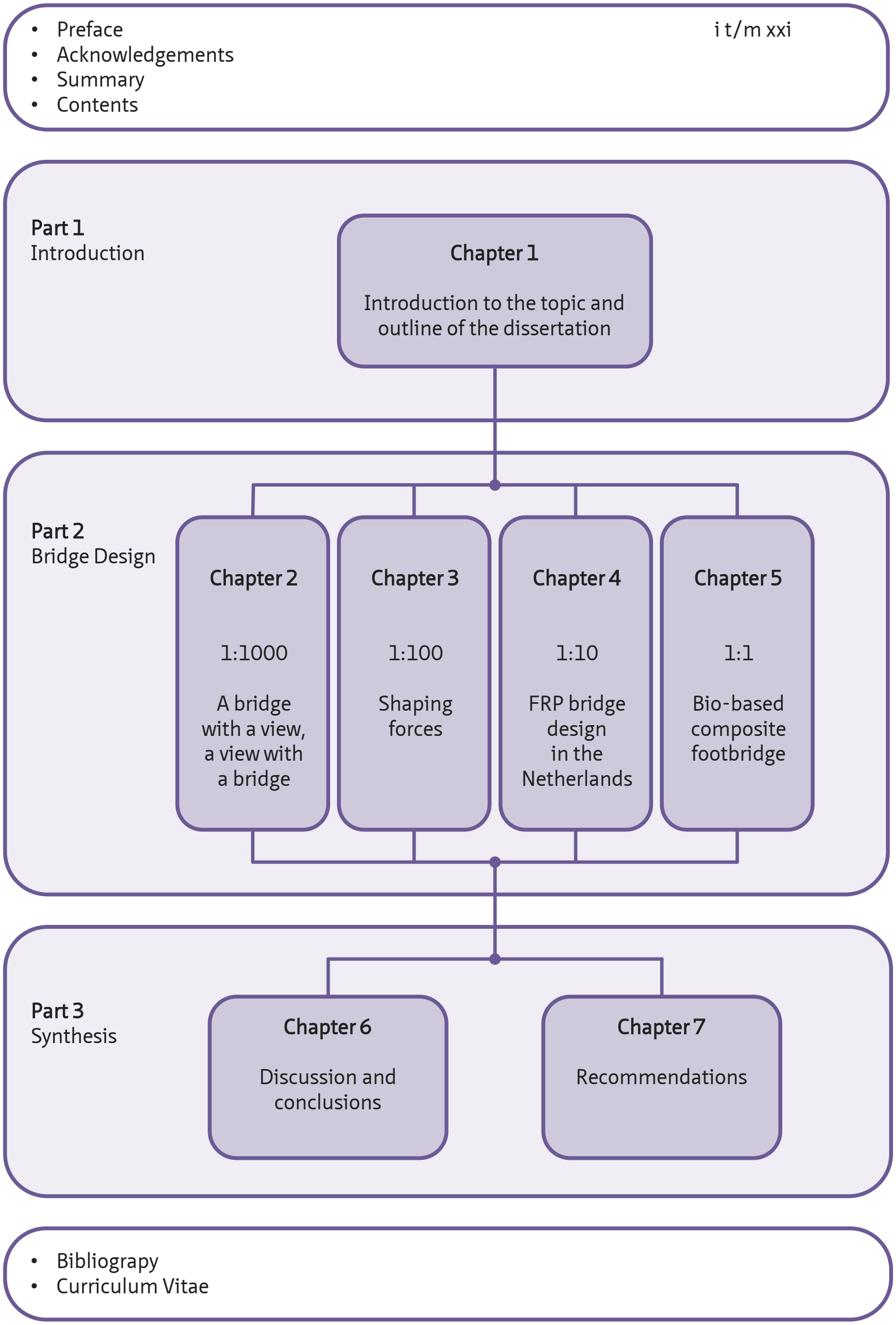

FIGURE 1.14 Structure of this dissertation.

§ 1.9 Structure of dissertation

The structure of this dissertation consists of three parts and seven chapters, each with its specific focus. Figure 17 presents these parts and chapters.

Part one is the current chapter and provides an introduction to the research. The research topic and the research aspects are briefly introduced. The changing role of the architect in the field of bridge design is analysed in an historical context. The role of the commissioning authorities is introduced. The problem of segregation of knowledge is introduced. The objectives and research questions are stated, a hypothesis is formulated and the methodology is discussed.

Part two of this dissertation comprise the theoretical framework of this research and addresses the topic of Bridge Design through four journal papers, here included in chapters 2 till 5. These chapters consist of journal papers that have been published, or are currently under review in the case of the last chapter, in various journals. These papers discuss the design of bridges at the scale of the landscape (chapter 2), the scale of the object (chapter 3), the scale of the detail (chapter 4) and at the scale of the materialization (chapter 5).

Part three is the synthesis and consists of chapter 6, an integrated discussion and conclusions of the research results, and chapter 7 that provides recommendations for the future of bridge design.

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PART 2 Bridge Design