Effectively processing the system performances of infrastructural systems in the tender phase, from the perspective of the Dutch contractor.

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**PREFACE**

This report is the final result of my graduation research and the conclusion of my time as a student at the Delft University of Technology. The graduation process was part of the master program Construction Management and Engineering and it has been a tough but very interesting process in which I have learned a lot about the tender process and the importance of the design decisions during the tender phase.

The research was focused on the system performances of infrastructural systems and the importance of the design decisions during the tender phase. Insufficiently processing the system performances in the tender phase could have a major (adverse) impact on the profit margin of the contractor. Every contractor wants to make profit, as much as possible, system underperformance could adversely affect this. In order to enhance the profit margin of contractors and increase the performances of the infrastructural systems, this research report is written. With the purpose to support the contractors in their decisions during the tender phase, in order to diminish the risk of system underperformance and optimise the profit margin. It has been a very interesting study in which many new subjects are studied that have broadened my knowledge. Therefore, I would like to thank the company, Ballast Nedam, for the opportunity they gave me. In particular I would like to thank Paul Warmerdam, my supervisor, for his great support during the graduation process. The discussions we had, your objectivity, critical but constructive remarks have helped me a lot. Also, I would like to thank Frank van der Woerd and all interviewees for their time, input and support during the graduation process.

In addition, I would like to thank my graduation committee, Marcel Hertogh, Rob Schoenmaker and Jan-Anne Annema for their support, criticism, objective viewpoint and discussions during the committee meetings.

Furthermore, I would like to thank my family, girlfriend and friends for their support and encouragements during my studies and especially in the past nine months.

Jasper Koppes,
September 2015.
SAMENVATTING

Dit onderzoeksrapport is een verkennende studie naar de rol van de systeem prestaties van infrastructurele systemen in de tenderfase en hoe om te gaan met de systeem prestaties in verschillende situaties, vanuit het perspectief van de Nederlandse opdrachtnemer. De aanleiding van dit onderzoek is een verschuiving in de Nederlandse infrastructuur sector. De overheid (opdrachtgever) heeft meer verantwoordelijkheden neergelegd bij de opdrachtnemer – de Nederlandse aannemerij. Dit heeft geleid tot een veranderende inhoud van het Design&Construct-contract (D&C) en de totstandkoming van integrale bouwcontract vormen – Design, Build and Maintain (DBM); Design, Build, Finance and Maintain (DBFM). Als gevolg van de integrale bouwcontracten worden de opdrachtnemers niet meer alleen betaald op basis van het gerealiseerde product maar ook voor de prestaties van het systeem.

Deze verschuiving vergt een andere aanpak en visie van de opdrachtnemer om te voorkomen dat het systeem niet voldoet aan de systeem prestaties. Omdat de opdrachtnemer afgerekend wordt op de systeem prestaties is het van belang om systeem prestaties op de juiste manier te borgen. Met als doel het risico op het niet voldoen aan de systeem prestaties te verkleinen en daarmee te voorkomen dat de winst marge lager uitvalt dan van te voren bepaald. Dit start al in de tenderfase, de (project) fase voordat het project daadwerkelijk begond is. Tijdens de tenderfase maakt de opdrachtnemer een aanbieding waarin al veel fundamentele beslissingen genomen moeten worden met betrekking tot de systeem prestaties. De tenderfase wordt echter gekenmerkt door een korte doorlooptijd, beperkt budget, beperkte hoeveelheid informatie en een hoge mate van onzekerheid of het project wel gewonnen wordt. Tijdens deze fase moet de opdrachtnemer continu afwegingen maken tussen de risico’s, project kosten en systeem prestaties. Tegelijkertijd is het lastig voor de opdrachtnemer om alle prestatie eisen tot in detail te analyseren en aan te tonen binnen het beschikbare budget en tijd. Een ander kenmerk van de tenderfase is de invloed op de systeem prestaties tegenover de laagste kosten. Tijdens de ontwerpfase en bouwfase worden fundamentele veranderingen aan het systeem duurder met een hogere kans op project vertragingen. De volgende probleemstelling staat centraal in dit rapport gebaseerd op de kenmerken van de tenderfase in combinatie met de problemen, geconstateerd op basis van interviews met experts, voortkomend uit de verschuivingen in de infrastructuur sector.

Binnen de organisatie van Nederlandse opdrachtnemers is de kennis beperkt wat betreft de systeem prestaties van infrastructurele systemen. Dit in combinatie met de beperkingen van de tenderfase is het lastig voor een opdrachtnemer om de risico’s van het niet voldoen aan de systeem prestaties te beperken, met als doel de winst marge voor de opdrachtnemer te optimaliseren.

Vanuit dit perspectief is onderzoek gedaan naar verschillende projecten en het belang van de systeem prestaties voor de opdrachtnemer. Hiervoor zijn verschillende infrastructurele systemen en bouwcontracten onderzocht. Er is vooral nog geen generiek methodiek toegepast binnen de organisatie van de Nederlandse opdrachtnemers om de systeem prestaties op een effectieve en onderbouwde manier te verwerken. Om meer inzicht te krijgen in het belang van de systeem prestaties en om een methodiek aan te reiken om de systeem prestaties te verwerken, is het volgende onderzoeksdoel opgesteld:

Het doel van dit onderzoek is het ontwikkelen van een beslissingsmodel dat kan worden gebruikt door Nederlandse opdrachtnemers in de tenderfase om het risico van het niet voldoen aan de systeem prestaties van infrastructurele systemen te optimaliseren.

Het onderzoek is gericht op de systeem prestaties van Nederlandse infrastructurele systemen en het ontwikkelen van een beslissingsmodel, deze bestaat uit drie variabele:
1. Type bouw contract – bepaalt het risico en consequenties voor de opdrachtnemer indien systeem niet voldoet aan de systeem prestaties.
2. Asset type – bepaalt complexiteit van het systeem en de kans op random systeem falen.
3. Analyse type – bepaalt met welke analyse de systeem prestaties op een effectieve en onderbouwde manier verwerkt kunnen worden in de tenderfase.

Systeem prestaties
Voordat het beslissingsmodel verder wordt toegelicht, is ingegaan op de systeem prestaties. Wat zijn systeem prestaties eigenlijk? De systeem prestaties kunnen worden beschreven in RAMS-prestaties wat een afkorting is van: betrouwbaarheid (R), beschikbaarheid (A), onderhoudbaarheid (M) en veiligheid (S). De systeem prestaties
kunnen worden uitgedrukt in de beschikbaarheid van het systeem wat beïnvloed wordt door de systeem veiligheid. Indien een systeem niet veilig is, moet het systeem worden gesloten zodat de gebruiker en omgeving geen gevaar lopen. De veiligheid van het systeem is vervolgens bepaald door de betrouwbaarheid en onderhoudsstrategie. Een onbetrouwbare systeem kan resulteren in meer systeem falen dan van te voren is bepaald. De onderhoudskeurheid van het systeem heeft een grote invloed op de onderhoudsstrategie. De onderhoudskeurheid bepaalt namelijk in welke mate het systeem op een efficiënte en meest kosten effectieve manier kan worden onderhouden. De RAMS-aspecten worden gedurende de gehele project life cycle bepaald en beïnvloed, echter worden in de tenderfase de meest fundamentele beslissingen genomen aangaande de systeem prestaties. Het is daarom van belang om al in de tenderfase de systeem prestaties mee te nemen in het ontwerp, op deze manier kan een systeem worden gerealiseerd dat voldoet aan de prestatie eisen tegenover relatief de laagste kosten. Tevens wordt de kans verkleind op noodzakelijke ontwerp aanpassingen en/of hogere onderhoudskosten als gevolg van verkeerde aannames aangaande de systeem prestaties in de tenderfase.

**Beslissingsmodel**

Het volgende beslissingsmodel (Figure 1) kan worden gebruikt door de opdrachtnemer in de tenderfase om de systeem prestaties op een meer effectieve en onderbouwde manier te verwerken. Zodat de kans verkleind wordt op het niet voldoen aan de systeem prestaties in de ontwerp-, bouw- en onderhoudsfase. Het model onderscheidt zeven situaties (A-F) die gekenmerkt worden door een risico profiel.

![Beslissingsmodel](image)

**Risico profiel**

Welke analyse methode moet worden gebruikt om de systeem prestaties op een juiste manier te kunnen borgen is afhankelijk van het risico profiel van de situatie. Het risico profiel wordt bepaald door het asset type en type bouwcontract. Uit interviews is gebleken dat opdrachtnemers momenteel een beperkt inzicht hebben in de consequenties van het niet voldoen aan de prestatie eisen (type bouwcontract) én de impact van de verschillende infrastructurele systemen op de systeem prestaties (asset type). Dit is daarom nader onderzocht in dit onderzoeksrapport. Vervolgens is geanalyseerd welke analyse methode toegepast kan worden en in welke situatie.

**Asset type**

Een infrastructureel systeem kun je opdelen in twee type assets: passieve en actieve assets. Passieve assets zijn de civiele componenten en hebben over het algemeen een lange levensduur van 50-100 jaar. Tevens hebben...
Deze assets zien een lage kans op random falen en zijn betrouwbare elementen. De kosten, risico’s en prestaties zijn bekend, de onderhoudsactiviteiten zijn eveneens bekend en hebben een beperkte invloed op het onderhoudsbudget en systeem beschikbaarheid. Passieve assets met een lagere levensduur (7-12 jaar) en met een grote impact op de onderhoudsactiviteiten en onderhoudsbudget zijn afzonderlijk en overgangsvoegen. Actieve assets zijn de elektronische en mechanische (E&M) elementen in een systeem en hebben een relatief korte levensduur van 10-15 jaar en een hogere kans op random falen vergeleken met de passieve assets. Deze componenten hebben dan ook een grotere impact op de systeem prestaties en dragen een hoger risico met zich mee. De impact van random falen is afhankelijk van het bouwcontract en is hieronder verder toegelicht.

**Bouwcontracten**

De gevolgen van het niet voldoen aan de systeem prestaties worden voornamelijk bepaald door het korte- of lange- termijn perspectief. Drie verschillende bouw contracten zijn onderzocht: het D&C, DBM en DBFM-contract. In het D&C-contract is de opdrachtnemer slechts verantwoordelijk voor het ontwerpen en bouwen van het systeem. De opdrachtnemer moet een systeem ontwerpen en realiseren dat voldoet aan de systeem prestaties maar de opdrachtnemer is niet verantwoordelijk voor de systeem prestaties over de lange termijn. Dit is wel het geval in DBM en DBFM-contracten waarin de opdrachtnemer naast het ontwerpen en realiseren ook verantwoordelijk is voor het onderhouden (DBM) én financieren (DBFM). Deze extra verantwoordelijkheden brengen tevens extra risico’s met zich mee die kunnen resulteren in het niet voldoen aan de systeem prestaties.

Indien het systeem niet voldoet aan de systeem prestaties zijn de gevolgen verschillend per bouw contract. In het D&C-contract zitten de minste risico’s voor de opdrachtnemer omdat het geen lange termijn verantwoordelijkheid heeft na het realiseren van het systeem. Als de systeem prestaties onvoldoende worden meegenomen in de tenderfase kan dit resulteren in hogere project kosten en eventuele project vertragingen omdat het ontwerp en/of constructie aangepast moet worden zodat het voldoet aan de prestatie eisen. In een D&C-contract zijn dit hoogstwaarschijnlijk slechts eenmalige kosten. Echter mag dit niet onderschat worden omdat ook eenmalige kosten een grote invloed kunnen hebben op de winst marge van het project.

In een DBM en DBFM-contract is de opdrachtnemer dus ook verantwoordelijk voor het onderhouden van het systeem en de systeem prestaties over de lange termijn. De relatie tussen de verschillende RAMS-elementen is hierdoor nog belangrijker geworden. Als de systeem prestaties onvoldoende zijn meegenomen in de tenderfase kan dit resulteren in eenmalige kosten ten behoeve van het aanpassen van het ontwerp en constructie maar ook in structurele kosten overschrijdingen doordat het systeem niet voldoende betrouwbaar is. Tevens kan de onderhoudstrategie niet voldoen doordat het systeem lastig te onderhouden is. Hierdoor moeten extra kosten gemaakt worden om het systeem op het juiste niveau te laten presteren. Noodgedwongen systeem aanpassingen kunnen eveneens resulteren in project vertragingen die uiteindelijk kunnen resulteren in een minder optimale onderhoudstrategie. Door de project vertragingen kan het zijn dat het systeem gefaseerd wordt opgeleverd waardoor de onderhoudstrategie niet meer volledig toepasbaar is. Doordat de delen die al opgeleverd zijn al degenereren en slijten door het gebruik terwijl het deel dat nog niet is opgeleverd pas later start met degenereren en slijten door gebruik. Uiteindelijk kan dit resulteren in hogere onderhoudskosten en een lagere systeem beschikbaarheid door een minder optimale onderhoudsstrategie.

In een DBFM-contract moet ook rekening worden gehouden met de extra kosten door project vertragingen als gevolg van het financieren van het project. De rente die de opdrachtnemer betaalt over de lening is deels gebaseerd op de opleveringsdatum van het project. Na oplevering krijgt de opdrachtnemer namelijk betaald voor het geleverde product en wordt het periodiek betaald voor de systeem prestaties. Indien het systeem later wordt opgeleverd wordt er pas later betaald voor het geleverde product en blijven de inkomsten vanuit de periodieke betaling uit. Terwijl de opdrachtnemer extra kosten moet maken om het systeem zo snel mogelijk af te ronden om zo snel mogelijk inkomsten te kunnen genereren. Uiteindelijk kan dit grote financiële gevolgen hebben voor de opdrachtnemer.

**Analyse methoden**

Verschillende analyse methoden kunnen gebruikt worden om de prestatie eisen op een effectieve manier te verwerken in de tenderfase om het risico te verlagen dat het systeem niet voldoet aan de prestatie eisen.
1. Expert Judgment (EJ)

EJ is een methode waarin gebruik gemaakt wordt van de kennis en ervaringen van experts, het is een relatief snelle methode maar ook een subjectieve methode. De toepasbaarheid van EJ wordt bepaald door de kennis en ervaringen van de experts en is een betrouwbare methode indien de opdrachtnemer zeer ervaren is met het te realiseren systeem. Middels EJ kan een inschatting gemaakt worden van de verwachte systeem prestaties maar is lastig te gebruiken om alternatieven af te wegen. Indien de systeem prestaties van verschillende alternatieven geanalyseerd moeten worden of een meer kwantitatieve inzage is vereist omdat de consequenties van het niet voldoen aan de systeem prestaties te groot zijn, moet een kwalitatieve of kwantitatieve analyse uitgevoerd worden.

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<thead>
<tr>
<th>Kwalitatief</th>
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<tr>
<td>Failure Mode Effect Criticality Analysis (FMECA)</td>
<td>Part Count Analysis (PCA)</td>
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<tr>
<td>Hazard &amp; Operability (HAZOP)</td>
<td>Reliability Block Diagram (RBD)</td>
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<td>Human Reliability Analysis (HRA)</td>
<td>Fault Tree Analysis (FTA)</td>
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<td>Event Tree Analysis (ETA)</td>
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<td>Markov</td>
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2. Kwalitatieve analyse

Middels een kwalitatieve analyse kan het faalgedrag van een systeem bepaald worden. De verschillende type methode zijn weergegeven in Table 1.

Een kwalitatieve analyse kan worden toegepast wanneer EJ niet meer toereikend is omdat de kennis en ervaring beperkt is met het te realiseren systeem of de risico’s aangaande de systeem prestaties zijn te groot om volledig te baseren op EJ. Middels bovenstaande methodes kunnen de faalmechanismen en gevolgen van falen in kaart gebracht worden met betrekking tot de toepassingen van het systeem (FMECA), veiligheid (HAZOP) en invloed van menselijk handelen (HRA). Met de kwalitatieve analyses is het mogelijk om de kritieke systeem elementen te bepalen, deze elementen kunnen de systeem prestaties negatief beïnvloeden. Door deze elementen al in een vroeg stadium te mitigeren is het mogelijk om de betrouwbaarheid van het systeem te verhogen en daarmee de beschikbaarheid. Een kwalitatieve analyse kan ook uitwijken dat de huidige onderhoudsbeleid van het systeem een knelpunt is wat een negatieve invloed kan hebben op de onderhoudsstrategie met als gevolg hogere onderhoudskosten. Door dit al in een vroeg stadium te mitigeren kunnen lagere Life Cycle Costs gerealiseerd worden. Een kwalitatieve analyse wordt tevens gebruikt als input voor een kwantitatieve analyse.

3. Kwantitatieve analyse

Een kwantitatieve analyse kan gebruikt worden om de betrouwbaarheid en het faal percentage vast te leggen in absolute cijfers. Deze inzichten kunnen ook gebruikt worden om te bepalen welke systeem elementen een groot risico zijn met betrekking tot de systeem prestaties. De verschillende methoden zijn weergegeven in Table 1.

De FTA is een veelvuldig toegepaste methode in de infrastructuursector en de Markov-analyse wordt zelden toegepast door de hoge complexiteit van de methode. DE PCA, RBD en FTA zijn voornamelijk gericht op de meest kritieke systeem elementen die een risico vormen voor de betrouwbaarheid van het systeem. De ETA is meer gericht op de gevolgen van falen, waarbij gekeken wordt naar de systeem elementen die nog wel werken. Om onveilige situaties te voorkomen na systeem falen. Een kwantitatieve analyse is een uitgebreide analyse die niet in elk project vereist is. Middels een kwantitatieve analyse is het mogelijk om met grote zekerheid de project inkomsten en uitgaven te bepalen. Tevens kan de betrouwbaarheid worden vastgelegd en gebruikt worden voor het bepalen van de juiste onderhoudsstrategie. Met deze output kan de opdrachtnemer de te verwachten kosten in kaart brengen van de onderhoudsactiviteiten. Door een hoge mate van zekerheid te hebben wat betreft de betrouwbaarheid en veiligheid van het systeem is het tevens mogelijk om de beschikbaarheid van het systeem vast te stellen wat uiteindelijk de systeem prestaties bepaalt. Dit is voornamelijk belangrijk in DB(F)M-contracten waarbij een duidelijk inzicht nodig is in de verwachte inkomsten en uitgaven met betrekking tot het rond krijgen van de project financiering bij de bank.
Conclusie
Om te voldoen aan het hoofddoel van dit onderzoek moet de hoofdonderzoeksvraag worden beantwoord, deze luidt:

_Hoe kan de opdrachtnemer de systeem prestaties van verschillende infrastructurele systemen op een effectieve manier verwerken in de tenderfase door gebruik te maken van het beslissingsmodel?_

De bouwcontracten, asset type en analyse methode combinerend resulteert in het beslissingsmodel zoals geïllustreerd in Figure 1. De systeem prestaties van systemen met voornamelijk passieve assets, ongeacht het contract type, kunnen worden geanalyseerd middels expert judgment. Mede omdat het risico profiel voor deze situaties laag is. Het faalgedrag van de systemen is bekend en de impact van de assets op de onderhoudsstrategie is beperkt omdat het niet veel onderhoud nodig heeft. De opdrachtnemer moet echter rekening houden met passieve assets met een relatief korte levensduur en een grote impact op de systeem prestaties, zoals bijvoorbeeld asfalt en voegovergangen. Dergelijke assets hebben een relatief korte levensduur van 7-12 jaar en een grote impact op het onderhoudsbudget door de hoge vervangingskosten.

Voor actieve assets is het minder eenvoudig. Voor deze type assets zijn meer uitgebreide analyses nodig om het risico op het niet voldoen aan de systeem prestaties te verkleinen. Voor een D&C-contract en een DBM-contract, met een onderhoudsperiode korter dan tien jaar, is geadviseerd een kwalitatieve analyse te maken. Middels de kwalitatieve analyse kan de opdrachtnemer de meest kritieke systeem elementen bepalen om deze vervolgens te mitigeren door de betrouwbaarheid van de onderhoudsstrategie te verhogen. Wat uiteindelijk een positief effect heeft op de veiligheid en beschikbaarheid van het systeem.

Voor een DBM-contract, met een onderhoudsperiode langer dan tien jaar, en een DBFM-contract is een kwalitatieve en kwantitatieve analyse geadviseerd. Middels de kwantitatieve analyse is het mogelijk de meest kritieke systeem elementen te bepalen, deze kunnen tevens worden gebruikt als input voor de kwantitatieve analyse. In deze situatie zijn hoogstwaarschijnlijk meerdere vervangingen nodig van subsystemen wat een grote impact kan hebben op het onderhoudsbudget en de beschikbaarheid van het systeem. Daarom is het van belang al in de tenderfase te bepalen welke systemen het kritiek zijn wat betreft de systeem prestaties, deze kunnen vervolgens worden gemitigeerd waarmee de systeem prestaties verhoogd kunnen worden.

Het moet worden benadrukt dat nadat het project is toegewezen aan een bepaalde partij of consortium, het mogelijk is dat verdere analyse gedaan moet worden naar de systeem prestaties. Echter, vanuit het oogpunt van de tenderfase en de daarbij behorende beperkingen is het niet mogelijk om alle systeem prestaties tot in detail te analyseren en te borgen. Daarom is geanalyseerd welke bouwcontracten de meeste risico’s dragen en welke infrastructurele systemen de grootste impact hebben op de systeem prestaties. Vanuit dit perspectief was het mogelijk om de situaties met de meeste risico’s te bepalen en hieraan de toepasbare methode te koppelen. Met als doel om de kans op het niet voldoen aan de systeem prestaties al in een vroeg stadium te verkleinen.

Aanbevelingen
Een aantal aanbevelingen is gedaan voor het verdere gebruik van het beslissingsmodel en voor vervolg onderzoek.

1. Verbeteren van de samenwerking tussen de ontwerp en onderhoudsafdeling met als doel om een meer geoptimaliseerd systeem te ontwikkelen tegen lagere kosten.
2. Verhogen van de kennis binnen het ontwerpsteam wat betreft de systeem prestaties en de onderhoudsaspectsen van de verschillende systemen. Dit zou moeten leiden tot het sneller en meer adequaat verwerken van de prestatie eisen in de tender- en ontwerpfase dat moet resulteren in lagere ontwerp kosten.
3. Momenteel is er een beperkte beschikbaarheid van empirische data van de actieve systeem elementen. Het verbeteren van het verzamelen van deze data moet meer inzicht verschaffen in de systeem prestaties over de lange termijn. Deze data kan vervolgens gebruikt worden om een meer accuraat ontwerp te maken.
4. Onderzoek doen naar de diepgang van de verschillende analyses, in de huidige analyse is dit niet meegenomen.
5. Verder onderzoek doen naar de onderhoudsstrategieën in relatie met de systeem prestaties. Dit onderzoek heeft zich voornamelijk gericht op de ontwerpafwegingen en minder op de best toepasbare onderhoudsstrategie.
6. Het is aanbevolen vervolg onderzoek te doen naar de kansen van risico's. Dit onderzoek is voornamelijk gericht op de bedreigingen van risico's; een gebeurtenis met een negatief effect voor de opdrachtnemer. Met als doel een project te realiseren met een lagere LCC en een hogere winst marge in combinatie met het mitigen van de bedreigingen.
This research report is an exploratory study into the role of system performances of infrastructural systems in the tender phase and how to cope with the system performances in different situations, from the perspective of the Dutch contractor. The motive of this research is a shift in the Dutch infrastructural industry, the government (client) has shifted more responsibilities to the Dutch contractor. This has resulted in a change of the content of the Design&Construct-contract (D&C) and the development of integral building contracts – Design, Build and Maintain (DBM); Design, Build, Finance and Maintain (DBFM). As result of the integral building contracts the contractor is not only paid for the realized system anymore but also for the system performances during the contractual period.

This shift requires a different approach and mind-set of the contractor in order to avoid a system that does not fulfill the performance requirements and encounter lower payments during the project life-cycle. The contractor is paid based on the system performances and therefore it is of importance to take these into account accurately, in order to diminish the risk of system underperformance and optimise the profit margin. The new approach is already needed in the tender phase, the phase prior to the start of the actual project is awarded. The tender phase is characterised by a limited budget, time, amount of available information and a high uncertainty if the project will be won. In spite of these limitations the contractor must develop a bid in which many fundamental decisions are taken with regard to the system performances. In order to develop the bid the contractor is constantly making trade-offs between the project costs, risks and system performances. Due to the time constraints it is difficult for the contractor to analyse and assure all the system performances within time and budget. Another characteristic of the tender phase is the influence on the system performance for the lowest price. Fundamental design adjustments in the design and construction phase are more costly and with a higher probability of project delays because the adjustability of the system is decreasing in time. The following problem statement is used as basis for this research and is based on the characteristics of the tender phase in combination with the problems, detected by interviews with experts, as result of the shift in the infrastructural industry.

**Within the organisation of Dutch contractors knowledge with regard to the system performances of infrastructural systems is lacking. This in combination with the tender phase characteristics makes it difficult for a contractor to limit the risk of system underperformance already in tender phase; with the purpose to optimise the profit margin of the contractor.**

From this perspective a research is conducted into the importance of system performances in different projects, from the viewpoint of the contractor. For this purpose multiple building contracts and infrastructural systems are analysed. Currently, no general methodology is integrated in the organisation of the Dutch contractor to process the system performances in the tender phase effectively and on a well-founded base. In order to gain a better insight in the importance of the system performances and a methodology to process the system performances in the tender phase, the following research objective is developed:

**The main objective of this research is to develop a decision-making model that can be used by contractors in tender phase in order to limit the risks for contractors of system underperformance and optimise the profit margin.**

The research is focused on the system performances of infrastructural systems of Dutch infrastructural systems and the development of a decision-making model. The decision-making model consists of the following three variables:

1. Type of building contract – determines the risk and consequences for a contractor in case of system underperformance.
2. Asset type – determines the complexity of the system and the probability of random failure.
3. Type of analysis – determines by the use of what analysis the system performances effectively and on a well-founded base can be processed in the tender phase.

**System performances**

Before the decision-making model is discussed, the system performances are further elaborated. What are system performances actually? The performances can be expressed in the terms of RAMS, which is an acronym of: Reliability (R), Availability (A), Maintainability (M) and Safety (S). The system performances can be defined...
as the availability of the system and is influenced by the safety. If the system is not safe the system will be closed in order to guarantee the safety of the user and surrounding. Consequently, the safety of a system is determined by the reliability and maintenance strategy. The reliability defines the frequency of failure, an unreliable system could cause more system failures than initially planned. The maintenance strategy is to a great extent determined by the maintainability of the system. The maintainability defines to what extent the maintenance activities can be conducted in an efficient and cost effective way. A proper maintenance strategy could have a positive effect on the reliability. The RAMS-elements are determined and influenced during the whole project life-cycle, but the contractor has the biggest influence on the system-performances in the tender phase. Therefore it is of big importance that the system performances are taken into account adequately in order to realise a system that fulfils the performance requirements. The probability of necessary design adjustments and/or higher maintenance costs as a result of wrong decision-making during the tender phase thereby diminished as well.

**Decision-making model**

The decision-making model is illustrated in Figure 2 and can be used by the contractor in the tender phase in order to effectively process the system performances on a well-founded base. With the purpose to diminish the probability of not fulfilling the performance requirements in the design, construction and maintenance phase. The model distinguished seven situations (A-F), which are characterised by the risk profile of the situation.

**Risk profile**

Which analysis should be used to diminish the risk of system underperformance in the tender phase depends on the risk profile of the situation and is determined by the asset type and building contract. The contractors are having a limited insight in the consequences of not fulfilling the performance requirements (type of building contract) and the impact of different infrastructural systems on the system performances (asset type). This is further examined in this research, consequently different types of analysis are studied and linked to the different situations.

**Asset type**

An infrastructural system can be split in two types of assets: passive and active. Passive assets are the civil components with a long life-time of 50-100 years and have a low probability of random failure. These costs, risks and performances are known by the contractor, the maintenance activities are known as well and have a
limited impact on the budget and system availability. Passive assets with a lower technical life-time (7-12 years) and with a big impact on the maintenance activities and budget are the asphalt layers and construction joints. Active assets are the electronic and mechanical (E&M) elements of a system and have a relatively short life-time of 10-15 years and higher probability of random failure compared with the passive assets. These elements have a bigger impact on the system performances and incorporate bigger risks. The consequences of random failure for a contractor depends on the building contract.

**Building contracts**
The consequences of not fulfilling the performance requirements are determined by the short or long-term perspective. Three different building contracts are examined: D&C, DBM and DBFM. Within a D&C-contract the contractor is only responsible for the design and construction of the system but is not responsible for the system performances over the long-term. Within a DBM and DBFM-contract the contractor should be aware of the long-term responsibilities, besides the design and construction responsibilities the contractor is also responsible for the maintenance (DBM) and financing (DBFM). These extra responsibilities incorporates also other risks and could increase the consequences of system underperformance.

If the system is not fulfilling the performance requirements the consequences for the contractor differ per building contract. In a D&C-contract the contractor encounters the lowest risks because the contractor is not responsible for the system performances after realisation. If the system performances are insufficiently taken into account in the tender phase it could result in higher project costs and possible project delays, due to the necessary design and construction adjustments in order to fulfil the performance requirements. This might result in just one-off costs, because the contractor is not responsible for system performances after realisation. But, these one-off costs cannot be underestimated because it could have a major impact on the profit margin.

In a DBM and DBFM-contract the contractor is also responsible for the maintenance of the system and the system performances over the long-term; the interrelationship between the RAMS-elements becomes even more important. System underperformance could result in just one-off costs to restore the system but it could also result in structural higher costs during the maintenance phase because the system is unreliable or unmaintainable. This could result in extra costs in order to let the system operate on the required performance level. Necessary design adjustments could also result in project delays and adversely affect the maintenance strategy. The project delays could result in partial completion and eventually result in a less applicable maintenance strategy. Because the completed parts are already degenerating but the unfinished parts are degenerating in another pace after completion. The maintenance strategy should therefore be adjusted and could result in higher maintenance costs and a lower system availability due to the less optimised maintenance strategy.

In a DBFM-contract the contractor should be aware of extra project costs due to project delays as consequence of financing the project. The interest rate that is paid by the contractor for the loan, is partly based on the completion date of the system. After completion the contractor is paid a one-off payment for the realised system and periodical for the system performances to reimburse the investments. If the system completion is delayed the contractor is not paid the one-off payment in time and the revenues from the periodical payments are also not paid. Besides the referred income, the contractor should also invest more to finish the system as soon as possible in order to generate income. Eventually, this could result in major financial issues for the contractor.

The contractor can enhance the profit margin and reducing the probability of system underperformance by diminishing the risks discussed for the different building contracts already in the tender phase. The methods to diminish the risk of system underperformance are discussed in the following section.

**Method of analysis**
Different types of analysis can be used in order to process the system performances in the tender phase in an effective way and to diminish the risk of system underperformance. Three types of analysis are separately discussed.

1. **Expert Judgment (EJ)**
EJ is a method based on the experiences and knowledge of the experts. It is a relatively quick but subjective method. The applicability of the EJ is limited by the knowledge and experience of the experts and is a very
reliable method in case the experts have sufficient knowledge and experience with a particular system. EJ can be used to estimate the expected system performances but is difficult to use for trade-offs between alternatives. If the system performances of different alternatives need to be assessed or a more quantitative insight is required because the consequences of system underperformance are too big, the contractor should use a qualitative or quantitative.

Table 2 Different methods to conduct a qualitative or quantitative analysis

<table>
<thead>
<tr>
<th>Qualitative</th>
<th>Quantitative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Mode Effect Criticality Analysis (FMECA)</td>
<td>Part Count Analysis (PCA)</td>
</tr>
<tr>
<td>Hazard &amp; Operability (HAZOP)</td>
<td>Reliability Block Diagram (RBD)</td>
</tr>
<tr>
<td>Human Reliability Analysis (HRA)</td>
<td>Fault Tree Analysis (FTA)</td>
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<td></td>
<td>Event Tree Analysis (ETA)</td>
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<td>Markov</td>
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</table>

2. Qualitative analysis

By using a qualitative analysis the failure behaviour of a system can be defined. The different methods to conduct a qualitative analysis are given in Table 1.

A qualitative analysis can be used in case EJ is not sufficient anymore due to the lacking knowledge and experience or the consequences of system underperformance are too big to fully rely on EJ. By using one of the methods given in the table above the failure mechanisms and consequences of failure can be determined with regard to the application of the system (FMECA), safety (HAZOP) and the impact of human involvement (HRA). Using the qualitative analysis it is possible to define the critical system elements, which could have an adverse impact on the system performances. By mitigating these critical elements it is possible to enhance the reliability of the system. A qualitative analysis can be used as well to assess the maintainability of the system and determine which system elements can be enhanced to optimise the maintenance strategy. By mitigating these aspects in an early project stage – tender phase – it is possible to realise a system with lower Life Cycle Costs (LCC) and a higher profit margin. A qualitative analysis is also used as input for the quantitative analysis.

3. Quantitative analysis

A quantitative analysis can be used to examine the reliability and failure rate in absolute numbers. These insights can be used to determine which system elements are a risk with regard to the system performances. The applicable methods are given in Table 1.

The FTA is the most often applied method in the infrastructure industry and the Markov-analysis is rarely applied due to the high complexity of it. The PCA, RBD and FTA are mainly aimed at defining the most critical system elements, which are jeopardising the reliability of the system. The ETA is more focused on the consequences of failure and can be used to analyse the elements that are still operational after failure. In order to minimise the risk of unsafe situations. A quantitative analysis is a comprehensive methodology and is not required in every project. It is possible to determine the reliability and used to define the maintenance strategy. The output can be used to map the expected maintenance costs. Having insight in the reliability, maintainability and safety of the system it is possible to determine the system availability with a high degree of certainty. By using these outputs the contractor is able to determine the expected revenues and expenditures with a high level of certainty. This can be very useful in a DB(F)M-contract in which a proper overview is required of the expected revenues and expenditures in order to get a loan from the bank.

Conclusion

To fulfil the research objective of this research the following main research question is answered:

How to effectively process the system performances of infrastructural projects in tender phase by the use of a decision-making model?

Combining the building contracts, asset types and types of analysis a decision-making model is developed as illustrated in Figure 2. The system performances of the infrastructural systems with mainly passive assets, regardless the type of building contract, can be analysed with expert judgment (situation A, C, E). Mainly because the risk profile of these situations is low. The failure behaviour of the systems is rather known by the contractors and the impact of the passive assets on the maintenance activities is limited, because these assets
requires not much maintenance. The contractor should be aware of the passive assets with a relatively short life-time and with a big impact on the system performances such as, asphalt layers and construction joints. The life-time of these assets is 7-12 years and have a big impact on the maintenance budget due to the high replacement costs.

Infrastructural systems with active assets more comprehensive analyses are required, in order to diminish the risk of not fulfilling the performance requirements. A qualitative analysis is advised for a D&C-contract (B) and a DBM-contract with a maintenance period shorter than ten years (D1). By using the qualitative analysis the contractor is able to define the critical system elements and mitigate these to enhance the reliability and maintainability of the systems. Eventually, this should result in a safer and higher availability of the system.

It is advised to conduct a qualitative and quantitative analysis for a DBM-contract with a maintenance period longer than ten years (D2) and a DBFM-contract (F). The qualitative analysis can be used to determine the most critical system elements and can be used as input for the quantitative analysis. Most likely multiple system replacements are necessary during the maintenance period and could have a big impact on the system availability and maintenance strategy. Therefore it is of importance to determine the critical system elements with regard to the system performances already in the tender phase. Consequently, these critical elements can be mitigated with the purpose to enhance the system performances.

It must be emphasized that after the project is awarded, the contractor might need to conduct additional analyses with regard to the system performances. From the perspective of the tender phase and the associated limitations it is not possible to analyse all the performance requirements into detail and assure them within budget. Therefore it is analysed which building contracts incorporate the most risks and which infrastructural system has the biggest impact on the system performances. From this perspective it was possible to define the situations incorporating the biggest risks for a contractor and link a suitable method to it. With the purpose to diminish the risk of system underperformance already in the tender phase.

**Recommendations**

Six recommendations are done with regard to the further use of the decision-making model and for further research.

1. Improve the cooperation between the design and maintenance department in order to develop a more optimised system for a lower price.
2. Enhance the knowledge within the design team with regard to the system performances and maintenance aspects of different infrastructural systems. This should result in quicker and more adequately processing the performance requirements in the tender and design phase, with the purpose to diminish the design costs.
3. Currently limited empirical data is available of systems with mainly active assets. Improving the data gathering should create more insight in the system performances over the long-term. These data can consequently be used to develop a more accurate systems for a lower price.
4. Further research should be conducted into the depth of the analyses. Currently no distinction is made but most likely not every situations requires the same in-depth analysis.
5. Further research should be conducted into the best applicable maintenance strategy in combination with the system performances. This research is mainly focused on the importance of the design decisions. Both can have a big impact on the system performances.
6. Further research should be conducted into the opportunities of risks, this research is mainly focused on the threats of risks; an event with a negative impact for the contractor. Using both risks a project can be realised with lower LCC and a higher profit margin.
# Table of Content

Preface......................................................................................................................... v
Samenvatting .................................................................................................................. vii
Summary ......................................................................................................................... xiii

**SECTION I: INTRODUCTION ................................................................................. 1**

1 Introduction ............................................................................................................. 3
   1.1 Motive of Research ......................................................................................... 3
   1.2 Problem Identification ................................................................................... 4
   1.3 Problem Statement ......................................................................................... 9
   1.4 Assumption ..................................................................................................... 9
   1.5 Thesis Outline ............................................................................................... 10

2 Research Design .................................................................................................... 11
   2.1 Research Objectives ....................................................................................... 11
   2.2 Research Questions ....................................................................................... 12
   2.3 Research Methodology .................................................................................. 14
   2.4 Scope and Limitations ................................................................................... 19

**SECTION II: ANALYSIS ....................................................................................... 21**

3 Risk Identification ................................................................................................ 23
   3.1 Risk theory .................................................................................................... 23
   3.2 Risks per building contract ........................................................................... 26
   3.3 Wrap-up Risk identification ......................................................................... 34

4 System Performances ............................................................................................ 37
   4.1 Survey set-up ............................................................................................... 37
   4.2 Infrastructure Systems .................................................................................. 38
   4.3 Infrastructure Subsystems ............................................................................ 40
   4.4 Wrap-up System Performances .................................................................... 41

5 Framework ............................................................................................................ 43

**SECTION III: CONCEPTUAL MODEL ............................................................... 45**

6 Methodology .......................................................................................................... 47
   6.1 RAMS-theory ............................................................................................... 47
   6.2 Interrelation of RAMS-elements .................................................................... 51
   6.3 Methodology ................................................................................................. 52
   6.4 Wrap-up Methodology .................................................................................. 56

7 Decision-making model ........................................................................................ 59
   7.1 Variables of decision-making model ............................................................. 59
List of Figures

Figure 1 Beslissingsmodel ................................................................. viii
Figure 2 Decision-making model ........................................................ xiv
Figure 1-1 System performances (based on (CENELEC, 1999)) ............................................. 4
Figure 1-2 Characteristics problems during life cycle of system (based on (Wubbenhorst, 1986)) .... 7
Figure 1-3 Value improvement over the life-cycle (based on (Hertogh, Bakker, Man, & Scholten, 2015)) 8
Figure 1-4 Tender phase trade-offs (Herder & Wijnia, 2012) ..................................................... 9
Figure 2-1 Research Overview ............................................................................. 14
Figure 3-1 Cost categorisations (based on (Woodward, 1997)) .................................................. 30
Figure 3-2 Systems condition in relation to maintenance activities (based on (Bogaard & Akkeren, 2011)) 31
Figure 3-3 Illustration of the DBFM-payment mechanism of the A15 MaVa project (retrieved from Ballast Nedam) .......................................................................................... 32
Figure 6-1 Simplistic illustration of failure behaviour (based on (Bakker et al., 2010)) .................. 48
Figure 6-2 Interrelations of RAMS (based on (Bakker et al., 2010)) ......................................... 52
Figure 7-1 Decision-making model .......................................................................... 65
Figure 8-1 Conclusion: Decision-making model ..................................................................... 76

List of Tables

Table 1 Verschillende methodes voor kwalitatieve en kwantitatieve analyses............................. x
Table 2 Different methods to conduct a qualitative or quantitative analysis.................................. xvi
Table 1-1 Building contract characteristics ............................................................................. 4
Table 2-1 Studied cases ........................................................................................................... 16
Table 2-2 List of interviewees .................................................................................................. 17
Table 2-3 List of survey participants ....................................................................................... 18
Table 3-1 Division of internal and external risks (based on (Akintola Akintoye et al., 1998; Grimsey & Lewis, 2002; Nicholas & Steyn, 2012) .......................................................... 24
Table 3-2 Definition of internal risks on (based on (Akintola Akintoye et al., 1998; Grimsey & Lewis, 2002; Nicholas & Steyn, 2012) ........................................................................... 25
Table 3-3 Project costs .......................................................................................................... 26
Table 3-4 Risks per building contract ..................................................................................... 35
Table 4-1 Studied cases .......................................................................................................... 37
Table 4-2 List of survey participants ....................................................................................... 38
Table 4-3 Scores of infrastructural systems ............................................................................ 39
Table 4-4 Scores of more impactful systems ........................................................................... 40
Table 4-5 Scores of less impactful systems ............................................................................. 41
Table 5-1 Framework ............................................................................................................. 43
Table 7-1 Complemented framework ..................................................................................... 61
Table 7-2 SWOT-analysis ....................................................................................................... 67
SECTION I: INTRODUCTION
1 INTRODUCTION

The introduction chapter consists of an elaboration of the motive of the research, including the tender phase characteristics, and the problem identification (1.2) that is summarised in a problem statement (1.3). The assumptions made in this research are described in paragraph 1.4. Finally a thesis outline is given in paragraph 1.5 that describes the content of the different sections and chapters.

1.1 Motive of Research

The motive of this research is the result of a shift in responsibilities of the government (client) in infrastructural projects. The government developed another vision in the past decade and decided to be less involved in the construction and maintenance activities of infrastructural projects. They now have a more steering role within the projects (Bakker et al., 2010). In the past the client was responsible for the maintenance and finance of a project, within the new vision they shifted these responsibilities to the contractor. This resulted in new type of building contracts – called integrated building contracts. The contractor was in the more ‘traditional’ contracts only responsible for the design and construction of an infrastructure project. Within the integrated building contracts they can also be responsible for the maintenance and finance of the projects (depending on type of building contract type).

The shift of responsibilities had multiple purposes from the perspective of the client. The most important purpose was to enhance the quality of the projects, by using the advantages of synergy. Awarding the design, construction and maintenance contracts separately results in most cases in a less optimised system (Koster et al., 2008). Combining the different contracts must be an incentive for the contractor to optimise the design, construction and maintenance. This might result in lower Life Cycle Costs (LCC) (Koster et al., 2008). Within the integrated contracts the contractor is paid differently for their activities. In the more ‘traditional’ building contracts the contractor is paid for the design and construction of a system – delivering a product. Within the integrated building contracts the contractor is also responsible for the maintenance – keeping the system available (system performances) by conducting maintenance activities. Contractors are not only paid for designing and constructing an infrastructure system anymore, they are also paid for the maintenance activities. As in the case of the following type of building contracts: Design, Build and Maintain (DBM); Design, Build, Finance and Maintain (DBFM). Within a DBFM-contract, contractors are responsible for the finance as well, besides the design, construction and maintenance. The integration of the finance, makes the contract even more complex and many risks stems from the complexity of the contract (Grimsey & Lewis, 2002). Within these contracts the system performances becomes even more important. The contractor is paid based on the system performances within the integrated contracts. The integrated building contracts makes the contractor responsible for a long period while they were initially responsible for the design and construction only. So, their approach must shift from short-term to long-term in case they must conduct an integrated contract. This is further discussed in Section II.

Not all building contracts that are put on the market are integrated building contracts. Within the more ‘traditional’ contracts, design and construct (D&C), the content is in some cases changed as well. To give the contractor a motive to enhance the quality of infrastructural projects within D&C-contracts, the client integrated performance requirements into the contracts.

As a consequence of the change in building contracts and awarding strategy, contractors might need to change their approach towards infrastructure projects. The contractor should shift from a short term vision to consider the system performances over a long-term. Because, the more ‘traditional’ contracts are focused on the short-term and the integrated contracts are focused on the long-term performances. This already starts in the tender phase. The phase before the project is actually awarded to a contractor. This phase is characterised by several limitations that makes it more difficult for the contractor to process the system performances already properly in the tender offer. This is further described in the following paragraph. Currently, for contractors it is not yet clear how to process the system performances in the tender phase. Not every project requires the same system performances, which depends on the type of subsystems. The importance of the system performances is also not the same for every project. Which depends on the building contract. So, contractors are struggling with integrating the system performances in tender phase. From this point of view a research is conducted into the role of system performances in the tender phase from the perspective of the contractor. The underlying
problems of a contractor with processing the system performances in tender phase is described in the following paragraph. An overview of the building contract characteristics is given in Table 1-1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Building contract</th>
<th>Approach</th>
<th>Focus of project</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Design &amp; Construct (D&amp;C)</td>
<td>Short term</td>
<td>Product delivery</td>
</tr>
<tr>
<td>2.</td>
<td>Design, Build and Maintain (DBM)</td>
<td>Long term</td>
<td>Performance delivery</td>
</tr>
<tr>
<td>3.</td>
<td>Design, Build, Finance and Maintain (DBFM)</td>
<td>Long term</td>
<td>Performance delivery</td>
</tr>
</tbody>
</table>

In order to understand the role of system performances in tender phase for contractors, the system performances of infrastructure systems must be defined. Simplistically described, system performances are the availability of a system. But then, what is availability? System availability is interrelated with other components. A system cannot be available if it is not safe. An unavailable or unsafe situation might be caused by an unreliable (sub)system or due to maintenance activities. Consequently, the maintenance strategy is partly determined by the maintainability of a system (Markeset & Kumar, 2004). In short, the system performances of an infrastructure system can be described by the integral relation between the reliability (R), availability (A), maintainability (M) and safety (S) and are called RAMS-performances. The system performances are determined during tender, design, realisation and maintenance phase. But the most fundamental decisions with regard to the system performances are taken during the tender phase; in order to keep the system available and safe, the contractor conducts maintenance activities. This is shown in Figure 1-1.

![System performances (based on (CENELEC, 1999))](image)

The use of RAMS within the Dutch civil infrastructure market is increasing. Clients are more and more describing the project specifications and performance requirements in terms of RAMS-performances. But currently it is relatively new in the market and contractors are not yet very familiar with the content of it and how to process these specifications in tender phase. In chapter 6 a set of methods is described that can be used by the contractor to determine the RAMS-performances. What specific problems contractors encounter with regard to the system performances is further discussed in the following paragraph.

### 1.2 Problem Identification

In order to gain a better understanding of the problems contractors encounter with assuring the system performances in tender phase interviews are conducted. These interviews are conducted with people within the organisation of the Dutch contractor Ballast Nedam. The main purpose of the interviews was to gain insight in the problems contractors are having with assuring the system performances in the tender phase. The interviews were aimed at gaining information about the experiences of experts with system performances and the tender phase. A further elaboration of the content of the interviews is given in paragraph 2.3. In order to keep the participants anonymous they are named by a number that is given in Table 2-2. In this paragraph grey boxes are given and are a brief summary of the problems contractors encounter with regard to the system performances.

The main issue for contractors is the shift from product delivery to performance delivery, which requires a different mind-set. Contractors must now focus on the long-term instead of short-term, which was the ordinary approach of contractors. Within D&C-contracts (including performance requirements) and integrated contracts as DBM and DBFM, contractors are responsible for the design, construction, maintenance and finance of the project. This is relatively new for a contractor and currently not part of the basic skills of project engineers. This
may be caused by the former role of Dutch contractors in the Dutch market – design and construct without being concerned with system performances and long-term goals.

Concluding, from origin the core business of contractors is: construction. Despite the fact contractors expanded their scope with design and operate and maintenance (O&M) in the past decade(s), a long-term vision is still lacking. As a result, limited knowledge of system performances over the long-term within the organisation of Dutch contractors (Interviewees 1, 3, 4, 5, 6).

**Identified problem 1:**

Limited knowledge of system performances over a long period within the organisation of Dutch contractors.

As described in the previous paragraph, the long-term vision with regard to the system performances starts already in the tender phase. From this perspective a new mind-set within the organisation of contractors might be necessary to process the system performances properly in the tender phase. According to Interviewee 1, the wrong question is being asked by the project organisation during tender phase. The project organisation must ask themselves: What is necessary to fulfil the contractual performance requirements? From this perspective, they can gather the required data and knowledge needed to develop an available and well performing system. Instead of thinking: the design is unknown and therefore it is difficult to develop a well performing system (Interviewee 1). Nevertheless, this way of thinking is not very surprising. It is the result of the short term approach. The contractors were not concerned with performance requirements or long term goals. Because it is not part of the common knowledge of the contractors they are also having difficulties with processing the data on system performances of infrastructural systems provided by subcontractors (Interviewee 6). Overall, it really depends on the capabilities and interests of the project organisation to what extent the system performances are understood and subsequently incorporated into the design (Interviewee 4, 5).

It is not only a problem of lacking knowledge or experience within the organisation of a contractor but also a problem of a lacking methodology. Currently, no methodology is integrated yet in the organisation of Dutch contractors that could be used to process the system performances of infrastructural systems effectively and on a well-founded basis. This might have an adverse impact on the process of processing the system performance in the tender phase.

**Identified problem 2:**

A general methodology is lacking within the organisation of Dutch contractors to process the system performances of infrastructural systems effectively in the tender phase.

So far, knowledge, experience and performance data issues are discussed. Besides these issues an organisational issue is noticed as well. This issue is also a result of the introduction of integrated building contracts. This can be traced back to the original core business of contractors: construction. From origin, contractors are not concerned with integrated contracts and cooperation between the different disciplines (design and maintenance) was limited. In order to develop an integral design in which the system performances and maintenance are integrated the different disciplines within the project must cooperate. Currently the cooperation between design and maintenance is lacking (Interviewees 1, 3, 4, 5, 6). This might result in cost overruns and project delays in later project phases due to necessary design adjustments (Interviewee 4, Wubbenhorst 1986). It could also result in excessive maintenance costs due to a bad maintainable system. A good cooperation between the different project disciplines is also acknowledged by Evbuomwan and Anumba (1998). They described the need for a different engineering approach: concurrent engineering, with the purpose to optimise the design and in order to develop an integral design.

**Identified problem 3:**

Within the organisation of a contractor, there is a lack of cooperation between the design- and maintenance and operate (M&O) departments.
Despite of the difficulties contractors are having with the system performances, in essence it is not necessarily a problem. It will become a problem (from the perspective of the contractors) in case it affects the profit margin of the contractors. It is assumed that the main purpose of a contractor is to make profit, as much as possible. System underperformance might affect this adversely in different ways, this is discussed in chapter 3. In order to limit the risks of system underperformance a certain methodology can be used; a set of methods to describe and determine the RAMS-performances. Unfortunately, within the organisation of Dutch contractors there is no methodology integrated yet to limit the risks already in tender phase of system underperformances (Interviewee 1, 2, 3, 4, 5, 6). Therefore one of the purposes of this research is to deliver a set of methods contractors can use to limit these risks in tender phase of system underperformance.

But before the set of methods is described, it is analysed how the system performances are integrated in the building contracts and infrastructural systems. The research is focused on the tender phase because the most fundamental decisions are taken during this phase and with that, the main system performances are set in this phase. The tender phase is a phase with some specific characteristics that are of importance in assuring the system performances.

1.2.1 Tender Phase
This research is focused on the tender phase which is the phase prior to the start of the actual project – before the actual project is awarded to a company. The success or failure of an infrastructural project depends on the decisions made during the tender process (Mohemad, Hamdan, Othman, & Noor, 2010; Shash, 1993). In principle, two major decisions must be taken by the contractor during the tender phase:
1. The first decision is about whether they participate in the project or not. If they decide not to participate, an opportunity loss might by incurred (Shash, 1993).
2. In case the contractor decides to participate in the tender. They have to make a price estimation of the future project. An estimation of the possible costs and the resources needed during the life cycle of the project (Shash, 1993).

The tender process is an uncertain and complex process (Lin & Chen, 2004). Basically due to the following two aspects (Shash, 1993):
- consequences of each alternative are uncertain;
- the large number of factors having a considerable effect on the decisions (Ahmad and Minkarah, 1988).

The tender process is based on the many objectives and priorities of different individuals within the organisation. Bias and inconsistency are inevitably, in case the decision making process is based on intuition, subjective judgement or emotion (Mohemad et al., 2010).

During the tender phase multiple companies compete on the same project and finally hand in a tender offer. The tender offer will include a price estimation, preliminary design and a risk indication. Based on these bids a winning tender offer is chosen by the client. The winning tender offer is chosen based on several awarding criteria. What awarding criteria are applied depends on the type of building contract.

The research is focused on the tender phase in which a winning project strategy must be developed. Developing the right project strategy in the tender phase is an iterative process. The tender manager is depending on the amount of resources made available by the board of the contractor. Resources as, number and quality of staff, budget and time available for tender activities. The project team must eventually make a preliminary design including a price estimation and risk indication.

Purpose of tender phase
The purpose of the tender phase is to get the project awarded. But, the tender offer must be realistic. With a proper risk indication and with a realistic price and in compliance with the project specifications. An unrealistic tender offer might cause problems during design, realisation and/or maintenance phase. Problems like, extra costs due to wrong calculations and design or planning mistakes. Overall, the purpose of the tender phase is to develop a tender offer with the lowest price and the highest value (based on interviews).

Value can be interpreted and defined in different ways. From the societal perspective a system has high value in case it is available and safe and it is realised without major project delays and cost overruns. A client wants a
system that fulfils the societal needs and demands the contractor to realise a system that is able to fulfil these requirements. A contractor is also eager to develop a system that is available, safe and realised without major cost overruns and project delays but partly for other reasons. With the main purpose that a contractor wants to make profit. Cost overruns and/or project delays might endanger this profit margin. From the perspective of the contractor high value can be seen as a well-performing system without or limited cost overruns and project delays.

**Tender phase characteristics**
The purpose of the tender phase is to develop a winning tender offer. Within the winning tender offer the whole project life cycle must be overseen and finally comply with the project specifications. Unfortunately, the tender phase is characterised by several limitations. The tender process is relatively short compared with the total project duration and the contractor has a limited budget to conduct the tender. Within this relatively short time period, with limited budget, the contractor must develop a preliminary design that is also feasible. The preliminary design is not very detailed and based upon a limited amount of information (Wubbenhorst, 1986). Based on the limited amount of information the contractor must make several assumptions that will be verified during the design phase. Despite the tender phase limitations the most fundamental decisions with regard to the system performances are taken during tender phase. Why these decisions are so vital, is described using the figures given in Figure 1-2 and Figure 1-3.

In Figure 1-2 three graphs are given that illustrates the characteristic problems for a contractor during the life cycle of a system; with regard to the knowledge level, system configuration and project costs. The first graphs shows the development of the knowledge level and the permitted ignorance of certain knowledge. Especially the knowledge is critical, because the contractor must develop a tender offer based on a low level of knowledge. This might cause problems because of the many uncertainties in the design.
The second graph shows determination of configuration and the ease of change of the system. The ease of change of the system is the biggest in the beginning. In short, the contractor has the most influence on the design in the beginning of the project life cycle and to a lesser extent in the design phase.

The third graphs shows the project cost development. In which the determination of the costs increases quickly in the early project phases. The influence on these costs is the other way around. The influence on the costs decreases during life cycle. So, in the beginning of the project the contractor has the most influence on the project costs.

Using the three graphs of Figure 1-2 it can be concluded that the influence on the costs and system design is the biggest during the tender phase. But, this cost determination and design development is based on a low level of knowledge. In addition to the three graphs another conclusion can be drawn. The highest system value can also be created in early project stages, see Figure 1-3. This figure shows a graph including two lines:
- green line shows the decreasing influence on the system value during life cycle;
- red line describes the increasing costs of system changes during life cycle.

For a contractor it is very important to make the right trade-offs during tender phase to avoid costly design changes with low added value in later project phases.

In the figures given above the project life cycle is given on the horizontal axe. The first stage of the project life cycle is the programme phase also known as the initiative phase. In this phase the client prepares the project requirements and puts them on the market using a certain procurement strategy. During this phase the contractor is not involved in the process. During the tender phase a group of contractors are developing a bid, in consortium (joint-venture) or individually, based on the project requirements. Only one contractor (or consortium) can win the bid and can starts with the design – design phase. The design phase is relatively long compared with the tender phase. During this phase the design is finished and the assumptions made during the tender phase will be verified and further elaborated. The influence on the value is decreasing, while the costs of change is increasing. The third phase is the realisation (construction) phase in which the actual system is realised, final phase is the usage phase or maintenance phase. The contractor can also be responsible for the maintenance phase, depending on the type of building contract. During this phase the contractor must keep the system functional and operational by conducting maintenance activities.

Tender phase strategy
In general the tender phase is about making trade-offs between the costs, risks and performances of a system. See Figure 1-4. For a contractor it is important to keep the price as low as possible, to enhance the chance of winning the project. From the perspective of the contractor it is important to understand the risks of a project. To have insight in the project elements that include the most risks and to mitigate or avoid these. Finally, the future design must fulfil the performance requirements, in order to make a chance of getting the project awarded.
Project costs
One of the products in the tender offer is an estimation of the project costs and a price determination. The project costs are based on a rough estimation of the design costs, construction costs, maintenance costs and expected performance and availability discounts. After winning the project there is limited room for discussion about the price. So the contractor must be certain about the estimation, that they can conduct the project with the estimated price. The tender price includes a profit margin for the contractor. This margin cannot be too high because then the tender price will be too high and the contractor will not win the project. In case the profit margin is too low, the contractor can lose money on the project. So the contractor must make trade-offs between the costs, risks and expected performances of a certain system. An optimum between these must result in a tender offer that is profitable for a contractor but also realistic to conduct and with a certain chance to win the tender as well.

Risks
In combination with the tender phase limitations the contractors must develop a winning project strategy. Within this strategy the contractor must find the balance between tender costs and the risk profile of the project (Interviewee 6). The tender phase is basically risk controlled. For the contractor it is really important that the indicated risks are manageable in the construction- and maintenance phase (Interviewee 4). In order to maintain the system performances and avoid cost overruns and project delays in later project phases due to unmanageable risks. In case of a high risk profile it can be decided to conduct an additional analysis on these risky project elements (Interviewee 5), with purpose to diminish the risk of these elements. From this perspective it is very important for contractors to be aware of the project elements that are containing the most risks. Unfortunately, due to the limited time and budget the contractor is not able to analyse all the project requirements in tender phase and assure them within budget.

1.3 Problem Statement
Based on the previous described problems of contractors with system performances the following problem statement can be set:

*Within the organisation of Dutch contractors knowledge with regard to the system performances of infrastructural systems is lacking. This in combination with the tender phase characteristics makes it difficult for a contractor to limit the risk of system underperformance already in tender phase; with the purpose to optimise the profit margin of the contractor.*

1.4 Assumption
Within this paragraph the assumptions made for this research are defined.

The final output of the research is a decision-making model (main objective) that must support contractors in their decisions during the tender phase. Decisions with regard to the system performances in the tender phase, and risks associated, of different type of infrastructural systems. The input for this model consists of three variables and is bounded by the tender phase. A phase with several characteristics that makes the process even more critical for a contractor. The three variables can be distinguished in two independent variables and one dependent variable. The two independent variables are the project complexity and the type of building contract. The dependent variable is a set of methods to analyse the system performance by mapping and mitigating project risks.
It is assumed that the type of project (project complexity), type of building contract (contract complexity) and, tender phase characteristics determines which method can be used by a contractor in the tender phase, to limit the risks for contractors of system underperformance of infrastructure systems.

1.5 Thesis Outline
The research report is divided in four sections.

Section I
Section I consists of the introduction of the research in which the motive and problem identification of the research are described (chapter 1) followed by an elaboration of the research design (chapter 2). The research design describes the research objectives, questions, methodology and scope and limitations. This chapter is used as guide during the research.

Section II
The analysis is described in Section II in which the risks and consequences for a contractor are identified and described per building contract (chapter 3). Chapter 4 includes an analysis of the impact of the different infrastructural systems on the system performances. The output of both chapters is used as input for the framework described in chapter 5, which is the final chapter of section II.

Section III
Section III consists of the completion of the framework described in chapter 5. The applicability of a set of methods is analysed and elaborated in chapter 6. The different methods are allocated to the different situations described in the framework and finally resulted in a decision-making model (chapter 7).

Section IV
The final section, section IV, includes the conclusion (chapter 8) and the discussion & recommendations (chapter 9).

The references are given in chapter 10 and the appendices are processed in the final chapter of this report (chapter 11).
2 RESEARCH DESIGN

The identified problems described in chapter 1 are translated in several research objectives (2.1) that consequently are converted into the research questions (2.2). How the research is conducted and the associated methodologies are elaborated in paragraph 2.3. The final paragraph (2.4) of this chapter consists of a description of the scope and limitations of the research.

The research design forms the basis for the research and is used as a guideline during the process.

2.1 Research Objectives

The research objective is divided in multiple sub-research objectives that together form the main research objective, which is given first.

Main research objective

The main objective of this research is to develop a decision-making model that can be used by contractors in tender phase in order to limit the risks for contractors of system underperformance and optimise the profit margin.

In order to develop a decision-making model that can be used by contractors in tender phase to limit the risk of system underperformance, insight in the system performances and consequences of underperformance is necessary. This information can be used to understand what possible losses or profits a contractor can incur. Currently this knowledge is lacking within the organisation of Dutch contractors and to narrow this knowledge gap insight must be gained with respect to the consequences for contractors in case of system underperformance and is the basis for the first research objective (objective 1). The second objective is aimed at gaining knowledge of the system performances of different infrastructural systems since this knowledge is lacking within the organisation of Dutch contractors (Interviewee 1, 3, 4, 5, 6). Within the organisation of Dutch contractors no general method is integrated yet, with the purpose to diminish the risk of system underperformance for a contractor and optimise the profit margin. Therefore, a set of methods is delivered contractors can use in tender phase to limit the risks of system underperformance (objective 3). In this report minimising the risks of system underperformance and optimising the profit margin is called optimising the risks of system underperformance.

The decision-making model consists of four variables: three independent variables; one dependent variables. The independent variables are the tender phase characteristics, type of building contracts (objective 1) and type of infrastructure (objective 3). Those situations determines what method should be used in order to limit the risk of system underperformance for a contractor. The set of methods (objective 3) that can be used are the dependent variables; it depends on the situation what method is suitable to apply.

For instance, whether method A is used or method B depends on the type of infrastructure (project complexity), type of building contract (contract complexity) and the tender phase characteristics (limited time, budget and information).

Objective 1

Create insight in the risks for contractors in case they do not or insufficiently take into account the system performances of infrastructural projects in tender phase.

The building contract determines whether a short- or long-term vision is required for the project and determines what type risks might occur. The outcome of a risk could be an opportunity or a threat for the contractor. By sufficiently processing the system performances it could be an opportunity to optimise the system; an opportunity to optimise the profit, by better assessing the risks. In case of insufficiently processing the system performances in tender phase it can be a threat; it might endanger the profit margin when the system is not performing according to the performance requirements. To understand what risks might occur in case the system performances are not taken into account in the tender phase, different building contracts are analysed.
To conclude, it is analysed what risks might occur in case the contractor insufficiently processes the system performance in tender phase. What building contracts are analysed is further described in paragraph 2.3.

**Objective 2**
Create insight in the (sub)systems of different infrastructural projects with the biggest impact on the system performances.

There is a lacking knowledge of system performances of infrastructural systems within the organisation of Dutch contractors (Interviewee 1, 3, 4, 5, 6). In order to develop a system that is in compliance with the performance requirements insight in the system performances of infrastructure systems is necessary. It is assumed that the system performances of the different infrastructural systems differ and therefore different infrastructural systems are analysed. To gain this knowledge a set of infrastructure systems is analysed to understand what subsystems have the biggest impact on the system performances.

To conclude, it is analysed what (sub)systems have the biggest impact on the system performances and a contractor must be aware of. The infrastructural projects analysed is described in paragraph 2.3.

**Objective 3**
Deliver a set of methods that is applicable in the tender phase and can describe and determine the RAMS-performances of infrastructural systems.

Within the organisation of Dutch contractors there is no general methodology integrated yet in the tender phase to optimise the risks of system underperformance (Interviewee 1, 2, 3, 4, 5, 6). A possible methodology is a set of methods that describes the RAMS-performances and can be either a qualitative as quantitative method. It can be used to describe, determine and monitor the system performances of infrastructural systems and is applicable in every project phase (Bakker et al., 2010). To understand what methods are applicable for what situation, a set of methods is analysed on their applicability in tender phase. The methods are assessed based on a set of criteria. These criteria are based on the independent variables with the purpose to deliver a set of methods that is applicable in the tender phase and for different situations.

### 2.2 Research Questions

To fulfil the different research objectives described above, the following research questions must be answered. To start with, the main-research question.

*How to effectively process the system performances of infrastructural projects in tender phase by the use of a decision-making model?*

The final output of this research is a decision-making model in which a distinction is made between the building contracts on one side and the infrastructural systems on the other side (independent variables). A set of methods is delivered that can be used by the contractor in tender phase to optimise the risks of system underperformances of infrastructural systems.

#### 2.2.1 Sub-research questions

The answers to the different research questions must form the answer to the main research question given above. The sub-research questions are:

**Risk identification**

1. What are the risks for a contractor in case they do not or insufficiently take into account the system performances of infrastructural systems in the tender phase?

The risks for a contractor that might occur during the project are depending on the type of building contract. Therefore it is analysed what the risks are per type of building contract in case the contractor insufficiently processes the system performances in tender phase. With the purpose to provide insight in the risks for a contractor in case they sufficiently process the system performances in tender phase.
The output of this analysis is a set of risks given per building contract that might endanger the profit margin of a contractor in case they insufficiently process the system performances in tender phase. This is described in chapter 3.

**System performances**

2. What infrastructural (sub)systems have the biggest impact on the system performances?

One of the problems to be solved is the knowledge gap of the contractor with regard to the system performances of infrastructural systems. To understand what (sub)systems have the biggest impact on the system performances an analysis is conducted on the impact of the different (sub)systems on the system performances. With the purpose to provide an overview of the (sub)systems with the biggest impact.

The output of this analysis is a list of (sub)systems ranked on impact to the system performances. This is described in Chapter 4.

**Methods to describe and determine the AMS-performances**

3. What methods are applicable to optimise the risks of system underperformance in the tender phase?

Within the organisation of Dutch contractors there is no methodology integrated yet in the tender phase to optimise the risks of system underperformance. To deliver a methodology, it is chosen to use a methodology that is based on the RAMS-principle. These methods can be used to describe, determine and monitor the system performances of a system. With the purpose to optimise the risks for contractor of system underperformance. This methodology is highly applicable for more advanced and relatively easy systems (Markeset & Kumar, 2004). Complex systems are more difficult to operate, diagnose failures, repair and/or restore failures and can be improved through a better design (Markeset & Kumar, 2004). This method is suitable for this analysis because less and more complex systems are analysed and the research is aimed at the tender phase in which a preliminary design is developed. Therefore, it is chosen to apply the methodology based on RAMS and analyse its applicability in tender phase.

The final output of this analysis is a set of methods that is applicable for contractors in the tender phase and can be used to optimise the risks of system underperformance. This is described in chapter 6.

In Figure 2-1 the problem description, research objective, research question, research method and the expected output is described for three different aspects: risk identification, system performances and RAMS-methods. The output of the different phases must supply the answer to the main research question. The final output of the research is a decision-making model to support contractors in their decisions regarding the assurance of system performances.
The research is a combination of a theoretical and practical analyses. With the theoretical analyses several literature studies are conducted on system performances, risks, building contracts and RAMS-methods. The practical analyses consists of case studies, surveys and interviews and are further discussed in the next paragraph.

The research is a combination of a theoretical and practical analyses. With the theoretical analyses several literature studies are conducted on system performances, risks, building contracts and RAMS-methods. The practical analyses consists of case studies, surveys and interviews and are further discussed in the next paragraph.

2.3 Research Methodology

In the previous paragraphs a set of research objectives and questions are described to tackle the problem. In order to answer the research questions several research methodologies are used. The different research methods used during the research are described per research objective, by using the literature of Verschuren and Doorewaard (2010).

The overall research is an exploratory study on the role of system performances for a contractor of different infrastructural systems in tender phase, distinguishing building contracts and infrastructure systems. With the final purpose to deliver a decision-making model that can be used by contractors in tender phase to optimise the risk of system underperformance. The construction industry has changed by the integration of building contracts and are now concerned with different type of building contracts from short-term to long-term. For both approaches different types of knowledge are needed. Knowledge about the different approaches and the consequences of system underperformance is currently lacking within the organisation of Dutch contractors. This research is partly aimed at narrowing the knowledge gap of Dutch contractors by providing insight in the consequences for contractors in case of system underperformance, distinguishing different building contracts. The other part of the research is the analysis and allocation of suitable methods to reduce the risk of system underperformance.

This research is mainly qualitative and is a form of empirical research in which predominantly qualitative data is used (Baarde, Goede, & Teunissen, 2001). This research must provide insight in the most critical system performances and the consequences for a contractor in case of system underperformance. Also it is aimed for to deliver a set of methods that can be used to optimise the risk of system underperformance. The main research methods are a literature research, case studies and qualitative interviews and surveys. The different methods used and for what reason is described below per research objective.

### 2.3.1 The risks of system underperformance

The importance of system performances can be described by analysing the consequences of system underperformance for a contractor by conducting several case studies. The first step in the research is to select
the cases to be studied. After conducting the case studies a set of interviews are conducted with experts to gain further in depth knowledge about the different projects. Besides the practical analyses, literature is studied on the risks and consequences for contractors in case of system underperformance. With the purpose to complement the practical insights with scientific information. Combining the output of the case studies, interviews and literature an overview of the risks and consequences for contractors can be given. The content and approach of the case studies and interviews is described separately.

Case studies

The case study method is an in depth methodology to gain specific and qualitative knowledge about certain topics (Verschuren & Doorewaard, 2010). The topics focused on in this research are the system performances and the consequences of system underperformances. The research is conducted at Ballast Nedam (BN) in Nieuwegein at the engineering department. BN is a contractor that competes on the Dutch civil construction market on Design&Construct (D&C); Design, Build and Maintain (DBM); and, Design, Build, Finance, and Maintain (DBFM), contracts. By the use of these type of building contracts the contractor is partly or completely responsible for the whole project life cycle from design to maintenance. These type of building contracts are analysed to determine the differences in risks between the short-term and long-term contracts. The first step in the case study research was to select a set of projects to analyse and to gain the practical insights needed.

Project selection

The aim is to develop a decision-making model that is applicable for a wide variety of projects. Therefore is chosen to analyse a set of projects with different building contracts and type of infrastructure systems. With the purpose to increase the applicability of the decision-making model. In order to select a set of projects the following criteria are used and discussed separately below.

1. Infrastructure projects

Within this research only infrastructure projects are analysed but infrastructure is still a very broad term. Infrastructure can be energy, water, transport or telecom and are all infrastructure assets with a very long lifespan (Herder & Wijnia, 2012). It is chosen to focus only on the water and transport infrastructure as this is also part of the scope of BN; the company the research is conducted. The Dutch water and transport infrastructure consists of a variety of systems that enables people to move themselves safely from A to B. These infrastructural systems are mostly part of an integral network. Within the network there may be some hierarchy in the impact of the infrastructural (sub)system on the total network performances. But very rarely there will be a key (sub)system that is responsible for a total network failure (Herder & Wijnia, 2012).

2. Type of building contract

The research is focused on the Dutch construction market and therefore only Dutch type of building contracts are discussed. The Dutch construction industry consists of the following type of building contracts (Pianoo, 2015c; Rijkswaterstaat, 2014):

I. Design and Construct (D&C) – The contractor is only responsible for the design and construction of the infrastructural system.

II. Design, Build and Maintain (DBM) – the contractor is also responsible for the maintenance, besides the design and construction.

III. Design, Build, Finance and Maintain (DBFM) – the contractor is responsible for the design, construction, maintenance and finance of the project.

IV. Engineering and Construct (E&C) – mainly applied for existing infrastructure to conduct maintenance activities. Comparable with a D&C-contract but with less detailed engineering (Pianoo, 2015b).

V. Performance contracts – the contractor is responsible for the design, construction and maintenance for a period of 3-7 years.

These contracts are based on the UAV-GC 2005 that is an abbreviation of Uniform Administrative Conditions of Integrated Building Contracts 2005 (in Dutch – Uniforme Administrative Voorwaarden – Geintegreerde Contractvormen 2005) (Bruggeman, Chao-Duivis, & Koning, 2010).
The system performances are set and realised during the tender, design and construction phase. During maintenance phase the system performances are maintained by conducting maintenance activities. To analyse the role of system performances within the realisation process and maintenance process both type of building contracts are analysed.

The E&C-contract is neglected because this type of building contract includes just a small part of engineering and is mainly applied for maintenance projects and existing systems (Piano, 2015c; Rijkswaterstaat, 2014); therefore not taken into account in this research. The performance contracts are also disregarded for the reason this type of building contract is not yet conducted by BN; they have no experience with this type of building contract. The content of the building contract is similar to the DBM-contract but not further analysed in this research.

3. Project is recently conducted (<3 years)
To be able to gather enough empirical and statistical data the project had to be conducted in the past three years or the project is under construction, design or is not awarded to BN. Otherwise there could be a chance the needed information is already archived and hard to get to.

The criteria described above is used to select a set of projects, see Table 2-1. Out of these projects multiple infrastructural (sub)systems are composed. These are further used to determine the impact of the systems on the system performance and is further discussed in the following subparagraph.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name project</th>
<th>Type of contract</th>
<th>Consortium</th>
<th>Client</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>A15 MaVa</td>
<td>DBFM</td>
<td>Yes</td>
<td>Rijkswaterstaat (RWS)</td>
</tr>
<tr>
<td>2.</td>
<td>A9 Gaasperdamerweg</td>
<td>DBFM</td>
<td>Yes</td>
<td>Rijkswaterstaat (RWS)</td>
</tr>
<tr>
<td>3.</td>
<td>Lock Limmel</td>
<td>DBFM</td>
<td>Yes</td>
<td>Rijkswaterstaat (RWS)</td>
</tr>
<tr>
<td>4.</td>
<td>Johan Friso lock (ship)</td>
<td>DBM</td>
<td>No</td>
<td>Province of Friesland</td>
</tr>
<tr>
<td>5.</td>
<td>A2 Tunnel Maastricht</td>
<td>D&amp;C/DBM</td>
<td>Yes</td>
<td>Rijkswaterstaat (RWS)</td>
</tr>
<tr>
<td>6.</td>
<td>Underpassing Elst</td>
<td>D&amp;C</td>
<td>No</td>
<td>ProRail</td>
</tr>
<tr>
<td>7.</td>
<td>N31 Harlingen</td>
<td>D&amp;C</td>
<td>No</td>
<td>RWS/Prov. Friesland/Mun. Harlingen</td>
</tr>
<tr>
<td>8.</td>
<td>Stenaline</td>
<td>D&amp;C</td>
<td>No</td>
<td>Port of Rotterdam</td>
</tr>
</tbody>
</table>

The selected cases are a variety of infrastructural systems from very complex to less complex. In total eight projects are analysed of which three conducted with a DBFM-contract; two with a DBM contract; and, three with a D&C-contract. The infrastructure systems analysed are road projects including multiple infrastructure systems as (movable) bridges and tunnels. Also a (ship) lock are analysed, an underpassing (tunnel < 250 metre), a deepened road and a quay wall. It is also noted if the project is conducted in a consortium. The information gathered from a project in consortium is very useful because it is not just from one company. It is analysed and processed by one or more companies and enhances the usability of the case studies and reliability of the final output of this research.

*Interviews*
A set of interviews will be conducted with the purpose to yield further knowledge on several subjects related to the projects. The motive to conduct interviews is that very valuable information can be gathered. The gathered data are experiences and thoughts of people in the work field, which is unique information that cannot be derived from the literature. These interviews are further used to understand the problems of contractors with system performances in the tender phase.

It is strived for to interview a variety of experts form the organisation of BN: experts of different levels and with different functionalities. Those experts are chosen based on their role within one of the cases described above. In total six experts are interviewed consisting of: two tender managers (tender phase), one design leader (design phase), two project managers (operate and maintenance phase) and one participant from higher management (all phases), see Table 2-2. To keep the experts anonymous they are named by their job function and discipline. In this research report is sometimes referred to the interviewees using the interviewee number, given in the first column of the table below.

---

1 Definition of consortium: a temporary cooperation between two or more companies to conduct a project.
Table 2-2 List of interviewees

<table>
<thead>
<tr>
<th>Interviewee No.</th>
<th>Job Function</th>
<th>Discipline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Management</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>Tender manager</td>
<td>Design</td>
</tr>
<tr>
<td>3.</td>
<td>Tender manager</td>
<td>Construction</td>
</tr>
<tr>
<td>4.</td>
<td>Project manager</td>
<td>Operate and maintenance</td>
</tr>
<tr>
<td>5.</td>
<td>Project manager</td>
<td>Operate and maintenance</td>
</tr>
<tr>
<td>6.</td>
<td>Design leader</td>
<td>Design</td>
</tr>
</tbody>
</table>

The interviews will be semi-structured in which the interview questions are used as a guideline. The interviews will be more or less a discussion of one hour, or more, in which a set of subjects will be discussed. The intended subjects to discuss are given below. The output of the interviews will be further elaborated on paper and sent back to the expert in order to get their approval. By sending back the elaborated interviews the expert has the opportunity to adjust or add information, in order to gain more reliable information that finally can be used as empirical data. No general interview format will be used because of the different backgrounds of the interviewees and therefore the content of the interviews might differ. The subjects discussed are described per project phase which are:

- **Tender** – All the interviewees have experience with the tender phase and therefore they are all questioned about their experiences with the tender process; the role of RAMS-performances (or performance requirements in general) in the tender process; the purpose of the tender phase. These questions are used as the start of the interview.

  Other subjects related to the tender phase that are discussed are: awarding criteria, position of operate and maintenance in the tender phase, detail level of preliminary design, feedback of client on bid, experiences of project team with RAMS-performances; who is responsible for the system performances in tender phase?; failure definitions.

- **Design** – After winning the project the project team starts with the design. Most often other project teams are involved in the process and have different experiences and thoughts about the design and the system performances. Some of the subjects discussed here have overlap with the subjects discussed with the tender process.

  The system performances are definitely set in this phase and therefore subjects as: main focus of design department; position of the RAMS-performances in the design process – experiences and methodologies used; difference in detail level between D&C, DBM and DBFM-contracts; combination of civil structures and installations – passive vs. active assets; reachability of the system; cooperation between different departments; risks of existing infrastructure, are discussed.

- **Construction** – No specific questions are asked with regard to the construction phase.

- **Operate & Maintenance** – The operate and maintenance (O&M) is the final phase in the project cycle that can take about 20 years. Clear considerations and decisions are necessary during tender phase to avoid cost overruns during the 20 years of maintenance. For this reason several questions are asked with regard to risks of insufficiently processing the O&M in tender phase but also the main risks of O&M are discussed.

  Other subjects related to the O&M discussed are, knowledge of RAMS-performance within the O&M-team; cooperation between different departments; influence in the different type of building contracts; maintenance strategies; focus of O&M-team – civil structures or installations;

Every interviewee is questioned at the end of the interview if they have any additional remarks on the use of system performances and methods to describe the RAMS-performances.

2.3.2 **Most impactful infrastructural (sub)systems**

The second step in the research is to provide insight in the system performances of different infrastructure (sub)systems. Using the case studies and interviews a list of infrastructure systems is composed. This list of
infrastructure systems is used in a survey to determine what (sub)systems are of importance with regard to the system performance. The final output of the survey is a ranked overview of the infrastructure (sub)systems; ranked from low impact on the system performance to high impact.

The current knowledge of Dutch contractors on system performances of infrastructure systems is limited, also literature is lacking that describes the system performances of infrastructure systems on a general level. Therefore is chosen to use a survey. The systems analysed consists of many (sub)systems and components, going into detail for every subsystem on the system performances is impossible during this research. Therefore is chosen to use a survey to rank the list of (sub)systems derived from the case studies, in order to develop an overview of the infrastructure systems ranked on the impact on the system performances. The survey consists of 2 parts:

1. ranking the impact of infrastructure systems on the system performances.
2. ranking the impact of infrastructure subsystems on the system performances.

The systems that are used in the survey and how the systems are ranked is further described in chapter 4.

The survey participants are experts working for many years on different type of projects, also in consortia, and currently within the organisation of BN. Same as for the interviews, the participants are chosen based on their disciplines and job functions within the organisation of projects. By doing so, knowledge from different angles can be gained by the survey and an integral solution to the problem can be developed. Table 2-3 gives an overview of the survey participants with job function and discipline. To keep the survey participants anonymous they are named survey no. 1 to survey no. 9.

<table>
<thead>
<tr>
<th>Survey No.</th>
<th>Job Function</th>
<th>Discipline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Project engineer (specialist)</td>
<td>RAMS-engineering and Tunnel safety</td>
</tr>
<tr>
<td>2.</td>
<td>Project engineer (specialist)</td>
<td>RAMS and Systems engineering</td>
</tr>
<tr>
<td>3.</td>
<td>Tender manager</td>
<td>Operate and maintenance</td>
</tr>
<tr>
<td>4.</td>
<td>Segment manager</td>
<td>Operate and maintenance</td>
</tr>
<tr>
<td>5.</td>
<td>Project manager</td>
<td>Construction</td>
</tr>
<tr>
<td>6.</td>
<td>Management</td>
<td>GWW</td>
</tr>
<tr>
<td>7.</td>
<td>Management</td>
<td>Construction</td>
</tr>
</tbody>
</table>

2.3.3  A set of methods to determine the RAMS-performances

The final step of the research is to deliver a set of methods that can be used by the contractor in tender phase to describe the RAMS-performances and optimise the risk of system underperformance. In order to gain this knowledge literature is studied. The final step in the research is a validation of the decision-making model.

Currently, no general method is integrated yet in the organisation of Dutch contractors to map and mitigate risks of system underperformance. For the contractors it is unclear what method is applicable for what situation to diminish the risk of system underperformance. In the previous subparagraphs the different situations are described and are used as input for the framework:

- consequences of system underperformance;
- impactful infrastructure (sub)systems.

A set of criteria is used to assess the applicability of the methods. Because a contractor can always use the most advanced method but this requires most likely more time, money and knowledge to be able to conduct the method. The criteria are based on the different variables described in the previous steps. Using the criteria it can be examined what method is applicable for what situation.

A variety of literature is used to develop a set of methods that are applicable in tender phase. Within the Dutch construction industry the main standard used, as it concerns RAMS, is the NEN EN 50126 (Part 1). This standard is used to gain further knowledge and understanding of the principle RAMS and what it is used for. The second standard used is the RAMS-guide, developed by Rijkswaterstaat – part of the Ministry of Infrastructure and one of the biggest clients of infrastructural projects in the Netherlands. They developed this standard to provide a general overview of the principle of RAMS and suitable methods to apply to describe, determine and monitor the system performances. Within the project specifications sometimes is referred to the RAMS-guide and
therefore used as first start to gain knowledge and understanding of RAMS and the methodology. After a set of methods is set-up the information is extended by the use of multiple handbooks and literature of the different methods in order to gain a well-founded set of methods based on a variety of literature.

**Validation**

The decision-making model is validated as final step of this research. A validation is conducted to provide (objective) evidence that the decision-making model, when in use, fulfils its intended purpose and supports contractors in their decisions with regard to the system performances of infrastructural systems (NEN, 2015). Due to the time constraints of the research the actual model cannot be implemented in the tender phase and measured over the whole project life cycle, therefore is chosen to use another validation method. It is chosen to present the model to the same group as used for the interviews for the reason that their knowledge, experience and thoughts are used to define the problems contractors encounter with system performances.

The presentation will be a discussion in which the development of the model is discussed and finally a SWOT-analysis is conducted. In order to prepare the experts for the validation a summary of the research is sent to them prior to the validation session.

During the presentation the different risks and infrastructure systems will be discussed with the purpose to elaborate how these are determined. Followed by discussing the different methods and why these methods are used for which situation. Currently, the contractors are lacking knowledge with regard to the system performances and the way how to process these in tender phase. By presenting the findings, the line of reasoning and the underlying thoughts can be discussed to provide further knowledge to the experts and to gather feedback on the choices made. Using the feedback of the experts a SWOT-analysis can be conducted to gather insight in the:

- strengths of the model;
- weaknesses of the model;
- opportunities of the model;
- threats of the model.

The validation must finally enhance the supportability and reliability of the outcome of the research, because wrong assumptions or any other choices made during the research could be corrected with as final purpose to optimise the model.

**2.4 Scope and Limitations**

To make sure the research is conducted in time and with satisfying quality, the scope and limitations are defined. The research is conducted at Ballast Nedam, a Dutch contractor competing on the Dutch construction market on infrastructure and building projects. In order to limit the scope, in this research is only focused on the infrastructural systems. The other limitations are:

1. **Tender Phase**

   The most fundamental decisions with regard to the system performances are taken during tender phase. A phase with limited resources and limited amount of available information. During the design and construction phase the final system performances are further developed. During the maintenance phase the system performances are mainly maintained or upgraded by conducting maintenance activities. In order to have the biggest influence on the system performances and to optimise the risk of system underperformance for contractors in later project phases the research is focused on the tender phase.

2. **Analysis of individual (sub)systems**

   The system performances of infrastructure systems is influenced by the singularity of (sub)systems but also by the combination of (sub)systems. Failure of one (sub)system might cause another (sub)system failure. The integral behaviour of (sub)systems is not part of the scope in order to keep the research practicable. For instance, a tunnel includes more than 50 subsystems. Analysing all these subsystems is not possible within the research period. Therefore is only focused on the single (sub)systems.

3. **Validation of decision-making model**

   The final output of this research is a decision-making model that must support contractors in their decisions during tender phase with regard to the system performances of infrastructure systems. Due to the time
constraints the model cannot be validated, by implementing it into the tender process. Depending on the project but most of the tender phases takes about three months to over a year. The design and construction process takes multiple years as well. In case maintenance is part of the project as well, the contractor is also responsible for the system for another 7-30 years. Due to the length of the projects and the limited time available for the research the model cannot be validated by implementation. Therefore is chosen to validate the model by presenting and discussing the model with experts of Ballast Nedam. With the purpose to validate the line of reasoning of the model.

3. RAMS(SHEEP)

An extension of RAMS is RAMSHE or RAMSHEEP, see below for elaboration. Both could be used as well to tackle the issues the construction industry encounters regarding the system performances of infrastructural systems. Nevertheless, these methods are tackling a wider range of aspects which makes them less contributive to the core question from the industry: deliver a methodology or set of methods that can be applied in the tender phase by the contractors with the purpose to process the system performances effectively and with that to diminish the risk of system underperformance. The system performances can be described in terms of RAMS (see chapter 1 – introduction) and therefore the scope is limited to the RAMS-aspects of a project to support the construction industry as good as possible.

The aspects outside the brackets are described briefly below, (RAMS)HE and (RAMS)SHEEP. Definitions are obtained from Bakker et al. (2010).

- **Security (S)** – the guarantee of a safe system/structure with respect to vandalism, terrorism and human errors.
- **Health (H)** – the feeling of good health with respect to the physical, mental and societal views.
- **Environment (E)** – to meet certain requirements which have been secured in Environmental Acts one suffices the rules of a good and clean environment. The environment can be seen as a physical environment wherein human life is even possible.
- **Economic (E)** – is the relation between the cost and benefits of a system. The aspect-economy is strongly related to the other RAMS-aspects because an increase or decrease of the RAMS-performances will have inevitably cost consequences. LCC and Cost-Benefit Analyses are proper tools to weigh possible alternatives.
- **Politics (P)** – besides rational decisions, certain decisions regarding a project are political loaded.

These aspects are disregarded for the following reasons. Security is neglected more often in the construction industry analyses due to the intentional behaviour. Which makes it difficult to incorporate in the RAMS-analyses. Health is disregarded because this is already partly taken into account in the health and safety legislation. Environment is handled in the environmental impact assessments (EIA) and therefore disregarded. The aspect economy is already partly incorporated in the research because of the optimization of the LCC and therefore disregarded as separate aspect. The aspect politics is aimed at decision-making on the basis of political grounds. Decision making policies are not a subject of the research.
SECTION II: ANALYSIS
3 Risk Identification

In the first chapter of this report the motive and problems of this research are described. One of the problems discussed is a limited insight in the consequences in case the contractor insufficiently takes into account the system performances of infrastructure systems in the tender phase. This chapter provides insight in these consequences and risks for a contractor. The consequences are the outcome of a risk and to understand what a “risk” actually is, a brief introduction to the risk theory is given first (3.1). Different risk categories are described and the relation between risk and system performances is discussed. It is assumed that the consequences for a contractor differs per type of building contract, therefore the building contracts are separately analysed on the risks that might occur (3.2). In the final paragraph (3.3) a brief summary is given of the analyses and findings of the analysis conducted in this chapter. After the analysis the first sub research questions must be answered.

What are the risks for a contractor in case they do not or insufficiently take into account the system performances of infrastructural systems in the tender phase?

The final output of this chapter is used as the input for the framework described in chapter 5.

3.1 Risk theory

First a brief introduction into the risk theory is given based on the literature of Nicholas and Steyn (2012).

They described project risk as “a function of the uniqueness of a project and the experience of the project team”, that can be described quantitatively or qualitatively (Grimsey & Lewis, 2002). Whether the risk is described quantitatively or qualitatively is based on the, project specifications and required accuracy. The contractor should examine up front what risk description is required: qualitative or quantitative. This determines what method should be used and what information is required in order to conduct the method. A quantitative analysis requires quantitative and qualitative data, this is further discussed in Section III.

Nicholas and Steyn described a risk as follows in the following formula:

\[ Risk = f(\text{likelihood}, \text{consequence}) \]

The likelihood can be described as, the probability that some particular event will occur and can be either high or low. The consequences of a risk can be defined as, the extent of the impact in case the event occurs. If at least one of the two is considered as large, the event is classified as risky. Companies are mainly focused on the biggest risks because of the high likelihood, extent of the consequences or a combination of both. High risks could stem from:

1. using an unusual approach;
2. attempting to develop a system while furthering technology at the same time;
3. developing and testing new equipment, systems, or procedures;
4. operating in an unpredictable or variable environment.

The consequence of a risk can be either positive or negative (Nicholas & Steyn, 2012; PMI, 2008). Risks are mainly seen as a threat, an event with an adverse impact on the project with a certain likelihood. But, risks can also be used as an opportunity, in the form of additional rewards, savings or benefits (Nicholas & Steyn, 2012). For both consequences the contractor can choose multiple response strategies. For risks with a negative impact the contractor can choose to avoid, transfer, mitigate or accept the risk. For risks that can be used as an opportunity the contractor can choose to exploit, share, enhance and accept the risk (PMI, 2008).

According to Miller (1992) risks can be described in forms of performances – revenues, costs, profit, market share. In other words, the risks of less system performances might result in lower revenues, profits or higher project costs for the contractor which should be minimised (mitigated). The contractor can also use risks as an opportunity to save money or increase (enhance) the project benefits. Within this research the main focus is on the risks with an adverse impact, but also the opportunities of risks will be described if these are noteworthy.

J.A.H. Koppes 23
Within this report two risk response strategies are discussed: accept and mitigate. If the contractor accepts the risk they can include the risk into the risk budget, which means a certain amount of money is saved and can be used in case the risk occurs during the project life-cycle. The amount of money is determined by the costs of the consequences of the event times the probability of occurrence. It will never be the case that the full amount of money is saved, the lower the probability of occurrence the smaller the amount (relatively) that is saved. The other possibility is to mitigate the risk by taking action with the purpose to diminish the risk of occurrence or minimise the impact of the event.

3.1.1 Risk categories

Three type of building contracts are analysed but the contractor is not equally experienced with all the building contracts. The D&C-contract is the most applied building contract in the Dutch infrastructure market (Pianoo, 2015a) and is well known by the Dutch contractors. The integrated building contracts are rather new and less known and might cause extra risks for a contractor due to lacking knowledge and experience with these contracts. To gain insight in the possible risks for a contractor a list of risks is developed based on literature described by Akintoye et al., Grimsey and Lewis, and Nicholas and Steyn. The content of these risks and how the list is composed by the different authors is discussed below.

List of risks

Akintola Akintoye, Taylor, and Fitzgerald (1998) composed a list of 26 risks based on several studies conducted by others. The study of Akintoye et al. was conducted to gain insight in the risk perception of the involved parties with Private Financed Initiative-projects (PFI). With the purpose to give an overview of the risks and the party that can be best responsible for. The three involved parties, the clients, contractors and lenders, ranked the 26 risks from their own perspective from very important to less important. The analysis of Akintoye et al. is very useful for this research because the PFI-projects are similar to DBFM-projects and the list is ranked by the contractors themselves. The list of Akintoye is supplemented by the literature of Grimsey and Lewis (2002) and Nicholas and Steyn (2012). Grimsey and Lewis (2002) evaluated the project risks of infrastructure projects with a Public Private Partnership arrangement. Within this evaluation they analysed different infrastructural projects and from the perspective of the various involved parties. One of the outputs of the evaluation is a list of nine risks that are always relevant in infrastructure projects with a PPP arrangement. The evaluation of risks in PPP-projects is very useful for this research because it represents the infrastructure market and is based on different literature and input of various parties. The risks described by Nicholas and Steyn are used to complement the list of risks.

Combining the three sources resulted in a list of 20 risks contractors should be aware of in infrastructure projects. The 20 risks are further divided into two risk categories: internal and external risks. Internal risks are risks that are in control of the contractor; external risks are risks that are not in control of the contractor (Miller, 1992; Nicholas & Steyn, 2012), see Table 3-1. Within the tender phase the contractor is focused on mitigating the most important risks and optimising the system performances as far as possible. The contractor is only able to mitigate the risks that are within their control and therefore is chosen to further analyse the internal risks and disregard the external.

<table>
<thead>
<tr>
<th>Internal risk</th>
<th>External risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance risk</td>
<td>Environmental risk</td>
</tr>
<tr>
<td>Risk of cost overrun</td>
<td>Development risk</td>
</tr>
<tr>
<td>Risk of project delay</td>
<td>Project life risk</td>
</tr>
<tr>
<td>Design risk</td>
<td>Regulatory and political risks</td>
</tr>
<tr>
<td>Construction cost risk</td>
<td>Economic climate risk</td>
</tr>
<tr>
<td>Market risk</td>
<td>Land purchase risk</td>
</tr>
<tr>
<td>Commissioning risks</td>
<td>Contractual risk</td>
</tr>
<tr>
<td>Operating risk</td>
<td>Residual risk</td>
</tr>
<tr>
<td>Safety risk</td>
<td></td>
</tr>
<tr>
<td>Payment risk</td>
<td></td>
</tr>
<tr>
<td>Financial risk</td>
<td></td>
</tr>
<tr>
<td>Tendering cost risk</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-1 Division of internal and external risks (based on Akintola Akintoye et al., 1998; Grimsey & Lewis, 2002; Nicholas & Steyn, 2012)
The risks that are most crucial to the corporates’ business are ranked the highest by the contractor; risks with a possible big (adverse) impact on the corporate business might threaten the profit level what is highly undesirable (Akintola Akintoye et al., 1998). The definitions of the internal risks are given below in Table 3-2.

### Table 3-2 Definition of internal risks on (based on (Akintola Akintoye et al., 1998; Grimsey & Lewis, 2002; Nicholas & Steyn, 2012)

<table>
<thead>
<tr>
<th>Internal risk</th>
<th>Risk description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance risk</td>
<td>The risk of not fulfilling the performance requirements specified up-front by the client.</td>
</tr>
<tr>
<td>Risk of cost overrun</td>
<td>The risk of a smaller profit margin due to higher costs than calculated up front (Akintola Akintoye et al., 1998).</td>
</tr>
<tr>
<td>Risk of project delay</td>
<td>The risk of not having the system completed at the scheduled and contractual agreed date (Akintola Akintoye et al., 1998).</td>
</tr>
<tr>
<td>Design risk</td>
<td>The risk of not fulfilling the performance requirements with the initial designed system (Akintola Akintoye et al., 1998).</td>
</tr>
<tr>
<td>Construction cost risk</td>
<td>The risk of increased construction costs due to a variety of reasons (Akintola Akintoye et al., 1998).</td>
</tr>
<tr>
<td>Market risk</td>
<td>The risk of not fulfilling the clients’ needs incorporated in the EMAT-requirements (Nicholas &amp; Steyn, 2012).</td>
</tr>
<tr>
<td>Commissioning risk</td>
<td>The risk relates to the possibility of the asset and service commissioning taking longer and how the asset is to be used upon completion (Akintola Akintoye et al., 1998).</td>
</tr>
<tr>
<td>Operating risk</td>
<td>The risk of an incorrect assessment of the operating and maintenance cost in tender phase (Akintola Akintoye et al., 1998; Grimsey &amp; Lewis, 2002).</td>
</tr>
<tr>
<td>Safety risk</td>
<td>The risk of unsafe situations during the realisation and maintenance period.</td>
</tr>
<tr>
<td>Payment risk</td>
<td>The risk of lower periodical payments than expected up front (Akintola Akintoye et al., 1998).</td>
</tr>
<tr>
<td>Financial risk</td>
<td>The risk of inadequate hedging of revenue streams and financing costs (Grimsey &amp; Lewis, 2002).</td>
</tr>
<tr>
<td>Tendering cost risk</td>
<td>The risk of high tendering costs due to the extent of the project.</td>
</tr>
</tbody>
</table>

3.1.2 **Risks and system performances**

System performances are described by the relation between the reliability, availability, maintainability and safety and are determined by two processes – see chapter 1:

1. design process;
2. Operate & Maintenance (O&M) process.

In the tender, design and construction phase the system performances are set but most fundamental decisions with regard to the system performances are taken during the tender phase (Wubbenhorst, 1986), see chapter 1. When the contractor wrongly assessed the system performances or insufficiently processed them in the tender phase it might result in lower system performances than required. This might have consequences for the contractor, which are discussed in the following paragraph. During O&M-phase the maintenance activities
are conducted by the contractor with the purpose to keep the system operational. The extent of the risks for a contractor of system underperformance depends on the type of building contract; whether the contractor has a short-term or long-term responsibility. Because system underperformance over a long period will have bigger financial consequences for a contractor than underperformance over a shorter period.

In short, system underperformance can be caused by two processes: design and realisation and O&M-activities and the extent of the consequences of system underperformance depends on the type of building contract. This is further discussed in the following paragraph.

It is assumed that the contractor wants to make as much profit as possible and system underperformance might adversely affect the profit margin. In 2013 the average profit margin of the main Dutch contractors (in infrastructure) was 1.1% and in 2012 it was 1.4% (Vrolijk, 2015). The low profit margin is partly a result of the crisis and the many competitors on the Dutch infrastructure market. Another cause of the low profit margin is insufficient risk management of the Dutch contractors, according to mister Bounen (Bounen, 2015). He noticed that contractors should make better risk estimations of the projects in order to make a more realistic price estimation. Part of the risk management is a proper estimation and assessment of the system performances. Any cost overruns or project delays due to system underperformance might result in a lower profit margin. In order to describe the financial consequences in terms of costs, the consequences of system underperformance are elaborated related to the project costs – the profit margin. By analysing the consequences and risks involved per building contract it can be defined what risks might endanger the profit margin. These risks can then be optimised by a method described in Section III. The cost categories that are used in the following paragraph to describe the financial consequences for a contractor are given per project phase in Table 3-3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Project phase</th>
<th>Cost category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Design phase</td>
<td>Design costs</td>
</tr>
<tr>
<td>2.</td>
<td>Construction</td>
<td>Construction costs</td>
</tr>
<tr>
<td>3.</td>
<td>Maintenance &amp; Operate</td>
<td>Maintenance costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Financing costs</td>
</tr>
</tbody>
</table>

The design costs are all the costs related to the design. The construction costs are all the costs related to the construction of the system. The maintenance costs are all the costs related to the maintenance activities – keeping the system available. The financing costs are the investment costs to realise the system and can be regained after realisation. These payments are based on the system performances and lower system performances will result in lower payments.

### 3.2 Risks per building contract

In the previous paragraph the risk theory is elaborated and a list of risks is defined and divided in internal and external risks. The list of internal risks are used in this paragraph to describe the risks for a contractor per building contract.

It is assumed that the risks differ per building contract, mainly caused by the short and long-term responsibilities of a contractor and the complexity of the contract; the more responsibilities incorporated in the contract, the more complex the contract might be for a contractor (Oostveen, 2013). Long- or short-term responsibilities are of big importance on the project strategy and determines the possible emerging risks for a contractor. In general the assessment and management of risks throughout the entire life-cycle might result in a reduction of the failure costs; early risk reduction might reduce the total project costs over the total project cycle (Honour, 2004; Parnell, Driscoll, & Henderson, 2008). This should be an incentive for the contractors to allocate the risks and manage these risks to reduce the project costs and possibly enhance the profit margin.

#### 3.2.1 Design & Construct (D&C-contract)

The D&C-contract is the most applied type of building contract on the Dutch infrastructure market (Pianoo 2015). Within the D&C-contract contractors are only responsible for the design and construction of an infrastructure system and in general there is no long-term incentive; contractors are not responsible for the system performances after realisation.

Situations in which long-term incentives are incorporated in a D&C-contract are:
- requested performance requirements by the client in the project specifications;
- strict safety or availability regulations related to a particular type of infrastructure;
- specific awarding criteria.

An awarding criteria could be: EMAT (Pianoo 2014) and is an abbreviation of Economically Most Advantageous Tender and is used to enhance the ratio of price/quality. Part of the EMAT-criteria could be maintainability and Life Cycle Costs (LCC).

Generally, the consequences of the risks in a D&C-contract can only occur during the design and construction phase and affect the associated project costs. In case long-term performances are incorporated in the awarding criteria, virtual bonuses are given to the contractor if they comply with the criteria — that eventually could reduce the fictitious tender price and increases the chance of getting the project awarded. This can be very beneficial for contractors in case they win the project, but they still have to realise their plans. Being too optimistic in order to comply with all the EMAT-criteria could result in a design that is hard to realise. Overall, the contractor should determine up front if the project includes long-term goals.

In case no long-term goals are incorporated and the contractor is only responsible for the design and realisation of a certain system, the consequences for a contractor are low. The contractor has no long-term responsibilities for the system performances and in case of insufficiently processing the system performances in tender phase it might result in extra engineering work, to adjust the design and construction. The extra engineering work are just one-off investments and after the adjustments the system will fulfil the performance requirements. In these cases the design and construction cost risks can emerge and affect the overall project costs negatively.

D&C-contracts including EMAT or other long-term performance requirements might include also another risk associated to the performance requirements. The contractor must assess the performance requirements based on the project specifications. Wrongly assessing these requirements can have multiple consequences. In the first place, the contractor might lose the bid due to wrongly assessed system performances and not satisfying the client with the bid. Secondly, in case of winning the bid, not all the virtual discounts can be gathered due to wrongly assessed performances. Third, the contractor must reassess the performance requirements to fulfil the clients’ needs (market risk). These consequences might result in extra design and construction costs and a lower profit margin.

Overall, the contractor should be aware of the infrastructural systems that incorporate strict regulations and requested performances requirements in a D&C-contract. But in general the consequences for a contractor in case of system underperformance are minor due to the short-term responsibility. Some of the infrastructure systems must comply with strict regulations and the contractor cannot neglect these in the tender phase. Wrongly assessed system performances might result in increased design, construction and market risks and possible higher project costs because of the probability of necessary design and construction changes to fulfil the performance requirements. After realizing the system, the consequences of a not performing system are not the responsibility of the contractor. Which can have a much bigger effect on the total profit margin. This could be the case for the integrated building contracts as DBM and DBFM, both separately discussed in the following two subparagraphs.

### 3.2.2 Design, Build and Maintain (DBM-contract)

The DBM-contract includes maintenance as well besides the design and realisation of an infrastructural system. This changes the responsibility of the contractor from short-term (D&C) to long-term (DBM). The contractor is responsible for the system for a certain period and must keep the system available by conducting maintenance activities. The maintenance period can be for a period of 7-30 years and has a great influence on the design and maintenance strategy.

In the previous subparagraph the importance of the system performances for a contractor in the tender phase and risks associated, is described from the perspective of the D&C-contract; a short-term contract, in which the contractor is only responsible for the design and realisation. The addition of the maintenance (M) to the D&C-contract makes the tender process more complex for a contractor and other trade-offs are needed. Trade-offs related to the design and maintenance strategy, to develop a well-performing system. The maintenance strategy of an infrastructure system requires a balanced consideration of the system performances and the
project costs over the entire life-cycle. Whereby, most of the maintenance strategies are developed based on minimized life-cycle costs (Frangopol & Liu, 2007). From this perspective the contractor might choose for a more robust system which is more expensive to realise but requires less maintenance activities and results in lower maintenance costs and LCC. The required maintenance activities are based on the design and maintenance strategy, both are further discussed below.

**Design**

The reliability and maintainability of a system and the associated system performances (availability and safety) are determined by the design of the system. The influence of the reliability and maintainability on the system performances and project costs are separately described below.

**Reliability of system**

The reliability of the system determines the initial availability and safety of a system and can be defined as “the probability that an item can perform a required function under given conditions for a given time interval (CENELEC, 1999).” An unreliable system most likely has a high probability that the system cannot perform its required function at a given time interval and might result in system underperformance. The CENELEC (1999) described reliability also in terms of:

- all possible system failure modes in the specified application and environment;
- the probability of occurrence of each failure or alternatively, the rate of occurrence of each failure;
- the effect of the failure on the functionality (system performance) of the system.

The reliability of a system influences the maintenance strategy and maintenance costs. ‘Cheap’ material might have a shorter technical lifetime – less reliable – and must be replaced more often than sustainable material, what in return could be more expensive over the long-term. An optimised maintenance strategy might result in lower LCC.

The A2-tunnel Maastricht project is a DBM-project with a maintenance period of 7 years, which means there is a limited need for optimisation with regard to the system performances. From this perspective the contractor decided to install Natrium-lighting instead of LED-lighting which are more expensive but requires less maintenance. If the contractual period was more than 10 years the contractor might have chosen for LED-lighting because of the high maintenance costs of Natrium-lights due to the lower reliability.

Another aspect of reliability is the redundancy of the system; a more redundant system is more reliable but, also more expensive to realise. A redundant system could result in lower life cycle costs due to the lower maintenance costs. In case this is not considered during the tender phase it might result in design and construction adjustments, which eventually results in higher design and construction costs and possible project delays (design and construction cost risks). If the system underperformance is noticed after realisation it might result in higher maintenance costs due to extra replacements and system repair (operating risk) in order to upgrade the system performances to the required level. The end-date of the project is incorporated in the contract between client and contractor and the contractor is paid based on the activities and product delivered. If the project delivery is delayed the contractor is forced to accelerate the process to finish it as soon as possible in order to be able to open the system (commissioning risk), which eventually requires extra resources.

**Maintainability of system**

The maintainability of a system is also set during the tender, design and realisation phase and can be defined as: “the aspect of maintenance that takes downtime of the systems into account. Designing for maintainability requires an evaluation of the accessibility and repairability of the inherent systems and their related equipment in the event of failure, as well as of integrated systems shutdown during planned maintenance” (Stapelberg, 2009). The CENELEC (1999) described the maintainability in terms of:

- the required time to conduct the planned maintenance activities;
- the time needed to detect, identify and locate the system defaults;
- the time needed to restore the failed system (unplanned maintenance).
A system that is difficult to access or to repair is less maintainable than a better accessible or repairable system and might eventually result in extra maintenance costs due to additional maintenance activities and delays.

In order to realise a system that is maintainable the maintenance activities should be incorporated in the tender process to develop a maintenance strategy. A system that is maintainable might initially result in higher realisation costs but it can strongly diminish the maintenance costs and result in lower LCC. During the tender and design phase the project team can discuss the system performances in combination with the required maintenance activities; to keep the system available and safe during the maintenance period (operating risk) (reference interviewee 4, 5).

For so far the importance of the design of a system on the reliability and maintainability of the system and the final system performances. Besides the design, the system performances are also influenced during the maintenance process – the actual maintenance activities. Which can have a major influence on the system performances and Life-Cycle Costs (LCC).

**Life Cycle Costs**

A contractor must consider the Life Cycle Costs, abbreviated to LCC, in the tender phase within building contracts with a long-term responsibility for the contractor – DBM and DBFM. The purpose of the LCC is to optimise the cost of purchasing, installing and maintaining the physical assets over the project life cycle (Kolarik, 1981; Woodward, 1997).

“The contractor should be aware of the possible additional value of a long-term outlook rather than attempting to save money over the short-term by purchasing assets with a lower initial purchasing costs” (Woodward, 1997).

In a long-term building contract as DBM and DBFM the contractor should consider the LCC with the purpose to optimise the profit margin. A more robust design might initially result in higher design and realisation costs but can strongly diminish the maintenance costs and reduce the LCC over the long-term. Because the maintenance period is in general a longer period than the design and realisation phase (see Figure 3-1) and reducing the maintenance costs can save money over the long-term.
Maintenance strategy

At first it must be emphasized that the design choices with regard to the reliability and maintainability, are of big influence on the maintenance strategy and LCC of a project. Another important aspect is the duration of the maintenance period. A (relative) short contract duration requires other trade-offs than a (relative) long contract duration (15-30 years). Within a project with a long project duration the (technical) installations must be replaced multiple times to be able to maintain the system performances. The technical lifetime of technical tunnel installations (TTI’s) of tunnel (sub)systems is generally 10-15 years (Rijkswaterstaat, 2012). Replacement of (technical) installations can be a very costly operation and in some cases the infrastructural system must be closed to be able to conduct the maintenance activities.

During the tender and design phase the maintenance strategy is developed based on the reliability and maintainability of the system and a completely finished system that is fully operational at the same time. In case of a project delay due to necessary design adjustments it could result in a partial completion of the system. This might result in a partly finished system whereby a part of the system is already in use and the other part is finished later. If so, the maintenance strategy might not be fully applicable anymore. Because the part of the system that is finished in time requires maintenance at another time, probably earlier, than the delayed part due to degeneration of the system. Eventually, this could result in more system closures, more maintenance activities and cost overruns as result of a less optimised maintenance strategy caused by the project delays.

After awarding the D&C-contract of the A2 Tunnel Maastricht the Maintenance contract was added by the client to the scope of the project. The M-contract was aimed at the Technical Tunnel Installations (TTI’s) and had a contract duration of 7-8 years. This is an odd decision by the client because with such a short maintenance period, the contractor is not triggered to optimise the system to its fullest. Because the TTI’s have a technical lifetime of 10-15 years and will (in theory) be functional during the whole contractual period.

Different maintenance strategies can be used for different purposes. Within the Dutch civil infrastructure market the risk-based maintenance (RBM) strategy is mainly used. Other maintenance strategies applied in other strategies as well are, Reliability Centred Maintenance (RCM); Total Productive Maintenance (TPM); Statistically Based Maintenance (SBM); and, Total Quality Maintenance (TQMain) (Al-Najjar, 1996; Murthy, Atrens, & Eccleston, 2002). Within this research only the RBM is further discussed.
Risk-based maintenance (RBM)

The purpose of the RBM-strategy is to “reduce the overall risk that may result as the consequence of unexpected failures of operating facilities” (Arunraj & Maiti, 2006). This strategy is focused on the high-risk components that will be more frequently and thoroughly inspected during the maintenance period. This strategy can be used to reduce the probability of failure of high-risk components, and subsystems, with the purpose to diminish the consequences of system failure. Using the RBM-strategy the contractor is able to determine what system elements requires more attention than others. Within the maintenance strategy two types of maintenance activities can be distinguished: preventive (planned) and corrective (unplanned) maintenance (Murthy et al., 2002), both maintenance activities are illustrated in Figure 3-2. In general, maintenance is used to restore the system conditions to the initial system conditions level by either planned or unplanned maintenance activities.

In Figure 3-2 three levels of system conditions are illustrated: good, sufficient and insufficient. Insufficient system conditions means a failed system and the contractor must immediately restore it – corrective maintenance. By corrective maintenance the contractor chooses to restore the system the moment it is failed – unplanned maintenance. The frequency of this type of maintenance is less equally divided which also result in more peak investments, an advantage of this method are the lower periodical costs. By applying a preventive maintenance strategy the contractor encounters a lower risk of unplanned unavailability due to system failure because frequent preventive maintenance is conducted – planned maintenance. The frequency of the maintenance is set in such a way that the system will fail less often due to system degradation. An advantage of the preventive maintenance strategy is a more equally divided spread of costs.

![Figure 3-2 Systems condition in relation to maintenance activities (based on Bogaard & Akkeren, 2011)](image)

According to Espling (2007) preventive maintenance has some advantages compared with corrective maintenance. It is more cost effective, higher quality and more dependable. What maintenance strategy to use depends on the trade-offs made by the project organisation including a combination of different aspects as, contract duration, requested reliability and maintainability of the system. Preventive and corrective maintenance is of bigger importance in the DBFM-contract due to the possible performance and availability discounts and the cost difference between preventive and corrective maintenance, this is further described in the following sub-paragraph.

**Overall**

A building contract including the maintenance-component requires other trade-offs compared with the D&C-contract. During the tender phase the contractor must consider the reliability of the different (sub)systems in combination with the maintainability of the system and eventually consider what maintenance strategy to
apply. In case they do not overthink this in the tender phase, it might result in higher project costs due to necessary design and construction changes or conducting more frequent maintenance to keep the system available. There where the costs of design adjustments are just one-off investments in a D&C-contract; the extra costs in a DBM-contract are most likely more frequent, because of the long responsibility and the systematically wrong strategy.

3.2.3  DBFM
The addition of the F-component – finance – to the DBM-contract makes the tender process even more complex, in comparison with the D&C and DBM-contract. Other trade-offs are necessary in order to make sure the system performs according to the performance requirements. The DBFM-contract is comparable with the DBM-contract with regard to the long-term responsibilities, except for the payment mechanism. Within a DBFM-contract the contractor is paid for the same activities as in the DBM-contract but, the contractor is also paid on the availability of the system – that is incorporated in the periodical payments. These payments from client to contractor are based on the system performances, a combination of system availability and maintenance activities. In this subparagraph the payment mechanism of a DBFM-contract is described. Followed by the importance of system performance within this type of building contract.

Payment mechanism
The main principle of the DBFM-contract is that contractors finances the project themselves and regain the investments during the project phases. In general the contractor is paid for the realised product and the system performances which are processed in two types of payment. Project documents of Ballast Nedam and literature are used to give a more detailed description of the payment mechanisms, an illustration of the payment mechanism of the A15 MaVa project is given in Figure 3-3.

![Figure 3-3 Illustration of the DBFM-payment mechanism of the A15 MaVa project (retrieved from Ballast Nedam)](image)

* Certificate of ‘nearly’ completion – in Dutch: tussen voltooingscertificaat
** Certificate of completion – in Dutch: voltooingscertificaat

Realised product
The first payment from client to contractor is after the system is realised. During realisation (design and construction phase) the contractor is responsible for financing the project. Once the system is realised the client pays the contractor for the finished product – called the one-off payment (in Dutch: eenmalige betaling).
Within the A15 MaVa project the contractor was initially paid € 250 million euro twice; in 2014 at nearly completion and in 2015 at system completion.

**System performances**
The second type of payments from client to contractor are periodical payments and are based on the system performances. The periodical payments are used to give the contractor an incentive to optimise the system performances already in the tender phase, in order to receive the maximum payments during the maintenance phase and to optimise the profit for the contractor (Koster et al., 2008). Within the A15 MaVa project a total of € 850 million euro could be gained over a period of 20 years (maintenance phase).

**Payment mechanism**
The periodical payments are based on the Net Availability Payments (in Dutch: Netto Beschikbaarheidsvergoeding – NBV) and is determined by the following formula: NAP = GAP – AC – PC:

1. **Gross Availability Payment - GAP**
   - in Dutch: Bruto Beschikbaarheidsvergoeding - BBV
2. **Availability correction (AC) – availability of system.**
   - in Dutch: Beschikbaarheidscorrectie - BC
3. **Performance correction (PC) - performance in terms of safety, process, maintenance and traffic hindrance.**
   - in Dutch: prestatie correctie – PC

See Appendix B – DBFM payment mechanism, for a more detailed elaboration of the payment mechanism.

The GAP is a fixed amount determined up front by the client. Within the AC’s and PC’s, fines and discounts are incorporated and are given by the client in case of underperformance. This must be an incentive for contractors to develop a system that performs according to contract to realise a profitable project as much as possible. The payment corrections should not act as a burden for the contractor, therefore the public client included penalty points in the payment mechanism. Both parties, client and contractor, are aware of the fact that every system could randomly fail, especially systems with mainly active assets (see chapter 4). These penalty points must stimulate the contractor to develop a safe and available system as much as possible. In case of a system failure the contractor must restore the system within a certain time period, called the recovery period (Koster, Hoge et al. 2008). As example a total of 850 million euro can be gained by the contractor during the maintenance phase in the A15 MaVa project and is a significant part of the total project sum. Therefore it is very important for the contractor to optimise the system performances in order to gain as much as possible profit.

**Performance Measurement System**
The system performances are measured by the use of a Performance Measurement System (PMS) in which the availability (AC) and performance corrections (PC) are incorporated. The PMS must be designed and developed by the contractors (contractual requirement), and is finally approved by the client before applied in the project. During the maintenance phase the contractor is also responsible for monitoring the performances with the PMS. The input for the PMS are two types of performance requirements:

1. A9 Gaasperdammerring: A and B-requirements
2. A15 MaVa: Kog and NKog-requirements.
   - Kog – Critical lower boundary (in Dutch: Kritische ondergrens)
   - NKog – Not critical lower boundary (in Dutch: Niet kritische ondergrens)

These requirements are linked with the system performances and payment mechanism. The difference between the two types of requirements is the consequence in case of not fulfilling the performance requirement. If the system is not performing up to a Kog-requirement direct fines are given; not performing up to NKog-requirements penalty points are given first. By a certain amount of penalty points the contractor gets a discount on the periodical payment. For every default the contractor is given a recovery period, determined up front, to restore the default. If the system is not restored within the recovery period the same penalty is given again.

**System availability vs. Performance discounts**
Insufficiently processing the performance requirements in the tender process of a DBFM-contract can affect four cost categories – design; construction; finance; maintenance. The design and construction costs are mostly...
one-off costs and caused by design flaws made in the tender and design process. Eventually design and construction adjustments might result in project delays which can have big consequences for the contractor in a DBFM-contract, especially for the costs of financing the project.

Financial risk
In a DBFM-contract the contractor finances the project in cooperation with lenders (financial institutes, banks). The money lend, is lend for a certain interest rate and is partly based on the expected end-date of the project and therefore very sensitive to delays. The moment the system is realised and commissioned, the contractor is paid the one-off payment. By a project delay the contractor is not paid the one-off payment on the initial date and extra resources (budget, staff and time) are needed to finish the project. This might result in increased financial costs due to extra project costs and a deferred income. Another cause of increased finance costs is an accumulating interest rate that can finally result in an ‘interest trap’. Flyvberg, Holm, and Buhl (2004) described the interest trap as “a combination of escalating construction costs, delays and increasing interest payments.” This might result in exceeded project costs that cannot be covered anymore by the project income; final result, project loss (Flyvberg et al., 2004).

Operating risk
Developing a maintenance strategy must be in coherence with the periodical payments with the purpose to realise an optimised system. During the tender phase the contractor must already consider a certain maintenance strategy to determine the possible income and expenditures over the project life cycle. This is a difficult task due to the limited amount of available information and time and budget constraints in the tender phase. Nevertheless, in case the contractor neglects this during tender phase it might result in more maintenance activities, in order to keep the system available. As described for the DBM-contract two maintenance activities can be distinguished: preventive and corrective. The preventive maintenance activities are planned and are less expensive. The system users are informed and they are able to change their route. The corrective maintenance is unplanned and more expensive, because the users are not able to prepare themselves by for instance, taking another route.

More maintenance activities means higher costs and extra system closures in order to conduct the required maintenance activities. This results in lower periodical payments due to higher performance and availability discounts. Eventually, this will result in lower profit margins for the contractor.

Overall
The DBFM-contract is comparable with the DBM-contract but the main difference is the F-component. At first, financing a project causes extra risks because a project delay might cause increased construction and financial costs. The financial costs might increase rapidly due to the accumulated interest rate and the deferred revenue from the project. To regain the investments the contractor is paid periodically by the client based on the system performances. Wrongly assessed system performances might result in a hard maintainable system and causes extra system closures. System closures will result in lower periodical payments due to more performance and availability discounts. Overall, the predictability of the project revenues and expenditures over the whole project life cycle are very important for a contractor because of the long-term responsibilities and the periodical payments that are based on the system performances. This requires many trade-offs in the tender phase in order to gain insight in the expected project costs and revenues.

3.3 Wrap-up Risk identification
In this chapter the consequences and risks for a contractor are analysed in case they do not or insufficiently process the system performances of infrastructural systems in the tender phase since the contractor is not very familiar with these risks and consequences associated. Within the analysis three types of building contracts are analysed, a short-term contract (D&C) and two long-term contracts (DBM and DBFM). A literature study was the main input for this analysis and is extended by the analysis of the project documents and output of the interviews with experts.
Within this research three risk response strategies are discussed and the main focus is on mitigating the risk of system underperformance:

1. accept the risk and incorporate the risk in the risk budget;
2. use the risks as an opportunity to enhance the profit margin;
3. mitigate the risk of system underperformances.

The most important risk for a contractor is the design risk due to insufficiently processing the performance requirements in the tender phase that can finally result in a system that is not fulfilling the system performances requested by the client. In order to fulfil these requirements the design and system must be adjusted what causes extra engineering work (extra design costs + extra time) and construction costs. This can have multiple consequences depending on the type of building contract. Within a D&C- contract it has minor consequences rather than one-off investments to restore the defaults. In spite the short-term character of the contract, the contractor should be aware of two aspects: requested performance requirements by the client and type of infrastructure, both can incorporate long-term goals that must be met in the tender offer. Otherwise, the contractor might not win the tender or after winning the tender the contractor must adjust the design because they wrongly assessed the system performances. Not meeting the performance requirements might result in extra risks for a contractor in a DBM-contract as commissioning and operating risks. Commissioning risk due to a delayed project completion that will result in extra costs because extra resources are needed to finish the project. The operating risk can possibly be caused by a system that is difficult to maintain or additional maintenance activities are required to keep the system operational. With as result, extra costs and lower system performance due to necessary system closure in order to restore the system safely. A project delay caused by necessary design adjustments might result in a partial completion of the systems that might have an adverse impact on the developed maintenance strategy. The maintenance strategy is partly based on the degeneration and usage of the system. Partial completion could cause different degeneration processes and a less applicable maintenance strategy, possibly additional resources are needed or extra system closures to conduct the maintenance activities. Being responsible for financing the project besides the design, construction and maintenance results in payment and financial risks for the contractor. Due to a project delay the system is not finished in time and the one-off payment cannot be paid from client to contractor. Also, the periodical payments are deferred and results in no revenues. This could have a major impact on the profit margin because extra resources are needed to finish the project in combination with the deferred income. Project delays could also result in an ‘interest trap’. The finance costs are sensitive to the time due to the interest rate, which is partly based on the end-date of the project and is endangered by additional design or construction work. Project delay might cause an accumulating interest rate that eventually will result in project losses due to an interest trap. The results are summarised in Table 3-4.

<table>
<thead>
<tr>
<th></th>
<th>D&amp;C</th>
<th>DBM</th>
<th>DBFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design risk</td>
<td>Design risk</td>
<td>Design risk</td>
<td>Design risk</td>
</tr>
<tr>
<td>Construction cost risk</td>
<td>Construction cost risk</td>
<td>Construction cost risk</td>
<td></td>
</tr>
<tr>
<td>Market risk</td>
<td>Market risk</td>
<td>Market risk</td>
<td>Market risk</td>
</tr>
<tr>
<td>Commissioning risk</td>
<td>Commissioning risk</td>
<td>Operating risk</td>
<td></td>
</tr>
<tr>
<td>Operating risk</td>
<td>Operating risk</td>
<td>Financial risk</td>
<td></td>
</tr>
<tr>
<td>Financial risk</td>
<td>Payment risk</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The output of this analysis is used as input for the framework and decision-making model described in respectively chapter 5 and 7. Contractors must be aware of the long-term responsibilities within the DBM and DBFM-contract because wrongly assessing the system performances or insufficiently processing the performance requirements in the tender phase might result in higher project costs and project delays. In order to diminish the risk of system underperformance the contractor cannot neglect the system performance in the tender phase and must develop an integral tender offer.
4 System Performances

As described in the first chapter is it unclear for contractors what systems have the biggest impact on the system performances. In order to provide this knowledge it is analysed what infrastructural systems have the biggest impact on the system performances. This is the second research objective and is formulated in the following research question.

*What infrastructural (sub)systems have the biggest impact (risk of failure) on the system performances?*

The sources used for this analysis are the project documents (derived from Ballast Nedam), interviews with experts and literature. Based on the analyses of these sources a survey is created and filled out by experts of Ballast Nedam, which is further described in paragraph 4.1. The outcome of the surveys is described in paragraph 4.2 and paragraph 4.3.

The final output of this chapter is used as input for the framework described in chapter 5.

4.1 Survey set-up

The system performances of an infrastructural system are determined by the combination of all subsystems and associated components and it is assumed that system performances per infrastructural system differ. Consequently, the impact on the system performances differ per infrastructural (sub)system and therefore a set of infrastructural systems is analysed to understand what subsystems have the biggest impact on the system performances. The described systems in Table 4-1 are analysed on the passive and active assets and the impact (risk of failure) on the system performances. A detailed description of the project selection is given in chapter 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name project</th>
<th>Consortium (Yes/No)</th>
<th>Type of contract</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>A15 MaVa</td>
<td>Yes</td>
<td>DBFM</td>
</tr>
<tr>
<td>2.</td>
<td>A9 Gaasperdammerweg</td>
<td>Yes</td>
<td>DBFM</td>
</tr>
<tr>
<td>3.</td>
<td>Lock Limmel</td>
<td>Yes</td>
<td>DBFM</td>
</tr>
<tr>
<td>4.</td>
<td>Johan Friso ship lock</td>
<td>No</td>
<td>DBM</td>
</tr>
<tr>
<td>5.</td>
<td>A2 Tunnel Maastricht</td>
<td>Yes</td>
<td>DBM/D&amp;C</td>
</tr>
<tr>
<td>6.</td>
<td>Underpassing Elst</td>
<td>No</td>
<td>D&amp;C</td>
</tr>
<tr>
<td>7.</td>
<td>N31 Harlingen</td>
<td>No</td>
<td>D&amp;C</td>
</tr>
<tr>
<td>8.</td>
<td>Stenaline</td>
<td>No</td>
<td>D&amp;C</td>
</tr>
</tbody>
</table>

The different projects given in Table 4-1 are composed based on a set of criteria (see chapter 2). The infrastructural network consists of many (sub)systems but not all (sub)systems can be examined due to the time constraints of the research and the complexity of the systems. From every project the most important infrastructural system is used in order to keep the research feasible, otherwise the scope of the research will be too comprehensive. In order to analyse the (sub)systems project documents and literature are studied and, interviews are conducted with experts of Ballast Nedam. Based on the outcomes of the analyses a survey is developed and filled out by experts of Ballast Nedam. The survey consists of multiple systems extracted from the project documents, literature and interviews. The analysis and outcome of the survey must provide insight in the infrastructural (sub)systems with the biggest impact on the system performances. This has resulted in the following list of infrastructural systems, which are used in the survey:

1. Fixed link / viaduct
2. Movable bridge
3. Tunnel
4. (Ship) lock
5. Dynamic Traffic Management-System*
6. Road construction**
7. Underpassing
8. Quay wall

*Dynamic Traffic Management-system includes all the subsystems related to the DTM-systems as, SoS (induction loops), matrix signs (MTM), DRIP’s, public lightning, steel portals, etc.
**Within the road construction systems, which is a discipline of the GWW, all aspects are included that are part of a road construction. Such as, water management, berm, berm protection, road layer, road marks, expansion joints, etc.**

The systems are ranked by the survey participants with a score from 1 to 8. A score of 8 means the biggest impact and a score of 1 the lowest impact. Consequently, the survey participants are questioned to name the 3 subsystems (of each system) with the biggest impact (risk of failure) on the system performances. Also, these subsystems are then scored. This time it is not ranked but scored with a number between 1 and 10. The total score of the 3 subsystems must be 10 and a subsystem can be scored with a minimum of 1. The subsystem with the biggest impact on the system performances is scored the highest.

The survey participants are experts working for many years on different type of projects, also in consortia, and currently within the organisation of Ballast Nedam. The survey participants are working in different disciplines and have different job functions within the organisation of projects. Knowledge from different angles is gained by the survey and with that, the final framework is developed by the use of multiple insights. It is assumed that by the use of a wide variety of participants a more reliable outcome can be generated. Table 4-2 gives an overview of the survey participants with job function and discipline. To keep the survey participants anonymous they are named survey no. 1 to survey no. 7. In case of a reference they are referred to their number.

**Table 4-2 List of survey participants**

<table>
<thead>
<tr>
<th>Survey No.</th>
<th>Job Function</th>
<th>Discipline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Project engineer (specialist)</td>
<td>RAMS-engineering and Tunnel safety</td>
</tr>
<tr>
<td>2.</td>
<td>Project engineer (specialist)</td>
<td>RAMS and Systems engineering</td>
</tr>
<tr>
<td>3.</td>
<td>Tender manager</td>
<td>Operate and maintenance</td>
</tr>
<tr>
<td>4.</td>
<td>Segment manager</td>
<td>Operate and maintenance</td>
</tr>
<tr>
<td>5.</td>
<td>Project manager</td>
<td>Construction</td>
</tr>
<tr>
<td>6.</td>
<td>Management</td>
<td>GWW</td>
</tr>
<tr>
<td>7.</td>
<td>Management</td>
<td>Construction</td>
</tr>
</tbody>
</table>

An example of the survey is given in Appendix C - Survey.

### 4.2 Infrastructure Systems

Before the results of the survey are discussed a brief elaboration is given of the two asset types an infrastructural system consists of.

#### 4.2.1 Passive vs. Active assets

In general, most of the infrastructural systems have a life span of 50-100 years (Herder and Wijnia 2012) and are very robustly designed and realised. These infrastructural systems consists of two types of assets: passive and active. The passive and active assets are further described as subsystems of infrastructure projects.

**Passive**

Passive asset behaviour is known by contractors and ‘limited’ attention is required for these type of assets. These assets have a very long lifetime and are part of the core business of contractors for many years; the costs, performances and risks are known by the contractors. Passive assets are for instance the concrete and steel elements in roads, bridges, tunnels and (ship) locks and forms the majority of the system. The passive assets are the civil components of a system.

According to Haasl, Roberts, Vesely, and Goldberg (1981) a static (passive) asset is less contributive to the daily functioning of a system. The system acts as a transmitter of energy or load. The performance of passive assets can be tested by for instance stress tests and heat transfer studies.

“**Within the infrastructure, passive assets provide the route by their existence, not by their operation**” (Wijnia and Croon -). 

From the perspective of this research passive assets are the static elements within the infrastructure projects, the civil component like, steel and concrete structures. The lifetime of these passive elements is about 50-100
years and the probability of random failure is relatively low. The impact of the passive assets on the maintenance strategy is low as well, because these asset requires not much maintenance activities. Passive assets with a shorter life-time and a bigger impact on the maintenance budget and system availability are the asphalt layers and construction joints. These assets have a lifetime of 7-12 years and a big impact on the maintenance activities and budget.

Active

The active assets are of a bigger concern to the contractors because of the relatively unknown performances, costs and risks. These type of assets are the more dynamic part of an infrastructural system and was not part of the core business of contractors for a very long-time. The active assets are also known as the electronic and mechanical (E&M) components of a system.

An active asset can also be called quasi-static or dynamic. This type of assets contributes in a more dynamic way to the daily functioning of the infrastructural systems by modifying system behaviour in some way. The performances of an active asset can be assessed by for instance studies of functional interrelationships (Haasl, Roberts et al. 1981). From the perspective of this research active assets are the dynamic elements within the projects, the E&M-components like, technical installations and energy supply. These assets have a relatively short lifetime of 10-15 years (Rijkswaterstaat, 2012) and a (relatively) high probability of random failure.

4.2.2 Results

The survey participants have different backgrounds and different motives within the projects, despite the differences they were rather unanimous with regard to the system performances of the eight infrastructural systems. In total eight infrastructural systems are ranked and further analysed in the following paragraph. At first the survey participants ranked the systems with a score of 1 – 8. The infrastructural system with the biggest impact on the system performances is scored the highest. A system could have a maximum score of 56 and minimum of 7. The output of the survey shows a clear distinction between the systems, four systems are scored relatively low compared with the other four systems that are scored twice as high. The four infrastructural systems that scored low are a quay wall, underpassing, fixed link and road construction. This could be explained by using the literature of Herder and Wijnia (2012). These infrastructural systems consists mainly of passive assets and these are known by the contractor. Therefore these type of infrastructural systems are scored relatively low on the impact on the system performances.

The remaining four systems that are scored relatively high are the DTM, (ship) lock, movable bridge and tunnel. These systems are a combination of passive and active assets. The active assets have a high probability of random failure and the failure behaviour is relatively unclear to the majority of the engineers within the organisation of Dutch contractors. These systems are therefore possibly assessed with a high impact on the system performances of infrastructural systems. Table 4-3 shows the distinction between the two groups of infrastructural systems based on the scores of the survey.

Table 4-3 Scores of infrastructural systems

Within the survey is asked to further specify the infrastructure systems. The survey participants are asked to give, for every system described above, the three most important subsystems. In order to give a more elaborated overview of the most important subsystems of infrastructure systems. This is further discussed in the following paragraph.
4.3 Infrastructure Subsystems

The survey described above showed a clear distinction between the different infrastructural systems on the impact on the system performances. The (sub)systems are also described based on the distinction: less impactful subsystems; more impactful subsystems. The survey participants are also questioned to name the three most important subsystems of the different systems. With the purpose to create further insight in the system performances of infrastructural systems and determine which systems incorporate a bigger risks to the system performances. In the elaboration of the subsystems a distinction is made between the passive and active assets.

Based on these two types of assets the subsystems are described. The subsystems are split in two parts, the less impactful systems and the more impactful systems. Per group the most important subsystems are given obtained from the survey. The subsystems are scored by the survey participants and these scores are given in the bars of the two figures. Then, it is described whether it is a passive or active asset in order to provide insight in the required knowledge needed, to be able to assure the system performances in tender phase.

4.3.1 More impactful subsystems

The more impactful systems are the Dynamic Traffic Management-system (DTM), movable bridge, (ship) lock and tunnel, see Table 4-4. These systems are a combination of passive and active assets. Whereas the less important systems were characterised by mainly passive assets, the more important systems are characterised mainly by active assets. This is can be explained by relatively high probability of random failure and the unknown failure behaviour of the active assets by contractors.

Table 4-4 Scores of more impactful systems

<table>
<thead>
<tr>
<th>MORE IMPACTFUL (SUB)SYSTEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DETECTION (SOS)</td>
</tr>
<tr>
<td>DTM</td>
</tr>
<tr>
<td>7</td>
</tr>
</tbody>
</table>

The numbers given in the bars are the scores given to the different subsystems by the experts. The higher the score the more important the system is ranked. The maximum score per system is eight, the lowest score a one.

4.3.2 Less impactful subsystems

The less impactful systems are the quay wall, underpassing, fixed bridge or viaduct and the road construction. Table 4-5 shows the four systems with associated subsystems. The main thing to be noticed is the asset type of the subsystems. All the subsystems are more or less passive asset systems. This also declares why these type of infrastructural systems are assessed as less critical. Because, the failure behaviour of the passive assets are rather familiar to the Dutch contractors.
The numbers given in the bars are the scores given by the experts to the different subsystems. The higher the score the more important the system is ranked. The maximum score per system is eight, the lowest score a one.

4.4 Wrap-up System Performances

It is analysed what infrastructural systems have the biggest impact on the system performances since this knowledge is limited within the organisation of a Dutch contractor. In total eight type of infrastructural systems are analysed that forms the basic systems of the Dutch infrastructural network.

This is analysed by the use of a survey that is filled out by experts with different background and job functions within Ballast Nedam. A survey is used because this knowledge is hard to gain on a general level from the literature. Some of the infrastructural systems analysed have more than 50 subsystems which is difficult to analyse within the time constraints of the research.

The survey gave a rather unanimous result in which the analysed infrastructural systems could be split in two parts. Four of the eight systems are scored high and are designated as important systems with a high impact on the system performances. The other four infrastructural systems are ranked low by the experts and have a low impact on the system performances of infrastructural systems. The difference in ranking can be declared by the use of two types of assets: passive and active. The failure behaviour of passive assets is predictable and generally known by contractors and, these assets have a very long lifetime of 50-100 years. Active assets are more dynamic assets, with a life-time of 7-12 years and a relatively unpredictable and less known failure behaviour by contractors. These assets have a bigger impact on the system performances and incorporates therefore a bigger risks with regard to the system performances.

The output of this analysis is used as input for the framework and decision-making model described in chapter 5. For contractors it is important to understand what infrastructural systems needs more attention than others in the tender phase, due to the time, budget and information constraints. Using the outcome of this analysis, contractors must be aware of the four infrastructure systems: DTM; movable bridge; (ship) lock; tunnel, because of the many active assets incorporated in the systems. The outcome of this analysis is used as input for the framework described in the next chapter (5).
5 FRAMEWORK

In the first chapter of this report the different type of variables (independent and dependent) are described that together will form the decision-making model. The first independent variable, the tender phase, is already described in the first chapter and is basically the research boundary. The other two independent variables are described in the previous two chapters which are the type of building contract and type of infrastructural system. Both variables are analysed and the output of these analyses are used as input for the framework described in this chapter. The framework forms the basis of the decision-making model that is completed with a set of methods in the following section, Section III. The set of methods can be used to describe and determine the system performances of different infrastructural systems.

It is chosen to use a framework because it provides a nice overview of the different situations. Per type of building contract and infrastructural system a certain methodology to describe and determine the system performances can be given.

In chapter 3 the risks per building contract are elaborated of the D&C, DBM and DBFM-contract. The D&C-contract is a short-term building contract in which the type of infrastructure or performance requirements could force the contractor to consider the long-term responsibilities. But the contractor will not be actual responsible for these system performances. Within the DBM and DBFM-contracts the contractor can be responsible for a period of 5-30 years after the design and realisation phase. Within these contracts the contractor encounters several other risks as, commissioning, operating, finance and payment risk. The extent of these risks can be increased in case the system performances are not sufficiently incorporated in the tender process that eventually will result in system underperformance.

In chapter 4 eight different infrastructural systems are analysed and ranked by experts of Ballast Nedam. The main difference between the infrastructural systems are the type of assets included in the system. Passive assets are more static with a very long lifetime of 50-100 years and the failure behaviour is well known by the contractors. The active assets are more dynamic assets with a shorter lifetime of 10-15 years and the failure behaviour is less known. The systems that are ranked high by the experts are the systems with many active assets. Within the tender phase the contractor must be aware of these type of systems.

Combining both outputs, of chapter 3 and 4, the following framework is developed, Table 5-1. In the following section the methods to describe and determine the RAMS-performances are described and included in the framework. After including the methods the framework is called the decision-making model and is the final output of this research.

<table>
<thead>
<tr>
<th>Asset type</th>
<th>System</th>
<th>D&amp;C</th>
<th>DBM</th>
<th>DBFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>Quay wall</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Underpassing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fixed link</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Road construction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active</td>
<td>DTM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Movable bridge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(ship) Lock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tunnel</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(RAMS-)METHODOLOGY
SECTION III: CONCEPTUAL MODEL
6 Methodology

In the previous section the consequences of system underperformance for a contractor are described (chapter 3). Followed by an elaboration of the impact of the different type of infrastructural systems on the system performances (chapter 4). The analyses conducted in both chapters provided insight in the importance of the system performances for contractors for different situations. The output of both chapters is used to develop a framework (chapter 5) that forms the basis for the decision-making model that is elaborated in this section.

One of the problems identified and described in chapter 1 is a lacking methodology to process the system performances effectively on a well-founded base, with the purpose to minimise the risk of system underperformance and optimise the profit margin. In order to fill this gap it is analysed what methodology is applicable in the tender phase. The system performances of infrastructural systems are more frequently described in RAMS-performances (based on project documents) – RAMS is an acronym of Reliability, Availability, Maintainability and Safety. Therefore is chosen to analyse the applicability of a methodology that can be used to describe, determine and monitor the RAMS-performances of infrastructural systems.

In this chapter three types of analysis are distinguished and describes the different methods. The three analyses are the final input for the decision-making model described in the following chapter. The methods are obtained from the RAMS-guide and supplemented by reliability engineering handbooks and directives.

Before the methodology is described the RAMS-principle is elaborated first in paragraph 6.1. In paragraph 6.2 the interrelations between the different RAMS-elements is discussed. The applicability of the different methods is discussed in paragraph 6.3. Finally, a summary of the chapter is given in paragraph 6.4. The output of this chapter provides the answer to the third and final sub research question:

What (RAMS-)methods are applicable to optimise the risks of system underperformance in the tender phase?

6.1 RAMS-theory

In the past decade RAMS has been introduced in the infrastructural industry as response to the changed role of the government (see chapter 1), which has changed the responsibilities of the contractor. In response they demanded for another approach in order to process the system performances more effectively in the tender phase with the purpose to diminish the risk of system underperformances. The project success is based on the system performances of infrastructural systems because the contractor is paid more often based on these performances. These performances are to a great extent determined in the tender phase, because in this phase fundamental decisions are taken with regard to the system performances. The methodology is a set of methods that can be used to describe, determine and monitor the system performances of every function of a system (Bakker et al., 2010).

Several literature has been written about RAMS and some of the literature is used to define the key aspects of RAMS to assess the applicability of it in the research. The used literature and definitions associated are separately described in Appendix D – Definitions of RAMS. By using the different definitions of RAMS the following conclusions can be drawn and describes the applicability of the methodology for this research. The methodology,

1. is applicable throughout the whole project life cycle;
2. can be used for individual systems as well for complex integral systems;
3. is applicable for as well the hardware as the software of a system;
   a. Earlier described in this report as the passive (hardware) and active (software) assets.
4. can be used for both qualitative as quantitative purposes;
5. has the purpose to keep the system up and running, by describing the reliability, availability, maintainability and safety of a system.

In the following subparagraphs the different RAMS-elements are separately described and provides background information on the content of the RAMS-elements. Besides the elaboration of the elements the content of failure is described. System failure might result in lower system performances and could have an adverse impact on the project success and the profit margin.

6.1.1 Failure
For a contractor it is important to understand how many times the system will fail, for how long the system will be failed, the impact of failure on the system and in which way the system will fail in order to assess the system performances. In other words, the contractor must have insight in the failure behaviour of the infrastructural systems during the tender phase with the purpose to minimise the risks of system underperformance in later project phases. Failure can be defined as (Bakker et al., 2010):

"An event, or collection of events, that causes a loss of the systems functionality."

In order to develop an infrastructural system that fulfils the required system performances, the contractor should be aware of the failure behaviour of the infrastructural systems.

Failure behaviour
The failure behaviour of the systems is not a linear process and can be distinguished by three phases (Bakker et al., 2010). The failure behaviour of a system is simplistically illustrated in Figure 6-1 and the three different phases are separately described below. This research is focused on the second phase.

1. Teething problems
The first phase is a non-linear process and is called the phase of teething problems. These teething problems could be caused by design and construction flaws. After system commissioning, the system might include several defaults that will result in system failure and can be solved by testing. During this phase the risk of system underperformance is significantly higher due to the teething problems. In case the contractor does not perform tests these problems will not be detected and resolved and might finally result in frequent system failure after commissioning. The probability of occurrence of teething problems is significantly higher by systems with many active assets. Because the probability of random failure is higher compared to the passive assets and, the failure behaviour is therefore less predictable.
During the tender and design phase the contractor should consider the test procedure in order to avoid a system that is not properly tested and will not fulfil the performance requirements after it is put in use. The content of the teething problems is not further discussed in this report.

“A proper test phase is no guarantee that no errors will occur, teething problems are taken into account. But, the amount of errors, 18 errors on 450 bridge movements, is in my opinion too much” according to Minister of Infrastructure and Environment. As result of the many errors after commissioning the Botlekbrug, Rijkswaterstaat started a research into the test procedures. Because the contractor fulfilled all the testing procedures but still too many errors occurred. Eventually, the reliability of is enhanced but this has resulted in extra project costs for the contractor. (Heijbrock, 2015)

2. Second phase
After the teething problems are solved and the probability of failure due to teething is diminished, the probability of failure is slowly (linear) increasing over time caused by the usage and degeneration of the system. In this phase the contractor should be aware of random failure of the system elements.

This research is focused on the second phase of the failure behaviour – the random failure of system elements. This phase is the longest phase in the project life cycle and has the biggest influence on the overall system performances. During the tender phase the influence on the design of the system and the associated system performances is the biggest (see chapter 1). From this perspective the contractor is able to diminish the risk of system underperformance due to random failure by considering the reliability and maintainability of the (sub)systems in the tender phase. Currently no general methodology is integrated in the organisation of the Dutch contractors to process the system performances of infrastructural systems on a well-founded base – one of the problems identified in chapter 1. For this reason a set of methods is analysed in paragraph 6.3 and used as input for the decision-making model. The decision-making model is the final output of this research and should support the contractor in the tender phase with processing the system performances more effectively.

The contractor should be aware of the difference in random failure between the active and passive assets. As described in chapter 4, the probability of random failure of active assets is higher than for the passive assets. Mainly caused by the shorter lifetime of the active assets and the more unpredictable failure behaviour of the active assets.

3. Ageing
In the third phase the probability of failure is rapidly increasing due to aging and degradation of the system components. In order to avoid system failure the contractor should consider system replacements. This is only necessary if the contractor is responsible for the maintenance – the DBM and DBFM-contracts.

The replacement of the (sub)systems is part of the maintenance strategy and is of big influence on the overall system performances. In order to determine an effective and efficient maintenance strategy, insight in the failure behaviour of the system is necessary. From that perspective the contractor is able to determine which system elements should be replaced or restored. During the tender phase the contractor should develop a maintenance strategy that prevents the system for failure by conducting preventive maintenance, tests and inspections. The content of the maintenance strategy is not further discussed in this research.

6.1.2 Availability
The availability describes whether a system is functional or not and is defined as “the ability of a system to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided” (CENELEC, 1999). In literature the availability is designated with an ‘A’.
The CENELEC (1999) described the availability in a function as: Availability = f(R, M, S). This function describes that the availability is determined by the relation between the reliability, maintainability and safety. It is difficult to process these elements as separate parameters because they all are related to each other. For instance, an unsafe situation could result in system closure. The unsafe situation could be caused by an unreliable system because the system is not properly maintained. The interrelationships are further discussed in the following paragraph.

For a contractor it is important to understand when a system is unavailable and for what reasons. Because the unavailability of a system might result in a lower profit margin depending on the project type. For instance, the consequences of not fulfilling the performance requirements in a D&C-contract can only occur in the design and construction phase and will have minor financial consequences for the contractor in comparison with the long-term building contracts – DBM and DBFM (see chapter 3). The following three causes of unavailability are distinguished (Bakker et al., 2010):

1. unavailability due to planned causes;
2. unavailability due to unplanned causes;
3. unavailability due to natural circumstances.

Unavailability due to planned and unplanned causes are closely related. The systems downtime due to planned causes (as preventive maintenance, inspection, testing) can decrease the systems unavailability due to unplanned causes (system failures). Because by testing, inspecting and conducting preventive maintenance the reliability of the system can be enhanced by mitigating the weak system elements that are noticed by the tests, inspections and maintenance activities.

This research is mainly aimed at the unavailability due to unplanned causes – random failure – and how this risk can be minimised, with the purpose to optimise the profit margin. The unavailability due to planned causes can be calculated by the contractor in the tender and design phase and should not result in any risks. It provides insight in the unavailability due to maintenance activities. The unavailability due to natural circumstances will not result in direct financial consequences for a contractor and is therefore neglected in this research. Nevertheless, the client could request the contractor to restore the system within a certain time period in case one of the natural circumstances occurs. But this is not further discussed in this research.

In short, the system performances can be expressed in terms of availability that is determined by the reliability, maintainability and safety of the system. Within this research the main focus is on the unavailability due to unplanned causes, which are random failure of system elements.

6.1.3 Reliability

Reliability can be formulated as the non-failure of an object or system (Bakker et al., 2010) and is defined as “the probability that an item can perform a required function under given conditions for a given time interval” (Birolini, 2013; CENELEC, 1999).

In general the reliability is designated by ‘R’ and can be used in a qualitative and quantitative way, for both another definition is given by Birolini. For qualitative reasons, reliability is defined as “the ability of the item to remain functional” (Birolini, 2013). From the viewpoint of quantitative reliability, it is about “the probability that no operational interruptions will occur during a stated time interval” (Birolini, 2013). It is the difference between the ability and probability, in which the probability is mostly given as a chance – an absolute number (Bakker et al., 2010).

The system reliability determines the frequency of failure and has a big influence on the system availability and required maintenance strategy. An unreliable system fails more frequently and results in a higher unavailability. The reliability is in the first place determined by the design, what components are used and what maintenance strategy is developed. Secondly, system failure can be minimised by conducting preventive maintenance but this can have an adverse impact on the system availability due to necessary system closures to conduct the maintenance activities. From this perspective the contractor should be aware of the maintainability of the system that determines the accessibility and repairability of the system. Important to consider the reliability in the tender phase to prevent cost overruns due to an unreliable system.
6.1.4 Maintainability

Maintainability describes how a system can be maintained and is defined as “the aspect of maintenance that takes downtime of the systems into account. Designing for maintainability requires an evaluation of the accessibility and repairability of the inherent systems and their related equipment in the event of failure, as well as of integrated systems shutdown during planned maintenance” (Stapelberg, 2009). The maintainability is designated with an ‘M’.

The maintainability is part of the maintenance strategy and to gain a better understanding of maintainability of a system, the maintenance principle is defined as well. Schoenmaker (2011) defined maintenance as “the set of activities that is needed to keep the required function(s) available at the agreed level of service”. This could be done by retaining or restoring the system into a specified state (Birolini, 2013). Thus, a distinction can be made between preventive and corrective maintenance. Preventive maintenance is conducted at predefined moments and must prevent the system for failure and should detect and repair hidden failures (retaining); corrective maintenance is conducted after a failure detection and applied to restore the system (Birolini, 2013).

The maintainability of a system is of great influence on the system availability as described earlier (chapter 1). A system with a low maintainability might result in higher maintenance costs due to extra time, staff, material needed to conduct the maintenance activities. Or, extra costs due to additional system closures necessary to conduct the maintenance activities safely. This is rather important to consider during the tender phase to avoid higher maintenance costs than initially calculated.

6.1.5 Safety

In principle the safety is determined by the elements reliability and maintainability and is defined by the CENELEC (1999) as “freedom from unacceptable risk of harm”. A system that is unreliable might fail more often and might result in unsafe situations or, an unmaintainable system that might result in safety issues during the maintenance activities. A safety evaluation must consider two aspects (Birolini, 2013):

1. an infrastructural system must be safe during operation
2. in case of failure, the system must fail safely.

Safety is a very important element and is incorporated in many regulations, for instance in the National Tunnel Directive (in Dutch: Landelijke Tunnel Standaard). System failure might cause unsafe situations with as result system closures.

For every infrastructure project a safety analysis should be conducted (Bakker et al., 2010). Multiple safety analyses could be conducted such as, internal and external safety and, the aid care (Brascamp & Heijink, 2007). Among these analyses multiple sub safety aspects are distinguished, for instance for an internal safety analysis (Brascamp & Heijink, 2007):

- constructional safety;
- fire safety;
- social safety;
- occupational safety;
- security.

In short, the safety criteria is determined by the RAM-aspects and should be taken into consideration very carefully in the tender phase because unsafe situations could result in immediate system closures.

6.2 Interrelation of RAMS-elements

In the previous paragraph the system elements are separately described but actually the RAMS-elements cannot be seen or analysed as individual. The descriptions given above provides knowledge of the different
individual aspects and in this paragraph the interrelationship between the RAMS-elements is discussed. This is described with the following generic principle of a tunnel system and illustrated in Figure 6-2.

The availability of a tunnel is related to the amount of system failures that could jeopardise the safety of the user and could result in a tunnel closure. The frequency of failure (reliability) and the time it takes to recover the system (maintainability) determines the availability. The reliability could be enhanced by conducting more preventive maintenance because the failure frequency is diminished. Unfortunately, the maintenance activities could have an adverse impact on the availability of the system due to necessary system closures. (based on Bakker et al., 2010)

The tender phase is characterised by the limited budget, time and information available. In spite of the limitations the contractor should consider the RAMS-performances as much as possible. To develop an optimised system with regard to the system performances. The contractor is constantly making trade-offs between the project costs, risks and the RAMS-performances. This might result in higher tendering (and design) costs but could diminish the construction and maintenance costs and might reduce the LCC. Because the system is more reliable and maintainable that eventually will result in a higher availability.

For some of the projects the RAMS-aspects should be analysed more thoroughly than in other situations because the consequences for a contractor of system underperformances are bigger. The consequences of system underperformance for a contractor depends on the building contract and asset type – further discussed as the risk profile of the project. Within a D&C-contract the consequences are limited to the design and construction phase. But within the DBM and DBFM-contracts the consequences for a contractor are bigger due to the long-term responsibilities of the contractor. This is further described in the next chapter. In order to diminish the risks of system performances and optimise the profit margin a set of methods is discussed in the following paragraph and fulfils the third research objective.

6.3 Methodology
In this paragraph the different types of analyses are elaborated which should be used to effectively process the RAMS-performances in the tender phase and enhance the system performances. Such a methodology, to process the performance requirements effectively on a well-founded base, was lacking. The RAMS-guide is used as input for this research to compose a set of methods that can be used by the contractors in the tender phase. Due to the research limitations it is not possible to analyse all the methods into detail and assess the applicability. Therefore is chosen to divide the set of methods into three groups that represents the types of analysis, which are:

1. Expert Judgement
2. Qualitative analysis
3. Quantitative analysis

The different types of analysis have different characteristics and purposes. Therefore the three analyses are separately examined and described below. These are consequently used as input for the decision-making
model that is developed in the following chapter. In the following sub paragraphs it is elaborated what the purpose is of the different analyses, how the analyses are conducted, what risks it could diminish and what the possible limitations are.

6.3.1 Expert Judgment (EJ)

Content Expert Judgment
The purpose of EJ is to assess the required system performances based on the knowledge and experiences of the experts (project engineers). EJ is mostly the first methodology that is used in the tender phase to examine the project specifications and to gain a proper overview of the project. This methodology can be both qualitative as quantitative and is a relatively quick method. It is mainly conducted by the use of brainstorm sessions, presentations, meetings and discussions with the purpose to gather information about the performances, costs, risks and the maintenance activities of infrastructural (sub)systems. Experts of several disciplines could assess the proposed design and optimise this design from the perspective of their own discipline (PMI, 2008).

EJ can be used to determine the project costs, risks of a particular design and the system performances associated. The knowledge and experiences gained in other projects can be used to examine the design, construction and maintenance costs. Also, the contractor is aware of the risks of system underperformance and these risks can be mitigated up front, with the purpose to enhance the system performances and profit margin (see chapter 3).

Advantage of the EJ method is the wide applicability, it is highly applicable in projects the contractors have sufficient experiences with and knowledge of. In other words, the applicability is bounded by the knowledge and experience of the experts. From this perspective the contractor should be aware of their own strengths and capabilities in order to use the EJ properly. Otherwise they could wrongly assess and determine the system performances and could have an adverse impact on the profit margin. If the required knowledge is lacking the contractor should hire experts with this particular kind of knowledge to compensate, with the purpose to avoid wrong decision-making.

EJ is less applicable to make trade-offs because it is difficult to oversee the whole system and the associated system performances, less applicable to determine an integral system. The methodology is a good start during the tender phase and is in many situations used as input for a qualitative or quantitative analysis that are more applicable to make trade-offs with regard to the system performances. This is further discussed in the following subparagraphs.

Applicability of expert judgment
During the tender phase the contractor wants to have insight in the critical system elements and the most important risks that jeopardise the RAMS-performances. By using the experiences and knowledge of the experts to assess the reliability and maintainability of the system, the risk of system underperformance can be diminished. But, it remains a subjective method and the contractor should be aware of this subjectivity. If the project contains a high risk profile such as, long-term building contracts (chapter 3) or unknown asset types (chapter 4), EJ might not be sufficient anymore to diminish all the risks that might result in system underperformance. The method is more applicable to determine the system performances rather than analysis all the critical system elements. The project in which system underperformance will have big consequences the contractor should consider more advanced methods as qualitative and quantitative analyses.

6.3.2 Qualitative analysis
The EJ described in the previous subparagraph is a relatively quick method based on the knowledge and experiences of experts and can be used as input for a qualitative analysis. Different methods can be applied to conduct a qualitative analysis which are discussed below. The methods discussed are:
- Failure Mode Effect (Criticality) Analysis (FME(C)A)
- Hazard and Operability (HAZOP)
- Human Reliability Analysis (HRA)
These methods are obtained from the RAMS-guide and supplemented with other literature as reliability engineering handbooks and directives.

Content qualitative analysis
The purpose of a qualitative method is to gain insight in the failure behaviour of the infrastructural systems and the consequences associated. This can be fulfilled from different perspectives, depending on the methodology. The three methods are rather the same but all with their own focus, technical, safety and human-aspect and are all conducted by an expert or group of experts that uses input from all related disciplines. With the purpose to develop an integral design that fulfills the required system performances. The FMECA is mainly aimed at failure mechanisms and critical system elements with the purpose to mitigate these failures and avoid system underperformance (Birolini, 2013; Gestel, Bouwman, & Reijnen, 2004). Unfortunately, the FMECA is a rather time consuming method because of the many data required (Bakker et al., 2010; Birolini, 2013; Gestel et al., 2004) which is a disadvantage in combination with the tender phase limitations. The HAZOP is focused on the potential hazards and operability problems (CEI/IEC, 2001) after a certain (sub)system failure. This method can be conducted to determine which (sub)systems are still functional after a certain (sub)system failure. The FMECA and HAZOP are rather similar in which the FMECA is more focused on the technical system applications and the HAZOP is more focused on the safety risks (Bakker et al., 2010; Gestel et al., 2004). The output of the FMECA and HAZOP cannot be quantified in absolute numbers. The failure mechanisms can be given a criticality factor to distinguish the different failure mechanisms and rank them on the criticality.

The third qualitative analysis is the HRA and is aimed at the human involvement in the system and its influence on the performances, safety and costs in case of system failure due to human involvement (Bakker et al., 2010; Swain, 1990). The HRA can be quantified by the use of the OPSCHEP-method (Bakker et al., 2010). Human behaviour data is lacking and it is hard to quantify due to the unpredictable behaviour of people, therefore it is difficult to gain reliable numbers for the human behaviour (Bakker et al., 2010; Swain, 1990).

The main input of the qualitative analysis is expert judgment, data of suppliers, directives and other related literature.

Limitations of qualitative analysis
The qualitative analysis is a more comprehensive methodology compared with the EJ, data and information of the system is necessary to conduct the analysis. This is more time consuming than EJ and results in extra costs to conduct the method, which will increase the tendering costs. But, the qualitative analysis provides a more grounded insight in the system performances because it is not only based on expert judgment.

Applicability qualitative analysis
A qualitative analysis could be necessary in situations in which EJ is not sufficient anymore because the knowledge and experience are lacking within the organisation and/or, the contractor requires a higher level of certainty in the tender phase with regard to the system performances. Because the risk profile of system underperformance is too high for the contractor.

A higher level of certainty with regard to the system performances could be requested in the DB(F)M-contracts, because the contractor is paid based on the system performances. The contractor is responsible for the system performances over the long-term in these building contracts and underperformance might result in lower system performances, which could be caused by an unreliable or unmaintainable system. From this perspective the contractor wants to diminish the risk of system underperformance because it will have an adverse impact on the profit margin, see chapter 3.

In order to minimise the consequences of system underperformance for a contractor the contractor could conduct a qualitative analysis in the tender phase. With the purpose to determine the most critical system elements that are jeopardising the system performances in an early project stage. In this phase the contractors have the biggest influence on the system performances. The output of the qualitative analysis can be used to mitigate the biggest risks and should eventually result in higher system performances.

6.3.3 Quantitative analysis
The following methods are derived from the RAMS-guide and can be used for a quantitative analysis:
Part Count Analysis (PCA)
- Reliability Block Diagram (RBD)
- Fault Tree Analysis (FTA)
- Event Tree Analysis (ETA)
- Markov

The content of these methods is supplemented with other literature as reliability engineering handbooks and directives. Prior to a quantitative analysis, the contractor should conduct a qualitative analysis to gather the input for a quantitative analysis.

**Content quantitative analysis**

The purpose of the quantitative methods is to create insight in the failure rate and reliability (in absolute numbers) of the infrastructural (sub)systems. The different methods are not even accurate and differ in complexity as well. By conducting a PCA the contractor can analyse the failure behaviour of the single components and sum the results. The total sum of the different components gives an indication of the failure rate (Bakker et al., 2010). It is a relatively easy method to apply but it is also not very accurate; it is just a rough estimation of the reliability and applicable for a small set of applications (Birolini, 2013). The PCA is not often applied in the infrastructure industry. The RBD-analysis can be used to assess the reliability and is applicable for systems in parallel and series (Cepin, 2011). A RBD-analysis is useful to determine the dependency between the components and the redundancy of the system (Bakker et al., 2010; Cepin, 2011). The most applied qualitative analysis in the infrastructure industry is the FTA and is applied to assess and improve the reliability (Bakker et al., 2010; Cepin, 2011). The method is based on a top event which is an undesired event from the reliability and safety point of view. This top event is predefined and it is analysed what the contribution of the different (sub)systems and components is to the occurrence of the top event (Bakker et al., 2010; Haasl et al., 1981). The FTA is applicable for both simple as more complex systems and is highly applicable to analyse the impact of the single components on the system performances. The FTA is an often applied methodology in the infrastructure industry but multiple analyses are necessary to examine different top-events. Just one top event can be examined per fault tree and is therefore a time consuming method.

The PCA, RBD and FTA are methods to analyse the most critical elements of the system and how these elements influences the reliability of the system. The ETA is focused on the consequences of failure and how to mitigate these consequences in order to limit the impact on the system and surrounding. The final quantitative method is the Markov-analysis which is a rather complex analysis and, for so far, not yet conducted in the tender phase.

The Markov-analysis is a stochastic process to analyse the RAM-aspects of systems (Cepin, 2011). This analysis can be used to examine the operating and failed state of a system (Cepin, 2011). Unfortunately it is a very complex method, hard to develop and to verify, especially for non-experts.

**Limitations of quantitative analysis**

A quantitative analysis is more expensive and time consuming, compared with the expert judgment and qualitative analysis, which could be an issue in the tender phase. Prior to a quantitative analysis a qualitative analysis should be conducted to gain the input for the quantitative analysis. For these type of analyses reliability data and other failure rate information is needed which should be derived from experts, directives and suppliers. In spite the extra costs and time it diminishes the risk profile and provides the contractor a more accurate insight in the expected system performances.

A qualitative and quantitative analysis is conducted in the tender phase of the lock Limmel project, which was a DBFM-contract. This lock had an important safety function because it had a water retaining function and therefore a high system reliability was requested. This made the contractor decide to hire a specialist and conduct a qualitative and quantitative analysis, in order to determine the reliability and be sure the system will fulfil the performance requirements.
**Applicability**

A quantitative analysis is a comprehensive analysis that is not necessary in every project. Such an analysis provides more certainty (in absolute numbers), compared with a qualitative analysis, if the system will fulfill the performance requirements. A qualitative analysis provides insight in the failure mechanisms and consequences and, can be used to optimise the system performances by mitigating the most critical elements. But the contractor will not have the system performances in absolute numbers which could be beneficial for some situations.

If the proposed design in the tender phase does not fulfil the performance requirements or, higher system performances are desirable, the reliability and failure data can be used to mitigate the low performance elements and optimise the performances. Both are interrelated and the design choices made in the tender phase will have a big influence on the maintenance activities like, required system closures, replacements, material, staff, etc., see chapter 3. This insight can be used to determine the expected revenues and expenditures over the whole project life cycle which is desirable in a DB(F)M-contract from the perspective of the contractor. Mainly because the contractor is responsible for the system performances for a long period and is paid based on these performances. Wrongly assessing the system performances could result in higher design, construction or maintenance costs (higher LCC) and a lower profit margin due to the higher project costs and lower revenues.

### 6.4 Wrap-up Methodology

Because the contractor is currently more paid based on the system performances of the infrastructural systems it is analysed by what methodology the system performances can be processed more effectively. In order to diminish the risk of system underperformance and a lower profit margin. The system performances are more frequently described in terms of RAMS, which is an abbreviation of:

- Reliability (R)
- Availability (A)
- Maintainability (M)
- Safety (S)

Therefore is chosen to apply a methodology that can be used to describe, determine and monitor the system (RAMS-) performances of infrastructural systems. The RAMS-guide is used as basis for the analysis of a set of methods that can be used in the tender phase. In total ten methods are examined and due to the time constraints of the research it was not possible to analyse all ten methods into detail. Therefore the set of methods is divided into three types of analyses:

1. Expert judgement (EJ)
2. Qualitative analysis
3. Quantitative analysis

The risk profile of the situation defines which method to use and is defined by the knowledge and experiences of the contractor with the realisation and maintenance of a certain system. In order to reliably determine the system performances in the tender phase; in other words, consist the system mainly of passive or active assets. Another aspect of the risk profile are the consequences for a contractor in case of system underperformance. The consequences for a contractor are determined by the type of building contract; short or long-term responsibilities.

EJ is a reliable method in case the contractor has sufficient knowledge and experience with the project and can be conducted relatively quickly. Nevertheless, it remains a subjective method and is not sufficient anymore in the case of the following two:

1. The knowledge and experience of the contractor with the system is not sufficient anymore to realise a reliable system that fulfils the required system performances.
2. The risk profile of the project is significant and the contractor requires a higher level of certainty about the expected system performances.

For those situations a qualitative and/or quantitative analysis should be more sufficient.
With a qualitative analysis the contractor is able to define the failure mechanisms and associated consequences. With this knowledge the contractor can determine the critical (sub)system elements with regard to the RAMS-performances, in order to mitigate these elements already in the tender phase. By mitigating the biggest risks the reliability and maintainability can be enhanced, with the purpose to improve the safety and availability of the system. A qualitative analysis cannot be used to optimise the system in absolute numbers, which could be helpful for different situations. In case the contractor requires insight in the expected system performances, in absolute numbers, a quantitative analysis could be conducted. This type of analysis can be used for a system with a critical safety function such as locks with a water retaining function.

With a quantitative analysis the contractor is able to assess and determine the reliability and maintainability of the system with a high level of certainty. A quantitative analysis could be useful as well for systems with a big share in the maintenance budget and activities or in DBFM-contracts to determine the expected revenues and expenditures during the project cycle. Prior to a quantitative analysis, a qualitative analysis should be conducted. The failure mechanisms and consequences of failure are used as input for the quantitative analysis.

For both analyses EJ is still needed to develop the analyses, besides EJ the contractor used data and information of suppliers and directives in order to determine the failure mechanisms, consequences of failure and the reliability of the system in absolute numbers. Downside of the qualitative and quantitative analyses is the time consuming procedure of gathering and conducting the analysis and requires more resources as time, money and staff, which is limited in the tender phase.

The output of this chapter is used as input for the decision-making model that is described in the following chapter. The decision-making model illustrates in which situation which type of analysis should be conducted. The situations are determined by the different building contracts: D&C, DBM and DBFM and, the asset type: passive and active.
7 DECISION-MAKING MODEL

The main objective of this research is to develop a decision-making model that can be used by contractors in the tender phase in order to diminish the risks of system underperformance for contractors and optimise the profit margin. In the previous chapters the different variables are analysed and elaborated.

The decision-making model distinguishes different situations which are based on the following three variables: building contracts, infrastructural systems and the tender phase characteristics. These variables are briefly described again in paragraph 7.1, same as the three different types of analysis elaborated in chapter 6. The complemented framework is described in paragraph 7.2 that defines the different situations of the decision-making model. Paragraph 7.3 describes the allocation of the different types of analysis to the different situations. In the final paragraph the output of the SWOT-analysis is discussed.

7.1 Variables of decision-making model

The four variables are briefly described in the following enumeration. The first three variables are the independent variables and determines the situation. The fourth variable is the dependent variable and is the type of analysis to process the system performances in the tender phase more effectively.

1. Tender phase characteristics

The tender phase is characterised by a limited budget, time and available information. In spite of the tender phase limitations the most fundamental decisions are taken with regard to the system performances during this phase. Within this phase the contractor must develop a winning tender offer and should make trade-offs between the project costs, risks and system performances. See chapter 1 for a more elaborated description of the tender phase.

One of the complexities of the tender phase is the uncertainty if the project will be won and the uncertainty about the consequences of the design decisions (Shash, 1993). The uncertainty of the design decisions can be narrowed by using adequate methods with the purpose to optimise the system performances and enhance the profit margin.

2. Risks for contractors in case of system underperformance

Three different building contracts are analysed and the risks and consequences per building contract are described. Within a D&C-contract the contractor is only responsible for the design and construction of the system. Any consequences of not fulfilling the performance requirements can occur in the design and construction phase. The contractor should be aware of the long-term responsibilities in the DBM and DBFM-contracts because these can have a major impact on the system performances and profit margin. These can be diminished by considering the RAMS-aspects and maintenance activities already in the tender phase and to integrate it in the design. This is elaborated in chapter 3.

In the tender phase the most fundamental design decisions are taken with regard to the system performances. Wrong decisions taken in this phase could result in system underperformance. This risk can be diminished by using the right methodology in the tender phase, to process the system performances.

3. Infrastructural systems

Within an infrastructural project the contractor could be responsible for multiple infrastructural systems. The complexity of eight different systems is analysed from the perspective of the contractor. This analysis has showed that the contractor is having the most difficulties with systems incorporating many active assets. Active assets are the electronic and mechanical systems and have a relatively short life time (10-15 years) compared with passive assets. Passive assets are the civil components with a long life-time of 50-100 years. The asphalt and construction joints are passive assets with a shorter life-time of 7-12 years. The main issue with active assets is the probability of random failure, which is higher compared with the passive assets. This jeopardises the reliability and availability of the system, the active assets are also less
known by the contractor. See chapter 4 for a more detailed elaboration of the different infrastructural systems.

Active assets have a less predictable failure behaviour due to the high probability of random failure. The impact of random failure can be diminished by using adequate methods in the tender phase. If the active asset incorporates a high probability of failure with an adverse impact on the system performances, the contractor could mitigate this risk already in the tender phase. Not every situation is even critical and therefore not a general methodology can be used.

4. Methodology
In total three types of analysis can be distinguished. The first methodology is the expert judgment (EJ), a relatively quick method but the reliability of the method depends to a great extent on the experience and knowledge of the contractor. It remains a subjective method and is difficult to use for trade-off purposes. The second method is the qualitative analysis. The qualitative analysis is based on EJ, directives and data of suppliers and provides a more grounded output. This analysis can be used to determine the failure mechanisms and consequences of failure. The output of the qualitative analysis can be used to optimise a system but not in a quantitative way. In case a quantitative insight is required due to the high risk profile of the project a quantitative analysis might be useful. This analysis provides insight in the reliability and failure rate of the system, which can be used to optimise the system and make trade-offs in a quantitative way. For this analysis also EJ, directives and data of supplier is required. For a more detailed elaboration of the three different types of analysis, see chapter 6.

The three variables described above defines the different situations. These situations are further elaborated in paragraph 7.2. In paragraph 7.3 the different types of analysis are allocated to the distinguished situations and the final decision-making model is described in paragraph 7.4. The decision-making model is eventually validated by a group of experts to enhance the reliability and supportability of the model. The output of the validation session is discussed in paragraph 7.5.

It must be emphasized that this is an exploratory study and this report is not a guide about which method must be applied by the contractor in the tender phase. This research will provide knowledge about the different risks and consequences for a contractor in the different building contracts and infrastructural systems. This research might support the contractor in the tender phase with the decision making process with regard to the system performances of infrastructural systems by providing a decision-making model.

“Any decision that we do make is based on our present knowledge about the situation at hand. This knowledge comes partly from our direct experience with the relevant situation or form related experience with similar situation. Our knowledge may be increased by appropriate tests and proper analyses of the results – that is by experimentation.” (Haasl et al., 1981)

7.2 Complemented framework
The framework described in chapter 5 is complemented and divided in seven squares, based on the type of building contract, type of infrastructure and length of the maintenance contract. The seven squares describes the distinguished situations. The eight infrastructural systems are divided in two groups of which the first group mainly consists of passive elements and the second group of active elements, see Table 7-1 and are elaborated in more detail in chapter 4. The group with mainly passive assets are the quay wall, underpassing, fixed link and road construction. The remaining four systems consists mainly of active assets and are the dynamic traffic management system, movable bridge, (ship) lock and tunnel system.
### Table 7-1 Complemented framework

<table>
<thead>
<tr>
<th>Asset type</th>
<th>System</th>
<th>D&amp;C-contract</th>
<th>DBM-contract</th>
<th>DBFM-contract</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>Quay wall</td>
<td></td>
<td>A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Underpassing</td>
<td></td>
<td>C</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td>Fixed link</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Road construction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active</td>
<td>DTM</td>
<td>B</td>
<td>D&lt;sub&gt;1&lt;/sub&gt;</td>
<td>D&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Movable bridge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(ship) Lock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tunnel</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The situations are given a letter from A-F and for the DBM-contract a distinction is made between the maintenance periods of longer or shorter than ten years. Those letters are also presented in the decision-making model as given in Table 7-1.

### 7.3 Method allocation

The distinguished situations are described per type of building contract and infrastructural system (passive or active) and per situation the most suitable analysis type is described.

The risk profile of the situation defines which method to use and is defined by the knowledge and experiences of the contractor with a certain system in order to reliably determine the system performances in the tender phase – the asset type. Another aspect of the risk profile are the consequences for a contractor of system underperformance – the building contract.

#### 7.3.1 Design and Construct (D&C-contract)

A D&C-contract is a short-term contract in which the contractor is not concerned with the performances of passive and active elements over the long-term. Within the tender phase the contractor should only consider the reliability, availability and safety (RAS). The maintainability is only a priority in case this is requested by the client in the project specifications. The severity of the consequences of not fulfilling the performance requirements in a D&C-contract depends on the type of infrastructure. Some of the infrastructural systems incorporates strict safety and performance regulations such as the tunnel, (ship) lock and movable bridge systems. A contractor must fulfil these requirements in order to comply with the performance requirements and diminish the risk of system underperformance after winning the bid.

The (financial) consequences for a contractor in a D&C-contract are minor and the main risks are incorporated in the design. If the system performances are insufficiently incorporated in the design the system might not fulfil the performance requirements, eventually this could result in extra design and construction costs and project delays due to necessary system changes.

**Passive**

In case of tendering for a project with mainly passive elements and based on the terms of a D&C-contract it is advised to use expert judgment. The probability of random failure and the risk of wrongly assessing the system performances of the passive assets is low. Because the contractors have significant knowledge and experiences with the performances, costs and risks of these assets. Therefore, the contractor can rely on the expert judgment for systems with mainly passive assets to determine the RAS-performances in the tender phase. In case maintainability specifications are requested by the client, EJ would still be sufficient because of the comprehensive knowledge and experiences of the contractor with the passive assets.
Active
In case of tendering for a project with mainly active elements and based on the terms of a D&C-contract it is advised to use a qualitative analysis. The probability of random failure of the active assets is higher compared with the passive assets and requires extra attention, because the failure behaviour is less predictable. The knowledge of the system performances of active assets within the organisation of Dutch contractors is also limited. This might increase the risk of wrongly assessing the system performances. Using a qualitative analysis the contractor is able to define the failure mechanisms, potential hazards, consequences of failure and regulations to determine the RAS-aspects. This output can be used to analyse whether all the performance requirements are incorporated in the tender offer. If not, the chance of winning the bid is lower and otherwise, the contractor must adjust the design after winning the bid. Eventually, this results in higher design and/or construction costs.

Within a D&C-contract the contractor is only responsible for the design and construction of the system and is not concerned with the long-term performances. From this perspective a quantitative analysis would be too comprehensive because there is a limited need for a quantitative insight in the system performances. Especially in combination with the tender phase characteristics, the limited budget, time and available information. Because a quantitative analysis is time consuming and requires specific data of the system.

7.3.2 Design, Build and Maintain (DBM-contract)
A DBM-contract is a long-term building contract in which the contractor is responsible for the maintenance as well, besides the design and construction. The maintenance period could vary from 7-30 years and the contractor should consider the LCC in the tender phase as well. The risks described for the D&C-contract also counts for the DBM-contract. Besides these risks, the contractor also encounters other risks due to the addition of the M-component.

If the system performances are insufficiently taken into account in the tender process it might result in necessary design and construction adjustments, which eventually could result in project delays. If the project is delayed the system is not commissioned in time and extra resources are needed to finish the system as soon as possible. Another aspect that should be taken into consideration in the tender process is the maintenance strategy which is of big influence on the system performances and maintenance costs. The maintenance strategy is determined by the reliability: how many times will a system fail over a certain time period, and the maintainability: how long will it take to restore the failure, in relation with the maintenance costs. Because a contractor must develop a tender offer with a competing price; in other words, low LCC. These aspects are determined by the design, developed in the tender and design phase. Optimising the reliability and maintainability might result in higher design and construction costs in order to develop a robust and well performing system but should result in lower maintenance costs over the long period. This might reduce the LCC and enhance the profit margin over the long term.

Passive
In case of tendering for a project with mainly passive assets and based on the terms of a DBM-contract it is advised to use expert judgment. Within a DBM-contract the contractor should be aware of the reliability and maintainability of a system in order to develop a maintenance strategy. The probability of wrongly assessing the reliability and maintainability is low, because the contractor has significant knowledge of the performances, costs and risks of the passive assets. Most of the passive elements are very reliable and just requires regular maintenance with the purpose to remain operational during the maintenance period. Because the probability of random failure is low for these type of assets and the contractors have sufficient knowledge and experience with these assets, EJ would be sufficient to determine the system performances.

Passive assets with a relatively low lifetime are asphalt and construction joints, which also have high replacement costs. These elements are part of the systems including a road construction. Generally, these assets need to be replaced every 7-12 years, which can have a big impact on the system availability and maintenance budget due to the required maintenance activities to replace the system elements. Due to the impact on the availability and the maintenance budget a qualitative and quantitative analysis should be conducted. The analyses should avoid project cost overruns during the design and maintenance phase due to wrongly assessing the impact of the maintenance activities for the asphalt and construction joints. This also counts for the DBFM-contract.
**Active**

By developing a system with mainly active assets the length of the maintenance period is of influence on the strategy. The lifetime of the active assets is (generally) about 10-15 years (Rijkswaterstaat, 2012) and the length of the maintenance period could vary between 7-30 years. Therefore a distinction is made between two maintenance periods:

- a maintenance period of maximum ten years;
- a maintenance period of ten years and longer.

The probability of random failure of active assets is higher compared with the passive assets and the failure behaviour is less known by the contractors. Therefore these type of assets requires extra attention in the tender phase to assess the reliability and maintainability of the active elements and reduce the probability of random failure. With the purpose to diminish the risk of system underperformance during the maintenance phase due to wrong assumptions and design decisions during the tender process.

A contractor that is responsible for a project with a maintenance period of maximum ten years is not fully encouraged to optimise the maintenance strategy and LCC. Because, active assets have a lifetime of (generally) 10-15 years and will remain operational during the maintenance period, which means no replacements are necessary. Replacements have a big impact on the maintenance strategy, systems availability and maintenance budget. Therefore, the contractor is limited forced to consider the reliability and maintainability in combination with the maintenance strategy with regard to the system performances (availability). The performances, costs and risks are relatively unknown by the contractors which increases the risk of wrongly assessing the system performances. This also increases the risk of necessary design changes and project delays with all associated risks such as, commissioning and operating risk. If the reliability and maintainability of the system are insufficiently incorporated in the design, it could affect the maintenance strategy negatively and result in higher maintenance costs, thus higher LCC. In order to diminish these risks it is advised to use a qualitative analysis for the projects with mainly active assets, a maintenance period of maximum ten years and based on the terms of a DBM-contract. A qualitative analysis provides insight in the failure mechanisms and associated consequences which must help the contractor to develop a well-performing system. The most critical project elements can be determined and mitigated in order to decrease the probability of system underperformance.

Replacements of active assets are necessary in a project with a maintenance period of ten years or longer because the active assets have a lifetime between the 10-15 years and it contains a high probability that the active assets will fail during the maintenance period. The reliability of the active assets is lower than for the passive assets and the probability of random failure is higher and should be taken into consideration by the contractor in the tender process. Random asset failure might result in system unavailability and extra maintenance activities. The additional maintenance activities are necessary to restore the system and will have a negative impact on the maintenance costs. Another aspect that is of influence on the system performances is the maintainability of the system because the maintainability influences the length and costs of the maintenance activities. The maintenance strategy that is developed during the tender phase should optimise the relation between the reliability and maintainability of the active assets. In order to reduce the LCC during the maintenance period and to develop a more competing price to get the project awarded. This can be realised by using a qualitative and quantitative analysis. With the qualitative analysis insight can be gained in the failure mechanisms and consequences of the possible failures in order to determine the most critical elements, elements with a high probability of failure or big impact on the system performances by failure. This information can then be used as input for a quantitative analysis that must provide insight in the failure frequency of a certain design. This might help the contractor to determine which (sub)systems are not performing according to the requirements. These (sub)systems must adjusted to diminish the risk of wrongly assessing the system performances. Using this information the contractor is able to optimise the system, by enhancing the reliability and maintainability, with the purpose to reduce the LCC and optimise the profit margin.

**7.3.3 Design, Build, Finance and Maintain (DBFM-contract)**

The contractual period of a DBFM-contract is 15-30 years (Koster et al., 2008), which means that even if the maintenance period is fifteen years the contractor must replace several active assets because the lifetime of these assets is in general between the 10-15 years. Therefore no distinction is made between the lengths of the maintenance period.
Within a DBFM-contract, the contractor should be aware of the aspects discussed for the D&C and DBM-contract as well. The addition of the F-component to the DBM contract increases the risks for a contractor in case of system underperformance. The contractor is not only paid for the realised product but also for the system performances during the project life cycle. These payments are periodical and two types of payments can be distinguished, see chapter 3 for further elaboration. System underperformance could result in lower periodical payments (payment risk). Also, a project delay due to necessary design adjustment as result of wrongly assessing the system performances in the tender phase could result in cost overruns (financial risk).

During the tender phase the contractor must consider the RAMS-elements (design) in combination with the maintenance strategy. Because the maintenance activities could diminish the system availability due to the frequency (reliability) of activities, traffic hindrance (maintainability) or safety issues. Unavailability has an adverse impact on the periodical payments and jeopardises the profit margin.

Part of the tender process is making a price indication and includes an overview of the expected revenues and expenditures. The price indication is based on the expected system performances and associated design, construction and maintenance costs. In case the contractor insufficiently incorporates the system performances in relation to the periodical payments it could result in higher LCC and a lower profit margin. Due to higher project costs (expenditures) and lower income (revenues).

**Passive**
The contractor is familiar with the performances, costs and risks of the passive assets. The passive assets have a long lifetime of 50-100 years, these assets are very reliable and the probability of random failure is low. Same as the risk of wrongly assessing the system performances, because the failure behaviour and required maintenance activities are rather known by the contractor. For these reasons expert judgment would be sufficient to assess the required system performances and diminish the risk of system underperformance. Most of the passive assets should not be replaced due to the long lifetime of the assets and high reliability. Therefore the urgency to optimise the LCC is low with regard to the system performances and asset replacements.

Passive assets with a shorter lifetime are the asphalt and construction joint elements. These elements should be examined by a qualitative and quantitative analysis due to the impact on the maintenance activities, system availability and maintenance budget. For a more detailed elaboration see the explanation given in the DBM-contract above.

**Active**
A DBFM-contract with mainly active assets incorporates the most risks because of the high probability of random failure of the active assets, in combination with the consequences for the contractor in a DBFM-contract in case of system underperformances. The probability of wrongly assessing the system performances is also higher because the contractor is lacking knowledge of the system performances of the active assets. From this perspective it is advised to use a qualitative and quantitative analysis in order to develop a system with optimised system performances and low LCC.

The qualitative analysis is used to determine the failure mechanisms and consequences of failure of the active assets with the purpose to determine the most critical system elements with regard to the system performances. Using this analysis the reliability and maintainability of a system can be determined and used to diminish the probability of random failure. This must contribute to a better performing systems and less design and construction adjustments after winning the bid, which will have a negative impact on the profit margin. The output of the qualitative analysis is also used to conduct a quantitative analysis. The quantitative analysis can be used to examine the availability of the system with the purpose to assess the periodical payments. Within a DBFM-contract it is very important for the contractor to have a proper overview of the expected revenues and expenditures. Using these insights the contractor is able to more accurately determine how much money is needed over the project life cycle in order to get a loan of the bank.

In case the proposed system design does not comply with the required system performances the contractor can decide to change the design in order to be sure the system fulfills the requirements. In order to assure the cash-flow to a certain extent during the project cycle and diminish the probability of system underperformance with all related consequences.
7.4 Decision-making model

In the previous paragraph a suitable methodology is allocated to the different situations distinguished by building contract and asset type. This is processed in a decision-making model given in Figure 7-1. The model consists of four columns in which the first column is the system type, this research is focused on the infrastructural systems. In the second column the different building contracts are given, which determines the consequences for the contractor. Three building contracts are examined: D&C, DBM and DBFM. The third column distinguishes the asset type: passive or active. The active assets have a higher probability of random failure and a shorter life-time than the passive assets. Therefore the active assets requires more attention than the passive assets. The fourth column shows the type of analysis that is linked to the different situations, three types of analyses are used: expert judgment, qualitative analysis and quantitative analysis. For a DBM-contract with mainly active assets two methods are given, which is caused by the length of the maintenance period in combination with the characteristics of active assets.

Some nuances should be made with regard to the decision-making model developed. The current model is rather generic and no distinction is made between the different subsystems and the depth of the analysis. For instance, for some of the passive assets a qualitative and quantitative analysis is necessary to examine the influence of it on the system performances. This is also described in the following paragraph as a weakness of the model. In the following subparagraph the most important subsystems are discussed, which could have a big impact on the system performances.

7.4.1 Subsystems

The decision-making model is rather generic and is a first setup in order to support the contractors in the tender phase. Some of the systems analysed consists of many subsystems, especially the systems with mainly active assets, and due to the time constraints of the research it was hard to go into detail. In order to say...
something more specific about the systems the outcome of the survey is used. A distinction is made again between the passive and active assets.

**Active**

Within the systems with mainly active assets an integral approach is rather important in order to determine the system performances and analyse the interrelationships of the subsystems. Nevertheless, some of the systems are more important than others and to discuss these elements the outcome of the survey is used. For the tunnel, lock and movable bridge systems a recurring subsystem is the 3B-control system. This system is used to guard, operate and control (in Dutch: bewaken, besturen en bedienen). This subsystem is an important element of the system and by failure the system cannot function anymore and will result in unavailability. For the movable bridge and (ship) lock the mechanical elements are of big importance in order to open and close the bridge a lock. For the tunnel the climate control system is of importance and in particular the ventilation. The climate control system measures the air quality and by failure the system is closed immediately. Other subsystems that are mentioned as most important are the safety system (movable bridge) and energy supply (tunnel and lock). The DTM system is a bit different compared with the tunnel, lock and movable bridge. This system provides the information to the road user and measures the traffic flow. Important subsystems are the detection (SOS), presentation (DRIP’s) and the processing system (MTM). If these subsystems fail the road user cannot be informed anymore for traffic jams, speed limitations or redirections.

The discussed subsystems should at least be taken into account during the tender phase because these assets have a big impact on the system availability by failure. Therefore, it is rather important to examine the expected performances over the project life-cycle in order to diminish the risk of system underperformance.

**Passive**

As discussed the passive assets are rather reliable and the probability of random failure is low. Nevertheless, some of the passive subsystems are mentioned as more impactful. The recurring elements are the construction joints and asphalt layer. Both elements are already discussed and have a big impact on the maintenance activities and budget. Another element mentioned multiple times is the water management. If the water management aspect is taken into account insufficiently it could result in a flooded underpassing or road and means the system is unavailable and also jeopardises the safety of the system user. The water management consists of multiple aspects such as, drainage and ditches and could have a big impact on the availability of the system.

These subsystems should be at least taken into account during the tender phase because it could jeopardise the system availability and eventually result in a lower profit margin.

### 7.5 Validation of model

The model is validated in order to provide (objective) evidence that the decision-making model, when in use, fulfils its intended purpose and support contractors in their decisions with regard to the system performances of infrastructural systems (NEN, 2015). The DBFM-contracts are relatively new building contracts (5-10 years) in the Netherlands and are difficult to assess the performances of the building contracts. Due to the following reasons it was difficult to implement the decision-making model into the tender phase and monitor the system performances:

- limited research period;
- the length of the different building contracts (maximum 30 years);
- difficulty to assess the current performances of the building contracts.

In order to assess whether the applied methodology was sufficient to process the system performances effectively during the tender phase. Therefore is chosen to present the findings described in this research and discuss it with experts to assess the applicability of the decision-making model. In order to prepare the experts for the validation a summary of the research is sent to them prior to the validation session.

The validation session is held with four experts of Ballast Nedam, they are active in three different disciplines with the purpose to gain feedback from different angles that must enhance the reliability and usability of the decision-making model. The disciplines they represented are:

- design;
- construction;
- operate and maintenance.
- tender manager

The validation session had other purposes as well, besides assessing the validity of the model. Presenting the findings of the research might enhance the supportability by the user (the experts). During the validation session they had the opportunity to give feedback on the model, by doing so ambiguities from their perspective could be resolved. The research was limited to a certain scope that might have limited the outcome of the research. Using the feedback of the experts these limitations could be noticed, their feedback is also used to determine recommendations for further research.

In order to gather this information a SWOT-analysis is conducted during the validation sessions to determine the: strengths; weaknesses; opportunities; threats.

The outcome of the SWOT-analysis is given in Table 7-2, the given remarks are separately described below.

Table 7-2 SWOT-analysis

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S</strong> Maintained, built upon or levered</td>
<td><strong>W</strong> Remedied, changed or stopped</td>
</tr>
<tr>
<td>Simplicity and clarity of the model.</td>
<td>Depth of analyses is not included in the model.</td>
</tr>
<tr>
<td>Model is applicable for about 80% of the building contracts used on the Dutch infrastructure market.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>O</strong> Prioritised, captured, built on and optimised</td>
<td><strong>T</strong> Countered or minimised and managed</td>
</tr>
<tr>
<td>Model can be used to compose the tender team.</td>
<td></td>
</tr>
<tr>
<td>By correctly assessing the system performances in the tender phase, the contractor could reduce the risk profile of the project.</td>
<td></td>
</tr>
<tr>
<td>Possibility to incorporate the decision-making model in the tender-model document of the company.</td>
<td></td>
</tr>
<tr>
<td>A proper risk assessment might result in a less competing price.</td>
<td></td>
</tr>
<tr>
<td>Difficulty of conducting the RAMS-analyses to the right extent – for some situations the analyses should not be into too much detail.</td>
<td></td>
</tr>
</tbody>
</table>

**Strengths**
The experts appreciated the simplicity and clarity of the decision-making model. By taking a couple decisions it is possible to determine the method to apply in the tender phase. Another strength of the model is the wide applicability, it is applicable for about 80% of the building contracts applied by Ballast Nedam. The other 20% are building contracts with a special content that are deviating from the main building contracts as D&C, DBM and DBFM.

**Weaknesses**
Within the model no distinction is made of the depth of the analysis. For some of the situations a more in-depth analysis is needed to determine the system performances in the tender phase, but this is not incorporated in the model. A distinction can be made, for instance, between types of locks. A lock with a water retaining function is most likely more complex than a lock without a water retaining function and requires a more comprehensive analysis in the tender phase to diminish the risk of system underperformance. Because
the consequences of failure are different and therefore a more comprehensive analysis is required for more complex systems and for systems with a more important function.

**Opportunities**
Before the tender process starts, the contractor must compose a tender team. By using the decision-making model the contractor is able to compose a tender team with the right knowledge. For instance, if a quantitative analysis must be conducted, the contractor should include somebody in the team that is able to gather the required data, conduct the quantitative method and process the output of the analysis. The decision-making model can be used to diminish the risk profile in case the risks are assessed correctly, which is the second opportunity. This could be very beneficial because a lower tender price could be realised and results in a bigger probability to win the bid.

**Threats**
A proper risks analysis might result in a less competing price but provides the contractor more certainty about the system performance of the developed system. The contractor is able to mitigate the risks with economically most advantageous control measures. For both the client as the contractor it is important to be aware of the risks. A contractor who did not calculated the risks properly could end up with a project with a high risk profile that is insufficient incorporated in the project budget. Eventually this could result in high project costs and a low profit margin. Another threat is the difficulty of conducting the RAMS-analyses to the right extent. Because it is not analysed to what extent the methodology should be conducted, it could occur that the method is conducted into too much detail.

**Overall opinion decision-making model**
The experts acknowledged the identified problems, risks per building contract and assessed the model as applicable in the tender process. Also, the assumptions made in this research are proven valid by the experts.

7.5.1 **Additional remark of experts**
One of the experts remarked that a project delay could influence the maintenance strategy negatively. A project delay could affect the whole system or a part of it, in case a part of the system is delayed and other parts are finished and in use on time. During the tender and design phase the maintenance strategy is developed based on a completely finished system and most likely the maintenance activities are matched to each other. In case a part of the system is already in use and the other part is finished a year after, the maintenance strategy might not be fully applicable anymore. Because the part of the system that is finished in time requires maintenance at another time, probably earlier, than the delayed part. Eventually, this could result in more system closures, more maintenance activities and cost overruns. This remark is processed in the report.
SECTION IV: Conclusion
8 Conclusion

This research report is an exploratory study into the system performances of infrastructural systems and how to process the system performances effectively in the tender phase. The main goal of this research was to develop a decision-making model that must support the contractors in the tender phase in their decisions with regard to the system performances. This objective is processed in a research question that is divided into three sub questions. The answers to the sub questions has provided the answer to the main research question and fulfils the main research objective.

This chapter consists of three paragraphs in which the answers to the research questions and the relevance of this research are described. In paragraph 8.1 the sub research questions are discussed, the answers to these questions are used to answer the final research questions and resulted in the decision-making model, this is described in in paragraph 8.2. Finally, the relevance of the research is elaborated in paragraph 8.3.

8.1 Sub conclusions

To fulfil the research objective and answer the main research question three sub research questions are developed. These questions are based on the problems analysed and discussed in chapter 1. Before the sub research questions are discussed the importance of the tender phase is elaborated first.

8.1.1 Tender phase

The first conclusion is with regard to the tender phase, the boundary of this research.

- The tender phase makes it difficult to analyse all the performance requirements into detail and assure them within time and budget. Also, the phase is characterised by the uncertainty if the project will be won and the consequences of the design decisions made in the tender phase in later project phases.

The tender phase is limited by time, budget and the amount of available information. In spite of the limitations, the most fundamental decisions with regard to the design and the final system performances are made during the tender phase. During this phase the contractor has the biggest influence on the RAMS-performances and the maintenance strategy and makes several assumptions with regard to the RAMS-elements. These assumptions will eventually be verified in the design phase, in this phase the contractor can use more resources and will analyse and assure all the project specifications into detail. If the assumptions made in the tender phase are wrong it could result in design and construction adjustments and a less applicable maintenance strategy; in other words, higher project costs, higher LCC and a lower profit margin.

From this perspective the contractor should be careful with their resources as staff, time and money and, they should be aware of the impact of the decisions made during this phase. Therefore a decision-making model is developed which provides an insight in which methodology can be used for what situation in order to process the system performances more effectively in the tender phase. With the purpose to diminish the risk of system underperformance and all consequences associated.

8.1.2 Sub question 1

Contractors have limited knowledge of the consequences of not fulfilling the performance requirements in the tender phase that might result in system underperformance. In order to narrow this knowledge gap the following sub research question is answered: What are the risks for a contractor in case they do not or insufficiently take into account the system performances of infrastructural systems in the tender phase?

The risk of insufficiently incorporating the system performances in the tender phase differ per building contract. The following is concluded:

- Within a D&C-contract the contractor should be aware of the regulations, EMAT-criteria and long-term project specifications that could incorporate long-term responsibilities for the contractor.
In general, system underperformances will not result in major consequences for the contractor due to the short-term characteristic of the building contract. Within a D&C-contract the contractor is only responsible for the design and construction. Because the contractor is not responsible for the system after system commissioning they are not forced to optimise the system with regard to the system performances. Nevertheless, the contractor cannot neglect the regulations, EMAT-criteria or other long-term specifications incorporated in the project specifications in order to win the bid. If the bid is won, but the specifications are not incorporated properly, it could result in higher design and construction costs in order to fulfill the performance requirements. Therefore the performance requirements should be taken into consideration very carefully in the tender phase, to diminish the risk of system underperformance and the associated extra project costs. Even, in a short-term building contract as the D&C-contract.

- A building contract with a long-term responsibility bears the most risks for a contractor in case the system performances are insufficiently taken into account in the tender phase.

Building contracts with a long-term responsibility are DBM and DBFM-contracts. Within these contracts the contractor is also responsible for system performances besides the design and construction responsibilities. Within a DBM contract the contractor is also responsible for the maintenance of the system; in a DBFM-contract, the contractor is also responsible for the financing. Within these projects another aspect is of importance: Life Cycle Costs (LCC). Focussing on the LCC, means focusing on the long-term. A contractor should aim at the costs over the long-term rather than minimising the purchasing costs. This could result in higher design and construction costs but strongly diminish the maintenance costs, which is desirable with the purpose to minimise the LCC. The importance of the system performance in the DBM and DBFM-contract is discussed in the following bullets.

- The reliability and maintainability determined by the design in the tender phase has a big impact on the maintenance strategy.

During the tender phase the contractor should also consider the maintenance strategy in combination with the design of the system. The design determines the reliability and maintainability of the system and has a great influence on the system performances after commissioning the system. The maintenance strategy depends on the reliability and maintainability of the system. Because the reliability defines how often the system might fail and, the maintainability determines what maintenance activities are required. Based on these aspects the contractor could consider a maintenance strategy. Wrongly assessing the reliability and maintainability will have an adverse impact on the maintenance strategy because it should be adjusted during the design phase. This could result in higher design and construction costs. Otherwise, it will result in higher maintenance costs due to more frequent system closures and, more staff and material needed due to the less optimised system.

- Project delays due to necessary design adjustments could result in a less applicable maintenance strategy.

Necessary design and construction adjustments due to wrongly assessing the system performances in the tender phase could result in project delays and partial completion of the system. This might jeopardise the applicability of maintenance strategy developed in the tender (and design) phase. Due to the partial completion the systems are degenerating in a different pace and maintenance activities are required on different moments. This could eventually result in more system closures, and a lower availability, in order to conduct the maintenance activities safely and consequently in higher maintenance costs.

- The revenues to reimburse the contractors’ investments in a DBFM-contract are strongly related to the system performances.

Within a DBFM-contract the contractor is responsible for financing the project and can reimburse its investments during the project life cycle. In the maintenance phase the contractor is paid a periodical payment based on the system performances. These performances are determined by the design decisions made in the tender phase, decisions with regard to the reliability, maintainability and maintenance strategy. If these considerations were inaccurate or insufficient it might result in lower system performances during the maintenance period. These lower system performances could have a bigger impact in a DBFM-contract than in a DBM-contract due to the periodical payments. The contractor is paid during the maintenance period a...
periodical payment that is based on the system performances. Thus, lower performances means lower revenues and a lower profit margin.

- A project delay in a DBFM-contract could result in an ‘interest trap’, which will have a major impact on the profit margin.

Another issue within the DBFM-contract is the ‘interest trap’ that could be caused by project delays as result of necessary design and construction adjustments. Due to the project delays the contractor is not paid the one-off payment on time and extra resources are needed to finish the project as soon as possible. The revenues after system commissioning are deferred as well and could result in an ‘interest trap’ in combination with the extra resources needed. Which means, the project revenues are lower than the project costs and results in a negative project balance.

8.1.3 Sub question 2
 Contractors have limited insight in the system performances of the different infrastructural systems and to narrow this knowledge gap the following research question is answered: What infrastructural (sub)systems have the biggest impact on the system performances?

The infrastructural system with the biggest impact on the system performances are the systems with mainly active assets or the passive assets with a big impact on the maintenance activities and budget.

- Infrastructural systems with active assets requires more attention than infrastructural systems with mainly passive assets.

Active assets are the electronic and mechanical (E&M) elements in an infrastructural system. These assets have a relatively short life-time of 10-15 years and a high probability of random failure. The failure behaviour of these assets is more unpredictable and makes it more difficult to accurately assess the performances in the tender phase. These type of assets incorporate therefore more risks with regard to the system performances of an infrastructural system. Also, because the contractor is less familiar with these type of assets and increases the risk of wrongly assessing the system performances. Therefore these assets requires more attention in the tender phase. Systems mainly consisting of active assets are: tunnel, (ship) lock, movable bridge and Dynamic Traffic Management-system.

- The contractor should be aware of passive assets with a relatively short life-time and a big impact on the maintenance activities and maintenance budget.

In general passive assets have a life-time of 50-100 years and a low probability of random failure. These assets requires less maintenance or replacements then the active assets, but there are some exceptions for the passive assets. Passive assets as asphalt and construction joints are assets with a relatively short life-time (7-12 years) and a big impact on the availability and maintenance budget. In case these assets must be replaced the system is unavailable because it must be closed in order to conduct the maintenance activities. This can have a big impact on the availability of the system and should be taken into consideration very carefully during the tender phase in order to assess the system performances correctly. Systems mainly consisting of passive assets are: road construction, fixed bridge or viaduct, underpassing and quay wall.

8.1.4 Sub question 3
 One of the problems identified was a lacking methodology to process the system performances effectively on a well-founded base, with the purpose to minimise the risk of system underperformance and to optimise the profit margin. In order to fill this gap, the following research question is answered: What methods are applicable in the tender phase to optimise the risk of system underperformance for a contractor?

The applicability of the ‘RAMS-methodology’ is examined, this methodology can be used to describe and determine the RAMS-performances. Three types of analysis are distinguished that could be applied in the tender phase to optimise the risk of system underperformance for a contractor. The characteristics of the different analyses are discussed in the following bullets.
Three types of analysis are distinguished in the tender phase and the applicability depends on two aspects:
- the level of knowledge and experience with a project;
- the risk profile of the project.

The following three types of analysis are distinguished based on the RAMS-guide and further discussed in the following bullets:

1. Expert Judgment
2. Qualitative analysis
3. Quantitative analysis

The risk profile is determined by the building contract and asset type. The bigger the risks for a contractor the higher the risk profile. As described above, a long-term building contract incorporates more risks for a contractor than a short-term building contract. In other words, these building contracts have a higher risk profile, see conclusion sub question 1. The other aspect influencing the risk profile is the asset type. A system consisting mainly of active assets incorporates more risks than a system with mainly passive assets, see conclusion of sub question 2.

Both aspects determines the risk profile and should be taken into consideration in the tender phase by the contractor with the purpose to determine the system performances correctly.

- Expert Judgment is applicable in case the contractor has sufficient knowledge and experience with the design, realisation and/or maintenance of a particular infrastructural system.

Expert Judgment is a type of analysis that is based on the knowledge and experiences of the contractor. It is a relatively quick method that can be used in the tender phase in case the contractor has sufficient knowledge with the system. It is a common method in the infrastructure industry and basically applied in every project. But, it remains a subjective method and the contractor should be aware of its own strengths and capabilities to be able to assess the system performances. Otherwise, the expert judgment is unreliable and could result in wrong decision-making in the tender phase with regard to the system performances.

- A qualitative analysis should be applied in situations in which the risk profile of the project is high and/or, the contractor is lacking knowledge and experience with the design, realisation and maintenance of the system.

A qualitative analysis can be used to determine the failure mechanisms and consequences of failure. The analysis is mainly used in situations in which expert judgment is not sufficient anymore due to the high risk profile of the project or the lacking knowledge or experience of the contractor with the system. By using the qualitative analysis it is possible to define the critical system elements, these critical system elements can then be mitigated, by enhancing the reliability and maintainability of the system. This will enhance the system performances and diminish the risk of extra project costs. Having insight in the critical elements can also be used as input for the maintenance strategy. The critical elements can be mitigated up front or taken into account in the maintenance strategy. For instance by conducting extra preventive maintenance to avoid system failure.

- A quantitative analysis can be used in situations a more accurate approach is required due to the high risk profile and/or the demand to have insight in the expected revenues and expenditures during the project life-cycle.

A quantitative analysis is applicable to define the failure rate and reliability of the infrastructural system in absolute numbers. Such an analysis should be applied in situations the risk profile is high due to the major consequences for a contractor in case of system underperformance. Using the output of the analysis it is possible to define the availability of the system. This will help the contractor to assess which components are critical and to what extent the system performances of these elements should be enhanced. Such an analysis is very beneficial in DBFM-contracts in which the contractor demands an overview of the expected revenues and expenditures over the whole project life-cycle.
Prior to a quantitative analysis a qualitative analysis is required in order to determine the failure mechanisms, which is used as input for the quantitative analysis.

8.2 Main conclusion
The main objective of this research was to develop a decision-making model that can be used by the Dutch contractor in the tender phase with the purpose to minimise the risk of system underperformance and optimise the profit margin. After analysing and answering the three sub research questions, discussed above, the main research question can be answered. The answer to the main research question fulfills the main research objective described in the first chapter, the main question is:

How to effectively process the system performances of infrastructural projects in the tender phase by the use of a decision-making model?

By what methodology the system performances of infrastructural systems should be processed depends on the situation and is bounded by the limitations of the tender phase as well. Within the decision-making model seven situations are distinguished by building contract and asset type, which are given a letter from A-F. Both aspects determines the risk profile of the project and defines what methodology is needed, because not every situation requires the same approach. The decision-making model is illustrated in Figure 8-1.

Expert judgment is sufficient in infrastructural projects including mainly passive assets. During the tender phase it is not necessary to conduct more comprehensive methods in order to determine the system performances. Because the contractor is familiar with the failure behaviour of the passive assets and is able to accurately assess the reliability, availability maintainability (if required) and safety. A more comprehensive methodology will costs more time and money, which is limited in the tender phase. Only the passive assets with a relatively short life-time and a big impact on the maintenance activities and budget requires a more detailed analysis. Such assets are, the asphalt and construction joints. If the performances of these assets are not taken into account sufficiently, it might affect the availability of the system due to the system closures. Also it could have an adverse impact on the profit margin.

Infrastructural systems including mainly active assets requires a more detailed analysis in order to assess the critical system elements and diminish the risk of system underperformance. Because the failure behaviour is more difficult to define due to the higher probability of random failure and the shorter life-time of the active assets. Also, the active assets are less known by the contractors and this could result in wrong decision-making with regard to the system performances of these assets. Therefore a more comprehensive analysis is required in order to minimise the risk of system underperformance. The following analyses are linked to the building contracts:

- For a D&C-contract (B) with mainly active assets and a DBM-contract with a maintenance period shorter than ten years (D1) a qualitative analysis is advised. Using the qualitative analysis the contractor is able to determine the most critical elements, which can be mitigated if needed. Eventually, this will result in higher system performance and a lower probability of system failure.
- For a DBM-contract with a maintenance period longer than ten years (D2) and a DBFM-contract (F) a qualitative and quantitative analysis is advised. Using both analyses the contractor is able to determine the most critical system elements and define the expected failure rate of the system. Both can be used to enhance the system performances by mitigating the biggest risks and to develop a maintenance strategy, which is based on the reliability and maintainability of the system.

The contractor could also decide to accept the risk of system underperformance of a particular subsystem and include this risk in the risk budget. In these cases the risks are noticed and in case the risk will emerge after winning the bid, the contractor at least saved money to respond to these risks and restore the system performances.

It should be emphasised that the type of analysis linked to the different situations does not mean, no further analysis is needed after the bid is won. Due to the constraints in the tender phase it is not possible to analyse all the project specifications into detail and assure them within time and budget. Therefore it is analysed which building contracts incorporates the biggest risks and, which infrastructural systems have the biggest impact on the system performances. From this perspective it was possible to determine the situations that incorporates
the biggest risks for the contractor and link a suitable type of analysis to the situation. After the bid is won, the contractor should conduct more analyses in order to further define the system performances.

![Decision-making model diagram](image)

**Figure 8-1 Conclusion: Decision-making model**

### 8.3 Relevance

The contribution of this research to the science, practice and society is described in this paragraph.

#### 8.3.1 Scientific relevance

The contribution of this research to science is the decision-making model. Currently, there is no literature that describes the way contractors should process the system performances in the tender phase and by doing so, what consequences can be diminished or optimised. The decision-making model discusses the way how contractors can cope with the system performances in different situations using a certain methodology.

In order to develop the decision-making model different aspects are examined which are:

- the risks for a contractor in case they do not or insufficiently take into account the system performances of infrastructural systems in the tender phase;
- the impact of different infrastructural systems on the system performances;
- the applicability of different methods to describe and determine the RAMS-performances.

These aspects are combined in a decision-making model that must support the contractor in the tender phase with regard to the system performances. This is a contribution to science because such model is not yet developed and can be of value for further research. This research has provided insight in the consequences for contractors in case they insufficiently processed the system performances in the tender phase which is a contribution to the scientific field. Also, the allocation of the RAMS-methods to the different situations is a contribution. Because current literature describes a more general application of the applicability, for instance the RAMS-guide, or is a more detailed description of the methods like handbooks or guides.
8.3.2 **Practical relevance**

The practical relevance of this research is large, because the outcomes of this research can be used by Dutch contractors in the tender phase and must narrow the knowledge gap of the contractors with regard to the system performances of different infrastructural systems and the limited insight in the consequences of system underperformance.

The identified problems described in chapter 1 are the first contributions to practice. It is made clear what problems they have with processing the system performances in the tender phase. In case they acknowledge the problems they can improve the tender phase by narrowing the knowledge gap with regard to the system performances.

As it is described in chapter 1 the contractors are having difficulties with processing the system performances in the tender phase for several reasons, such as:

- The contractor is having limited knowledge of the system performances of infrastructural systems over the long-term;
- Within the organisation of Dutch contractors a methodology is lacking to process the system performances effectively and on a well-founded basis.
- Within the organisation of a contractor, there is a lack of cooperation between the design and maintenance and operate department.

For this reason a decision-making model is developed and must support contractors in the tender phase with processing the system performances more effectively and to diminish the probability of system underperformances. System underperformance might result in excessive project costs and project delays, which will have an adverse impact on the profit margin and LCC.

The validation session has shown that the research has a large practical contribution. The experts assessed the model as applicable and possibly helpful in the tender phase. They were positive about the simplicity and clarity of the model and saw the decision-making model as an opportunity to enhance the tender process.

8.3.3 **Societal relevance**

Infrastructure systems are very important for the economy, from both financial as safety aspect. Failing tunnels, bridges or locks might result in high economical costs due to traffic jams or flooding’s and jeopardises the safety of the environment. Also, the infrastructure systems are financed with public money and means that everybody is paying for the tunnel, bridge or other infrastructural system. By using the decision-making model in the tender phase the contractor might be able to develop a system with lower LCC, which means less public money is needed to finance the project.

From the societal perspective it is very important the contractor properly processes the system performances in tender phase and develops a system that fulfils its performance requirements.
9 DISCUSSION & RECOMMENDATIONS

This chapter consists of the discussions (9.1) and recommendations (9.2).

9.1 Discussion

This study was an exploratory study that has provided extra knowledge with regard to the risks and (financial) consequences for a contractor in case they insufficiently take into account the system performances in the tender phase. The problems identified by conducting interviews with the experts, provided a good insight in the struggles for a contractor with the system performances. The decision-making model developed is a first start in order to effectively process the system performances on a well-founded base. One of the last steps in this research process was a validation session with four experts of Ballast Nedam. The experts were rather positive about the model and the main conclusion of this validation session was the high simplicity and clarity of the decision-making model. The model also provided the opportunity to incorporate the decision-making model into the tender process documents of Ballast Nedam, with the purpose to diminish the risk of system underperformance after winning the tender. This has proven the high applicability of the model and value of it to the Dutch infrastructure industry from the perspective of the experts of Ballast Nedam.

9.1.1 Findings

The contractor should be aware of the importance of the long-term responsibility in combination with the more complex systems. These complex systems consists mainly of electronic and mechanical (E&M) subsystems as part of the tunnels, movable bridges and lock systems. In case they insufficiently take into account the system performances in the tender phase the contractor should be aware of the adverse consequences over the long-term. Consequences as, higher project costs and project delays, due to necessary design and construction adjustments, that eventually might result in higher LC and a lower profit margin.

One of the problems identified at the start of the research was the lacking cooperation between the design and operate and maintenance (O&M) department. This research on the other hand, described the importance of the integration of the maintenance in the design process with the purpose to develop an optimised system design in the tender phase. Therefore, it might be beneficial for a contractor to enhance the cooperation between the design and O&M-department with the purpose to diminish the LC of the project. This research did not go into detail about how the cooperation could be enhanced, which is a more organisational issue and was not part of the scope. This research focused more on the importance of an integral approach by the use of the RAMS-elements. Whereby a good cooperation between the designers and maintenance engineers is vital to develop an integral system that fulfils all the performance requirements.

Another problem identified was the lacking knowledge of the contractors with regard to the system performances of infrastructural systems. This could be a result of the past, in which the contractor was not concerned with long-term goals and system performances of infrastructural systems. For instance in D&C-contracts or the traditional building contracts in which the contractor was only concerned with the construction of an infrastructural system. The contractor is competing for different projects with different systems and different building contracts and this research has provided knowledge and insight in the importance of the system performances in these different situations. The knowledge gap with regard to the system performances incorporated in the different projects is narrowed by this research.

To be concise, this research has been a contribution to the infrastructure industry by the development of a decision-making model that can be used in the tender phase to process the system performances more effectively. But, the research was limited to a certain extent in order to be able to conduct the research in the given time period with sufficient quality. The limitations of this research are described in the following sub paragraph.

Assumption

The main assumption made in this research is described in chapter 1. This assumption states that the method to be used in the tender phase by the contractor is determined by:

- the complexity of the infrastructural system;
- the type of building contract;
- tender phase characteristic.
Now the research is finished it can be concluded that this assumption was correct. The complexity of the infrastructural systems is determined by the passive and active system elements. The infrastructural systems that mainly consists of active assets are assessed as more complex with a bigger impact on the system performances; in other words, these systems incorporate a higher risk of system failure for a contractor. The type of building contract showed the importance of the long-term perspective of the building contracts. The DBM and DBFM-contracts incorporate more risks than the D&C-contract, which is a short-term building contract. The tender phase is limited by the time, budget and available information that influences the process of determining the system performance of the infrastructural systems. Combining these variables has resulted in seven different situations that are described in the decision-making model.

9.1.2 Limitations

Within the research several choices are made in order to define the scope and might have resulted in several limitations in the research. These limitations are:

1. The problems and applicability of the decision-making model are only analysed and discussed within one company – Ballast Nedam – and might diminish the generalisation of the output of this research. The validity and reliability of the model can possibly be enhanced if the research is extended by information from other Dutch organisations, in spite the fact that the experts involved in this research are also active in consortia.

2. Within the decision-making model different decision possibilities are incorporated that are advised to use in order to process the system performances more effectively. Unfortunately it is not described to what extent the analysis should be conducted. Because not every project requires the same in-depth analysis. This might result in an inadequate use of the different methods and eventually an infrastructural system that does not fulfil the performance requirements as specified by the client up-front.

3. Within this research the main infrastructural building contracts are analysed as the D&C, DBM and DBFM-contracts and covers about 80% of the Dutch construction market. Other contracts that are not incorporated in the research and are also currently less applied in the infrastructural industry are for instance the Engineering and Construction (E&C), performance contracts and maintenance contracts (Pianoo, 2015c; Rijkswaterstaat, 2014). These building contracts requires less design work but could also include system performances a contractor should fulfil with the design. Insufficiently processing the system performances in the tender phase for these building contracts could have an adverse impact on the profit margin as well.

4. The research is mainly focused on the down-side (threats) of risks and less at opportunities for contractors. The downside as in, extra project costs, project delays, lower profit margin and higher LCC. On the other hand, it must be emphasized that every mitigated risks with an adverse impact on the system performances is an opportunity to enhance the system performance and profit margin of the contractor.

5. The applied validation is chosen due to the time constraints of the research. The building contracts, especially the DBM and DBFM-contracts are long-term contracts and therefore it was not possible to measure the system performances during the whole project cycle. With the purpose to assess whether the methodology chosen in the tender phase was sufficient or not to process the system performances effectively.

6. Another limitation regarding the validation is the group size used for the validation session. All disciplines, tender, design, construction and maintenance, gave their feedback. But in total the decision-making model is validated by four persons which is rather low. The reliability and usability could be enhanced if the group was bigger. Unfortunately this was not possible due to several circumstances.
9.2 Recommendations

Within this paragraph recommendations are given for further research and the use of the decision-making model.

9.2.1 Recommendations for the use of the model

The experts assessed the model as applicable and helpful in the tender phase with the purpose to process the system performances of infrastructural systems more effectively. Nevertheless, some recommendations are made to further improve the process of describing and determining the system performances in the tender phase:

1. In order to enhance the system performances over the long term, the contractor should improve the cooperation between the design and operate and maintenance department (identified problem 3). A lacking cooperation might result in a less optimised system and higher LCC due to the poor communication, information sharing and a design that is not optimised in both ways. By improving the cooperation these problems can be limited and a better tender offer can be realised.

2. Improve the knowledge within the design team with regard to the system performances and the maintenance aspects of a system. Especially for the systems that are classified as complex, such as: tunnels, locks, movable bridges and DTM-systems. These companies are more familiar with the use of system performances in the tender phase. Currently it is learning on the job, this process could be accelerated if the design decisions and trade-offs made during the tender and design process with regard to the system performances and maintenance are documented. These trade-offs can be used in future projects by the design team and might contribute to a system that complies with the system performances against lower design costs – lower LCC.

9.2.2 Recommendations for further research

The following recommendations are made with regard to further research that must contribute to a better insight and knowledge of the system performances of the infrastructural systems by contractors and how to cope with these system performances in the tender phase:

1. Enhance the data gathering within the company with regard to the system performances of the active assets. Currently the Dutch infrastructure industry is lacking empirical data of the system performances of the active assets. This makes it more difficult to assess the required system performances in combination with the lacking knowledge on how to process the system performances in the tender phase effectively. A comprehensive database might enhance the insight in the system performances and could be used by the project engineers to make their trade-offs between different system elements.

2. Further research with regard to the depth of the analyses. Currently no distinction is made in the depth of the analyses. A system consists of many subsystems and components and not every system requires the same analysis with the same depth. In this research no distinction is made between the depths of the analyses which could be beneficial in order to make the decision-making model more situation specific. Having a better insight in which analysis should be applied and to what extent might accelerate design process and diminish the tender and design costs. Eventually this could result in lower LCC and a bigger chance to win the bid.

3. This analysis is mainly aimed at improving the process of taking the system performances into account in the tender phase with the purpose to diminish the risk of system underperformance. The system performances are influenced for a significant part by the chosen maintenance strategy. This was not part of the scope but could be beneficial for a contractor to conduct further research with regard to the ‘best’ applicable maintenance strategy.

4. A risk can be seen as a threat and as an opportunity. In this research is mainly focused on the threats of the risks. By mitigating these threats it is possible to enhance the system performances. On the other side using the risk as an opportunity to optimise the system performances could result in lower LCC and a higher profit margin, especially in combination with mitigating the threats. This is not
discussed in this research and it is recommended to conduct further research into the opportunities of the risks.
10 References


CEI/IEC. (2001). Hazard and operability studies (HAZOP studies) - application guide.

CENELEC. (1999). NEN-EN 50126 - 1: Railway application - The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS) (pp. 8-10). Brussels.


# Appendices

The following appendices are incorporated in this research report:

<table>
<thead>
<tr>
<th>No.</th>
<th>Appendix name</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Appendix A</td>
<td>Abbreviations</td>
</tr>
<tr>
<td>2</td>
<td>Appendix B</td>
<td>Payment mechanism DBFM-contract</td>
</tr>
<tr>
<td>3</td>
<td>Appendix C</td>
<td>Description of content of survey</td>
</tr>
<tr>
<td>4</td>
<td>Appendix D</td>
<td>Definitions of RAMS</td>
</tr>
<tr>
<td>4</td>
<td>Appendix E</td>
<td>Methods to describe RAMS-performances</td>
</tr>
</tbody>
</table>
APPENDIX A — ABBREVIATIONS

The following abbreviations are used in this report.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Availability Correction</td>
</tr>
<tr>
<td>AD</td>
<td>Availability Discount</td>
</tr>
<tr>
<td>AV</td>
<td>Availability Value</td>
</tr>
<tr>
<td>BN</td>
<td>Ballast Nedam</td>
</tr>
<tr>
<td>BP</td>
<td>Bonus Percentage</td>
</tr>
<tr>
<td>D&amp;C</td>
<td>Design &amp; Construct</td>
</tr>
<tr>
<td>DBFM</td>
<td>Design, Build, Finance and Maintain</td>
</tr>
<tr>
<td>DBM</td>
<td>Design, Build and Maintain</td>
</tr>
<tr>
<td>DRIP</td>
<td>Dynamisch Route Informatie Paneel</td>
</tr>
<tr>
<td>DTM</td>
<td>Dynamic Traffic Management</td>
</tr>
<tr>
<td>E&amp;C</td>
<td>Engineering &amp; Construction</td>
</tr>
<tr>
<td>EIA</td>
<td>Environmental Impact Assessments</td>
</tr>
<tr>
<td>EMAT</td>
<td>Economically Most Advantageous Tender</td>
</tr>
<tr>
<td>ETA</td>
<td>Event Tree Analysis</td>
</tr>
<tr>
<td>FM(E)(C)A</td>
<td>Failure Mode Effect (Criticality) Analysis</td>
</tr>
<tr>
<td>FTA</td>
<td>Fault Tree Analysis</td>
</tr>
<tr>
<td>GAP</td>
<td>Gross Availability Payment</td>
</tr>
<tr>
<td>HAZOP</td>
<td>Hazard &amp; Operability</td>
</tr>
<tr>
<td>LCC</td>
<td>Life Cycle Costs</td>
</tr>
<tr>
<td>LVH</td>
<td>Lost Vehicle Hours</td>
</tr>
<tr>
<td>MaVa</td>
<td>Maasvlakte-Vaanplein</td>
</tr>
<tr>
<td>MTM</td>
<td>Motorway Traffic Management</td>
</tr>
<tr>
<td>NAP</td>
<td>Net Availability Payment</td>
</tr>
<tr>
<td>NS</td>
<td>Nuisance Space</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operate &amp; Maintenance</td>
</tr>
<tr>
<td>PC</td>
<td>Performance correction</td>
</tr>
<tr>
<td>PCA</td>
<td>Part Count Analysis</td>
</tr>
<tr>
<td>PFI</td>
<td>Private Financed Initiative</td>
</tr>
<tr>
<td>PD</td>
<td>Performance Discount</td>
</tr>
<tr>
<td>PPP</td>
<td>Public Private Partnership</td>
</tr>
<tr>
<td>RAMS</td>
<td>Reliability, Availability, Maintainability and Safety</td>
</tr>
<tr>
<td>RAMSHE</td>
<td>Reliability, Availability, Maintainability, Safety, Security, Health and Environment</td>
</tr>
<tr>
<td>RAMSSHEEP</td>
<td>Reliability, Availability, Maintainability, Safety, Security, Health, Environment, Economic and Politics</td>
</tr>
<tr>
<td>RAS</td>
<td>Reliability, Availability and Safety</td>
</tr>
<tr>
<td>RBD</td>
<td>Reliability Block Diagram</td>
</tr>
<tr>
<td>RBM</td>
<td>Risk Based Maintenance</td>
</tr>
<tr>
<td>RCM</td>
<td>Reliability Centred Maintenance</td>
</tr>
<tr>
<td>RWS</td>
<td>Rijkswaterstaat</td>
</tr>
<tr>
<td>SBM</td>
<td>Statistically Based Maintenance</td>
</tr>
<tr>
<td>SoS</td>
<td>Strength, Weaknesses, Opportunities and Threats</td>
</tr>
<tr>
<td>SWOT</td>
<td>Strength, Weaknesses, Opportunities and Threats</td>
</tr>
<tr>
<td>TPM</td>
<td>Total Productive Maintenance</td>
</tr>
<tr>
<td>TQMain</td>
<td>Total Quality Maintenance</td>
</tr>
<tr>
<td>TTI</td>
<td>Technical Tunnel Installation</td>
</tr>
</tbody>
</table>
APPENDIX B – DBFM PAYMENT MECHANISM

This appendix describes the DBFM payment mechanism. The 2 DBFM-projects described are: A15 MaVa and A9 Gaasperdammerweg. The payment structure described below is obtained from the DBFM project specifications of the A9 Gaasperdammerweg and the A15 MaVa projects. Both payment mechanisms are mainly the same, only the multiplier is calculated differently. Also, the requirements used in the payment structure are called different: Kog- vs Nkog-requirements (A15 MaVa) and A- and B-requirements (A9 Gaasperdammerweg). Nevertheless, the content of both type of requirements are the same.

This is further described below. It depends on the payment period but in general the formula is as follows:

\[ NAP = (X) \times GAP - AC - PC \]

NAP – Net Availability Payment (in Dutch Netto Beschikbaarheidsvergoeding, NBV)
GAP – Gross Availability Payment (in Dutch Bruto Beschikbaarheidsvergoeding, BBV)
AC – Availability correction (in Dutch Beschikbaarheidscorrectie, BC)
PC – Performance correction (in Dutch Prestatiecorrectie, PC)
X – a factor that is influenced by the payment period and a percentage (20% or 40%).

Availability correction
AC is determined by the formula: \[ AC = \sum AD_{pr} + AD_{cr} \]
\[ AD_{pr} – Availability Discount preventive lane closure \]
\[ AD_{cr} – Availability Discount corrective lane closure \]

The \( AD_{pr} \) \& \( AD_{cr} \) are determined by the formula \[ AD_{pr} = \sum (AV_{pr} \times m_{pr}) - NS_{pr} \]
\[ AV_{pr/cr} – Availability Value of a preventive or corrective lane closure \]
\[ m_{pr/cr} – multiplier for a preventive or corrective lane closure \]
\[ NS_{pr/cr} – preventive or corrective Nuisance Space for a certain payment period \]

A lane closure occurs in case:
- the system does not perform according to the A-categories
- it is requested by the contractor for the purpose of construction or maintenance activities.

The multiplier (m) is determined by:
- \( m_{pr} = LVH_{preventivelaneclusion} \)
- \( m_{cr} = LVH_{correctivelaneclusion} \)

Lost Vehicle Hours (LVH’s) are quantified up front by the client and divided over the different payment periods.

The Nuisance Space (NS) is determined by:
- \( NS_{pr} = LVH_{maxpreventivelaneclusion} \times AV_{pr} \)
- \( NS_{cr} = LVH_{maxcorrectivelaneclusion} \times AV_{cr} \)

The \( AV_{pr} \) and \( AV_{cr} \) are determined up front and are respectively €15 and €25.

Performance correction
PC is determined by the formula: \[ PC = GAP \times (PD - BP) \]
\[ PD – Performance Discount percentage \]
\[ PD = total amount of penalty points \times 0,1 \]
\[ BP – Bonus Percentage \]

BP is a certain percentage depending on the value of performance discount in the previous payment periods. With a maximum value of 0,3% and lowest value of 0%.
APPENDIX C — SURVEY

The following survey is used to gain data from the experts within the organisation of Ballast Nedam to provide insight in the (sub)systems with the biggest impact on the system performances. To keep the survey anonymous the participants are named by their function and discipline. An overview of the participants is showed in the following table:

<table>
<thead>
<tr>
<th>Survey No.</th>
<th>Job Function</th>
<th>Discipline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Project engineer (specialist)</td>
<td>RAMS-engineering and Tunnel safety</td>
</tr>
<tr>
<td>2.</td>
<td>Project engineer (specialist)</td>
<td>RAMS and Systems engineering</td>
</tr>
<tr>
<td>3.</td>
<td>Tender manager</td>
<td>Operate and maintenance</td>
</tr>
<tr>
<td>4.</td>
<td>Segment manager</td>
<td>Operate and maintenance</td>
</tr>
<tr>
<td>5.</td>
<td>Project manager</td>
<td>Construction</td>
</tr>
<tr>
<td>6.</td>
<td>Management</td>
<td>GWW</td>
</tr>
<tr>
<td>7.</td>
<td>Management</td>
<td>Construction</td>
</tr>
</tbody>
</table>

Enquête

<table>
<thead>
<tr>
<th>Naam</th>
<th>Bedrijf</th>
<th>Functie</th>
<th>Datum</th>
</tr>
</thead>
</table>

Als onderdeel van mijn afstudeeronderzoek wil ik inzicht krijgen in de systeem prestaties van bepaalde infrastructurele systemen. Daarom wil ik u vragen de onderstaande vragen te beantwoorden. Enquête bestaat uit 2 delen (± 15 min.) en ik wil u vragen (indien mogelijk) de enquête uiterlijk XX-XX-XXXX terug te sturen. Bij voorbaat dank!

DOEL ENQUETE

Het doel van deze enquête is om de infrastructurele (sub)systemen te rangschikken naar impact op de systeem prestaties (risico van falen) voor de aannemer.

DEEL I

Tabel 1 bestaat uit een 8-tal systemen afgeleid van de case studies. Ik wil u vragen de verschillende systemen te scoren met een cijfer van 1 t/m 8 naar impact op de systeem prestaties (risico van falen).
- 1 is minste impact;
- 8 is meeste impact.

tabel 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Systeem</th>
<th>Ranking (1-8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Vaste brug/viaduct</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Beweegbare brug</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Tunnel</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Sluis</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>DVM*</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Wegenbouw**</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Onderdoorgang</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Kade Constructie</td>
<td></td>
</tr>
</tbody>
</table>

* Dynamisch Verkeersmanagement-systeem (DVM). Alle subsysteem gerelateerd aan het DVM-systeem zoals SoS (inductielussen), matrixborden (MTM), DRIP’s, openbare verlichting, portalen, etc.

Voor deze enquête wordt onder de wegenbouw, dat onder de discipline van de GWW valt, alle aspecten verstaan die onderdeel zijn van een weg constructie zoals, waterhuishouding, (midden)berm, bermbveiliging, verharding, markering, groenvoorziening, voegovergangen, etc.
**DEEL II**

Tabel 2 is een afgeleide van tabel 1 en bestaat uit 2 onderdelen. Ik wil u vragen tabel 2 aan te vullen op de volgende punten:

- geef eerst per systeem maximaal 3 van de meest risico volle subsystemen aan die een grote impact hebben op de systeem prestaties (minder is ook toegestaan);
- verdeel vervolgens 10 punten (score) over de 3 subsystemen waarbij geldt: des te hoger de score, des te groter de impact op de prestaties. Waarbij elk subsysteem een minimale score moet hebben van 1.

---

**Tabel 2**

<table>
<thead>
<tr>
<th>No.</th>
<th>Systeem</th>
<th>Subsysteem (max. 3)</th>
<th>Score (1-10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Vaste brug</td>
<td>1.1</td>
<td>Som 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Beweegbare brug</td>
<td>2.1</td>
<td>Som 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Tunnel</td>
<td>3.1</td>
<td>Som 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Sluis</td>
<td>4.1</td>
<td>Som 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>DVM</td>
<td>5.1</td>
<td>Som 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Wegenbouw</td>
<td>6.1</td>
<td>Som 10</td>
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<td></td>
<td></td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Onderdoorgang</td>
<td>7.1</td>
<td>Som 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.3</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Kade Constructie</td>
<td>8.1</td>
<td>Som 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.3</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX D – DEFINITIONS OF RAMS

Below four definitions of RAMS are given. These definitions are used to describe and understand the RAMS-theory.

RAMS definition by Stapelberg

“This methodology provides the means by which complex engineering designs can be properly analysed and reviewed. Such an analysis and review is conducted not only with a focus upon individual inherent systems but also with a perspective of the critical combination and complex integration of all the system and related equipment, in order to achieve the required reliability, availability, maintainability and safety” (Stapelberg, 2009).

RAMS definition by CENELEC

“RAMS is a characteristic of a system’s long term operation and is achieved by the application of established engineering concepts, methods, tools and techniques throughout the lifecycle of the system. The RAMS of a system can be characterised as a qualitative and quantitative indicator of the degree that the system, or subsystems and components comprising that system, can be relied upon to function as specified and to be both available and safe” (CENELEC, 1999).

RAMS definition by Bakker en Blom et al.

Within the Leidraad RAMS – sturen op prestaties, no clear definition was given. The definition given below is a combination of explanations given in the first two chapters of the standard.

“The purpose of RAMS is to map the coherence between the reliability, availability, maintainability and safety, and to process this in a traceable procedure using different RAMS-methods. This concerns both physical systems as well as the software that controls the physical system” (Bakker et al., 2010).

RAMS definition by Wagner

“The RAMS analysis can be seen as a risk concept that describes the primary performances of all the functions of a system, like a primary flood defence system. A RAMS analysis can be used in every stage of the life cycle and can be applied on a complete system but also for small components within a network” (Wagner, 2012)
APPENDIX E — METHODS TO DESCRIBE RAMS-PERFORMANCES
In this appendix a more detailed elaboration is given of the described methods in chapter 6.

Qualitative
In this subparagraph the qualitative methods are described based on the criteria described above.

Expert judgment
Using the comprehensive knowledge and experience of experts to assess the design on its strengths and weaknesses. This is a very subjective method in which the opinions and judgements of experts can differ strongly. Nevertheless, it is a method that can be used easily to gain quick insights in particular systems. This method can be used both qualitatively as quantitatively.

Failure Mode Effect (Criticality) Analysis (FME(C)A)
By decomposing the name FME(C)A the purpose of the method can be described. Based on a list of standard deviations it can be described how the components can fail (failure mode) and what the consequences of failure (effect) will be on the system (Gestel, Lamper, & Mineur, 2008). If the failure severity is of interest the criticality factor is involved as well. The criticality factor is a level of severity that describes the risk of damage or loss of performances. The main purpose of the FME(C)A is to develop measures to prevent the system for failure or to minimize the effect of failure (Birolini, 2013; Gestel et al., 2004); it is a method to do a reliability analysis (Gestel et al., 2004).

The FME(C)A should be conducted by the total project team, including all disciplines, with the purpose to develop an integral result. It is an easy method to apply but time consuming for complex systems (Birolini, 2013) due to the many data required (Bakker et al., 2010; Gestel et al., 2004). It is recommended by Birolini (2013) to concentrate on the critical parts of the system, in particular where redundancy appears. By using the FME(C)A in an early project stage weak links in the system can be determined and solved. Which might result in a better design and lower costs in realisation and/or maintenance phase (Gestel et al., 2004).

According to Gestel et al. (2004) three FMECA phases can be distinguished: 1) Concept phase; 2) Design phase; 3) Realisation phase. The research is focused on the tender phase in which the concept of the system is developed. Therefore, the focus is on the principles of FMECA. During the tender phase the failure behaviour of the system is analysed. Which components do not perform according to the requirements and due to what reasons? The outcome of a FMECA analysis in tender phase is an overview of the functions of the system; possible failure mechanisms; critical system functions; design adjustments to prevent system failure (Gestel et al., 2004).

A FME(C)A analysis can be used as input for the Fault Tree Analysis (FTA) which is a quantitative method (Bakker et al., 2010). The FTA is a schematic representation of the causes that result in an unplanned event (top event). This top event is defined up front and describes just one particular failure state (Gestel et al., 2004).

HAZard & OPerability (HAZOP)
The HAZOP is comparable with the FME(C)A-method. The FME(C)A is focused on the technical system applications while the HAZOP is focused on the safety risks (Bakker et al., 2010; Gestel et al., 2004). The HAZOP method is mainly applied in the petrochemical industry in which the operability of the plants is very important. In this industry it is important to understand which processes are still working after a certain failure.

The HAZOP is a systematic approach conducted in a team to minimize the risk of missing essential elements. Every team member must support and correct others ideas to build up a well-founded and reality based analysis (Kletz, 2001). While the FME(C)A can be quantified (to a certain extent), the HAZOP is not quantifiable. The outcomes of the analysis can only be ranked from critical to not-critical. Another disadvantage of the method, is that the results of the analyses of the expert teams could differ strongly, depending on the experience and assumptions of the team (Bakker et al., 2010).

CEI/IEC (2001) described the HAZOP as: “a structured and systematic technique for examining a defined system, with the objective of:
- **Identifying potential hazards in the system.** The hazards involved may include both those essentially relevant only to the immediate area of the system and those with a much wider sphere of influence, e.g. some environmental hazards;

- **Identifying potential operability problems with the system and in particular identifying causes of operational disturbances and production deviations likely to lead to non-conforming products.”**

One of the main characteristics of the HAZOP is the systematic use of guide words – also known as failure definitions. Guide words are used to identify deviations from the system design and use these deviations as “triggering devices” to stimulate the project team to analyse what the cause of the deviation is and what the consequences of the deviations are (CEI/IEC, 2001). The HAZOP is a method that is always conducted in a team, preferably an integral team with multiple disciplines (CEI/IEC, 2001; Gestel et al., 2004).

**Human Reliability Analysis (HRA)**

The human behaviour can have a big influence on the reliability, availability, maintainability and safety of a system. The difficulty of human behaviour is the unpredictability of an individual person, especially when this person is under a lot of stress and facing an unexpected event (Birolini, 2013).

“Disregarding of design and manufacturing flaws, experience show that in emergency situations more than 80% of the safety related system failures are caused by human errors during operation or maintenance (false detection, diagnosis, action planning or execution).”(Birolini, 2013)

The growing complexity of systems and the increasing economic and safety losses in case of failure, made the HRA more important. The more reliable a system becomes, the higher the impact of human activities (Swain, 1990). The HRA is applied in situations with a high human involvement. The method analyses possible failures of the human as factor in the total system and it shows which elements in the system it influences. The main goal of the HRA is to map the human error probabilities and to trace down weak spots in the system. With this method the human factor is included in the failure analysis and is highly applicable in situations with a high rate of human activities. The effect on the system by human failure is examined in terms of, degraded system performance, safety or costs. The HRA is most of the times applied as part of the Probabilistic Risk Assessment (PRA), as part of man-machine systems (Bakker et al., 2010; Swain, 1990).

Any disadvantages of the HRA are:

- There is a lack of human performance data that makes it hard to apply a reliable HRA. In response expert judgment is used as input for estimates, which could have a high subjective level (Swain, 1990).

- The human behaviour is not a constant factor (Bakker et al., 2010).

- Difficult to quantify the expert judgment (Bakker et al., 2010).

The HRA can be quantified by the OPSCHEP-model, developed by Rijkswaterstaat. With the OPSCHEP-model different roles of the human involved can be included as, manager, operator and renovator. Also, different kind of failures can be distinguished as, omission default (in recovery) and selection default (in recovery). Unfortunately, the failure rates are difficult to quantify and the correction rates are subjective (Bakker et al., 2010).

**Quantitative**

In case the risk of failure must be quantified several quantitative analyses can be applied. These are discussed below.

**Parts Count Analysis (PCA)**

With the PCA the failure rate of the total system can be determined, by analysing the failure behaviour of the single components and sum the results. The total sum of all the different components gives an indication of the failure rate (Bakker et al., 2010). Unfortunately, it is a linear approach of the system failure and gives not a realistic insight in the failure behaviour; it is just a rough estimation. Another issue is the lack of failure definitions of the components which makes the failure mechanisms difficult to measure. Overall, it is an easy method to apply but is mainly limited to a small set of applications (Birolini, 2013).

An additional aspect of the PCA-method, the contractor must be very careful with the use of reliability data of components. The theoretical reliability features can deviate from practice and can influence the real reliability. This is proven by professor Brombacher from the University of Technology in Eindhoven (Bakker et al., 2010).
Reliability Block Diagrams (RBD)
The RBD can be used to analyse the systems and assess the reliability (Cepin, 2011). A method that provides a chain description of the system (Bakker et al., 2010) and applicable for systems in parallel or series (Cepin, 2011). By using a RBD the dependency between components, or a set of components, and the redundancy of the system becomes visible. It is a very useful method to assess the reliability and to identify the single point of failure. Overall, it is a relatively easy method to use but expert knowledge is required to assess the system. The graphical representation simplifies the insight in the failure behaviour of the system. This method is mainly used and applied for quantifying the reliability and to divide the system to a certain detail level (Bakker et al., 2010; Cepin, 2011).

Fault Tree Analysis (FTA)
The FTA is a well-known approach in many industries and is applied to assess and improve the reliability and safety of a system (Cepin, 2011). The FTA is based on a predefined top event. The top event is an undesired event that is critical from the reliability and safety point of view. This top event is predefined and it is analysed what the contribution of the different (sub)systems and components are to the occurrence of the top event (Bakker et al., 2010; Haasl et al., 1981).

With the FTA all possible ways that could lead to the top event are analysed. Within the analysis the environment and other associated activities of the system are included. The qualitative Fault Tree (FT) is just a description and graphical representation of the possible ways to the top event. In essence the FTA is a qualitative method. The quantitative FT is an analysis in which the probabilistic data is included (Haasl et al., 1981).

The method is very useful to analyse complex systems by dividing the system in different sections. Multiple failure conditions and factors can be determined. An advantage of the FTA is to determine the influence of the failure behaviour of the single components to the top event. In addition to the FTA the system reliability, availability and safety can be modelled (Bakker et al., 2010; Cepin, 2011). Unfortunately, the tests are done in a steady-state, which is not always representative for the real situation. Despite that, the output of the model is still very accurate thanks to the used probabilistic data. Another disadvantage is, that only one top event can be modelled per analysis. For other top events a new model must be developed (Bakker et al., 2010). From that point of view it is a time consuming method. To develop a FTA expert knowledge is needed on the failure behaviour and data of the particular (sub)systems. But, the final output of the FTA can be understood by non-experts as well.

Event Tree Analysis (ETA)
The event tree can be used to determine the system reliability and to quantify the risk if a certain event might occur (Kenarangui, 1991). The ETA has a different purpose than the previous described RAMS-methods. The other methods are used to determine the critical system components. With the purpose to trace the weak spots in the system and to come up with measures to prevent or limit the risk of the occurrence of the top event. The ETA can be used to analyse the consequences in case of occurrence of the top event. From the analysis, mitigation measures can be developed to minimise the effects on the system and surrounding due to the top event. This method is also a probabilistic risk assessment tool and is highly applicable for safety systems or safety functions (Cepin, 2011).

Combining the ETA and FTA shows a clear overview of the cause-effect relation of a certain top event. The ETA is comparable with the FTA. The ETA can be used as a qualitative and quantitative method and the models can be understood by non-experts. The same as with the FTA, only one top event per model can be modelled and is analysed in a steady-state (Bakker et al., 2010). To develop an ETA expert knowledge is needed on the failure behaviour and data of the particular (sub)systems. But, the final output of the ETA can be understood by non-experts as well.

Markov Analysis
The Markov-analysis is a continuous stochastic process to analyse the RAM-aspects of systems. The current state is used as input and the future states are independent of previous states (Cepin, 2011). Two type of states are distinguished (Cepin, 2011):

1. Operating state – the system is still running, nevertheless, some components could be failed but without a system failure as result.
2. Failed state – one or more components are failed with as result, total system failure.
It is a comprehensive method to simulate the dependency and recovery possibilities, with the purpose to define the system conditions. It is a very detailed analysis and results in an elaborated system description in just one model. But, it is a very complex method and hard to develop and verify, especially for non-experts.

**Dynamic**

Dynamic models are very complex and applicable in situations in which the effects of the time- and order dependency are important. The quantitative methods as, RBD, FTA, ETA and Markov, can be also applied as dynamic methods to model the effects on the RAMS-performances. Nevertheless this is too complex and also not applicable in the tender phase, due to the time and budget constraints. Therefore not further discussed in this research.