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On Decision-Making for Sewer Replacement

Wouter van Riel

On Decision-Making for Sewer Replacement

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College van Promoties
in het openbaar te verdedigen
op 6 juli in 2016 om 12:30 uur

door

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Wouter van Riel, 2016

Summary

Sewer systems are urban underground infrastructures for collecting and transporting wastewater and storm water to a treatment facility, which discharges it onto surface water. A properly functioning sewer system is important to society, because it provides two essential services: protection of public health and prevention of urban flooding. As such, appropriate management of sewer systems, termed sewer asset management, is required in order to continue their service provision. An important aspect within sewer asset management is decision-making for sewer replacement, which is the topic of this thesis.

Sewer asset management typically is a public responsibility. As such, one could expect the responsible organisations can justify their decision-making, and it is efficient and effective for lowest public costs (cost-effective). To this end, decision-making transparency is required. This seems difficult however, because sewer asset management is surrounded by technical and social complexity. This has two consequences. First, the difficulty to analyse, understand and predict structural condition and hydraulic sewer system performance. Second, difficulties in the many interactions between relevant stakeholders, their interests and negotiations between them. These effects decrease decision-making transparency, which is not preferred considering public accountability and cost-effectiveness. Next to that, the urban drainage sector typically assumes that better information about system performance, particularly structural condition, leads to better operational management.

Decision-making for a single actor is usually comparable with rational decision-making. This means: a sequential process of clearly defining a problem, obtaining information to weigh decision alternatives and making a decision. Objective information is important in this process. Multi-actor decision-making, also referred to as political decision-making, is different from the single actor process. The actors reason from their own interests, positions and values, and do not always have an equal objective. Hence, they may need to negotiate and make compromises in their decisions. Objective information is less important here than in the rational process. The extent to which it is important is yet unknown.

This leads to the question, “Does higher quality information about structural condition lead to other or improved decision-making, when compared to the situation encountered in current practice?”

The objective of this thesis is to describe the actual decision-making processes and underlying information use in sewer asset management, in order to assess whether variations in information quality influence decision-making outcome. Interviews, a questionnaire and a serious game were applied for data collection, because the actual decision-making processes are not documented. Serious gaming was applied because it allows to study real actors, both individually and in groups, in a custom-built simulation environment.

The use of information and intuition in sewer replacement decisions was explored in a first round of interviews. Intuition is regarded as a success factor in decision-making in the perspective of ‘Naturalistic Decision Making’, or as a basis for bias in the perspective of ‘Heuristics and Biases’. The common ground is that intuitive decision-making stems from experience and cognitive pattern making. Decision-making for sewer replacement was found to involve the consideration of three aspects, each of which has multiple underlying information sources: the technical replacement need, the potential synergy from collaboration with other public works, and organisational preferences. A sewer asset manager appeared to combine these aspects in risk analyses, where particularly the probability of some effect, for example pipe collapse, showed to be estimated through intuitive judgments. It seems logical intuition is preferred to analytical reasoning, given the complex context the sewer asset manager operates in. Physical feedback of the sewer system to its manager, as a result of an applied replacement strategy, is hardly noticeable, because of the robustness of the sewer system itself the relatively long time it takes before this feedback occurs. Consequently, chances of learning from a chosen course of action are limited. As such, the preconditions for intuition to be skilled (sufficient regularity and opportunity to learn), are not met.

A second round of interviews extended this analysis by exploring the actual decision argumentation of executed sewer replacement projects in the Netherlands. Both the decision-making process and the content were analysed. Twenty-eight unique information sources were identified, which were found to be combined in a large variety of ways. Camera inspections, pipe age and planning of road works were mentioned most often. Approximately half of the projects was found to be initiated through a single actor decision-making process, which showed to resemble rational decision-making. The other half was initiated through a multi-actor decision-making process, showing characteristics of political decision-making. This means: multiple infrastructure managers cooperated, during which a mix of information and interests led to compromises about whether, where and how work could be executed simultaneously.

The results of the projects analysis did not reveal insights into how sewer asset managers mutually value the individual information sources and whether they share a frame of reasoning about this value. Therefore, a digital questionnaire was distributed to all Dutch municipalities. This questionnaire contained paired comparisons between the ten information sources mentioned most often in the projects analysis. Two aspects were analysed: the perceived importance of information for hypothetical sewer replacement decisions and the extent to which the respondents are concordant with each other, i.e. a shared frame of reasoning. Camera inspection footages were found

to be valued most and pipe age was valued least. The respondents showed to be quite consistent per individual, implying their answers could be considered as reliable. They showed to be concordant as a group, meaning that the respondents have a similar framework of reasoning for judging about the relative value of the information sources. The respondents had the opportunity to give feedback at the end of the questionnaire. This feedback revealed that most of the respondents found it difficult to make general comparisons without having a practical context. This indicates decision-making in practice may be steered by other mechanisms than purely combining information sources.

A serious game was built for further decision-making analysis, since decisions for sewer replacement are often initiated through multi-actor decision-making. This game, 'Maintenance in Motion', simulates single and multi-actor operational decision-making for infrastructure replacement. It aims to investigate the influence of information quality on replacement decisions, for single and multi-actor decision-making. To this end, four game types were designed. The game objective is addressed by analysing differences in game results between the game types, where the game types are:

- single actor decision-making and perfect information about object state,
- single actor decision-making and imperfect information about object state,
- multi-actor decision-making and perfect information about object state, and
- multi-actor decision-making and imperfect information about object state.

Players manage drinking water, gas, sewer or street infrastructures, where each infrastructure was modelled as four equal and independent objects. They are challenged to manage their infrastructure as cost-effectively as possible, when playing individually. When playing as a group, they are challenged to balance their individual goal with their team goal (increasing overall infrastructure quality to minimize failure while minimizing overall public costs). The effect of the group effort, i.e. team utility, was measured by a different criterion than cost-effectiveness per individual, because the best strategy per actor depends on the choices of others. The game was designed as an experimental research instrument that allows for hypotheses testing concerning the relation between game outcome and player behaviour. Consequently, it was designed such that it had a relatively small solution space, measurable variables and a quantitative outcome analysis. As such, the final game model is a heavily simplified version of infrastructure management in reality.

The game was played with actual infrastructure managers in twenty-five sessions at eighteen different organisations. The game results proved to be valid and inferences could be made from them, based on analysis of the players' applied management actions and answers to a questionnaire distributed after each gaming session.

Results from the gaming sessions show that when players were presented with perfect instead of imperfect information about infrastructure condition, in a single actor decision-making environment, they managed their infrastructure more cost-effectively. The availability of perfect instead of imperfect information about infrastructure condition hardly changed game outcome in terms of team utility. Moreover, despite the availability of the team utility score, collaboration typically led to higher costs (approximately 30 % on average) compared to the situation in which they would not collaborate. These results suggest that group choices are primarily based on negotiations that lead to compromises, instead of analytical reasoning as a group.

The presented results about actual decision-making for sewer replacement show a large gap between decision support models and decision-making in reality. Intuitive reasoning and dynamics of multi-actor decision-making are outside the scope of these models, but influence actual operational decision-making to a large extent. Increasing information quality about structural condition is only to a certain extent beneficial for increased cost-effective management. Such efforts would be meaningful particularly in single actor decision-making environments. As such, the current challenge for increased decision transparency and cost-effectiveness is unlikely to be solved by the current type of decision support tools for sewer asset management.

More research could be executed on development of multi-criteria decision support tools that can incorporate tacit next to explicit knowledge. Second, the underlying motivations of group decisions could be thoroughly examined, in order to understand why collaborative choices are made. If transparency is created in this respect, it allows for assessing whether and where decision-making may be improved. A new serious game could be developed that serves as a training tool, allowing players to experience realistic feedback from their asset management strategies. Next to that, it may be possible to test and evaluate management strategies, alternative ways of budget allocation and organisational setups. Sewer asset managers in current practice could realise that neither every information source is relevant at all times, nor do these give perfect information. Sewer operators should be able to judge the impact of the uncertainties on the decisions they need to make on a day-to-day basis in order to motivate their choices properly, even in unpredictable decision-making processes.

Samenvatting

Riolering is een belangrijke stedelijke infrastructuur die zorgt voor de inzameling van afval- en hemelwater en transport naar een zuiveringsinrichting, waarna het stedelijk afvalwater op oppervlaktewater wordt geloosd. Een goed werkende riolering is van groot maatschappelijk belang, omdat deze twee belangrijke diensten levert: bescherming van de volksgezondheid en ontwatering van het stedelijk gebied. Goed rioleringsbeheer is dan ook noodzakelijk om deze dienstverlening in stand te houden. Een belangrijke activiteit binnen het rioleringsbeheer is het besluiten tot rioolvervanging, het onderwerp van dit proefschrift.

Over het algemeen zijn publieke organisaties verantwoordelijk voor rioleringsbeheer. Van deze organisaties mag men dan ook verwachten dat zij hun besluitvorming kunnen verantwoorden, en dat deze efficiënt en effectief is voor zo laag mogelijke maatschappelijke kosten (doelmatig). Hiervoor is transparante besluitvorming noodzakelijk. Het is echter lastig om transparantie te verhogen omdat rioleringsbeheer omgeven is door technische en sociale complexiteit. Dit heeft de volgende effecten. Ten eerste is het moeilijk om systeemprestatie (hydraulisch en objecttoestand) te analyseren, te begrijpen en te voorspellen. Ten tweede is het moeilijk om de vele interacties tussen relevante actoren, hun belangen en onderlinge onderhandelingen te begrijpen. Deze effecten verlagen de transparantie van besluitvorming, hetgeen onwenselijk is in het kader van verantwoording van publiek bestuur en doelmatigheid. Daarnaast wordt in de rioleringssector veelal gedacht dat betere informatie over systeemprestatie, met name objecttoestand, leidt tot betere operationele besluitvorming.

Besluitvorming voor één actor lijkt veelal op rationele besluitvorming. Dit houdt in: een stapsgewijs proces van een eenduidig probleem definiëren, informatie vergaren om alternatieven te wegen en een besluit nemen. Objectieve informatie speelt hierin een belangrijke rol. Multi-actor besluitvorming, ook wel politieke besluitvorming genoemd, verloopt anders dan één-actor besluitvorming. De actoren redeneren vanuit verschillende belangen, posities en waarden, en hebben daarnaast niet altijd hetzelfde doel. Om deze redenen zijn de actoren genoodzaakt om te onderhandelen en compromissen te sluiten wanneer zij samen besluiten willen nemen. De rol van objectieve informatie is hier een stuk kleiner dan in het rationele model. De grootte van deze rol is echter nog onbekend.

Dit leidt tot de vraag: “Zorgt kwalitatief betere informatie over objecttoestand voor andere of betere besluitvorming, vergeleken met de huidige situatie?”

Het doel van dit proefschrift is de werkelijke besluitvormingsprocessen en het onderliggend gebruik van informatie te beschrijven voor rioolvervanging, om vervolgens na te gaan of variaties in informatiekwaliteit de uitkomst van besluitvorming beïnvloeden. Er is gebruik gemaakt van interviews, een enquête en ‘serious gaming’, omdat informatie over de werkelijke besluitvormingsprocessen niet gedocumenteerd zijn. Serious gaming is toegepast omdat hiermee het gedrag van personen, zowel per individu als per groep, bestudeerd kan worden in een zelf gebouwde simulatieomgeving.

In een eerste ronde interviews is een verkenning gemaakt van het gebruik van informatie en intuïtie in rioolvervangingsbeslissingen. Intuïtie wordt gezien als een succesfactor in het theoretisch kader van ‘Naturalistic Decision Making’ of als bron van fouten in het kader van ‘Heuristics and Biases’. Beide hebben gemeen dat intuïtieve besluitvorming voortvloeit uit ervaring en cognitieve patroonherkenning. Besluitvorming voor rioolvervanging bleek gebaseerd te zijn op het in acht nemen van drie aspecten, die elk vervolgens zijn opgebouwd uit verschillende informatiebronnen. Deze drie aspecten zijn: de technische vervangingsbehoefte, potentiële meerwaarde uit samenwerking met andere publieke werken, en organisatorische voorkeuren. Een rioleringsbeheerder combineert deze aspecten in risicoanalyses, waarin vooral de kans op een gevolg intuïtief geschat wordt. Het bleek logisch dat intuïtie wordt verkozen boven analytisch redeneren, vanwege de complexe context waarin de rioleringsbeheerder werkt. Een fysieke terugkoppeling van de riolering naar de beheerder, als gevolg van een toegepaste beheerstrategie, is nauwelijks merkbaar door de robuustheid van de riolering zelf en de lange tijdsspanne waarover deze terugkoppeling zich over het algemeen manifesteert. De kans om iets te leren van het handelen wordt hiermee sterk verkleind. Om deze redenen wordt niet voldaan aan de gestelde voorwaarden (voldoende regelmaat en kansen om te leren) voor vakkundige intuïtie.

In een tweede ronde interviews is voorgaande analyse verder uitgebouwd via een verkenning van de beslissingsargumentatie van uitgevoerde rioolvervangingsprojecten in Nederland. Hierbij zijn zowel de inhoud als het proces van besluitvorming geanalyseerd. Dit leidde tot achtentwintig unieke informatiebronnen die werden gecombineerd op veel verschillende manieren. Camera inspecties, buisleeftijd en planning van wegwerkzaamheden werden het vaakst genoemd. Ongeveer de helft van de onderzochte projecten werd geïnitieerd via een één-actor besluitvormingsproces. Deze processen leken op rationele besluitvorming. De andere helft van de projecten werd geïnitieerd via een multi-actor besluitvormingsproces. Hierin bleken karakteristieken van politieke besluitvorming terug te komen. Dit hield in: samenwerking tussen twee of meer actoren, waarbij een mix van informatie en belangen leidde tot een onderhandelingsproces waarin compromissen werden gemaakt over of, waar en hoe werk gezamenlijk zou kunnen worden uitgevoerd.

De resultaten van voorgaande interviews toonden echter nog niet aan hoe rioleringsbeheerders bronnen van informatie waarderen ten opzichte van elkaar en of zij een gedeeld denkkader hiervoor hebben. Om deze reden is een digitale enquête verspreid naar alle Nederlandse gemeenten met gepaarde vergelijkingen tussen de tien meest genoemde informatiebronnen uit voorgaande projectenanalyse. Twee aspecten zijn hierbij geanalyseerd: de ervaren waarde van informatie voor hypothetische rioolvervangingsbeslissingen en de aan- of afwezigheid van een gedeeld denkkader om deze waarde in te schatten. Camera inspecties werden als meest belangrijk ervaren en buisleeftijd het minst. De antwoorden van de respondenten zijn betrouwbaar, omdat zij behoorlijk consistent waren per individu. De respondenten bleken overeenstemming te hebben in de wijze waarop zij de informatiebronnen waardeerden. Dit houdt in dat een gedeeld denkkader aanwezig is. De respondenten hadden de mogelijkheid om feedback te geven na afloop van de enquête. Uit deze feedback bleek dat de respondenten het moeilijk vonden om generieke vergelijkingen te doen zonder informatie over de context te hebben. Dit impliceert dat besluitvorming in de praktijk waarschijnlijk gestuurd wordt door meer mechanismen dan puur het combineren van informatiebronnen.

Aangezien besluitvorming voor rioolvervanging deels afhangt van onderhoud aan andere infrastructuren, is voor verdere analyse een serious game gebouwd. Dit spel, ‘Maintenance in Motion’, simuleert één- en multi-actor operationele besluitvorming voor vervanging van infrastructuur. Het doel van dit spel is de invloed van informatiekwaliteit op vervangingsbeslissingen te kunnen onderzoeken, voor zowel één- als multi-actor omstandigheden. Om deze reden zijn vier speltypen gemaakt. Het speldoel wordt bereikt door verschillen in spelresultaten tussen de speltypen te analyseren. Deze speltypen zijn:

- één-actor besluitvorming en perfecte informatie over objecttoestand,
- één-actor besluitvorming en imperfecte informatie over objecttoestand,
- multi-actor besluitvorming en perfecte informatie over objecttoestand, en
- multi-actor besluitvorming en imperfecte informatie over objecttoestand.

Spelers beheren elk een drinkwater-, gas-, riolering- of weginfrastructuur, waarbij iedere infrastructuur gemodelleerd is als vier dezelfde en onafhankelijke objecten. De spelers worden uitgedaagd om een balans te vinden in hun individuele doel (doelmatigheid) en hun groepsdoel (verhogen kwaliteit infrastructuur en minimaliseren publieke kosten). Het nut van groepshandelen is beoordeeld met een ander criterium dan doelmatigheid, omdat de beste strategie per actor namelijk afhangt van de strategie van anderen. Het spel is ontworpen als een experimenteel onderzoeksinstrument om hypothesen te toetsten over de relatie tussen spelresultaten en gedrag van de spelers. Om die reden heeft het spel een relatief kleine oplossingsruimte, meetbare variabelen en een kwantitatieve resultatenanalyse. Het uiteindelijke spelmodel is daarom een behoorlijk versimpelde versie van infrastructuurbeheer in de praktijk.

Het spel is gespeeld met infrastructuurbeheerders uit de praktijk in vijfentwintig sessies bij achttien verschillende organisaties. Uit analyse van de toegepaste beheermaatregelen van de spelers en de antwoorden op een enquête verspreid na afloop van iedere spelsessie bleek dat de spelresultaten valide zijn en conclusies kunnen worden getrokken op basis van de verkregen resultaten.

Resultaten van de spelsessies tonen dat spelers doelmatiger beheren, in één-actor situaties, wanneer zij perfecte in plaats van imperfecte informatie krijgen over de huidige objecttoestand. De beschikbaarheid van perfecte in plaats van imperfecte informatie over de huidige objecttoestand veranderde de uitkomst van het groepshandelen nauwelijks. Ondanks de beschikbaarheid voor de spelers van informatie over het groepsresultaat leidde samenwerking in de meeste gevallen tot hogere kosten (gemiddeld circa 30 %), vergeleken met de situatie wanneer de spelers niet zouden samenwerken.

De gepresenteerde resultaten over besluitvorming voor rioolvervanging laten een groot gat zien tussen beslissingsondersteunende modellen en besluitvorming in de realiteit. Intuïtie en de dynamiek van multi-actor besluitvorming vallen buiten het aandachtsveld van deze modellen maar beïnvloeden besluitvorming in sterke mate. Het verhogen van de nauwkeurigheid en betrouwbaarheid van informatie over systeemprestatie is slechts gedeeltelijk bevorderlijk voor de doelmatigheidsverhoging van de huidige beheerpraktijk. De meerwaarde van dergelijke inspanningen geldt vooral voor één-actor besluitvormingsprocessen. De huidige uitdaging voor verhoging van transparantie en doelmatigheid in rioleringsbeheer wordt daarmee waarschijnlijk niet behaald door de huidige typen beslissingsondersteunende modellen.

Onderzoek zou kunnen worden uitgevoerd naar een kosten-batenanalyse omtrent verhoging van informatiekwaliteit versus nut voor beheer. Ook zouden de onderliggende motivaties in multi-actor besluitvorming nader onderzocht kunnen worden om te begrijpen waarom groepskeuzen gemaakt worden. Als meer transparantie hierin kan worden verkregen, kan worden nagegaan of, en waar, besluitvorming kan worden verbeterd. Een nieuwe serious game zou kunnen worden gebouwd voor trainingsdoeleinden, waarin spelers realistische feedback krijgen van hun toegepaste beheerstrategie. Daarnaast kunnen verschillende beheerstrategieën, alternatieve wijzen van budgettoedeling en alternatieve organisatiestructuren worden getest en geëvalueerd. Rioleringsbeheerders in de praktijk zouden moeten beseffen dat geen enkele informatiebron altijd relevant of perfect is. Beheerders zouden het effect van onzekerheid moeten kunnen beoordelen om hun keuzes goed te motiveren, ook in onvoorspelbare besluitvormingsprocessen.

Contents

Appendices

1 Introduction

1.1 Context and development of sewer asset management

Sewer systems are urban underground infrastructures for collecting and transporting sewage from houses and commercial buildings, possibly mixed with excess storm water, to a treatment facility which discharges it onto surface water. Sewer systems are critical infrastructures, because they provide essential services to society (Murray and Grubesic, 2007) protecting public health and preventing urban flooding. For example, the transition from cesspools to sewer systems triggered a decrease in death rate of approximately 30 (in 1850) to 8 (today) deaths per 1000 persons per year (Geels, 2006) (original in Mackenbach, 1992). Appropriate management of sewer systems, termed sewer asset management from here on, is required in order to continue their service provision.

The history of sewer systems goes back to the Indus Valley Civilisation, 3300-1300 BCE, during which covered drains were used to transported wastewater (Gray, 1940). It took until the 19th century before large scale sewer systems were constructed in European and American cities, with London being one of the first to undertake this effort, motivated by ‘the Great Stink’ in 1858 (Geels, 2006). Before that, cesspools and barrels were the primary faecal waste collection systems. Next to that, increased attention was paid to the relation between infectious diseases and exposure to drinking water contaminated with faecal bacteria (e.g. Snow, 1855). The effluent was typically discharged outside the urban area in natural streams. The transition to sewer systems proceeded until the 1930s. It continued after the Second World War, particularly during 1950-1970, as a result of the accelerated urbanisation. Wastewater treatment plants were built in order to reduce pollution load to surface waters.

Sewer asset management used to receive little attention. In the Netherlands, attention for sewer asset management started to increase in the mid-1980s. It is defined here as the set of activities required to maintain the performance of the system. Examples of such activities are cleaning, replacement, budget allocation and strategy formulation. System performance consists of two interrelated aspects:

- Hydraulic performance, being the discharge and storage capacity of the system. Sufficient discharge capacity prevents urban flooding, whereas sufficient storage capacity limits emissions of wastewater to surface water (environmental performance). Acceptable environmental performance is a precondition for acceptable hydraulic performance.
- Structural condition of the individual objects, including sewer pipes, gully pots and manholes.

Sewer system performance is typically maintained through repositioning, in areas with uneven soil settlement such as the west of the Netherlands, and replacing individual objects. The structural condition of individual pipes is rated in condition states by means of visual inspections (see CEN, 2011). Replacement is defined here as replacement of a pipe by another, irrespective of the newly installed pipe diameter.

Before the mid-1980s in the Netherlands, management practices had been about fixing incidental problems when noted, such as collapse of pipe segments, leakages, or malfunctioning for other reasons. Given the low frequency of problems, this approach was believed to be cost-effective. Yet, during the 1980s, the breakdown frequency increased considerably due to the use of inferior concrete and casting methods in the 1950s and 1960s. Next to that, many Dutch municipalities had insufficient available funds for replacement of sewers (adapted from Oomens, 1992). These developments raised public and political awareness of the need for a more systematic approach to sewer management (Thissen and Oomens, 1991). A major change was initiated in the Netherlands in 1993, because the 'Environmental Management Act' became effective. This Act introduced the municipal duty of care for sewer systems and the obligation for municipalities to present a strategic municipal sewerage plan every five years. This plan describes policy objectives and costs for managing the sewer system. The costs for sewer asset management are fully covered by issuing taxes to households and companies. The treatment of wastewater and the control of surface water quality are responsibilities of water boards, being independent governmental bodies. Both the duty of care and the legal obligation to present strategic sewerage plans is internationally unique.

From the 1980s to 2010, Dutch municipal management efforts focussed on two additional aspects. First, areas outside city centres were connected through pressurised sewers. Approximately 22 % of the current sewer system length is of the pressurised type (RIONED Foundation, 2009). Second, after the 1990s, pollution load to surface water was preferred to be reduced further by increasing system storage capacity and changing system design from combined (one pipe for both wastewater and storm water) to separate (one pipe for wastewater and local infiltration and/or transport of storm water through pipes). Since the financial crisis in 2008, attention for system maintenance has grown further, focussing on explicit motivation of management efforts. To this end, the concept of risk based decision-making was introduced, which includes additional aspects to base decisions on, for example health, liveability, sustainability, climate resilience and image (STOWA and RIONED Foundation, 2014). Yet, this conceptual approaches have not been adopted in current guidelines, which are described in the European Standard EN 752 (CEN, 2008) and, for the Netherlands, in Urban Drainage Guidelines (in Dutch: Leidraad Riolering).

Almost 100 % of Dutch properties are currently connected to a sewer system, which is comparable to Germany, Switzerland and the UK. Other Western European countries have sewer connectivity rates of 76-95 % and Eastern Europe 50-75 %. Approximately 1.5 billion Euro per year is currently spent in the Netherlands for management of the 120,000 km of sewers (RIONED Foundation, 2013). This equals about 88 Euro/inhabitant/year. The largest portion of this budget, approximately 50-60 %, is deployed for sewer pipe replacement (obtained from multiple Dutch strategic municipal sewerage plans). The annual sewer replacement rate in the Netherlands ranges between 1 and 2.5 %, depending on the assumed sewer lifetime. The annual inspection rate is approximately 10-15 %.

Sewer asset management was set up by adopting principles from systems theory and cybernetics for a structured approach. The principles of De Leeuw's control paradigm (De Leeuw, 1974) were adopted (figure 1.1) in the work of Oomens (1992) to create a rational process model with all relevant activities for sewer asset management. The control paradigm is an open system model in which a controller, controlled system and environment interact, where the term open refers to interaction with an environment.

The controller's ability to successfully control its system depends on five preconditions for effective control.

1. The controller has an objective and an evaluation mechanism to check whether the goals are met.
2. The controller has a model of the controlled system to predict the effect of potential control actions.
3. The controller has information about the environment and the controlled system.
4. The controller has sufficient control actions to cope with the variability of the system.
5. The controller has sufficient information processing capacity to transform incoming information into effective control actions that are in line with the objectives.

Adopting this rational process model can be seen as a logical choice at that time, because of the need for a structured and straightforward approach and the pragmatic application for municipalities (Oomens, 1992).

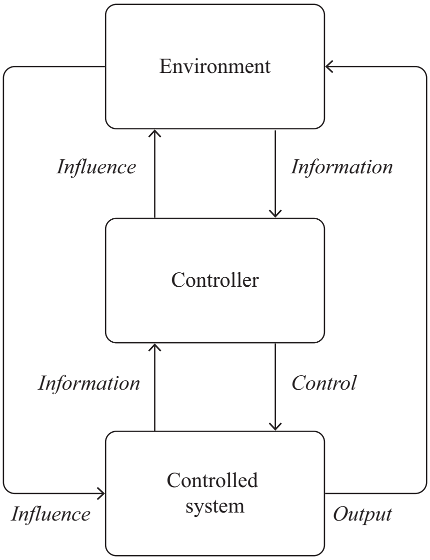

Figure 1.1: De Leeuw's control paradigm (De Leeuw, 1974)

1.2 Current challenges

Sewer asset management typically is a public responsibility. As such, public accountability applies, implying preconditions could be specified for the entities responsible for sewer asset management. These are: the obligation to explain and justify a course of action, and efficient and effective management at lowest public costs. Especially this latter precondition, defined as cost-effectiveness by Katz and Kahn (1978), has received increased importance the last decade. Decision-making transparency is required in order to meet these preconditions. This is important because it could enhance the integrity of public governance, could improve performance, and provides managers and citizens with input for judging the fairness, effectiveness and efficiency of governance (Bovens, 2005) Decision-making for sewer asset management is, however, not transparent enough to specify its level of cost-effectiveness or to assess whether, where and how it could be improved.

Decision-making transparency could be increased by addressing both substantive rationality, the extent to which sound actions are chosen, and procedural rationality, the effectiveness of the procedures used to choose actions (Simon, 1978, p. 9). Yet, decision-making for sewer systems, is embedded in a complex system, where complexity is defined as consisting of a high number of interacting physical and social elements (Bar-Yam, 1997; Sterman, 2000). In order to understand the behaviour of a complex system, it is important to understand not only the behaviour of the individual parts, but also how they act together to form the behaviour of the whole (Bar-Yam, 1997; Bijker et al., 1987). This complexity can be separated in two types: system and process complexity.

System complexity refers to the many interactions among physical infrastructure components and their direct environment. Sewer systems are large underground networks consisting of pipes, manholes, gully pots, overflows and pumps. All these objects are used with a variety in shape and dimensions. The performance of a sewer system depends on joint and individual functioning of the objects in relation to the (movement of) surrounding soil, groundwater, surface water, other physical objects and human activities such as traffic movement. Even processes that occur within the pipe are to a large extent unknown, including sediment transport, fat accumulation and concrete degration over time due to biological composition and degradation of the wastewater (Ashley et al., 2004). As such, it may be considered logical that analysing and predicting sewer system performance is difficult. The effect of this physical complexity is that many effects of these interactions, in terms of failure mechanisms, are largely unknown. That also counts for the relation between object and system failure. Physical feedback of the sewer system about failure development is almost unobservable, because of the robustness of the sewer system and the relatively long time it takes before this feedback occurs. Given that sewer systems are underground, makes it even harder to observe or measure some aspects of system performance over time.

A challenge regarding system complexity is the difficulty to analyse and understand structural condition and hydraulic performance, despite the large number of studies devoted to this topic (e.g. Alegre, 2000; Ashley and Hopkinson, 2002; CEN, 2008; Carey and Lueke, 2013; Chughtai and Zayed, 2008; Egger et al., 2013; Fenner et al., 2000; Ferreira et al., 2011; Johansen et al., 2007; Kleidorfer et al., 2013; Le Gauffre et al., 2007; Marzouk and Omar, 2012; Matos et al., 2003; Sægrov, 2005; Scheidegger et al., 2011). First, the data required to accurately assess structural condition and predict failure rate, is not available. In turn, this diminishes the effectiveness of prediction models for practical purposes. This data would support evaluation of management strategies and prediction of system performance to see whether potential control actions have any effect (preconditions 1, 2 and 3 of the control paradigm in figure 1.1). It has been believed, both in the Netherlands and elsewhere, that the necessary data to accurately evaluate and predict system performance and structural condition could be obtained. This requires prediction tools and data. Considering structural condition, available deterioration models are based on visual inspections and link system age to condition states (Baur and Herz, 2002; Egger et al., 2013; Scheidegger et al., 2011). A general disadvantage of visual inspections is that it is difficult to convert observed defects on object scale to physical status and performance judgments on network to system scale. Second, time series are usually unavailable, decreasing the predictive power of the observations. Third, visual inspection is limited to observations at the inner pipe. Fourth, human observations are prone to errors due to cognitive limitations in information processing, hampering repeatability (Dirksen et al., 2013). And fifth, information about the physical environment of sewer pipes is not included, but do influence the occurrence and severity of defects. Moreover, a link between system age and condition state is relatively meaningless if this relation excludes actual failure probabilities. Despite these drawbacks, visual inspections are widely applied to assess pipe quality and serve as prime decision motivation (Van Riel et al., 2014b). In practice, this is essentially the only source of information sewer asset managers may use as a reference for decision support. Difficulties in assessing system performance result in an unclear relation between system performance and required sewer asset management. Consequently, the required sewer asset management effort to achieve a predefined service level is undefined.

Process complexity refers to the many interactions between relevant stakeholders and their interests. Decision-making in sewer asset management is a process of interaction, in which the physical system boundaries are dynamic. Adjacent networked infrastructures are typically preferred to be rehabilitated simultaneously, motivated by reduction of costs, nuisance to citizens and traffic disruption. Figure 1.2 shows an example of a typical Dutch street cross section with several networked infrastructures. The involved infrastructure managers are presented with a planning problem with a complex context (Parsons and Wooldridge, 2002; Rittel and Webber, 1973). The managers remain sovereign over their infrastructure, but negotiate and make compromises about whether, when, how and to what extent works are integrated. Although the initial motivations for joint rehabilitation seem relevant, the outcome of such multi-actor decision-making processes is usually unpredictable due to unpredictable human group behaviour. Decisions for system rehabilitation are influenced by interests of other actors in or outside the organisation the sewer asset manager operates. Examples are reputation issues towards citizens and politicians, political preferences for water management strategies, budget allocation or power and culture. Literature describing sewer asset management from an organisational decision-making perspective, including actor interaction aspects, is limited. Oomens (1992) is one of few sources that approaches sewer asset management from such an organisational perspective, describing a comprehensive overview of all activities of the sewer management process. This description takes on a rather rational systems perspective for decision-making that is also applied to the interaction with other actors. As such, the influence of value trade-offs and intuitive decision-making is omitted in this work, which seem however, influential in sewer asset management (Johansen et al., 2007) or other sociotechnical complex systems (Gough and Ward, 1996; Westmacott, 2001).

Decision-making support, in the form of standards, guidelines or decision support models (including failure prediction and maintenance optimisation models), describe decision-making from a rational systems perspective (De Bruijn and Herder, 2009). These assistance tools propose to base decisions mostly on ‘objective’ information from the sewer system, for example pipe age, camera inspection images and hydraulic models. An example is shown in figure 1.3, depicting the process for sewer performance assessment from the European Standard EN752 ‘Drain and sewer systems outside buildings’ (CEN, 2008).

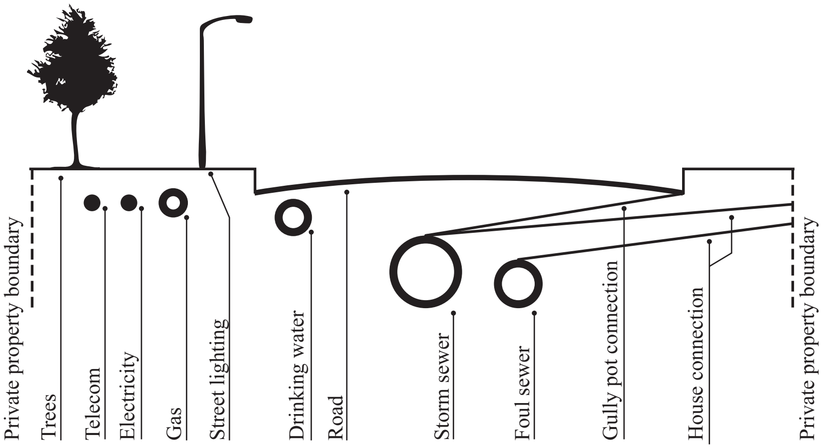

Figure 1.2: Several networked infrastructures at a typical Dutch residential street

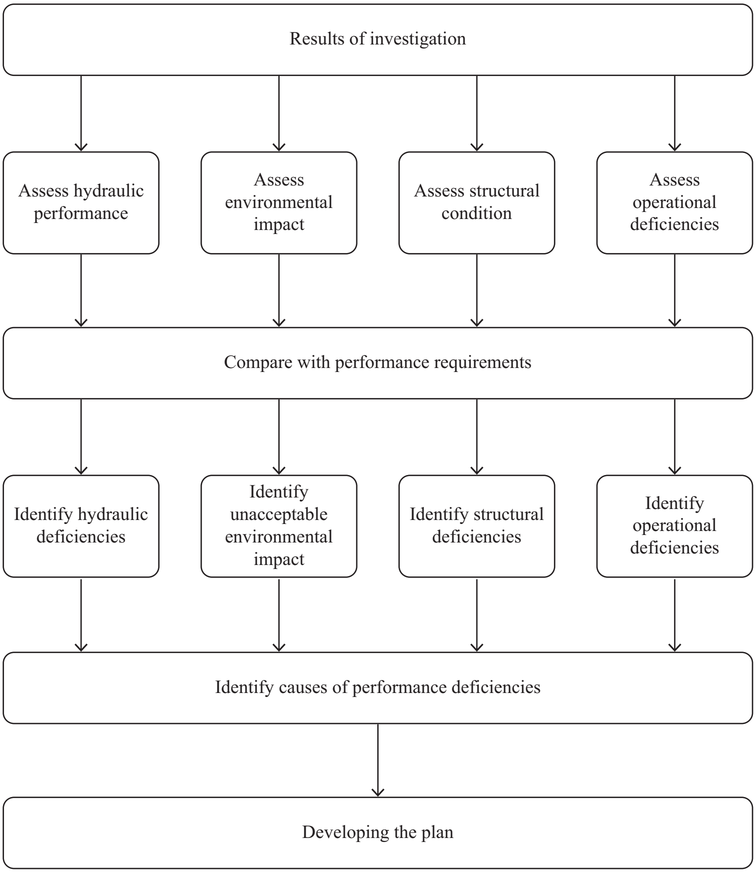

Figure 1.3: Process for sewer system performance assessment (CEN, 2008)

The sewer system management process in this standard has a rational character, depending on four information sources, which have to be compared with reference values to identify deficiencies and, subsequently, develop a plan. Interaction with other relevant actors, being part of the actor perspective (De Bruijn and Herder, 2009), is hardly addressed in the standard, because its focus is on objective information from the sewer system and its physical environment.

The consequence of this limited data availability and quality, complex context and negotiations between actors is that it hampers decision transparency. This leads to a situation where a fundamental question for sewer asset managers often remains unaddressed: why is a decision for implementing a measure actually taken? This notion undermines public accountability. In the urban drainage sector, it is typically assumed that extensive and good quality information about the system performance, especially structural condition, leads to better operational management. This leads to the question, does better information quality about structural condition (substantive rationality) lead to other or improved decision-making (process rationality), when compared to the situation encountered in present practice?

This question has been quantitatively addressed for individual decision-making (Chorus et al., 2007; Keller and Staelin, 1987), but not yet for multi-actor settings. On an individual level, increased quality of information about choice attributes increases the quality of decision outcome (Chorus et al., 2007; Keller and Staelin, 1987), but this effect decreases as the quantity of available information increases (Keller and Staelin, 1987). Group decision-making may outperform individual decision-making, because groups have advantages in terms of information processing and elimination of individual errors (Chalos and Pickard, 1985; Kocher and Sutter, 2005). On the other hand, group decision-making may suffer from 'groupthink', a psychological phenomenon triggering the individuals to seek harmony in a group decision-making process, although this harmony could lead to irrational outcomes (Janis, 1972). It is essentially unclear whether sewer asset management benefits from increased information quality about structural condition.

1.3 Views on decision-making processes

Decision-making theory generally distinguishes two main types of decision models: rational and political models. Decision-making in reality often has characteristics of both model types.

The rational model displays decision-making as a single actor oriented, stepwise and data driven approach. The involved decision-maker defines goals; defines alternative means for attaining them; evaluates the consequences of each alternative; and chooses the alternative most likely to attain the goal. In other words, the *Homo economicus* approach. In the course of time, the rational model of decision-making has undergone some modifications. Decision-makers consider only some alternatives, have limited information quantity and quality, and stop searching for a solution when they have found a satisfactory one for them, i.e. decision-makers simplify (Simon, 1955; Stone, 1988). Next to that, a rational process does not guarantee a rational outcome, because substantive rationality may be limited (Simon, 1978), i.e. the needed data is unavailable or ambiguous.

The political view on decision-making emphasises that decisions are made by multiple actors. Actors are driven by different interests, e.g. following from their positions, roles, beliefs and values, which could change over time (March, 1994). Next to that, decision-makers often do not exactly know or have different perceptions about the problem and goal and the best way to reach it. Information processing is limited and consequences cannot be evaluated as unambiguously as suggested by the rational model (Etzioni, 1967; Lindblom, 1959). As a result, processes are less structured and staged than assumed by the rational model. The political view includes processes of cooperation, bargaining and making compromises which inevitably occur when more than one decision-maker is involved.

1.4 Objective, research questions and outline

Decision-making transparency is required considering public accountability and assessing cost-effectiveness. As such, this thesis aims at describing the actual processes and use of information in decision-making for sewer replacement, in order to assess whether variations in information quality influence decision-making. The focus is on decision-making for sewer replacement, because replacement works consume the largest portion of budget.

The aim is divided into the following fundamental research questions:

1. How does a sewer asset manager decide about sewer replacement?
2. How does a group of infrastructure managers decide upon joint public works?
3. How do variances in information quality influence decision outcome, both for individuals and groups?

Case study research is chosen as approach because of the explorative character of this study. Interviews, questionnaires and serious gaming are used as data collection methods, given the absence of documentation about actual decision-making processes for sewer replacement. A serious gaming approach was applied, because it is believed to be among the best methods for understanding complex systems, because it allows to incorporate real actors and interactions, physical rules, mental and computer models, and individual and collective goals (Bekebrede and Mayer, 2006, p. 278). The individual chapters elaborate on how each data collection method and analysis techniques were applied.

Figure 1.4 shows the relation between the three research questions and the applied methods to answer them.

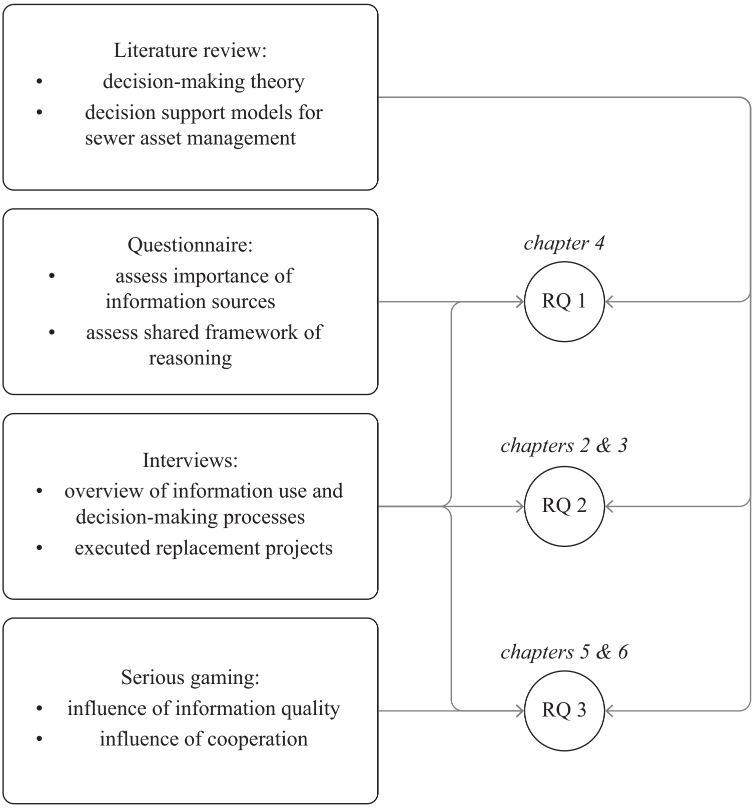

Figure 1.4: Relation between research methods and questions (RQ)

Chapter 2 describes sewer asset management from the perspective of the responsible management entity. It focuses on the use of objective information and intuition in decision-making for sewer replacement. The findings from chapter 2 are validated in chapter 3, which analyses the decision-making argumentation of executed sewer replacement projects. Emphasis is put on rational single actor versus political multi-actor decision-making. Chapter 4 elaborates on chapter 3 by assessing the relative importance of the consulted information sources. To this end, a digital questionnaire was sent to all Dutch municipalities. Then, chapter 5 presents the design considerations, setup and calibration of a serious game, 'Maintenance in Motion', to simulate single and multi-actor operational decision-making for infrastructure management. Chapter 6 presents the results obtained from the gaming sessions with infrastructure managers at Dutch municipalities, consultancy firms, drinking water companies and water boards.

2 Individual decision-making: intuition versus information

2.1 Introduction

Sewer systems are vital urban infrastructures, requiring appropriate asset management to safeguard serviceability and to balance service life versus costs for rehabilitation. The basis of appropriate sewer asset management is sound decision-making, based on reliable data and information. Yet, decision-making for sewer asset management is inherently complicated, because it is embedded in a complex socio-technical system. Sewer asset managers face this complexity through various constraints, described in section 2.2.

These constraints force sewer asset managers to make intuitive decisions to fit the situation at hand, diminishing transparency of the decision-making process. Intuition is similar to expert judgment, both using tacit knowledge as a basis formed by experiences. Intuition is regarded as a success factor in decision-making in the concept of 'Naturalistic Decision Making (NDM)' (Klein, 2008), or as basis for bias in the concept of 'Heuristics and Biases (HB)' (Tversky and Kahneman, 1974). The common ground is that intuitive thinking and decision-making stems from experience and cognitive pattern making (Gobet and Chassy, 2009; Simon, 1983; Zsambok and Klein, 1997). The judgments and decisions called intuitive come to mind on their own, without explicit awareness and without an explicit evaluation of the validity. A fire fighter feels that a house is dangerous and a chess player sees a promising move (Kahneman and Klein, 2009, p. 519). When judgments about sewer systems are based on tacit knowledge, it is difficult to recall their underlying trade-offs and argumentations and, considering investments, whether budgets are deployed properly.

This chapter is based on: Van Riel, W., Langeveld, J.G., Herder, P.M. & Clemens, F.H.L.R., 2014. Intuition and information in decision-making for sewer asset management. *Urban Water Journal*, 11 (6):506-518.

Still, as intuition is to a large part based on experiences and cognitive pattern making, the question is whether sewer asset managers base their decisions on ‘relevant’ experiences and patterns, and therefore employ skilled or flawed intuitive thinking in such socio-technical systems. It is unclear which and how information sources are used in deciding upon sewer system rehabilitation, and to what extent replacement decisions are influenced by intuition. This observation is not essentially different from any other decision-making process, but in order to improve current sewer asset management, this study assesses the availability and use of information in decision-making for sewer system replacement.

2.2 Intuitive decision-making and relation with sewer asset management

Intuition is a topic studied intensively for decades, emerging from the fields of philosophy and psychology (e.g. Jung, 1921). Intuitive decision-making is deeply embedded in the evolutionary history of *Homo Sapiens*, being probably the most dominant mode of risk assessment and survival (Slovic et al., 2004). Due to its influence in decisions, it cannot be omitted from decision-making analysis. Two aspects about intuition are considered important for this study: conditions under which intuition is preferred over analytical reasoning, and circumstances influencing the success of intuitive decision-making.

Simon (1947) related intuitive thinking to organisational behaviour and concluded that the perfectly rational *Homo economicus* has to be replaced by a man of limited knowledge and information processing capacity, *Homo stultitia*, i.e. rationality is bounded. Simon (1992, p. 155) describes intuition as decision-making behaviour that is speedy and for which the expert is unable to describe in detail the reasoning or other process that produced the answer, being “nothing more and nothing less than recognition”. To the view of Simon (1983), intuition is assembled through learning and experience and stored in long-term memory. Simon stressed the advantages of intuitive decision-making, which were later incorporated in the approach of ‘Naturalistic Decision Making (NDM)’ that emerged in 1989 (Klein, 2008). NDM postulates that under conditions of time pressure, ambiguity and changing conditions experts can make good decisions without having to consciously perform extensive, multi-attribute analyses. This is explained by the ‘recognition-primed decision (RPD) model’ (Klein, 1989; Zsambok and Klein, 1997) describing that people are able to make successful intuitive decisions by employing their experience to recognise problems as similar to problems previously experienced. An opposite view was initiated by the ‘Heuristics and Biases (HB)’ approach by Tversky and Kahneman (1974), who showed systematic cognitive biases accrue from reliance on judgmental heuristics, caused by a number of fallacies and miscomputations inherent in human information processing. These intuitive judgments arise from simplifying heuristics, not from specific experience. Consequently, such intuitive judgments are less likely to be accurate and are prone to systematic biases (Kahneman and Klein, 2009, p. 519). The common thought of the

NDM and HB approaches is that, regarding dual process models, intuitive judgments are produced by 'system 1 operations' in the brain, which are automatic, involuntary, and almost effortless. In contrast, the deliberate activities of 'system 2 operations' are controlled, voluntary and effortful, demanding cognitive effort. These two opposite views towards intuition pose the question of how skilled intuition can be distinguished from heuristic-based intuition (Kahneman and Klein, 2009).

When is intuition likely to be used in decision-making? Agor (1986) surveyed 200 'highly intuitive' managers on issues related to the use of intuition. He found that the conditions under which intuition 'functioned best' included:

- uncertainty,
- absence of precedent,
- requirement to use limited or ambiguous data and information,
- existence of equally plausible alternatives, and
- time pressure.

Similar characteristics were later described by (Orasanu and Connolly, 1993, p. 7), listing eight factors that give rise to the use of intuitive judgments.

- III-structured problems. The decision problem does not present itself in a neat and complete form, resulting in no single or correct answer.
- Uncertain dynamic environments. Decision-making takes place in a world of incomplete and imperfect information and changing environments.
- Shifting, ill-defined, or competing goals. The decision-maker is expected to be driven by multiple purposes, not all of them clear, some of which will be opposed to others.
- Action/feedback loops. The traditional decision models are concerned with an event, a point in time at which the single decisive action is chosen. In contrast, it is much more common to find an entire series of events, a string of actions over time that are intended to deal with the problem, or to find out more about it, or both. Action/feedback loops may also generate problems. Actions taken and results observed may be only loosely coupled to one another, making it hard to attribute effect to cause.
- Time stress. Decision-makers in these settings will often experience high levels of personal stress, with the potential for exhaustion and loss of vigilance. Second, their thinking will shift, characteristically in the direction of using less complicated reasoning strategies (Payne et al., 1988).
- High stakes.

- Multiple players. Many problems of interest involve not a single decision-maker, but several, perhaps many, individuals who are actively involved in one role or another. It can be hard to make sure all team members share the same understanding of goals and situational status so that relevant information is brought forward when needed in the decision process.
- Organisational goals and norms. The organisational setting is relevant to the decision-making process in two ways. First, the values and goals that are being applied will not be simply the personal preferences of the individuals involved. Second, the organisation may respond to the decision-maker's various difficulties by establishing more general goals, rules, standard operating procedures, service doctrine, or similar guidelines.

When is intuition considered to be skilled? Skilled intuition was defined by Simon (1992, p. 155) as "nothing more and nothing less than recognition". According to Kahneman and Klein (2009, p. 520), the recognition model implies two conditions must be satisfied for an intuitive judgment to be genuinely skilled. First, skilled intuitions will only develop in an environment of sufficient regularity, which provides valid cues to the situation. For instance, poker or chess games. In these situations, a relation can be observed between a decision and the effect of the decision (performance). How does this relate to sewer asset management? For several decisions, a relation between decision and performance can easily be observed. For example, changing the hydraulic properties of a sewer system by decreasing the diameter of several pipes or closing a combined sewer overflow. This will inevitably change the hydraulic performance, being noticed at the first rain event. For system replacement however, such a relation between decision and performance is absent, because the time between a replacement decision and its effect exceeds the professional life of sewer asset managers. Second, in case sewer pipes are replaced before their technical end of life, the replaced pipes' condition is not checked and to what extent replacement is required.

A second condition for intuition to be skilled is that people must have an adequate opportunity to learn the relevant cues. For example, a chess player or musician requires years of deliberate practice to get skilled (Ericsson, 2006). Related to sewer asset management, learning is meant to take place through evaluation of the applied replacement strategy. Yet, the evaluation step is absent in European legislation (see CEN, 2008). In practice, the effect of a replacement strategy is not evaluated, resulting in a limited learning opportunity.

Similar to skilled intuitions, incorrect intuitions also arise from memory, and are caused for example by inadequately checking intuitive choices, or by attribute substitution (i.e. a difficult question is replaced by an easier one, while they do not have a high correlation) (Kahneman and Klein, 2009, p. 522). As such, incorrect intuitions are likely to develop in 'wicked' situations (see Rittel and Webber, 1973), due to limited regularity (Hogarth, 2001). Moreover, professionals could develop overconfidence about the accuracy of their judgments, leading to an illusion of skill (Arkes, 2001).

A way to augment professional judgment is by the use of algorithms or other forms of decision support tools. Yet, these must remain under adequate human supervision, to provide monitoring of their performance. This is however difficult, because people tend to get more passive and less critical when such tools are in charge without giving feedback. This is defined as automation bias (Skitka et al., 1999).

Overall, intuitive decision-making is fast, because the brain draws conclusions by recognition from a few observations. Intuition, tacit knowledge and non-conscience pattern-making assist humans as their ‘mental butlers’, because these require little cognitive effort (Bargh and Chartrand, 1999, p. 476). It can provide successful decisions in professional contexts in complex conditions, under circumstances of regularity and opportunities to learn.

2.3 Research approach

The aim of this chapter is to increase understanding of the decision-making process regarding sewer system replacement. Case study research seems appropriate for this purpose, given the explorative and practical character of this study.

2.3.1 Case studies and data collection

The decision-making process and current use of information was assessed at seven municipalities in the Netherlands. Eighteen interviews were conducted at seven Dutch municipalities, ranging in population size from approximately 50,000 to over 750,000 inhabitants. These municipalities constitute approximately 15 % of total population (Statistics Netherlands, 2012) and approximately 9 % of the total sewer length in the Netherlands (RIONED Foundation, 2009). Table 2.1 shows several characteristics of the municipalities included for the study in this chapter.

Table 2.1: Characteristics of included municipalities

Municipality	Nr. of inhabitants at 01-01-2011[1]	Population density[2]	Sewer length*	Available budget for 2012*	Available budget per inhabitant	Available budget per km sewer pipe
	(-)	(inh./km^2 land)	(km)	(M Euro)	(Euro/inh.)	(k Euro/km)
Almere	190,655	1,469	1,100	8.7	45.6	7.9
Amsterdam	779.808	4,700	3,811	64.9	83.2	17.0
Barneveld	52,490	298	624	9.1	173.4	14.6
Breda	174,599	1,379	1,050	13.5	77.3	12.9
Ede	108,285	340	986	9.6	88.7	9.7
Rotterdam	610,386	2,987	2,906	51.2	83.9	17.6
The Hague	495,083	6,046	1,439	33.3	67.3	23.1

* Data is extracted from the strategic municipal sewerage plan per municipality

[1] (Statistics Netherlands, 2012)

[2] (Statistics Netherlands, 2009)

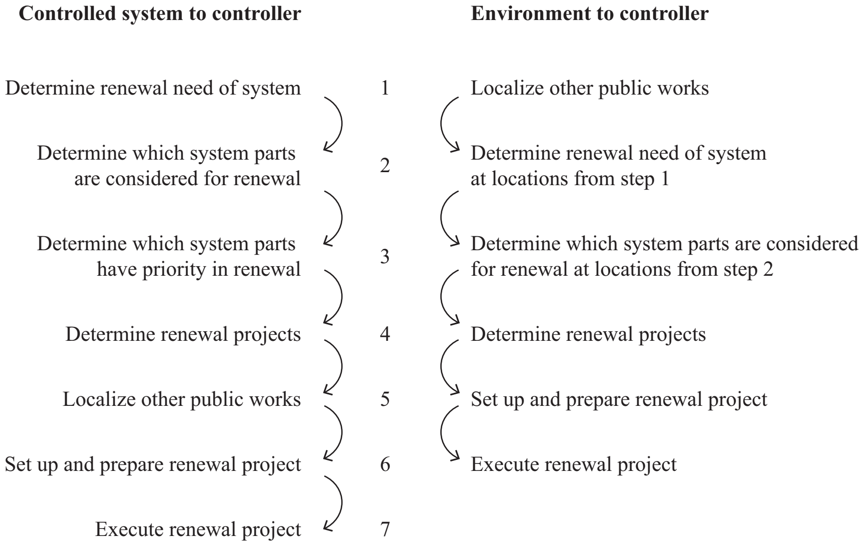

Figure 2.1: Flow charts used during interviews

The interviewees were selected as follows: first the heads of the 'sewer system departments' were selected based on their willingness to participate in an interview and asked to participate. Second, the department heads appointed one or two additional interviewees (dependent on the municipality's staff size), requested by the authors, whom they thought to be relevant to be interviewed.

An in-depth (face to face) and semi-structured interview setup was chosen to collect data. This approach was chosen, because of the explorative character of the study and the complexity of the subject. It allows flexibility during the interview regarding structure, content and questions, which are framed by a network of topics that will be addressed. Semi-structured interviews suit the explorative character of this study. The in-depth interview was chosen, because of the complexity of the subject and to allow maximum diversity in the responses.

The interviews were guided by the flowcharts in figure 2.1. These were used to assist in discussing the decision-making process and information use. The flowcharts had been prepared based on the results of four exploratory interviews with experts in the urban drainage sector. The starting point of each flowchart differs, related to information flow in the control paradigm. As depicted in section 1.1, two information flows can be distinguished, which relate to external of internal impulse for system replacement: from controlled system to controller and from the environment to controller.

Through the flowcharts, the following topics were addressed in chronological order: justification and completeness of flowcharts, information sources per step, budget allocation and identification of organisational levels. The interviewees described these topics in a general sense, based on their knowledge and experience.

Seventeen of eighteen interviews were digitally recorded, approved by the interviewees. Afterwards, the interview recordings were fully transcribed. The transcript of the not recorded interview was sent to the interviewee for review.

Dutch municipalities are legally obliged to present a strategic municipal sewerage plan every five years, which are often publicly available. Each of these plans contains a specific section about decision argumentation for sewer replacement. Data was extracted from these sections.

2.3.2 Data analysis

Three types of data were analysed: interview data about the decision process, interview data about the use of information in the decision process, and data about the use of information in the decision process from the strategic municipal sewerage plans.

The first data source is analysed by open coding, both in-vivo and descriptive. The open coding approach was sufficient, because the objective was to describe the decision process by using preliminary flow charts.

The second data source, interview data about the use of information and intuition in the decision process, is analysed by content analysis. This is defined as “a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use” (Krippendorff, 2004, p. 18). The steps for content analysis involve coding, making categories of the codes and abstraction, with the purpose of describing a phenomenon (Elo and Kyngäs, 2008). This type of analysis is usually appropriate when existing theory or research on a phenomenon is limited. A specific type of content analysis, summative content analysis, was applied in this study. This type starts with identifying and quantifying words and contents with the purpose of exploring usage, and adds the underlying meaning of these words and contents (Hsieh and Shannon, 2005, p. 1283). Typically, the keywords used for coding are identified before and during data analysis, derived from interests of researchers or literature review (Hsieh and Shannon, 2005, p. 1286). Summative content analysis fits more to the objective of this study than regular content analysis, because of study’s focus on assessing usage of information and intuition in the decision process of sewer system replacement. The following steps were taken.

1. Open coding. The interview transcriptions were screened and in-vivo and descriptive coding was applied to the words and phrases to indicate each described information source and intuitive judgment used in the decision process. The identified keywords and phrases for the analysis of information usage were derived from literature and interviews with experts in the urban drainage sector. The use of intuition was analysed by coding expressions reflecting intuitive thinking processes, including ‘feeling’, ‘interpretation’, ‘common sense’ and ‘intuition’. All codes were counted afterwards.
2. Axial coding. The interrelationships between the codes were identified in order to make code groups and categories.

3. Identify meaning. The underlying meaning of the keywords, code groups and categories is interpreted.

After identifying the information groups and their meaning, the actual use of this information is confronted with literature about intuitive decision making in section 2.2. The reason to do this, is to identify the balance between rational reasoning and intuitive judgments, and to evaluate the success of potential intuitive judgments.

The strategic municipal sewerage plans' section about sewer system replacement were analysed by in-vivo coding of keywords in the text, in order to search for explicitly described information sources.

2.4 Results and discussion

2.4.1 The decision-making process

The interviewees indicated that the decision-making process for sewer system replacement, shown in figure 2.2, is a combination of the two flowcharts (figure 2.1) presented to them. The starting point in the process is the five-year budget allocation. According to the municipal sewerage plans, the five-year budget is determined based on pipe age and camera inspection. More specifically, the interviewees indicated that the five-year budget is allocated based on the costs for the projected yearly replacement works in 'km per year' (quotient of total sewer length and expected lifetime). The yearly budget is allocated as one fifth of the five-year budget. Individual replacement projects are initiated from the budget, based on the replacement need of the system (hydraulic or structural), and potential synergy from cooperating with other public works.

The decision process in figure 2.2 shows discrepancy between strategic and operational decision-making. The budget is allocated before and on other grounds than the operational activities. On a strategic level, decision-making for replacement is based on pipe age and quality. For the operational activities, sewer asset managers include other sources of information in the form of potential synergy from cooperation with other public works. Cooperation with other public works when feasible, usually with road works, provides opportunities for reducing nuisance and costs by combining excavation works and sharing costs for reconstruction of the surface level. The discrepancy is caused by the fact that pipe age and camera inspections are the only quantitative sources of information, to which sewer asset managers can refer for making a strategic decision about the five year budget allocation. This does not count for opportunities for synergy in integrated public works, which is a relevant aspect for operational activities.

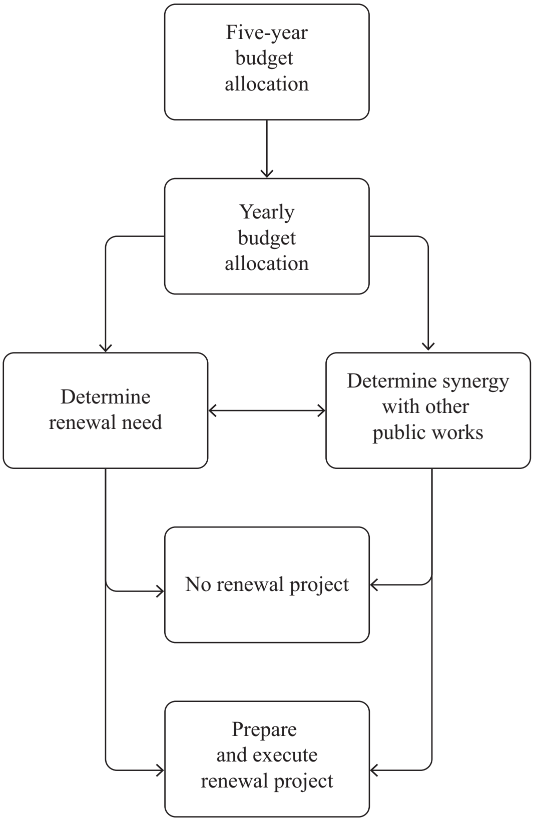

Figure 2.2: Decision-making process for sewer system replacement.

2.4.2 Information in the decision-making process

Open coding of the interview transcriptions resulted in identification of twenty-one information sources, as shown in figure 2.3. Through axial coding, the information sources were grouped, based on a common topic the information sources refer to. The groups of information were categorised by further abstracting and relating them to the decision process in figure 2.2. As figure 2.3 shows, six groups were identified, which can be put in three categories, being the technical replacement need, potential synergy from cooperation with public works, and organisational preferences. Several individual information sources are discussed in the following paragraphs.

2.4.2.1 Deciding about sewer system replacement need

As figure 2.3 shows, the technical need for sewer system replacement is based on two aspects: judging the structural and hydraulic performance of the system. Each of these aspects is judged by various information sources, of which municipalities collect data. The structural performance is considered as the most dominant aspect for judging about the technical need for sewer system replacement, and also forms the basis for strategic the budget allocation, as described in section 2.4.1.

Pipe age and camera inspections were mentioned most often for the structural performance. Pipe age is considered as an approximation of the pipe failure probability, because it is generally assumed that sewer pipes have a technical service life of 60 to 80 years. As such, pipe age is often used as a first indicator for the technical replacement need. Other information related to pipe age, is the concrete quality at the year of pipe construction, which varied during the last decades.

Camera inspections are used to observe sewer pipes internally. Every observed defect, for example cracks or blockages, is noted by the inspector according to a coding system described in the European Standard EN 13508-2 (CEN, 2011). The inspector also judges the severity of each individual defect by a one (no damage) to five (severe damage, replacement required) classification system, which is also described in the EN 13508-2. After inspection, the overall damage severity of the inspected sewer branch is judged, and potential actions are planned accordingly. A disadvantage of this visual inspection technique is that it is difficult to convert observed defects on object scale to physical status and performance judgments on network to system scale. Next to that, time series are usually unavailable, decreasing the predictive power of the observations. Furthermore, Dirksen et al. (2013) concluded that assessment of camera inspections images introduces significant uncertainty in the overall condition assessment.

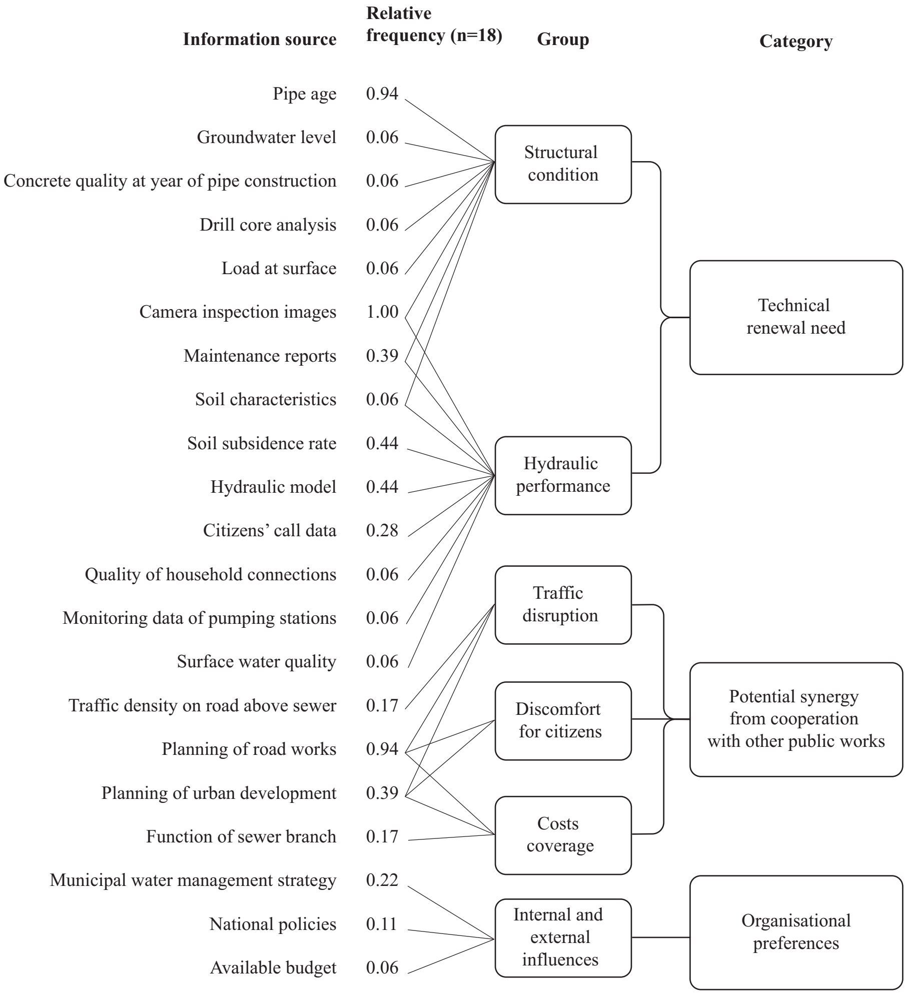

Figure 2.3: Identified information sources (grouped and categorised) consulted for sewer system replacement, obtained from eighteen interviews.

Nine information sources are linked to the hydraulic performance of the sewer system. Hydraulic modelling is used to check whether the hydraulic performance of the sewer system meets its objectives. Korving (2004) showed however, that significant uncertainty for decision-making is introduced by hydraulic modelling. Soil settlement rate is used for determining the need for sewer system replacement, in particular for municipalities located on soft soil, because it changes hydraulic performance of gravitational systems without pile foundation. Dirksen et al. (2012) described the relation between soil settlement and sewer system performance. Yet, no reference model for soil settlement is available to assist sewer asset managers, preventing assessment of the settlement severity and, consequently, the system replacement need.

Citizens' call data are complaints from citizens who call the municipality about flood occurrences, stench or other sewer system related aspects. For the replacement decision process, this information source relates to a decreased hydraulic performance when multiple complaints are registered, repetitively over time. Data from maintenance reports is the actual feedback from operational activities, for example (planned) repair works. After these maintenance works, potential defects and causes are reported, which are dealt with when needed. Both data from citizens and maintenance reports are usually not a direct reason to replace sewer systems, but add up to the replacement need when repetitive calamities are reported.

2.4.2.2 Deciding about synergy from cooperation with other public works

As previously described, sewer asset managers try to cooperate with other public works to benefit in three ways: reduce traffic disruption, reduce discomfort to citizens and reduce costs for excavation and surface level reconstruction. Discomfort to citizens relates to decreased accessibility to their homes and living next to a construction site. The synergy is not quantitatively expressed, except for the cost reduction, but is a certain qualitative weighing process undertaken by sewer asset managers.

As figure 2.3 shows, the planning of road works and urban development projects are mentioned most often for judging about the potential synergy. The interviewees indicated that planning procedures for combining sewer works with other public works are not documented, but are part of the organisations' cultures, being based on 'common sense'. This may be true for some replacement projects, but this cannot be generalised due to the variability of the replacement works. Some interviewees experienced fruitful cooperation procedures, simply because their desks are at the same office room of a road manager, allowing quick coordination. On the other hand, due to differences in temporal and spatial planning scales of other public works, planning of sewer works does not necessarily match with these other works. Hence, in many cases when there is opportunity for integrated public works, sewer asset managers weigh the potential synergy with the technical replacement need.

Nuisance or discomfort for citizens was described as an important aspect to integrate sewer works with other public works. The underlying argumentation is that citizens are not pleased when streets are reconstructed in year one, and soil is excavated again in year two to replace sewer pipes. As the interviewees described, it is an aspect of communication with, and reputation of, the organisation towards its citizens. No guidelines are available in these situations for assistance in this weighing process, causing sewer asset managers to find ad hoc solutions that fit the situation at hand. On the other hand, this flexibility is appreciated.

Deciding about the potential synergy is an undocumented and unguided trade-off. This hampers repetition of actions in comparable situations, making it difficult to justify and evaluate decisions.

Related to the control paradigm in section 1.1, shifting the system from sewer system to public space makes the system boundaries of both the controller and controlled system dynamic instead of fixed. From a theoretical perspective, it is therefore questionable whether the depicted control paradigm (De Leeuw, 1974) is useful for framing sewer asset management, because it relies on a clear distinction between controller and controlled system. In other words, is it possible, and preferred, to observe and analyse sewer asset management isolated from other activities in public space? A possible solution to this issue can be found in Mintzberg's organisational structuring (Mintzberg, 1980), and more specifically, the divisionalised organisation. In short, such an organisation consists of multiple divisions that have a good deal of autonomy. The crucial aspect is to find a mechanism to coordinate the goals and performance of the separate divisions with those of the entire organisation (Mintzberg, 1980, p. 335). Related to sewer asset management, a coordination mechanism may be implemented that regulates planning of public works in space and time.

2.4.2.3 Organisational preferences

Three information sources were categorised as organisational preferences. These are municipal water management strategy, national policies and the available budget. Municipal water management strategy, as well as national policies, guidelines about required surface water quality are information sources about the preferences of the organisation regarding system type and layout, and the way the organisation wants to manage its system. For example, many municipalities in the Netherlands currently, have the strategy to build separate instead of combined sewer systems. Another example is national guidelines about the required surface water quality. The available budget is also an organisational preference and relates to the preference about how the budget is deployed. The information sources about organisational preferences are usually not a direct reason to replace sewer systems, but add up in the overall weighing process.

2.4.3 Intuition in the decision process

In each interview transcription, keywords reflecting the use of intuition were identified. This intuitive thinking is used for interpreting collected information, and converting this into decisions about the technical replacement need and potential synergy from cooperation with other public works.

Replacement decisions are actually based on a combination of five implicit risk analyses, in which risk is the product of probability and consequence. Implicit in this sense means that it is not treated as a separate and deliberate step in the decision process in which both probability and consequence are quantified to serve as a basis for decisions. The risk analyses relate to the information groups described in figure 2.3. The following risk consequences were identified:

1. pipe collapse (insufficient structural performance),
2. insufficient hydraulic performance,
3. nuisance or discomfort for citizens and related reputation of the organisation,
4. costs for excavation works and surface level reconstruction, and
5. traffic disruption due to excavation works.

The probability in the risk analyses, determined by one or two persons per municipality, is estimated by intuitive judgments in the following manner. Data about pipe age and camera inspections are converted into a qualitative approximation of the remaining technical sewer system lifetime and probability of pipe collapse. Some interviewees stated that is it very likely their conclusions about replacement need, based on pipe age and inspections, may vary from day to day. Research showed however, that pipe age combined with camera inspections are insufficient to conclude about these aspects, because knowledge about deterioration processes is still limited (Ana et al., 2009; Baur and Herz, 2002; Chughtai and Zayed, 2008; Dirksen et al., 2012; Stone et al., 2002).

Also the probability and severity of nuisance to citizens and traffic disruption is estimated based on intuitive judgment. No specifications are however available that distinguish severe from mild. Of course, it is common sense to assume that traffic disruption will be higher for a busy three-lane motorway than for a dead end street. It is however difficult to judge about less obvious situations. Similar is judging about nuisance for citizens.

Because of an absence of accurate and repeatable risk estimates, sewer asset managers have developed a risk aversive replacement strategy, i.e. better to be safe than sorry. In practice, this means that sewer pipes are replaced without having an accurate estimation of the remaining service life. By doing so, service availability is ensured, and calamities, for example pipe collapse, hardly occur. This is also affected by the available budget, which is large enough to allow proactive replacement of sewer systems, with hardly any occurrences of pipe collapse.

2.4.4 Confrontation with literature

Intuitive decision-making can be expected, considering the conditions that give rise to such judgments (see section 2.2). Several factors from Orasanu and Connolly (1993, p. 7) are addressed and related to the results from this study.

- Ill-structured problems. The decision problem does not present itself in a neat and complete form, resulting in no single or correct answer. From the collected sewer system data, it is difficult to decide what the actual structural and hydraulic performance is, and whether system replacement is needed. Next to that, there is the difficulty of estimating the extra potential disruption to traffic and discomfort to citizens when sewer works are not integrated in other public works.

- Uncertain dynamic environments. Decision-making takes place in a world of incomplete and imperfect information. The decision-maker has information about some part of the problem, but about others. The available information is limited in quality and quantity, requiring intuition to convert the information into decisions. No data and methods are available to accurately quantify probability in the risk analyses.

- Shifting, ill-defined, or competing goals. The decision-maker is expected to be driven by multiple purposes, not all of them clear, some of which will be opposed to others. An example the situation when an area is being redeveloped, while the current sewer system is still functioning well. On the one hand, replacement is not technically needed. On the other hand, cost reduction from shared excavation works may outweigh the loss of functional value of the current sewer system.

- Action/feedback loops. Pipe deterioration processes are still not fully understood, making it difficult to attribute effect to cause. Next to that, it is difficult to assess whether the actual replacement of sewer pipes also contributes to better system performance, because hardly any failures occur. Third, multiple changes in organisational preferences regarding system layout and requirement led to different asset management strategies.

- Multiple players. A sewer asset manager has to consult multiple actors in the municipality, each of them potentially having different goals and need for information.

The complexity of the socio-technical system in which sewer asset management is embedded, is expressed by the multitude of interactions and interrelations a sewer asset manager has with its environment. He/she collects data from various sources, but has to cope with limitations of the data itself and interests of other actors and influences. As a result, hard information is of limited importance, giving opportunity for decision-making driven by intuition.

The second aspect about intuition to be confronted with literature is its chances of success. Section 2.2 described two conditions must be met for intuition to be skilled: sufficient regularity and learning opportunities. The two conditions are not met. First, the environment does not have sufficient regularity; it does not provide valid cues to the situation, because the available data does not sufficiently allow to actually judge about the sewer system performance or synergy from integrating public works. As a consequence, the relation between decision and performance is difficult to observe, in particular for sewer replacement. Second, there is hardly opportunity to learn, since hardly any failure events occur. This means that a sewer asset manager is not able to gather relevant experience, because a risk aversive replacement strategy is chosen. This is positive from the perspective of service availability, but probably also results in a too high sewer system quality. Next to that, the effect of an applied replacement strategy is not evaluated. As such, sewer asset managers deprive themselves of their right to learn.

2.5 Conclusions and recommendations

The objective of this chapter was to assess the availability and use of information and intuition in decision-making for sewer system replacement. The following conclusions are drawn.

Sewer asset managers use their best available knowledge to ensure sewer service availability for citizens. Yet, this is a difficult task, because of the complexity of the sociotechnical system that surrounds sewer asset management. Ensuring service availability means that sewer pipes need to be replaced, due to a variety of reasons. Deciding on where and when to replace pipes is a task demanding input from various sources of data, including pipe quality, pipe age, soil settlement rate, planning of road works, water management strategies and available budget. These data sources do, however, not allow sewer asset managers to predict system performance or determine the synergy from cooperating with other public works, or even combining these two aspects. Under such circumstances including uncertainty, dynamic environments, absence of precedents, limited data and multiple players, it is likely that intuitive judgment is opted over rational reasoning. Intuition is used to make replacement decisions to ensure continuity of the day-to-day practice. This leads to the situation where sewer pipes might be replaced without knowing the remaining lifetime, which can be seen as a form of a risk aversive attitude (precautionary principle). Because the intuitive decisions are not documented, it hampers justification, accountability, repetition and evaluation of decisions.

The use of intuition in sewer replacement decision is however, not skilled, because the two conditions for intuition to be skilled (sufficient regularity and learning opportunity) are not met. The already developed intuitions have a high chance of being incorrect, because of limited regularity of the situation where sewer asset management is embedded in (Hogarth, 2001). A potential driving force of this is the heavy reliance on pipe age and camera inspections and converting information from these items into decisions.

A first recommendation to sewer asset managers is to start documenting the decision argumentation for replacement works. This will create an opportunity to learn from the trade-offs and valuations made in the decision-making process. Second, it is recommended to set up and use failure event databases. This will allow systematic assessment of system performance and effectiveness of fault-clearing services. Two examples are the uniform registration of failures in wastewater systems (SUF-SAS) (Korving et al., 2007) and the USTORE failure database for water distribution networks, set up by KWR Watercycle Research Institute. This creates the relevant opportunity to gain experience, learn and eventually develop intuition that is professionally skilled. Third, it is recommended to document the entire decision process for sewer replacement and evaluate this after several years, helped by observations from the physical system, in order to increase chances for learning and gaining experience.

This chapter contributes to increased understanding of the current issues the sewerage sector is dealing with regarding transparency of the decision-making processes. A next step is to assess the actual influence or weight of each individual information source, with the purpose of assessing the relevance of (investing in) increased information quality about the sewer system. This can be undertaken in a qualitative way (using interviews and thematic or interpretative phenomenological analysis) or quantitatively by using choice experiments.

3 Individual and group decision-making: theory and practice

3.1 Introduction

The urban drainage sector is challenged to provide equal or better service levels, at lower costs, defined as cost-effective (Katz and Kahn, 1978). Yet, decision-making processes for sewer asset management, especially for operational decision-making, have hardly been empirically analysed so far (Van Riel et al., 2014b), limiting transparency of such decision-making processes. Research about sewer asset management has mainly focussed on describing normative decision frameworks, i.e. decision support tools, instead of analysing decision-making in reality (e.g. CEN, 2008; Carey and Lueke, 2013; Chughtai and Zayed, 2008; Egger et al., 2013; Fenner et al., 2000; Kleidorfer et al., 2013; Le Gauffre et al., 2007; Marzouk and Omar, 2012; Sægrov et al., 2006; Scheidegger et al., 2011). This limited knowledge about actual operational decision-making impedes determining or improving cost-effectiveness of urban drainage, because decision transparency is required to assess whether decision-making may be improved. In contrast to classical decision theory and its assumption of perfect rationality (Drucker, 1967; Simon, 1955), decision-making in reality is mostly characterised by complex contexts (Allison, 1971; Lindblom and Woodhouse, 1993; Rittel and Webber, 1973; Stone, 1988). This contrast between theoretical and real decision-making is the topic of this chapter.

From a theoretical point of view, decision support models for sewer asset management suggest measures to sewer asset managers to maintain a preferred system state. Most decision support tools require extensive good quality data sets, which are not always available in practice (Ana and Bauwens, 2007; Fletcher and Deletić, 2008). From a practical view, how suggestions from decision support tools are put into practice is outside the scope of these tools, but is part of actual decision-making. Then, a

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This chapter is based on: Van Riel, W., Van Bueren, E., Langeveld, J., Herder, P., & Clemens, F. (2016). Decision-making for sewer asset management: Theory and practice. *Urban Water Journal*, 13(1):57-68.

sewer asset manager has to balance his various professional responsibilities, possibly in cooperation with other infrastructure managers. Cooperation is relevant to reduce public costs and nuisance (Van Riel et al., 2014b). Given these practicalities, the decision-making process could be characterised as a process of compromises and negotiations, instead of merely analytical reasoning, especially in multi-actor settings (Allison, 1971; Lindblom and Woodhouse, 1993; Stone, 1988; Sylvan et al., 1990). Related to sewer asset management, such processes particularly occur when responsibilities and planned works of different urban infrastructures overlap and the involved managers prefer a collective planning process. The involved decision-makers are presented with a planning problem with a complex context (Geldof and Starhe, 2006; Parsons and Wooldridge, 2002; Rittel and Webber, 1973). The managers remain sovereign over their infrastructure, but negotiate and make compromises about when, how and to what extent works are integrated, i.e. they influence one another's choices and have distributed decision power.

The direct consequence of this complex context, limited data availability and quality, and negotiations between involved actors is that the decision-making processes and outcomes for sewer asset management are less predictable than assumed by the rational model of decision-making. Other criteria than system performance become influential, decreasing decision transparency and, potentially, cost-effectiveness. Given the lack of empirical data concerning this decision-making, this chapter addresses the question: how do sewer asset managers make decisions and to what extent do they address the complexity of the decision-making environment? The actual decision-making processes made by sewer asset managers are analysed by the multiple streams framework that considers decision making as a political, dynamic process (Kingdon, 1995). The focus is on operational activities. Decision argumentations of 150 sewer replacement projects in the Netherlands serve as empirical data for the analysis.

3.2 Rational versus political decision-making

Decision-making theory generally distinguishes two main types of decision models: rational and political models. Decision-making in reality often has characteristics of both model types.

3.2.1 The rational view

The rational model displays decision-making as a stepwise and data driven approach. Decision-making is portrayed from a single actor. The actor may be a person, a group, an organisation or a government, as long as it is seen as a single entity. The involved decision-maker defines goals; defines alternative means for attaining them; evaluates the consequences of each alternative; and chooses the alternative most likely to attain the goal. Data acquisition and analysis play key roles and require a decision-maker to consider all possible alternatives, and evaluate all possible consequences of each (Stone, 1988, p. 185). The ideal view of a rational decision-making process is characterised as follows:

- a single decision-making actor,
- a stepwise process,
- data lead to information and knowledge,
- evaluation of alternatives and their consequences leads to an objectified decision, and
- a key decision point in time.

In the course of time, the rational model of decision-making has undergone some modifications. The most prominent one is the recognition that people operate with bounded rationality (Simon, 1955). Decision-makers consider only some alternatives, have limited information quantity and quality, and stop searching for a solution when they have found a satisfactory one for them, i.e. decision-makers simplify (Stone, 1988, p. 185). Next to that, a rational process does not guarantee a rational outcome, because substantive rationality may be limited (Simon, 1978), i.e. the needed data is unavailable or ambiguous. Consequently, intuition is opted over analytical reasoning.

Decision support tools (examples mentioned in section 1.2) for sewer asset management are based on a rational perspective. Suggestions for measures are proposed by a sequential process that starts with data analysis, often beginning with pipe age and condition, and criteria for alternatives to solve a perceived problem. This problem perception usually concerns insufficient system performance.

Lindblom (1959) and Etzioni (1967) criticised the rational model for being unrealistic and undesirable in multi-actor settings. Both authors claimed that problems, goals and values cannot be predefined, information processing is limited and consequences cannot be evaluated as unambiguously as suggested by the rational model. Application of a rational model in a multi-actor setting can only be successful when the involved actors agree about values, problems, goals and alternatives. As long as differences in facts persist, analysis cannot settle differences (Lindblom and Woodhouse, 1993). The rational view excludes processes of cooperation, bargaining and making compromises which inevitably occur when more than one decision-maker is involved.

3.2.2 The political view

The political view on decision-making emphasises that decisions are made by multiple actors. Actors are driven by different interests, e.g. following from their positions, roles, beliefs and values. Their preferences, assumptions and values can change over time (March, 1994). Next to that, decision-makers often do not exactly know or have different perceptions about the problem and goal and the best way to reach it. As a result, actor behaviour is dynamic and leads to processes which are less structured and staged than assumed by the rational model. Decision-making according to political models is characterised as follows:

- It is a group effort of negotiating and making compromises (Allison, 1971; Sylvan et al., 1990).
- Goals, values and interests and perceptions of these may differ from person to person, affecting their decision behaviour (Allison, 1971).
- Data is available, but much of it is qualitative, not recorded, or regarded as ambiguous (Lindblom and Woodhouse, 1993).
- Cause and effect relationships are difficult to identify and to evaluate, due to the many interacting actors and variables.
- The process is interactive, leading to circular processes without clear beginnings or endings (Lindblom and Woodhouse, 1993).

These aspects often create a murky process. Nevertheless, several typologies have evolved over time, often in response to each other, to describe and analyse multi-actor processes (see Cohen, 1960; Etzioni, 1967; Kickert et al., 1997; Lindblom, 1959). One such political model is the ‘streams model’ (Kingdon, 1995). The streams model portrays three streams (problems, solutions and participants) that float around in policy processes. Solutions search for problems or events that will increase their likelihood of adoption. Suddenly, they become elevated, because they are seen as solutions to a perceived problem. These events are termed ‘windows of opportunity’. For example, an opportunity for sewer pipe replacement at a location where a road will be rehabilitated to reduce excavation costs and distortion to liveability.

3.3 Research approach

The aim is to increase understanding of the operational decision-making process regarding sewer replacement within its context. Case study research is appropriate for this purpose, given the explorative character of this study.

3.3.1 Case study and data collection

The selected cases are sewer replacement projects initiated by Dutch municipalities. A project is a defined set of activities to replace sewer pipes at a predefined location, with a given budget and time limit. The length of pipe replacement per project in the Netherlands generally ranges from ten to five hundred metres. Several other relevant characteristics of sewer asset management in the Netherlands are described in chapter 1.1.

Sewer asset managers were considered the prime data source from which decision argumentation of sewer replacement projects was retrieved. Interviewing was chosen as data collection method, because the decision argumentation is not registered. The interviewees were selected in a snowball sampling procedure. The heads of the sewer system departments' at ten municipalities involved in the 'Urban Drainage Research Program' were contacted and asked to name the employee(s) responsible for initiating sewer replacement projects. Those employees were then contacted and asked to participate in an interview about decision argumentation of sewer replacement projects. One municipality outside the research program was asked to participate too, to include an additional relatively small municipality (fewer than 25,000 inhabitants). This led to a selection of thirteen male experienced sewer asset managers, who were interviewed in eleven interviews between December 2012 and April 2013. The municipalities at which they work range in population size from approximately 10,000 to over 750,000 inhabitants. Together, these municipalities compose approximately 17 % of the total population (Statistics Netherlands, 2013) and 15 % of the total gravitational sewer length in the Netherlands (RIONED Foundation, 2009, p. 6). Table 3.1 shows characteristics of the included municipalities and their sewer systems. The variety in municipality characteristics was expected to yield a broad spectrum of decision-making processes, from simple to rather complex.

Table 3.1: Characteristics of included municipalities

Municipality	Nr. of inhabitants at 01-01-2013[1] (10^3)	Population density[1] (inh./km^2 land)	Sewer length* (km)	Issued sewer tax per household 2013* (Euro)	Available tax per household per km of sewer (Euro/km)
Almere	195	1,506	1,100	110	0.10
Amsterdam	799	4,822	3,811	155	0.04
Barneveld	54	305	624	154	0.25
Breda	178	1,413	1,050	180	0.17
Ede	110	345	462	176	0.38
Rotterdam	616	2,956	2,906	189	0.07
Ruchpen	22	346	117	192	1.65
Scherpenzeel	9	682	48	215	4.48
The Hague	506	6,178	1,439	126	0.09
Utrecht	322	3,412	1,147	223	0.19
Woudenberg	12	337	61	160	2.62

* Data is extracted from the municipal sewerage plan per municipality.
* The sewer length is the total length of gravitational sewers.
[1] (Statistics Netherlands, 2013)

An in-depth semi-structured interview setup was chosen, because of the explorative character of the study. It allows flexibility during the interview regarding structure, content and questions, which are framed by a network of topics that will be addressed, and allows maximum diversity in the responses. Beforehand, the interviewees were asked to make a list of finalised replacement projects, chronologically going back in time to avoid any selection by the interviewees, which could introduce bias. These lists were used to structure the actual interviews. The respondents were asked to recall every single argument per replacement project that led to its initiation. Answers were considered to be sufficient when, after probing and discussion, the interviewees could not recall any additional relevant information.

The interviews were conducted in a quiet meeting room at each municipality, to keep the attention focussed on the actual conversation. The interview duration was set in advance at ninety minutes, which appeared to be sufficient. Ten of eleven interviews were digitally recorded, approved by the interviewees. Afterwards, the interview recordings were fully transcribed. The transcript of the not recorded interview was sent for review.

3.3.2 Validation of interview data

The method of data collection and absence of documentation do not allow checking the reliability of the interviewees' descriptions. Therefore, the collected data were peer group validated by presenting it to a group of Dutch experts from the urban drainage sector for feedback. It was concluded from this session that the presented data well reflected their expectations and experiences of decision-making in practice. Next to that, the data indeed reflected a broad spectrum of decision-making processes, creating a representative data set, in terms of quality, of Dutch sewer replacement projects.

3.3.3 Data analysis

Decision-making analysis focussed on assessing why and how sewer replacement projects were initiated. An information source is defined as every possible factor that influenced the decision-making process for initiating a project, including objective data or organisational policies. Two aspects were considered. First, the variety and usage intensity of information sources, to allow comparison with the rational model and available decision support tools. Second, interaction between information sources. Analysing interaction allows to observe two aspects: addressing context complexity and weighing processes in which compromises are made.

Directed content analysis was applied to analyse the interview transcripts. The objective of a directed approach to content analysis is to validate or extend theory, where prior research is used to identify key variables as initial coding categories. The codes were summed at the end for further analysis, making this approach similar to summative content analysis (Hsieh and Shannon, 2005). The steps for content analysis involve coding, making categories of the codes and abstraction, with the purpose of describing a phenomenon (Elo and Kyngäs, 2008). The following steps were taken:

1. Open coding. The interview transcripts were coded in Atlas.ti (version 6.2). Predetermined coding variables were obtained from (Van Riel et al., 2014b). New variables were added when necessary.
2. Axial coding. The descriptions of equal variables varied from interviewee to interviewee. Therefore, similar variables were merged into unique variables. Groups of variables were defined.
3. Identify meaning. The underlying meaning of the keywords, code groups and categories was interpreted.
4. Summation. All unique individual variables were summed.

All unique combinations of information sources were visualised in a graph using Gephi (version 0.8.2 beta), open source software for network visualisation. A graph is a network representation, consisting of vertices (nodes) and edges (connections). An edge between two vertices indicates interaction or connection between the vertices. Edges may be assigned weights, in order to represent importance or lengths. An important graph parameter is node degree, being the number of edges per node. The weighted degree per node was calculated by summing the edge weights connected per node (Boccaletti et al., 2006, p. 199). The weighted degree per information source represents usage intensity. The graph is meant to visualise the diversity and intensity of information sources relevant for operational decision-making of sewer replacement projects.

The decision-making processes for initiating sewer replacement were described by the streams model (Kingdon, 1995) and using examples from the interview transcripts. References to locations or persons in the examples were modified for anonymity.

3.4 Results and discussion

The eleven interviews yielded 150 sewer replacement projects, from which the decision argumentation was reconstructed. The projects were executed between 2003 and 2013. The following two paragraphs describe the content and the process of sewer replacement decisions.

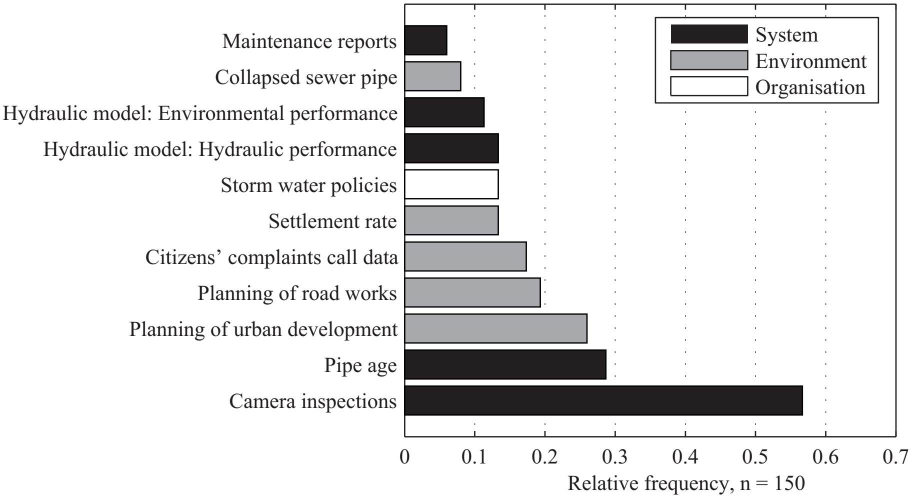


Figure 3.1: Indicated information sources as decision argumentation with $f > 5$

3.4.1 Sewer replacement decisions: content

The decision argumentation reveals that a wide variety of information sources were involved in initiating a replacement project. Appendix A gives the complete list of twenty-eight unique information sources. Figure 3.1 shows the information sources mentioned more than five times, i.e. frequency $f > 5$.

Approximately 70 % of the sources listed in appendix A is case-specific information. This case-specific information represents the diversity of specific local circumstances that influenced operational decision-making for sewer replacement. The other 30 % is information typical for decision support tools (see examples in section 1.2), including camera inspections, pipe age and hydraulic modelling results. These sources relate to the first information type 'system information'. This was to be expected, given the focus on these sources in sewer asset management education.

Specific local circumstances, information availability and advances in information systems and processing capacity differ per municipality. Consequently, identification frequencies should not be interpreted as information importance or relevance.

The second information type, information about the sewer system's environment, represents context. These sources were usually identified as supplementary to information about the sewer system itself. Examples are planning of road works or soil settlement rate. Environment information influenced the operational planning of replacement works, or gave insights into interactions between the system and its physical and social environment. For example, soil settlement and its effect on structural or hydraulic performance. More than system information, environment information triggered experience and 'gut feelings' for deciding about sewer replacement, because no objective values, criteria or guidelines are available for decision support (Van Riel et al., 2014b). Consequently, the involved decision-maker(s) relied on what he/she thinks is best to cope with situation at hand. The third type, organisation information, concerns organisational preferences about urban water strategies concerning system type and layout. Organisation information is information from a strategic organisational level, because it concerns directions for long term system development.

Part of the analysis concerned the interaction between information sources. Approximately one third of the analysed projects was motivated by a single information source. Figure 3.2 shows the amount of sources per replacement project. The 'single source projects' were initiated based on results of the analysis of traditional data (camera inspections or hydraulic modelling) or calamities. Calamities became apparent through an observation or unforeseen event revealing unacceptable system performance.

Two-thirds of the analysed projects were motivated by two or more information sources. For these projects, the sewer asset manager combined information sources to decide about sewer replacement. Figure 3.3 visualises all combinations, which the interviewees mentioned.

The graph in figure 3.3 has the following characteristics:

- The graph is undirected: there is no order (direction) in the way information is combined.
- The graph is weighted: weights are added to the edges. A weight is the frequency of a combination.
- The graph does not contain looped or parallel edges.

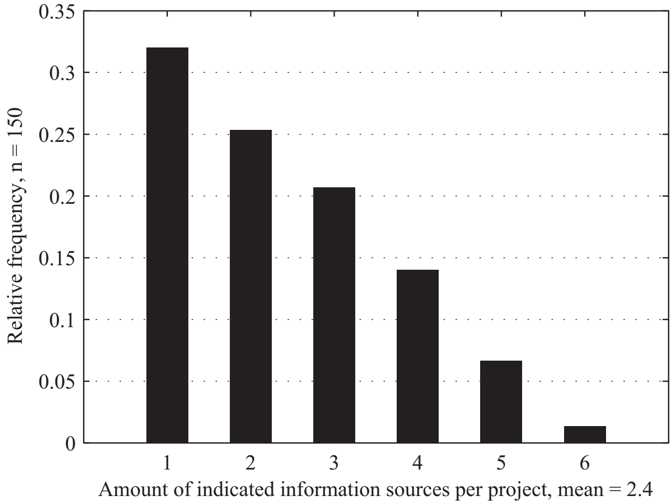


Figure 3.2: Number of information sources per replacement project

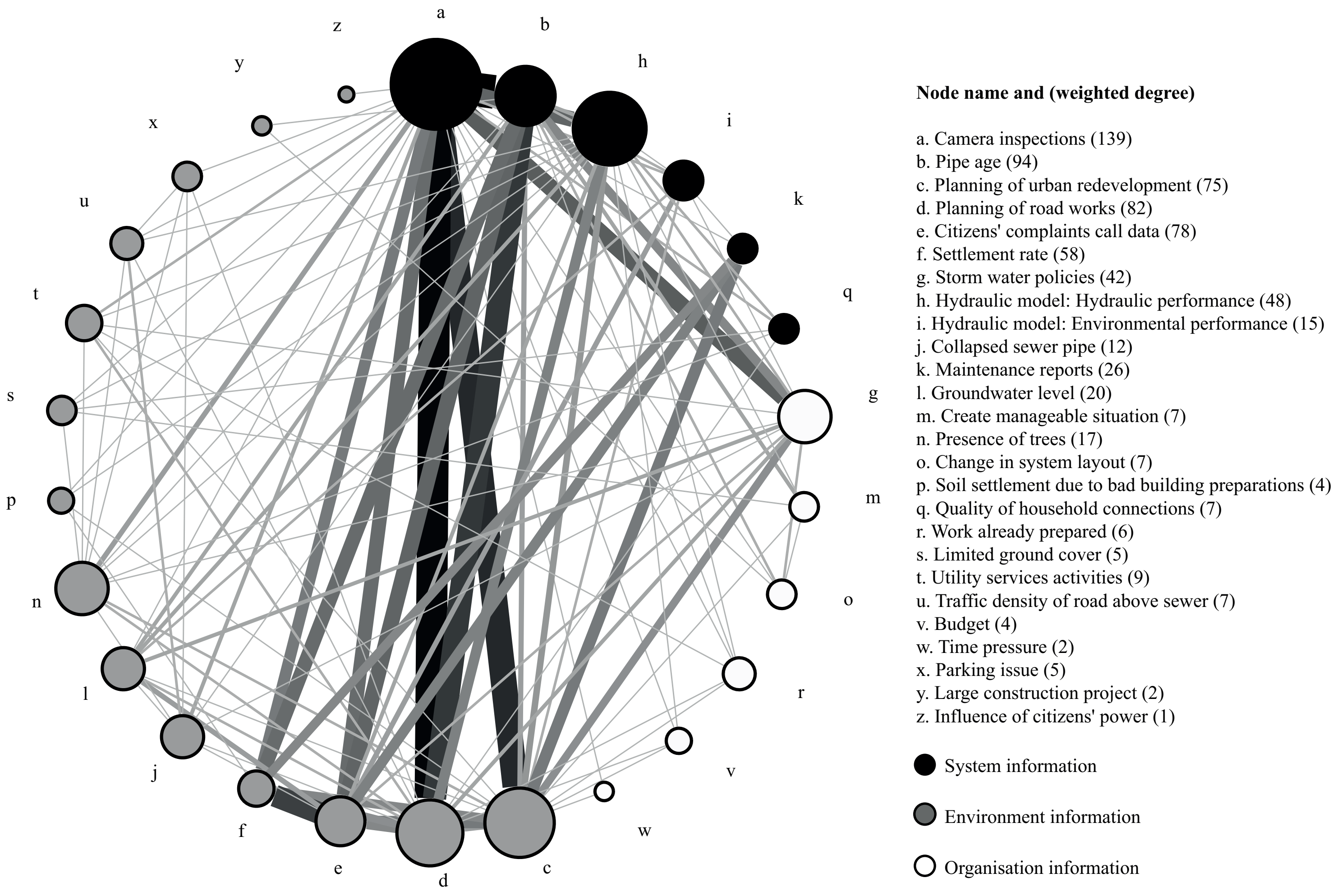


Figure 3.3: Network graph of all information combinations. Node size represents degree. Edge thickness and colour intensity represent weight (frequency) of connection.

First, the graph shows that the majority of sources, twenty-six of twenty-eight, were combined in some way. The top five of combinations with their weights are:

1. Camera inspections Pipe age: 26
2. Camera inspections Planning of road works: 24
3. Camera inspections Planning of urban redevelopment: 20
4. Pipe age Planning of road works: 18
5. Citizens complaints Settlement rate: 17

Conventional information sources, such as camera inspections or pipe age, were often mentioned (visualised by edge weight) as basic decision argumentation. The diversity of combinations between sources reflects that sewer asset managers incorporated specific local circumstances in deciding about sewer replacement. In other words, they incorporated the complexity of their decision-making context.

The listed information sources in figure 3.3 match the ones listed in figure 2.3. Yet, the analysis of the executed replacement projects yielded more specific local circumstances that were not listed in figure 2.3, including presence of trees and creating a manageable situation.

Weighing processes is another aspect interpreted from figure 3.3. When information sources were combined, these were weighed in order to opt for pipe replacement. The majority of sources were supplementary to information about the sewer system. The available information usually did not provide straightforward answers regarding the desirability of pipe replacement. Sewer asset managers fine-tuned their perceived need for pipe replacement by consulting case-specific information and their intuition. Figure 3.3 shows this notion by the variety of interactions between nodes.

In general, combining sources may further strengthen a sewer asset manager's confidence in choosing for pipe replacement, but this is not necessarily true. Information, in particular interests of other actors, may create contradicting perceptions about the need for pipe replacement. The next section will describe that.

3.4.2 Sewer replacement decisions: process

The decision-making process for sewer replacement differed per project type. Based on the typology in section 3.2, the following project types were distinguished from the 150 analysed projects.

- Single actor projects:
  - Calamities. Reactive management due to sudden damages. Initiated by the sewer asset management department. (9 % of analysed projects).
  - Projects entirely based on the replacement strategy from and initiated by the sewer asset management department (40 % of analysed projects).

- Multi-actor projects. Projects involving two or more actors in the initiation phase, which may be planned upfront or ad-hoc (51 % of analysed projects).

The following paragraphs describe the decision-making process for each type. Actual project descriptions from the interviewees serve as examples.

3.4.2.1 Single actor calamity projects

The sewer pipe replacement projects of this type were executed because of pipe damage. This was caused by either unforeseen deterioration or damage inflicted by others during excavation works. The initiation of such projects was straightforward. The event was noted, pipe quality data obtained and the problem solved (see example 1).

> Example 1. *"Potholes kept on occurring. The sewer pipes were heavily deteriorated by a connected pressurised pipe to the gravitational system, resulting in heavy corrosion from sulphuric acid. The pipe was 'eaten' to a large part. Potholes kept on occurring, leading to a quick camera inspection. Then it was found that the pipe was in very poor condition, and was quickly replaced afterwards."*

This type of decision-making processes proceeded rather rational and fast. A single actor had decision power and sequential steps led to a clear choice based on data analysis. Decision-making was driven by a sense of urgency: sewer pipe collapses and potholes are considered to be prevented at all times, because safety is at stake and hydraulic performance may be limited.

3.4.2.2 Single actor planned projects

Planned sewer replacement projects were initiated because of two main reasons. The first was operational information: analysis of conventional data (camera inspections and hydraulic models) revealing insufficient performance. The second reason for planned replacements resulted from strategic information: organisational preferences and policies about surface water quality and system layout. Where data analysis could directly lead to initiation of a replacement project, this was not the case for organisational preferences and policies. Information was weighed before decisions were made. The following two examples illustrate the difference.

> Example 2. *"The sewer appeared to be in poor condition, based on camera inspections. After the sewer project was initiated, the urban development department joined our replacement project."*

> Example 3. *"Based on inspections, the pipe quality in this area appeared to be moderate. Second, the municipality prefers to change the system's type, layout and dimensions. It was preferred to replace the combined system by a separate one and to discharge on two locations, in order to meet the demands of the national legislation."*

The decision-making process in example two was rather rational. Again, one actor had decision power and sequential steps led to a clear choice based on data analysis. A problem became apparent, often unacceptable pipe quality, and the pipes were replaced at some point in time depending on the perceived priority. Generally, the available decision support tools (see examples in section 1.2) are particularly useful in situations where primarily pipe condition is the dominant criterion such as example two, because they provide techniques to predict pipe condition and weigh this with other aspects. By doing so, it assists a sewer asset manager in setting replacement priorities more confidently.

In example 3, pipe quality information interacted with preferences and policies. Pipe quality appeared neither poor nor good, but moderate. From this perspective, the need for replacement was not evident. Yet, an additional problem appeared on the agenda as well, the changed legislative demands, which shed another light on the evaluation of costs and benefits of pipe replacement. In terms of the policy streams model, it seemed that there were two political events that contributed to the opening of a window of opportunity. It is unknown how much time this weighing process took, and to what extent each of the information sources influenced a replacement decision. Still, this project also reflected characteristics of rational decision-making. There clearly was a single actor with decision power in charge and the process evolved in sequential steps, starting with determining pipe quality, which eventually led to a choice partly based on data analysis.

3.4.2.3 Multi-actor projects

Sewer replacement projects of this type were initiated in negotiation processes between two, such as a road manager and a sewer manager (example 4), or more actors (example 5). In these projects, a mixture of information and interests developed into a negotiation process in which compromises were made.

> Example 4. *"The project was initiated by road management. Based on camera inspections, pipe quality was insufficient, which led to cooperation with road rehabilitation. The sewer needs to hold out for another twenty years. Sometimes, you can decide to join other works based on pipe age and inspections."*

The decision-making process started differently than in the single actor projects where system information performed as initiator. Here, another actor provided an opportunity, a possibility to integrate works in time and space. A weighing process followed, in which the following aspects are balanced in light of organisational preferences and policies (Van Riel et al., 2014a):

- development of system performance and related failure risk,
- investment costs for the rehabilitation/replacement works, and

- benefits of integrating works in terms of costs, distortion of liveability (nuisance to citizens, businesses and transportation) and related organisational reputation.

In example 4, the sewer asset manager decided to join road rehabilitation instead to execute sewer replacement separately at a later stage. Example 5, public works in a busy city centre, further expands the negotiation process.

> Example 5. *"When street A will be excavated anyway, sewer pipes there should be replaced as well. An urban rehabilitation plan for the entire area was set up. The system did not perform well. One of the sewer works was street B, because of a hydraulic bottleneck. District heating (part of the power distribution company) wanted to expand their capacity as well. Next to that, camera inspections revealed poor pipe quality at street B. Later inspections revealed the pipes to be in good condition instead. So, was the inspection correct? Nevertheless, the process was already in motion, meaning we could not opt-out any more. The agreements with the power distribution company were far advanced. The project just had to proceed. Despite that, the sewer at street B had to be replaced before the sewer at street A, because of traffic and hydraulics. The sewer at street B probably could have been kept for five to ten years, with today's knowledge. The entire street B was excavated and given a new design. This could have been postponed as well."*

Multiple decision-makers were directly involved in the decision-making process in example 5: sewer asset management, road management, urban redevelopment and the power distribution company. The start of the process was unclear. It could have been insufficient sewer performance, road performance, capacity of district heating or design of surface level. Information about the sewer system revealed a hydraulic bottleneck and poor pipe quality. Yet, the conclusion about pipe quality was reversed afterwards (camera inspections are not always consistent as shown by Dirksen et al. (2013). The interviewee described that despite the interpretation of the data, the project proceeded, because it was already in motion. This suggests that system information was subordinate to other involved interests. Moreover, the interviewee stated that, while looking back, the executed works could have been postponed for some time.

Several characteristics of political decision-making are recognisable. First, a problem perception, in terms of insufficient system quality or performance, was not apparent for a sewer asset manager. It only became apparent when actors shared their information about their preferred public works. Second, the perceived sewer replacement need increased when more actors were included in the decision-making process. The involved actors, including the sewer asset manager, combined information about their own system's performance with information about potential synergy from integrating the public works. At some point, a joint problem perception was reached, i.e. the occurrence of the window of opportunity, after which sewer works are initiated or added to the already planned public works. The joint problem perception means: the involved infrastructure managers do not want to miss the opportunity for integration of works, in order to share excavation costs and minimise nuisance to traffic and citizens, and to prevent negative reputation (Van Riel et al., 2014b). Third, the weight of each individual information source towards a final decision varied over time in a decision-making process, and also varied from project to project.

3.4.3 Theory versus reality

Approximately half of the analysed sewer replacement projects were decided upon in a rational decision-making process, focussed on solving a perceived problem. A problem presented itself through routine data analysis or a calamity and an appropriate measure was selected to solve it. When works of other infrastructure managers did not overlap, the sewer asset manager could initiate replacements single-handedly. In such situations, the differences between theoretical and actual decision-making are relatively small and more related to the content than the process of decision-making. This relates to the use of particular case-specific information, which is outside the scope of decision support tools.

The difference between theoretical and actual decision-making increased as soon as a sewer asset manager became involved in public space management. Then, decision-making relied on negotiations between actors. This operational decision-making process could be described by the streams model, portraying the floating and collision of problems, participants and solutions (Kingdon, 1995).

Problems exist in the perception of the involved actors who perceive its presence or absence. A problem perception may concern a combination of insufficient system performance, missing an opportunity for integrating works or unconformity with urban drainage legislation. The problem perceptions floated around and became coupled when other relevant actors became aware of each other's problem perception. Other relevant actors are infrastructure managers who work in overlapping space and time. Then, solutions (e.g. pipe replacement, road rehabilitation and redevelopment of surface level) developed into an answer to that perceived problem. When problem perceptions, relevant actors and solutions collided, a window of opportunity opened. Then, collective action was likely, i.e. probable integration of infrastructure works in space and time.

The opening of the window of opportunity is often quick: a fruitful conversation between a sewer manager and a road manager whose office desks are almost adjacent (both managers work at the same municipal organisation in the Netherlands). In such situations, the amount of problem perceptions, actors and solutions is relatively small. Yet, the process may take longer and get complex when more relevant actors and interests become involved, as illustrated by example 5. In the decision-making process, the influence of objective data about the sewer system might become subordinate to other criteria during negotiations, although it may lead to a starting point of the decision-making process.

Several typical differences between theoretical and actual decision-making for sewer replacement are:

- Decision power and budgets are divided over several actors. Each actor could decide for himself to join or leave the decision-making process, but is not in charge alone. Each involved actor can influence where, when and with whom works are executed.
- Compromises are to be made by negotiation, instead of fixed choices.
- Decisions are made in one mixed process with development of problem perceptions, instead of sequential steps.
- Actors' interests also steer the process, instead of merely objective data.

3.4.4 Synthesis and consequence

From a theoretical perspective, data is converted into information, into knowledge and into wisdom. Knowledge is needed for decision-making and action (Bellinger et al., 2004; Choo, 1996; Rowley, 2007). From a practical perspective, decision-making relies on context as well, which consists of actors' interests or specific circumstances.

Decision-making transparency is hampered by two practical challenges. The first is to create relevant knowledge from reliable data, which is not always available (Ana and Bauwens, 2007). The second is the consideration of interests of other actors and specific local circumstances.

The available decision support tools (see examples in introduction) are primarily suitable for strategic planning. Operational decision-making, especially in multi-actor settings, is beyond the scope of these tools. Then, the decision-making process may seem unclear from a sewer asset manager perspective. This is not necessarily a problem, but it becomes a hurdle when one prefers to increase decision transparency and cost-effectiveness. In multi-actor settings, the environment includes other actors, all of whom are hoping to maximise their utility, i.e. being most cost-effective. When they cooperate, and inevitably make compromises, the notion of an optimal strategy for a given actor is less meaningful, because the best strategy per actor depends on the choices of others. This notion requires team utility to be evaluated by a criterion other than cost-effectiveness, reflecting group payoff (Kraus, 1997; Parsons and Wooldridge, 2002; Sandholm, 1999). 'Sense' (Weick et al., 2005) or 'satisfaction' (Simon, 1955) are examples of evaluation criteria for group payoff, related to management of public infrastructure in this study.

3.5 Conclusions and recommendations

The objective of this chapter was to analyse how decisions for sewer replacement were made, what sources of information were used and to what extent these address the complexity of the decision-making environment. It is concluded that the current challenge for increased decision transparency and cost-effectiveness is unlikely to be solved by the current type of decision support tools for sewer asset management (see examples in section 1.2). This is caused by a more complex decision environment in reality than theoretical models portray, in which context is relatively influential. The theoretical models assume rational decision-making for problem solving related to system performance, which was applied in approximately half of the sewer replacement decisions. Still, the used information sources showed more variety than support tools require, because specific local circumstances were addressed as well.

Multi-actor decision-making processes initiated the other half of the projects, having the following characteristics. First, the process is driven by negotiations in addition to data analysis. Second, problem perceptions are not evident upfront but develop by increasing involvement of actors and awareness of each other's interests. Third, a window of opportunity opens after a joint problem perception has been reached. This joint problem perception concerns the idea that infrastructure works should be executed collectively instead of separately.

Decision-making in multi-actor settings is steered by more elements than the rational model prescribes, as the analysis showed. Although this conclusion seems evident from the available literature about multi-actor settings, it has not been tested for sewer asset management until now.

Although actual decision-making for sewer replacement is also driven by political decision-making, this does not automatically mean that efforts to increase rationality are undesirable. It helps to increase decision support in situations in which decision-making may be approached rationally, i.e. argue about replacement need more confidently. As soon as projects affect the management of public space, multi-actor settings become influential, and the rational approach alone does not suffice. Users of current decision support tools should be aware of the occurrence of multi-actor decision-making processes and limitations of these tools to cope with these processes.

More research is needed to improve sewer asset management towards increased decision transparency for higher cost-effectiveness. First, the influence of information quality on decision-making could be tested. Second, the effectiveness of the current management design and decision model, and its potential to increase cost-effectiveness, in light of multi-actor decision-making, could be assessed. And third, potential improvements in the organisational design to cope with complexity and effects on decision-making could be explored and implemented.

4 Individual decision-making: valuing information

4.1 Introduction

Increasing transparency for sewer asset management, for example for sewer replacement decisions, is difficult due to system and process complexity (see section 1.2). To this end, multiple decision support systems have been developed over time to assist sewer asset managers in optimising their maintenance planning, where 'optimal' may refer to, for example, lowest life cycle costs. These systems generally contain a mathematical optimisation procedure (single or multi-objective), a deterioration process and maintenance strategies. These normative decision support tools propose maintenance strategies over time to help the managers with their decision-making (Egger et al., 2013; Liu and Frangopol, 2005; Lounis and Daigle, 2013; Marzouk and Omar, 2012; Sægrov et al., 2006; Tscheikner Gratl et al., 2016). A general drawback of these tools is that they fail to meet decision-making in reality. First, the measures these tools propose are based on a relatively small set of data input: pipe age, CCTV inspection data and parameters about sewer system dimensions. Second, support tools that do include additional decision-making criteria (i.e. information source), for example criticality of the sewer pipes or road works, use arbitrary and static weights for each decision criterion.

Decision-making in reality, however, is based on a relatively large set of interrelated information sources, where the importance of each source varies per replacement project, depending on unique local circumstances and personal preferences of a sewer asset manager (Van Riel et al., 2014b, 2016b). Figure 3.3 illustrates this by showing the relations between a wide variety of information sources that served as decision argumentation for 150 executed replacement projects. Although the graph in figure 3.3 suggests some sources seem more important than others, no information is available yet about the actual relative importance of information sources.

This chapter is based on: Van Riel, W., Langeveld, J., Herder, P., & Clemens, F. (2016). Valuing information for sewer replacement decisions. *Water Science & Technology.* in press.

The objective of this chapter is to assess the weight of individual information sources for sewer replacement decisions, i.e. the extent to which each source is appreciated or valued by decision-makers. Two aspects are considered here. First, the perceived importance of information sources for hypothetical sewer replacement decisions, and second, the presence or absence of a shared frame of reference for judging about this relative importance. To this end, specific contextual information is excluded from the study. Further insight into these relative importances creates better understanding of the decision-making behaviour of sewer asset managers. This understanding is required to increase decision transparency and cost-effectiveness in sewer asset management.

4.2 Research approach

4.2.1 Data collection instrument

A digital questionnaire was set up in 'Survalyzer' (software for online surveys), containing pairwise comparisons between relevant decision criteria. These criteria, the variables, were selected from (Van Riel et al., 2016b), in which decision argumentation of 150 sewer replacement projects in the Netherlands was analysed through interviews. Table 4.1 lists the mentioned decision criteria from these interviews mentioned most often. It is essentially the same information as presented in figure 3.1. Here a distinction is made between the actual source and the information that is obtained from it. Yet, for readability and consistency, these are all referred to as information source, although this is not entirely accurate. The right column shows how often the information source was mentioned, normalised with respect to the total number of replacement projects. A project is a defined set of activities to replace sewer pipes at a predefined location, with a given budget and time limit. The length of pipe replacement per project in the Netherlands generally ranges from ten to five hundred metres.

Table 4.1: Indicated decision argumentation mentioned more than five times

Source	Obtained information	Relative occurrence frequency
CCTV inspection images*	Pipe quality	0.57
Citizens' complaints calls*	Insufficient hydraulic performance	0.29
Complaint calls, feedback from maintenance activities	Gaps in the road*	0.26
Hydraulic model	Hydraulic performance*	0.19
Hydraulic model	Environmental performance*	0.17
Sewer system management database	Pipe age*	0.13
Road manager	Planning of road works*	0.13
Urban planner	Planning of urban development*	0.13
Soil settlement measurements	Soil settlement differences*	0.08
Storm water policies*	Preferences for system type or layout	0.06

* mentioned by the interviewees as such and included in the questionnaire in this wording

Citizens complaint calls concern feedback of the public about blocked gully pots, occurrence of stench or blocked household connections. These aspects may indicate insufficient hydraulic performance. Information about the occurrence of potholes or gaps in the road's surface are typically caused by ingress of soil in the sewer, influencing the stability of the road on top. This information is usually obtained through complaints calls or through feedback from maintenance activities. Hydraulic performance concerns the system's transport capacity to minimise flooding. Environmental performance relates to the system's storage capacity in order to minimise overflow of wastewater on surface water. Both aspects are obtained from a hydraulic model. Pipe age is data retrieved from the sewer system management database. It typically serves as an indicator for pipe quality for operational replacement decisions. Pipe age is important for strategic decisions as well, since it is the basis for long term budget allocations. The planning of road or urban development works are communicated internally at the municipality. This may be through ad-hoc face to face discussions or through collective planning procedures. Uneven soil settlement rates may cause open joints, fractures, loss of storage capacity and fouling for sewer sections without pile foundations. Soil settlement differences on a network level are measured by measuring the sewer invert level at the location of a manhole. settlement differences on pipe level are measured by analysing the sewer's slope profile with the CCTV tractor (Dirksen et al., 2014). The obtained measurement data is converted typically by means of intuitive reasoning and rules of thumb into judgments about the severity of the settlement rates, and consequently, need for sewer pipe replacement. Storm water policies relate to the organisational preferences about urban water strategies concerning system type and layout. This decision criterion concerns the long term urban drainage strategy, including measures to cope with climate change (Kleidorfer et al., 2013), and is usually not a direct reason to replace sewer pipes but supplementary to other decision criteria.

The questionnaire was tested and adjusted twice before it was completed. Feedback of the first test session showed the wording of some variables were to be changed and the number of included variables were to be reduced from fifteen to ten. A maximum of ten variables was selected to minimise fatigue effects when filling in the survey. A second test was initiated to create a dataset that was used to evaluate the data analysis procedures for inconsistencies. The wording in the introduction and variable names were slightly changed for clarity. The final questionnaire started with an introduction of the research and an example how to weigh and fill in the paired comparisons. Second, the respondents were asked about their gender, age, years of working experience, whether they work at a municipality and whether they work in an area prone to soil settlement. Third, the ten variables were randomly offered in a complete design (Street and Burgess, 2007) in forty-five pairs, asking respondents for a preference for one variable per pair. At the end, the respondents were thanked and asked for feedback.

4.2.2 Sample selection

The target population is Dutch sewer asset managers. As such, judgmental sampling was applied. RIONED Foundation (centre of expertise in urban drainage in the Netherlands) was asked to distribute the survey, because they have contact data of all urban drainage departments at Dutch municipalities. On 25 November 2013, they e-mailed an invitation for participation in the survey to all 407 municipalities in the Netherlands (one e-mail per municipality). A reminder was sent at 3 December to increase the response.

4.2.3 Data analysis

The questionnaire was anonymous, implying no data about the respondents, their organisation and their sewer system was collected. Such metadata is not relevant here, because specific context is explicitly omitted from the questionnaire in order to assess whether a shared frame of reasoning is present.

The intangible property, weight or importance of information, was assessed by applying Thurstone's law of comparative judgment, case V (Thurstone, 1927a). Another common approach for comparative judgment is to use the Analytic Hierarchy Process (AHP), developed for multi-criteria decision-making (Saaty, 1987). The AHP is essentially an expansion of the pairwise comparison approach, creating a hierarchical structure of the decision criteria that are evaluated by paired comparisons. The main difference between the comparison procedure is that comparing pair through Thurstone's approach requires the respondents to express a preference only, while the AHP requires the respondents to rate each preferred variable, usually on a 1-9 scale. The reciprocal of the given rate is associated with the variable in the same pair that is not rated, i.e. $a_{ij} = 1/a_{ji}$. Hence, the AHP method puts an additional cognitive load on the respondents.

Thurstone's model assumes that a variable's quality is normally distributed on a psychological scale. It describes that different people may have different opinions on the quality of a variable. Each variable's T quality score (the perceived value) is taken to be the mean quality of the corresponding normal distribution. Each respondent N is presented with every $0.5 \cdot (T^2 - T)$ possible pair of T items, and is asked which of two items is more favourable to the issue in question. An individual chooses the alternative with the highest perceived utility, which he realises from the quality distributions of the two variables in the pair under consideration. For each pair of items the proportion is obtained (the empirical probability) of times one variable was judged to be more favourable than the other. From the empirical probabilities of each pair, the mean quality score of each variable can be calculated using the normal cumulative density function.

A respondent is not always consistent in his comparative judgment from one occasion to the next. An inconsistency occurs whenever a circular triad is present in the judgments (Kendall and Babington Smith, 1940). A circular triad is illustrated as follows: item A is preferred over B, B over C, and C over A. The greater the number of circular triads in the data, the more inconsistent a respondent is said to be (Thurstone, 1927b). Consistency in the AHP approach is assessed with the 'consistency ratio' (Saaty, 1987). It is interesting to assess whether individual consistency is correlated to the working experience of the respondents, because working experience is typically regarded as important to make sound decisions in sewer asset management. Next to internal consistency, validity of the results may also be analysed by determining concordance between judges by applying statistics described by Kendall (1938) and Kendall and Babington Smith (1940).

The following aspects were analysed.

1. The questionnaire results from Survalyzer were converted to a $T \cdot T$ comparison matrix for all respondents.
2. The mean quality scores per variable were calculated from the empirical probabilities in the comparison matrix.
3. The coefficient of consistence, *zeta*, per respondent was calculated. *Zeta* is the ratio of the number of circular triads each respondent makes and the maximum possible number of triads. A *zeta* of 0 equals complete inconsistency and 1 equals complete consistency (Cohen, 1960).
4. Kendall's *tau* test for every $0.5 \cdot (T^2 - T)$ possible pair of respondents was applied to assess concordance between respondents. This non-parametric test computes the correlation between ranked data, with the test result *tau* ranging between -1 for complete disagreement and 1 for complete agreement. 0 equals no correlation.
5. The coefficient of agreement was calculated to assess concordance for the entire sample. This statistic, u, represents the extent of concordance for all judges together, where $u = 1$ equals complete agreement (Cohen, 1960).
6. The relation between the number of years of working experience and individual consistency was assessed. Kendall's *tau* test was used to test whether both variables are correlated.

The assumptions underlying the law of comparative judgment, case V are debatable (see Sjöberg, 1962), especially equal and independent variance for all variables and between respondents. Yet, it is a reproducible approach to analyse intangible properties of information that provides plausible results. Next to that, the participants make choices in hypothetical situations, which can differ from their choice behaviour in reality. The goal of this study is however, not to mimic reality, but to identify a general framework of reasoning.

Table 4.2: Sample characteristics (n = 177) with rounded percentages

Gender	Male 92 %	Female 8 %			
Age (years)	<30 25 %	30-39 33 %	40-49 27 %	50-59 14 %	60≥ 7 %
Working experience (years)	<10 25 %	10-19 33 %	20-29 27 %	30-39 14 %	40≥ 2 %
Work at municipality?	Yes 98 %	No 2 %			
Municipality in settlement prone area?	Yes 31 %	No 68 %	Not working at municipality 2 %		

4.3 Results and discussion

4.3.1 Sample characteristics

The final response rate was 43 %, yielding 177 completed responses from 407 invitations. 106 respondents (26 %) left the questionnaire before finishing it, resulting in a non-response of 31 %. The average completion time was 10.4 minutes. Table 4.2 shows several sample characteristics of the 177 completed responses.

The respondents not working at a municipality were excluded from the data for further analysis, resulting in a final sample size of 174.

The average age of the respondents is 46 years and the average working experience is 17 years, which indicates the urban drainage sector is relatively aged and experienced.

4.3.2 Variables' quality scores

The ten selected decision criteria were put onto a relative psychological scale, shown in figure 4.1. The scale unit is expressed in the number of standard deviations from the mean quality score. The numbers do not have intrinsic meaning: they may be shifted by choosing another zero point or scale size and, thus, only indicate the relative distance between the points. Here, the least important variable was chosen as zero.

Figure 4.1 shows that sewer asset managers perceive camera inspection images as the most important information source from these ten variables. This can be explained by the fact that performing and evaluating inspections is normalised and often used in practice as the primary source of information, despite the drawbacks of the method (Dirksen et al., 2013). Information about road or urban development works was found to be important considering the initiation of sewer replacement projects (Van Riel et al., 2016b). Apparently the respondents value camera inspections higher than information about the planning of other public works. It is surprising that citizens' complaint calls were valued relatively high. The municipal complaint registration and solving procedures are usually found to be ineffective in practice. Gaps in the road is valued relatively high, although this type of information requires immediate action. Yet, such gaps typically do not occur along the length of the sewer section, implying local repair works are preferred over replacement of pipes. Environmental performance is considered less important than hydraulic performance. Loss of storage capacity may be compensated by an increased cleaning frequency. Yet, replacing individual pipes may only partly compensate loss of storage capacity, because environmental performance relates to the scale of the catchment while the replacement project relates to object scale. This may be the explanation for its positioning on the scale. Storm water policies are positioned plausibly on the scale since this is supplementary to other decision criteria. Pipe age is considered least important for operational sewer replacement decisions, although it was mentioned as a criterion in 13 % of the executed replacement projects (see table 4.1). Overall, information about pipe quality obtained by CCTV data is valued higher than any other type of information, including information about the planning of other public works or measures for climate adaptation.

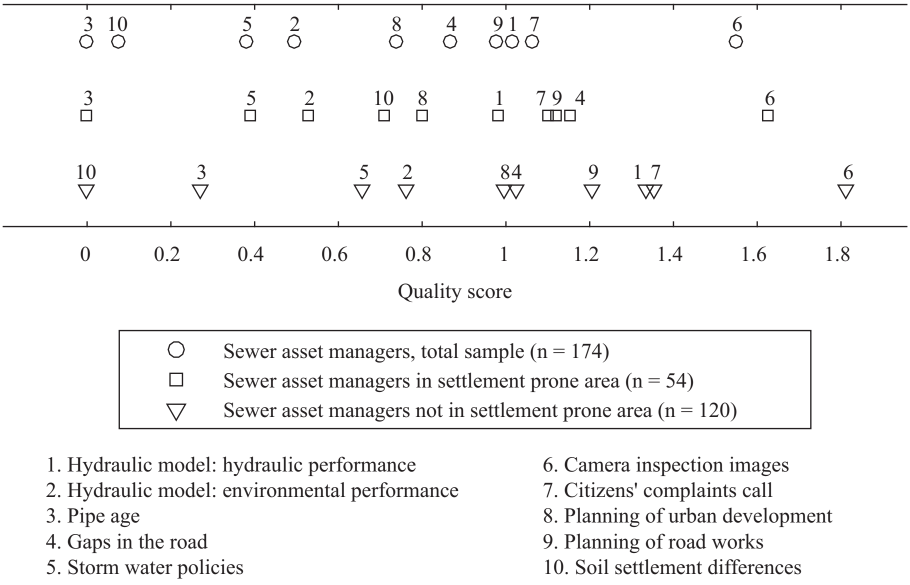


Figure 4.1: Scale values of perceived importance of information for sewer replacement decisions

Several differences can be observed between the respondents working in areas with and without the influence of soil settlement. First, information about soil settlement was considered least important for areas that were not prone to it. This information source is considered significantly, and logically, more important in areas prone to settlement. Second, camera inspections were considered more important in areas that are not prone to settlement. A possible reason is that an important failure mechanism in stable soils (pipe degradation) is easier detectable by camera inspection than an important failure mechanism in settling soils (change of storage capacity and hydraulic performance). Therefore, the usefulness of the information source might be perceived higher, depending on local soil conditions. Third, hydraulic models to assess hydraulic and environmental performance were also considered more important in areas that are not prone to settlement. A possible explanation is that hydraulic models have a higher chance of producing useful results, at least for dry weather conditions, because of a lack of data about uneven changes in sewer pipe gradients and effect on hydraulic performance.

4.3.3 Consistency and concordance

Are the respondents' answers consistent? As indicated in section 4.2.3, the spread between the variables is an indication of the perceived quality difference. It is also an indication of the respondents' capability to discriminate between the variables' qualities. Figure 4.2 shows the *zeta* statistics in a cumulative probability distribution.

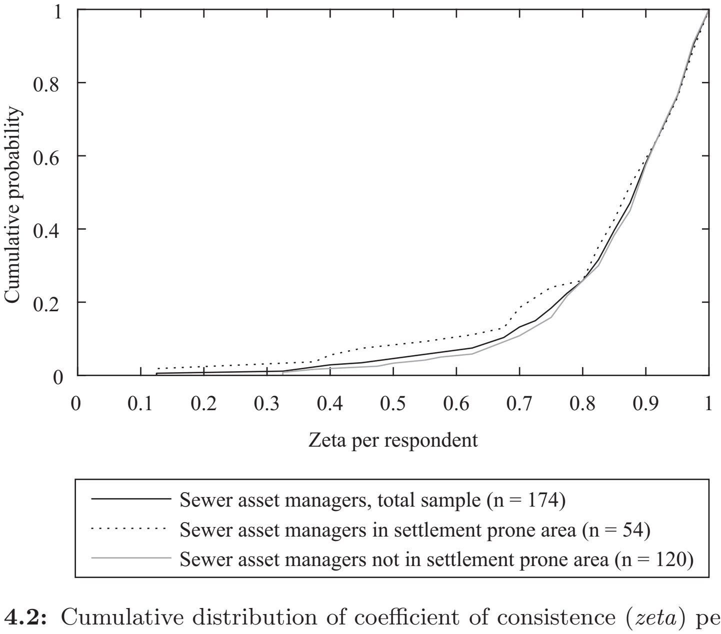


Figure 4.2: Cumulative distribution of coefficient of consistence (*zeta*) per respondent

Figure 4.2 shows that the majority of the respondents, approximately 70 %, have a *zeta* value of at least 0.8. This means that the group is fairly consistent in their judgments, implying that they are capable of discriminating between the variables. Thus, it is concluded that most of the respondents are trustworthy judges. It also implies that small differences between variables qualities are probably caused by the fact that the quality differences is small, i.e. almost equally important information.

Figure 4.3 shows the relation between the years of working experience and their individual coefficient of consistence. It shows no clear relation between the coefficient of consistence and the number of years of working experience. The result from Kendall's *tau* test ($\tau = 0.76 \cdot 10^{-2}$) shows both variables are approximately uncorrelated. These results suggest that the assumption of more working experience equals higher consistency does not hold.

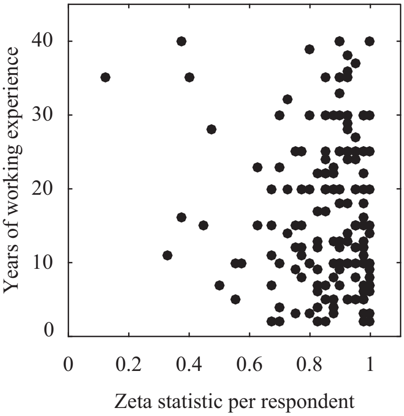


Figure 4.3: Relation between coefficient of consistence (*zeta*) and years of working experience

Do the respondents agree with each other, regardless of their consistency? Figure 4.4 shows the results in a cumulative distribution function. Agreement means that respondents agree both in their consistencies and their inconsistencies. The data in figure 4.4 is approximately normally distributed, implying the sample mean is the best estimator to judge about their overall concordance. The sample means are higher than zero (approximately 0.2), indicating reasonable concordance between the judges. This suggests the presence of a shared frame of reference for judging the relative value of decision criteria. The coefficient of agreement supports this suggestion.

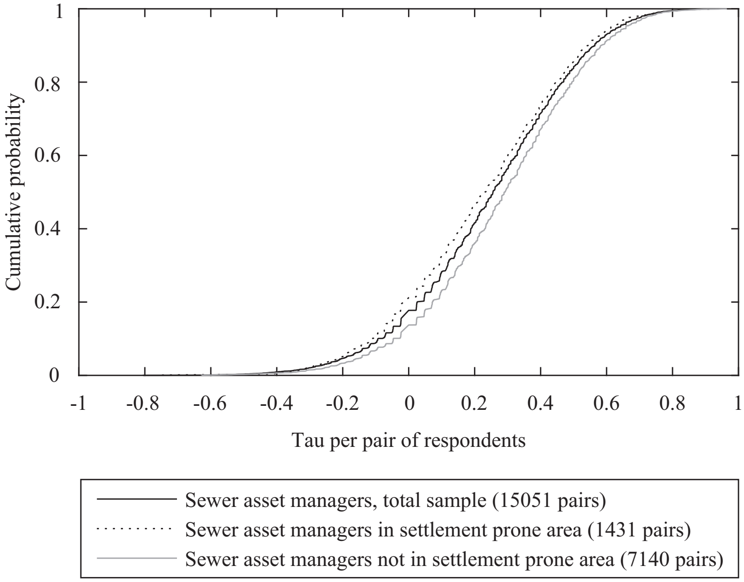


Figure 4.4: Cumulative distribution of coefficient of concordance (tau) between pairs of judges

The coefficient of agreement u for the total sample equals 0.21. For settlement prone areas: $u = 0.19$. For areas not prone to settlement: $u = 0.24$. These results show that sewer asset managers in areas not prone to settlement agree slightly more with each other compared to the other groups. Figure 4.1 supports this result by a larger spread of the variables. All three u values are statistically significant at the 95 % confidence interval ($p << 0.001$). These results mean that the respondents show significant agreement in their judgments, i.e. the judging is not done at random and a common line of thinking is apparent.

The applied Thurstone's model of paired comparison may be used to produce weights in multi-criteria decision support models. Yet, given the importance of specific local circumstances, the paired comparison procedure would have to be repeated for every setting the decision support tool is applied to.

4.3.4 Relation to decision-making in reality

The unique circumstances of a real sewer replacement project were omitted in this study. This could decrease the agreement between respondents, because they judge about their preferences from different perspectives, i.e. they use different frames of reference for their judgments. Several respondents mentioned that in the feedback section at the end of the questionnaire. They found it difficult to make a preference judgment at each pair, because they missed context. For example, in replacement project 1, they would prefer variable A over B, but would choose variable B over A in replacement project 2 depending on local circumstances. The content of these comments show that deciding about sewer replacement is an art of fine tuning, combining and negotiating about available information and interests of other actors, due to a variety of local circumstances. This does not mean however, that a common frame of reference is absent.

4.4 Conclusions

This study aimed at analysing the perceived importance of decision criteria in hypothetical sewer replacement decisions and the presence of a shared frame of reasoning among Dutch sewer asset managers. It is concluded that conventional CCTV images are valued most and that the majority of decision criteria are supplementary to this decision criterion. It suggest that the theoretical replacement strategy is primarily system oriented. This conclusion supports the analysis of the executed replacement projects.

A shared frame of reasoning about the relative value of decision criteria is indeed present. Despite the important influence of specific local circumstances, sewer asset manager appear to be comparable in their manner to judge about the importance of information.

Working experience is not correlated with consistency in judging about the value of information. The described results allow taking a peek into the way sewer asset managers weigh or value sources of information relevant for initiating replacement decisions. Although this shared frame is present, the respondents' feedback implies that purely combining information sources cannot drive the decision process for sewer replacement, although this is essentially how current decision models portray sewer replacement decisions. The trade-off of interests, values and information other than conventional camera inspections images plays a prominent role, which is neglected in current decision models for sewer asset management. Therefore, it is recommended to introduce relevant intangible decision factors into current decision models. To do so, decision processes in sewer asset management should be analysed in relation to their context due to the important influence of specific local circumstances. In order to close the gap between support tools and reality, model developers could pay more attention to multi-criteria decision support tools that can incorporate tacit next to explicit knowledge. Of course, the incorporated tacit knowledge needs to be properly motivated and evaluated frequently, because it should remain transparent for every user and insights may evolve over time.

The presented results illustrate how Dutch sewer asset managers make their replacement decisions. Despite specific local circumstance influencing sewer replacement decisions in reality, a common frame of reasoning about the relative value of decision criteria is present. This might be explained by the sewer asset management education in the Netherlands. As such, it may be interesting to study the existence of a common frame of reasoning in other countries, having differences in for example education provision, organisational setup and culture, sewer asset management challenges, perception of citizens and available budget.

5 Individual and group decision-making: game setup

5.1 Introduction

Among engineers, it is generally considered that extensive and good quality data about infrastructure performance is most important for making sound decisions regarding infrastructure maintenance. Multiple decision support systems have been developed for various infrastructures to assist managers in optimising their maintenance planning. These systems generally contain an mathematical optimisation procedure (single or multi-objective), a deterioration process and maintenance strategies. These normative decision support tools propose maintenance strategies over time to help the actual infrastructure managers with their decision-making (e.g. Egger et al., 2013; Liu and Frangopol, 2005; Lounis and Daigle, 2013; Marzouk and Omar, 2012; Sægrov et al., 2006; Tscheikner Gratl et al., 2016). The operational decision process, however, often occurs as a multi-actor planning problem, because of preferred integrated rehabilitation of adjacent infrastructures, motivated by reduction of costs and nuisance to traffic and citizens. Each infrastructure has its own technical and functional lifetime, and corresponding rehabilitation strategy in space and time. Yet, these are located on top of or right next to each other. The combination of an overall preference for integrating public works and differences in spatio-temporal rehabilitation strategies causes the involved decision-makers to make compromises about whether, where and when they cooperate. This implies decision-making is based on negotiations between different stakeholders in addition to the data (Allison, 1971; Lindblom and Woodhouse, 1993; Stone, 1988; Sylvan et al., 1990). As a result, the influence of available information about an infrastructure's performance might become subordinate to other criteria during negotiations (Van Riel et al., 2016b). The quality of the underlying data itself, for example closed circuit television (CCTV)

This chapter is based on: Van Riel, W., Post, J., Langeveld, J., Herder, P., & Clemens, F. (2016). A gaming approach to networked infrastructure management. *Structure and Infrastructure Engineering.* in press.

footages to determine structural condition of sewer pipes, has been shown to be error prone (Dirksen et al., 2013; Van der Steen et al., 2014) and does not allow to predict structural condition. As a consequence, it leaves the involved managers to rely on intuition (Van Riel et al., 2014b). This leads to the question, does more accurate data about actual a system's structural condition lead to other or better decision-making?

This question has been quantitatively addressed for individual decision-making (Chorus et al., 2007; Keller and Staelin, 1987), but not for multi-actor settings. Since sewer rehabilitation works are often combined with other public works, a research tool has been developed that incorporates both the concepts of information quality and human interaction. To that end, this chapter introduces a first suggestion for such a research instrument in the form of a serious game, 'Maintenance in Motion'. The presented serious game should not be seen as a normative decision support tool to support infrastructure management in practice. Instead, the game is a descriptive instrument to analyse the influence of information and cooperation in the decision-making of infrastructure managers in reality.

5.2 Serious games: what and why?

The previously portrayed decision-making for urban infrastructures occurs within a complex system (see section 1.2). In order to increase understanding in such complex decision-making environments, methods are needed that incorporate both the concepts of system and process complexity. Serious gaming (or gaming simulation) is a method that allows to do so, where the term 'serious' refers to 'gaming with a purpose beyond pure entertainment'. The game itself can be defined as a rule-based formal system with a variable and quantifiable outcome, where different outcomes are assigned different values, the player exerts effort in order to influence the outcome, the player feels attached to the outcome, and the consequences of the activity are optional and negotiable. The term 'quantifiable outcome' means that the game outcome is unambiguous (Juul, 2003).

Simulation games are a simplification of a part of reality, allowing participants to experiment with decision-making and reflect on the outcomes. These experiences are relevant for a better understanding of how complex social-technological systems work. In such games, multiple people enact a part of reality in order to gain understanding and learn from their experience. This notion of understanding and learning leads to a typology of three game types (De Caluwé et al., 2012; Mayer and Veeneman, 2002).

- Research: the game is a research environment that allows experimental manipulation and observation of players. The game initiator is focused on learning through the game in order to get empirical data or develop theory. The game presented in this chapter is a research game.

- Learning: the game is an experiential environment that allows the players to learn about the system at hand.
- Intervention: the games is an experimental environment in which both researchers and participants can make inferences for real decision-making.

Games have been particularly developed to increase understanding in land-use planning problems for research or training purposes, for example in agricultural contexts (e.g. Martin et al., 2011; Speelman et al., 2014) or urban contexts (Cecchini and Rizzi, 2001; Mayer et al., 2005, 2004; Wärneryd, 1975). The game presented in this chapter is an urban planning research game. Typically, urban planning games support decision-making in reality, and thus, provide a learning environment. These games are usually open games, in which the game outcome is not predefined but discovered during interactions (Mayer et al., 2005). Open research games typically have an almost unknown solution space, requiring interpretive analysis methods like observations or group discussions. Yet, this hampers reproducibility, systematic comparison and testing of hypotheses about the relation between game outcomes and player behaviour. Closed research games on the other hand, typically contain relatively small solution spaces, measurable variables and quantitative outcome analysis. These characteristics are relevant for experimental game purposes. Experimental gaming research differs from game theoretical research. Game theory is concerned with the, usually mathematical, analysis of interacting decision-makers. Game theory assumes the decision-makers act perfectly rational and strategically by taking into account their expectation of other decision-makers' behaviour, in order to maximise some utility function (Osborne and Rubinstein, 1994). In contrast, gaming assumes agents are not rational, goals are partly unknown and agents display opportunistic behaviour (Mayer and Veeneman, 2002).

According to game theory, games are competitive or cooperative. Competitive games require players to form strategies that directly oppose the other players in the game, for example chess. In contrast, cooperative games model situations involving two or more individuals whose interests are neither completely opposed nor completely coincident. The word cooperative is used because the two individuals are supposed to be able to discuss the situation and agree on a rational joint plan of action (Nash, 1953). A third category exists, collaborative games, in which all the participants work together as a team, sharing the payoffs and outcomes. The game presented in this chapter includes collaborative simulation. Collaboration as a team differs from cooperation among individuals in that cooperative players may have different goals and payoffs where collaborative players have only one goal and share the decision rewards. The challenge for players in a collaborative game is working together to maximise the team's utility (Zagal et al., 2006, p. 26).

5.3 Game design

This section includes a description of the game design process and game calibration methods. Both aspects are commonly absent in literature containing game development.

Designing a simulation game essentially consists of the following steps: analysing the system and problem being addressed, transforming this analysis into a conceptual framework of reality and transforming this framework into a game (Duke, 1980, 2014).

5.3.1 System analysis and conceptual model

The system and problem to address were analysed from a sewer system perspective, consisting of two steps. First, an overview of current decision-making for sewer pipe replacement was obtained by literature review and interviewing sewer asset managers at Dutch municipalities. Emphasis was put on retrieving the variety of motivations for deciding upon sewer pipe replacement (Van Riel et al., 2014b). Second, actual sewer pipe replacement projects were analysed, through interviews, in terms of decision argumentation and decision-making process. This analysis illustrated the variety of trade-offs sewer asset managers had to make, especially when integrating their works with other public works. The most relevant actors were urban planners, street managers, flora and fauna managers and utility service managers. It was found that decision-making in reality for replacing sewer pipes has both rational and political characteristics (Van Riel et al., 2016b). From a rational point of view, decision-making is portrayed as choosing the alternative that reduces the perceived problem most. The political point of view on decision-making focusses on multi-actor settings and processes. Thus, a hybrid conceptual model for the game design is needed that contains both perspectives, reflecting the concepts of system and process complexity. Figure 5.1 shows this model, combining a rational single actor model and a multi-actor political model for operational decision-making. Whenever one actor is involved, the model is rational. As soon as two or more actor become involved, the model reflects dynamics of multi-actor decision-making (negotiations, making compromises and seeking opportunities).

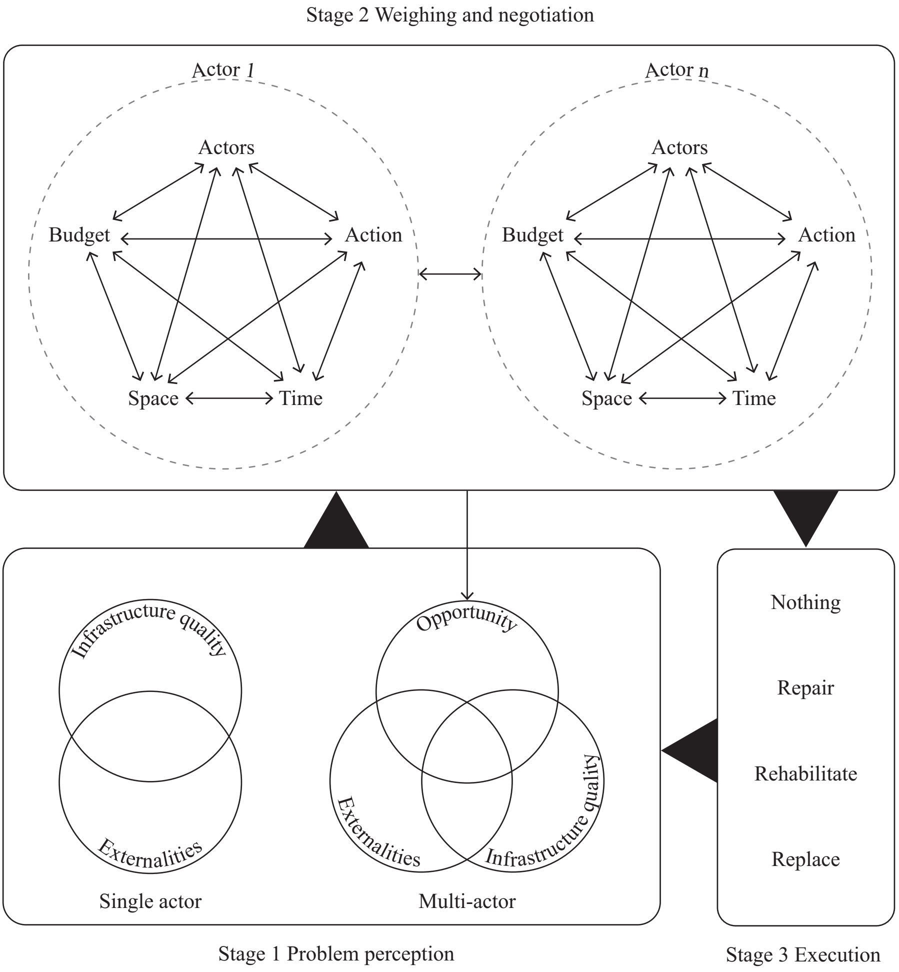


Figure 5.1: Conceptual model of decision-making for urban infrastructure rehabilitation

Problem perception starts with a combination of analysis of infrastructure quality and externalities such as organisational strategy or national legislation. When a manager perceives a problem in light of his organisational strategy, i.e. presumed or projected insufficient system performance, works are planned. This planning can be time or condition dependent. Then, a weighing and negotiation stage is entered in which the planned work is prepared for potential execution. The involved infrastructure manager balances five interacting elements to choose some action. These elements are:

- actors: who is available to integrate works with,
- action: what action is needed,
- time: when is an action needed,
- space: how much action is needed, and
- budget: what is the available budget?

These five elements are weighed, in light of the problem perception, from which a choice for some action is determined and executed in the last stage. Multiple actors may be involved, possibly influencing each other's weighing process, which causes an actor's problem perception to be redefined through opportunity to integrate works. For example, a sewer manager did not plan any replacement works at a particular location, but still decides to so when he notices road rehabilitation is to be executed there. In other words, actors could display opportunistic behaviour.

5.3.2 Building the game model

The game's objective is to answer two main questions regarding operational decision-making for public infrastructures. First, what is the influence of information quality on decision outcome? And second, what is the effect of cooperation between involved actors on decision outcome? To answer these questions, an experimental research setup was chosen that allows hypotheses testing about the relation between game outcome and player behaviour. The core idea of the game is that the players have complete freedom in how to manage their infrastructure, given their predefined objective. Analysis of the positioning and spread of the player performance scores answers the two research questions. Due to the experimental setup, the game needs a relatively small solution space, measurable variables and a quantitative outcome analysis. The players should let go of their own day-to-day frameworks for reasoning, in order to focus their decision-making on what is presented in the game itself and limit the influence of intuitive reasoning. In order to maximise the future player sample size, it should be possible to play the game with people with different levels of knowledge or experience in infrastructure management. These considerations for research setup, framework for reasoning and maximising sample size require the game to be an extensively simplified reality. Moreover, increasing complexity by including a large number of interacting components would put a relatively high cognitive load on the players, which would not be beneficial for gameplay and results (Sweller, 1988).

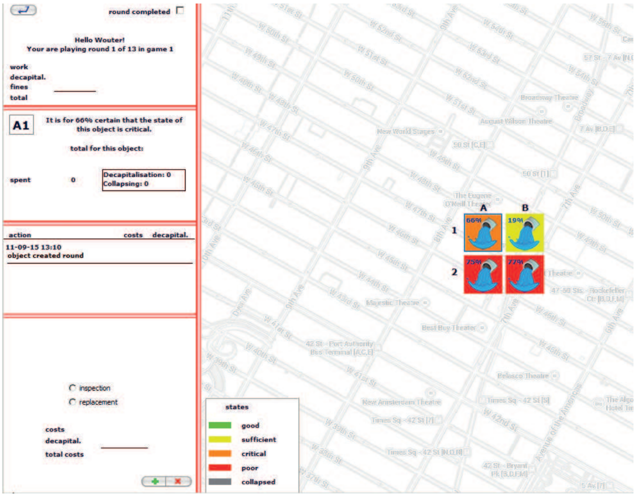
Building a game model involves developing a variety of elements. From all game design elements (Duke, 2014), the most relevant for this game are presented here. These are game scenario, game procedures (rules and mechanics) and player involvement techniques.

5.3.2.1 Game scenario

The game simulates operational decision-making regarding management of an imaginary infrastructure. The game world contains four infrastructures managed by four individual players: gas, sewer, street and drinking water. Each infrastructure consists of separate objects that deteriorate and require management over time. Each object is associated with a random initial quality level, which in turn is associated with a cost for rehabilitation. The goal of each player is to manage its infrastructure as cost-effective as possible. Figure 5.2 shows a screen shot of Maintenance in Motion.

Since the game intends to address the combined influence of information quality and player negotiations, reflecting system and process complexity, four gaming simulations were set up that are played sequentially:

1. single player game with perfect information about infrastructure quality,
2. single player game with imperfect information about infrastructure quality,
3. multi-player game with perfect information about infrastructure quality, and
4. multi-player game with imperfect information about infrastructure quality.



round completed ☐

Hello Wouter!
Your are playing round 1 of 13 in game 1

work
decapital.
fines
total

A1 It is for 66% certain that the state of this object is critical.

total for this object:

spent 0

Decapitalisation: 0
Collapsing: 0

action	costs	decapital.
11-09-15 13:10 object created round		

○ inspection
○ replacement

costs
decapital.
total costs

Figure 5.2: Maintenance in Motion, example of sewer player

The term ‘single player game’ means non-cooperative: players play without coalitions, i.e. they are assumed to act independently, without collaboration or communication with any of the others (Nash, 1951, p. 286). In the multi-player or collaborative games, players first make non-cooperative choices (planning stage) and then enter a collaborative phase where they discuss potential collective rehabilitation on equal locations in the grid (execution stage). This sequential process is based on the conceptual model in figure 5.1. The gameplay sequence is depicted in figures 5.3 and 5.4, showing the game flowcharts for the single and multi-player simulations. More detailed versions of flowcharts are presented in appendix B.

In the multi-actor games, the players are explicitly explained upfront to operate as a single entity, e.g. a municipality, to manage their infrastructure from a public point of view in order to address the main game objective. This concept of a single entity may differ from reality, where multiple entities can have different objectives, and where water companies, sewer operators and gas utilities each aim at achieving their own goals most cost-effectively, despite higher public costs.

Information about infrastructure quality is reduced to an aggregate variable, a colour, which in reality consists of a variety of underlying information sources. The primary function of information about an infrastructure’s quality is to plan actions in time to manage its functioning. Information quality is defined as “the information inherent usefulness to consumers in assessing the utility of an alternative” (Keller and Staelin, 1987, p. 200). As such, perfect information would be 100 % certainty about both the current and future state of an object in order to time replacement perfectly. Yet, in order for the game to reflect reality in this regard, perfect information is defined here as having 100 % certain information about the objects’ current state only, i.e. the observable state equals the actual state. The players can only guess the future state, based on the given information about the deterioration process. Imperfect information is defined here as having uncertain information about the objects’ quality, i.e. the observable quality may differ from the actual quality. Note that these definitions of perfect and imperfect differ from the game theoretical definitions, where perfect information assumes the game participants are fully informed about each other’s moves (Osborne and Rubinstein, 1994).

In the multi-player games, useful information to a players relates to the actions of other players as well, next to object state. Therefore, players are informed about each other’s actions by a ‘joint checkbox’ (figure 5.5), which facilitates collaboration. Checked implies a players prefers to replace; unchecked implies a player prefers not to. Players can check or uncheck their own checkbox as many times as needed to assess whether cooperation is worthwhile or not.

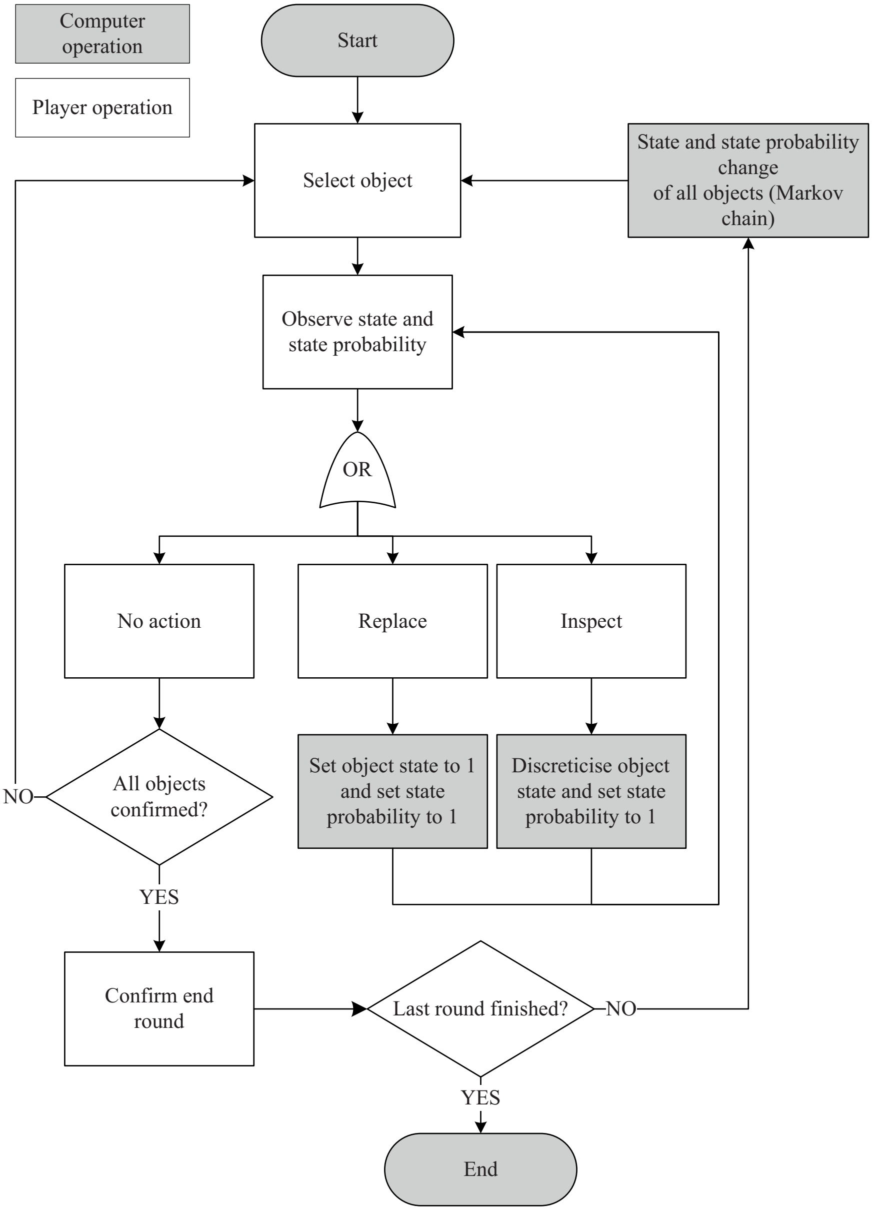


Figure 5.3: Game flowchart of single player game

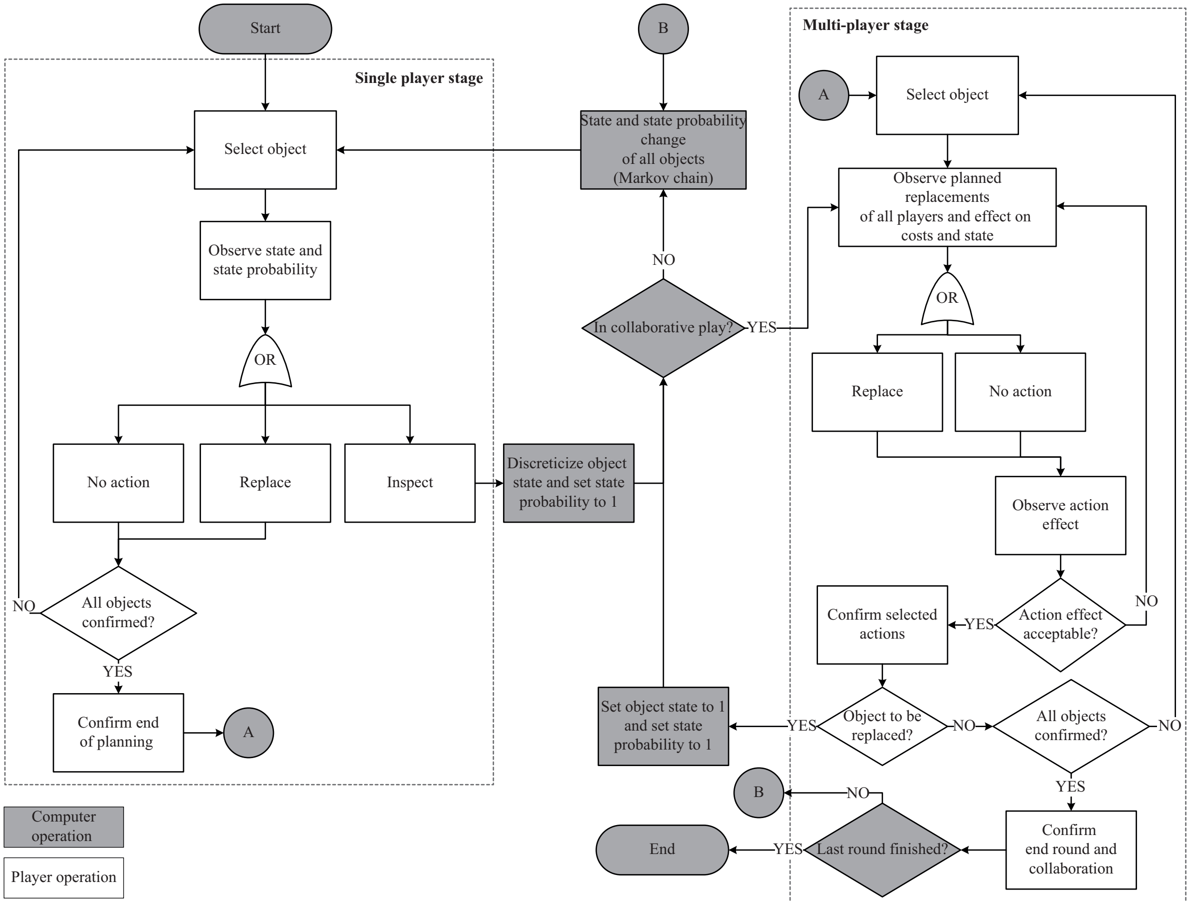
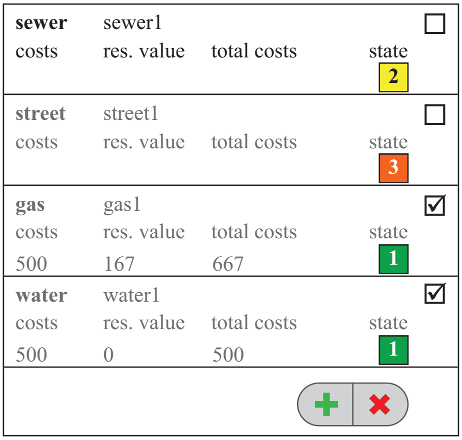


Figure 5.4: Game flowchart of multi-player game



sewer sewer1 ☐
costs res. value total costs state 2

street street1 ☐
costs res. value total costs state 3

gas gas1 ☑
costs res. value total costs state
500 167 667 1

water water1 ☑
costs res. value total costs state
500 0 500 1

Figure 5.5: Joint checkbox for group decision support

A typical Dutch residential street is used as a reference system, which serves as the basis for the physical and financial infrastructure interactions. Figure 1.2 shows a cross section of this reference system. Gas, drinking water, roads and sewers are considered to be the most important infrastructures in this system. This reference system to base the game on has the following characteristics:

- the total street is approximately 12 m wide,
- gas pipes and water with diameters between 60 and 150 mm, located away from the street axis at 60 to 100 cm below street level, and
- sewer pipes with a 300 mm diameter, located at the street axis at least 1 m below street level.

In this reference system, sewer replacement causes the street to be rehabilitated as well, because of the depth and width of the excavated trench and additional works on replacing gully pots and house connections. Street rehabilitation costs amount to 40 to 60 % of the total costs. Replacement of gas pipes and water mains often occurs through smaller trenches at which the street is locally repaired, inducing an increased deterioration rate of the corresponding street section. Table 5.1 lists the included physical and financial interactions. The numbers in table 5.1 are generalisations from practical experiences.

Table 5.1: Player interaction matrix with financial and physical effects

Combined with	Street replacement	
	Yes	No
Gas	10 % reduction of street replacement	Faster object deterioration
Sewer	60 % reduction of street replacement	600 fine, street object goes to s_1
Water	10 % reduction of street replacement	Faster object deterioration

This reference system is expected to be simple enough for the players to comprehend most interactions, while including enough complexity and dynamics to mimic decision-making in reality. The included complexities are uncertainty about current object state (when presented with imperfect information), an unknown deterioration process, physical interactions between infrastructures and negotiations among the players.

5.3.2.2 Game procedures

Deterioration model and available actions

Infrastructures are inspected in practice, according to a predefined frequency, to observe their current condition and deterioration over time. The inspection data is usually summarised as discrete condition classes, underlying a variety of statistical infrastructure deterioration models. Infrastructure deterioration is complex and not completely understood, calling for a stochastic model. Examples are cohort survival models, (semi-)Markov models, logistic regression models and poisson models (Ana and Bauwens, 2010; Black et al., 2005; Egger et al., 2013; Scheidegger et al., 2011). A Markov model was chosen to model deterioration in the game, because of its general application to a variety of infrastructures, applicability for individual objects, relative simplicity of condition state transition and availability of a condition state probability that is useful for risk based decision-making (Ana and Bauwens, 2010).

A system containing decision-makers, a set of actions and a state transition function can be described by a Markov decision process (MDP). An MDP is a mathematical model that is concerned with optimal strategies of a decision-maker who must make a sequence of decisions over time with uncertain outcomes. In MDPs, the sequence of actions taken to make decisions assumes that the environment is completely observable and the effects of actions taken are deterministic. If this assumption does not hold, the effects of actions taken are non-deterministic. Decision-making in such environments can be modelled by a partially observable Markov decision process (POMDP). The involved agent cannot observe the actual state, but maintains a probability distribution over the hidden states. This is referred to as the 'belief state'. The basic mechanics for both the MDP and POMDP is that an agent takes a set of actions to control the system at each state in order to maximise some expected reward (Ibe, 2013).

The MDP here is a discrete-time discrete-state probabilistic system that is represented by the tuple $(S; A; \mathbf{R}; \mathbf{P})$, where

- S is a finite set of N states (i.e. condition classes), in this case, $S = \{1, 2, 3, 4, 5\}$. s_1 resembles 'new', s_5 resembles 'failure',
- A is a finite set of K actions that can be taken at any state, in this case $A = \{a_0, a_1, a_2\}$, where a_0 represents 'no action', a_1 represents 'replace' and a_2 represents 'inspect',

- **R** is the reward matrix that varies per action. In this case, no reward is associated with a_0 and negative reward (costs) is associated with a_1, and
- **P** is the transition matrix that varies per action. A transition matrix contains the probabilities p_{ij} by which the process moves from state s_i to state s_j in one step. It is assumed that applying action a_1 results in the process moving from a state s_i to s_1 with probability 1. The transition matrix for action a_0 models the autonomous infrastructure deterioration process. Section 5.4.1 describes the setup of the transition matrix in more detail.

Time inside the game is modelled as rounds, during which game time stands still. In each round, players can opt for three choices per infrastructure object: inspect, replace or do nothing. Deterioration of the infrastructure objects occurs when going to the next round. This process is unobservable for the players. For the game with imperfect information, an object's true state is also unobservable for the players, leaving the player to rely on the visualised state. Inspection allows them to see the real state. The state per object that is visualised on the computer screen is a discretisation of the state probability vector **u**. This discretisation occurs by uniform sampling from the inverse cumulative state probability vector. The state that corresponds with that particular interval is the visualised state for that object.

In simulations with imperfect information, the cumulative state probability is visualised in each object as a percentage. Inspecting objects discretises the state, equally to the aforementioned process, and sets the state probability of the discretised state to 1. Such a process is referred to as a wave function collapse (Stamatescu, 2009). This assumes inspection gives perfect information about the actual object state. For simulations with perfect information, the state probability of the visualised state is always 1.

The initial state of each object per infrastructure is randomly drawn from a uniform state distribution, excluding the last state (collapse). This gives an initial state probability vector $\mathbf{u} = [0.25\ 0.25\ 0.25\ 0.25\ 0]$.

The game includes a limited number of physical interactions between infrastructures, listed in table 5.1. Whenever a sewer object is replaced, the street object is replaced as well. Since the street is locally repaired after gas or drinking water pipe replacement, it is assumed this causes a faster deterioration of the corresponding street section. In the game, this is modelled by equally dividing the first entry in **u** over the other four entries. This change in **u** is attributed once; after running the Markov chain, a new **u** is produced and the object deteriorates at its original rate. In the single player games, these physical interactions cause the street player to be confronted with random changes to his objects, because he does not have information about the actions of the other players.

A Matlab script of this described game engine is presented in appendix D.

Rewards

Three types of rewards are included in the game: replacements costs, collapse costs and inspection costs. Replacement costs for the included infrastructures were obtained from unit costs listings as described in practical guidelines for managers to approximate budget levels (CROW, 2004; Grontmij, 2005; RIONED Foundation, 2007). The associated costs ratios were used to set the replacement costs at 500, 500, 1,000 and 750 for gas, drinking water, sewers and streets respectively. Collapse costs were approximated to be five times the replacement costs. Inspection costs were modelled as a percentage of the replacement costs (see section 5.4.2), since inspection is not worthwhile if replacing an object would be cheaper.

Individual and team performance

A player's objective is to manage his infrastructure as cost-effectively as possible, i.e. the ratio of input versus effect (Katz and Kahn, 1978). In reality, cost-effectiveness is a multi-dimensional evaluation criterion. In this game, it is limited to the relation between expenditures and object failure, resulting in a two dimensional player performance or solution space. To mutually compare player performance, the expenditures are not analysed in terms of absolute costs, but by determining the mean residual value of all rehabilitated objects. To do so, a linear residual value scheme per object state is assumed: s_1 1, s_2 2/3, s_3 1/3, s_4 and s_5 0. The number of collapses are normalised as well over the number of objects and played rounds, giving the failure probability. It is assumed that both the residual value score and failure probability score have equal weight.

In the multi-actor simulations, a criterion is needed to reflect team utility or group pay-off. Cost-effectiveness becomes unsatisfactory as performance criterion, because the best strategy per actor depends on the choices of others (Kraus, 1997; Parsons and Wooldridge, 2002; Sandholm, 1999). To this end, the included criteria to reflect group pay-off are $\Delta\, costs$ and $\Delta\ infrastructure\, quality$. These variables represent the difference at the planning and execution stage in the multi-actor simulations, reflecting the difference between individual and collective choices (see conceptual model in figure 5.1). The cost difference relates to planned and executed replacements. Infrastructure quality is determined by a modification of the 'infrastructure value index' (Alegre et al., 2014), where instead of object age, the residual value per object is used to obtain a mean infrastructure quality. This method assumes each object, for all players, has equal weight. Both $\Delta\, costs$ and $\Delta\ infrastructure\, quality$ are converted to relative changes to obtain a similar two dimensional player performance space, but then for group pay-off.

Group pay-off or cooperation rewards are attributed at the multi-actor simulations when players prefer to rehabilitate at the same object location. Cooperation effects can be gained through cooperation with the street player. The reason for this is the street infrastructure deteriorates fastest, and consequently, has most cooperation opportunities. Table 5.1 lists the player combinations and the associated effects included in the game.

A fine of 600 is administered when a sewer object is replaced and the corresponding street object is not, in order to mitigate the street player seeking opportunistic behaviour. This fine forces the group to judge about the best available options: advancing or delaying replacement with associated consequences. If this fine would not be administered, the street player has incentive to not participate in the gameplay since his street object is replaced for free by the sewer player (see physical interactions in table 5.1). The fine is administered to the entire group, because they operate as a single entity. The level of this fine was set at 600, resulting in higher total costs with the street object in state s_1 or s_2 and lower total costs when in state s_3, s_4 or s_5, irrespective of the player combination, but assuming the non-street objects to be in s_4 or s_5. Such a fine does not exist in reality, but it creates a relevant dynamic gameplay here forcing the players to actively engage in the gameplay.

The players are to balance their individual goal, cost-effectiveness, with their team goal, increasing overall infrastructure quality to minimise collapses while minimising overall public costs. It is up to them how to pursue their goal.

Data registration system

The data registration system stores the data relevant for further analysis. Each registered data record contains the following items:

- date and time of record creation,
- game type (information: perfect/imperfect and cooperation: yes/no),
- object id,
- user id,
- round number,
- object state modification action, including ‘object created’, ‘inspect’, ‘replace’, ‘no action’, ‘new round’, ‘planned replace’ and ‘collapse’,
- object state modification action costs,
- object state before and after object state modification action,
- cumulative state probability vector before and after object state modification action, and
- visualised state probability before and after object state modification action.

5.3.2.3 Player involvement techniques

Having players involved is at least of equal importance for research purposes as having an acceptable game model, because it triggers the players to act enthusiastically. To do so, gaminess is to be maximised as reasonably achievable. Gaminess is defined as "a quality of liveliness that makes a game enjoyable to players" (Duke, 2014, p. 177). Reducing gameplay complexity to an acceptable level is important to increase gaminess. Reducing complexity is an inevitable consequence of the choice for an experimental research setup, being a limited set of measurable variables. Section 5.3.2.2 described part of the applied simplifications to build the game, including the game scenario and state transition model. The following additional game design complexity reductions were implemented:

- the city to manage only contains the infrastructure to manage; there is no interaction with other urban objects, for example inhabitants, traffic or housing and business districts,
- the infrastructures consist of independent objects with equal importance that are homogeneously spaced,
- the number of player cooperation effects is limited to interaction with street objects,
- decision-making argumentation. In reality, infrastructure managers make their operational rehabilitation decisions in light of their long term strategies, and may be influenced by a large variety of information sources at the operational level (Van Riel et al., 2016b). This large variety is reduced to a limited set of arguments in order to address the game objective. These arguments are:
    - current object state and associated replacement costs,
    - prediction about future object state and associated replacement costs,
    - synergy from collaboration with the other players in terms of costs and infrastructure quality.
- players have unlimited budgets, indicating all operational decisions are in line with any possible long term strategy.

Despite unlimited budget and complete freedom in the choices players can make, players are instructed to pursue their objective, being cost-effective, as good as possible. Reference scores (section 5.4.3) allows to test the ambiguity of their management strategies.

5.4 Game calibration and testing: methods

Calibration is defined here as fine-tuning individual components to assess whether these jointly function as expected, within general margins of acceptability (Duke, 2014, p. 99). This definition differs from the usage of calibration in a modelling context, where it can be defined as “estimating model parameter values that enable the model to closely match the behaviour of the real system it represents” (Gupta et al., 1998).

5.4.1 Transition matrix

The transition matrix determines the deterioration rate and speed of the gameplay. A matrix was set up for this game with the following assumptions:

- state transitions occur in a positive direction only, thus $p_{ij} = 0$ for $i > j$,
- state transition may occur with more than one state per step,
- the final state s_5 (failure) is an absorbing state, thus $p_{55} = 1$,
- the probability the chain remains in any state, i.e. p_{ii}, other than p_{55}, is equal. (thus, $p_{11} = p_{22} = p_{33} = p_{44}$),
- the cumulative probability of going to any other state equals 1 p_{ii}, where the probability of moving to the next state, starting from p_{ii+1}, decreases by a factor ten.

These considerations result in the following matrix:

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & 0.1p_{12} & 0.01p_{12} & 0.001p_{12} \\ 0 & p_{22} & p_{23} & 0.1p_{23} & 0.01p_{23} \\ 0 & 0 & p_{33} & p_{34} & 0.1p_{34} \\ 0 & 0 & 0 & p_{44} & p_{45} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.1}$$

with

$$p_{ij} = \frac{1 - p_{ii}}{\sum\limits_{n=j}^{m} 10^{j-m}}, \; i = j - 1 \; and \; j = \{2, 3, 4, 5\} \tag{5.2}$$

where m is the number of states.

An important parameter of interest here is the time to absorption, being the expected number of steps t_i before the process hits an absorbing state, given that the chain starts in a non-absorbing or transient state. An absorbing state is a state from which the process cannot escape, in this case s_5. To get t_i, the 'fundamental matrix' $\mathbf{N}$ must be obtained from the transition matrix. The product of the fundamental matrix and a vector $\mathbf{c}$ of ones gives vector $\mathbf{t}$, whose ith entry is t_i (Ibe, 2013, pp. 74-75).

$$\mathbf{t} = \mathbf{N}\mathbf{c} \tag{5.3}$$

with

$$\mathbf{N} = \sum_{k=0}^{k=\infty} \mathbf{Q}^k = (\mathbf{I} - \mathbf{Q})^{-1} \tag{5.4}$$

where $\mathbf{I}$ is a k-by-k identity matrix, with k being the number of transient states. Then:

$$\mathbf{Q} = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ 0 & p_{22} & p_{23} & p_{24} \\ 0 & 0 & p_{33} & p_{34} \\ 0 & 0 & 0 & p_{44} \end{bmatrix} \tag{5.5}$$

As such,

$$\mathbf{N} = \begin{bmatrix} \frac{-1}{p_{11}-1} & \frac{p_{12}}{(p_{11}-1)(p_{22}-1)} & -\frac{(p_{13}+p_{12}p_{23}-p_{13}p_{22})}{((p_{11}-1)(p_{22}-1)(p_{33}-1))} & \frac{(p_{14}+p_{12}p_{24}-p_{14}p_{22}+p_{13}p_{34}-p_{14}p_{33}+p_{12}p_{23}p_{34}-p_{12}p_{24}p_{33}-p_{13}p_{22}p_{34}+p_{14}p_{22}p_{33})}{((p_{11}-1)(p_{22}-1)(p_{33}-1)(p_{44}-1))} \\ 0 & \frac{-1}{p_{22}-1} & \frac{p_{23}}{((p_{22}-1)(p_{33}-1))} & -\frac{(p_{24}+p_{23}p_{34}-p_{24}p_{33})}{((p_{22}-1)(p_{33}-1)(p_{44}-1))} \\ 0 & 0 & \frac{-1}{p_{33}-1} & \frac{p_{34}}{((p_{33}-1)(p_{44}-1))} \\ 0 & 0 & 0 & \frac{-1}{p_{44}-1} \end{bmatrix}$$

The transition matrix is equal for all four included infrastructures. Yet, in order to reflect differences in deterioration rate, the number of steps through the transition matrix after finishing a round differs per infrastructure. Therefore, the associated state probability vector is

$$\mathbf{u}_{i+1} = \mathbf{u}_i \mathbf{P}^v, \ v = \{1, 1, 2, 4\} \tag{5.6}$$

where v is a set of relative transition speeds, based on infrastructure lifetimes of 120, 120, 60 and 30 years for gas, drinking water, sewers and streets respectively. These number are based on generalisations from utility managers.

It is now possible to set p_{ij} from equation (5.2) to a value that lets the game operate at a speed suitable for all infrastructures. Suitable in this sense means that it is not too fast for the street infrastructure and not too slow for the gas and drinking water infrastructure, given the expected available gaming time.

5.4.2 Inspection costs and effect

Players may have incentive to either inspect all objects if the inspection costs would be a too small percentage of the replacement costs and to inspect none of the objects if the inspection costs would be a too high percentage. Hence, the inspection costs are to optimised instead of set a priori, matching the game parameters and dynamics. This minimises the influence of inspection costs on player behaviour. The reasoning is as follows. In the game, the total inspection costs depend on the costs per inspection and the number of inspections. The number of inspections depends on a player's inspection strategy, being some object state uncertainty threshold that needs to be exceeded before inspection is opted for. Given a replacement strategy and a range of inspection thresholds, the distribution of total costs could be determined (replacement, collapse and inspection) for predefined inspection costs as a ratio of replacement costs. This notion allows to set the inspection costs with the objective of making the total costs independent from the inspection threshold, preventing a player from either inspecting nothing or everything in order to reduce costs. To this end, simulated annealing was applied to the optimisation problem. Simulated annealing is a probabilistic heuristic optimisation algorithm for determining the global minimum of a given objective function (Kirkpatrick et al., 1983).

$$\min_{x \in (0,1)} \left(\sum_{i=1}^{n} \left(y - f\left(x_i\right)\right)^2 \right) \tag{5.7}$$

The objective function here is the residual sum of squares. Prediction y is the mean total costs with an inspection threshold of zero, normalised for the number of steps through the underlying Markov chain. Prediction y was determined through Monte Carlo simulation, where the number of Monte Carlo simulations were related to obtaining stable y predictions. The following modelling assumptions were applied:

- replacement strategy: replace at s_4 or s_5,
- information is imperfect: state discretisation does not set the state probability in $\mathbf{u}$ to 1,
- number of steps through the Markov chain (with $\mathbf{P}$ from equation (5.1)): 100,

- Markov chain transition speed: 1, 1, 2 and 4 for gas, drinking water, sewer and street infrastructure respectively, and
- relative object replacement costs: 1, 1, 2 and 1.5 for gas, drinking water, sewer and street infrastructure respectively.

Monte Carlo simulation was applied to obtain a distribution of the optima from the simulated annealing procedure, given the random character of the underlying Markov chain. The same modelling assumptions were applied as for obtaining y. 200 simulations were run, each time with a random starting point from a uniform distribution. The lower and upper bounds were set to 0 and 1 respectively. Based on the central limit theorem, the distribution of global minima should approximate normality. An object's visualised state may be and state probability is affected by inspecting an object, due to the applied discretisation procedure. Thus, inspecting an object influences the rate at which an object reaches s_5, because the discretisation procedure is random. Hence, the relation between inspection and object failure probability was assessed. Two cases were analysed: with and without physical interactions. The following modelling assumptions were applied:

- replacement strategy: replace in s_5,
- information is imperfect: state discretisation does not set the state probability in $\mathbf{u}$ to 1,
- inspection is applied,
- number of steps through the Markov chain (with $\mathbf{P}$ from equation (5.1)): 100,
- Markov chain transition speed: 1, 1, 2 and 4 for gas, drinking water, sewer and street infrastructure respectively, and
- number of Monte Carlo simulations: 200.

Any change in failure probability over inspection threshold could be explained by the state probability distribution of inspected objects.

5.4.3 Solution space for random replacement

A reference solution space was computed, to allow comparison with future gaming results regarding the player performance score space. Two cases were assessed: with and without physical interactions. The reference solution space is based on the following modelling assumptions:

- replacement strategy: replace in s_5 and randomly when not in s_5,
- information is imperfect: state discretisation does not set the state probability in $\mathbf{u}$ to 1,
- inspection is applied randomly,
- number of steps through the Markov chain (with $\mathbf{P}$ from equation (5.1)): 100,

- Markov chain transition speed: 1, 1, 2 and 4 for gas, drinking water, sewer and street infrastructure respectively,
- implementation of residual value scheme, and
- number of Monte Carlo simulations: 200.

The solution space for street objects was based on an increased deterioration rate whenever drinking water or gas was to be replaced. The increased deterioration rate of street objects due to replacement of gas or water objects was modelled by equally dividing the probability of the object being in s_1 over the probabilities of the other states. The influence of this assumption on the failure probability was determined through sensitivity assessment. To this end, the model output, mean failure probability for street objects, over a range of random replacement probabilities were related to differences in w. w is the state probability vector index, representing the cumulative state probability in u at s_w. Perturbations were applied one-at-a-time and changes in input were not normalised, because this is ordinal data. The following modelling assumptions were applied:

- $w = \{1, 2, 3, 4\}$,
- replacement strategy: replace in s_5 and randomly when not in s_5,
- information is imperfect: state discretisation does not set the state probability in $\mathbf{u}$ to 1,
- inspection is not applied,
- number of steps through the Markov chain (with $\mathbf{P}$ from equation (5.1)):100,
- Markov chain transition speed: 1, 1, 2 and 4 for gas, drinking water, sewer and street infrastructure respectively, and
- number of Monte Carlo simulations: 200.

5.5 Game calibration and testing: results and discussion

5.5.1 Transition matrix

Figure 5.6 shows the relation between p_{ii} in $\mathbf{P}$ and t_1, where t_1 is the expected number of steps for an infrastructure object to go from s_1 to s_1. A value for all p_{ii}, except for p_{55}, of 0.8 was chosen for the game settings. The combination of the assumed infrastructure lifetimes (see section 5.4.1), transition matrix and chosen value of 0.8 result in each step through the Markov chain resembles approximately six years. This value was obtained by dividing the assumed infrastructures lifetimes (section 5.4.1) by t_1 with $p_{ii} = 0.8$.

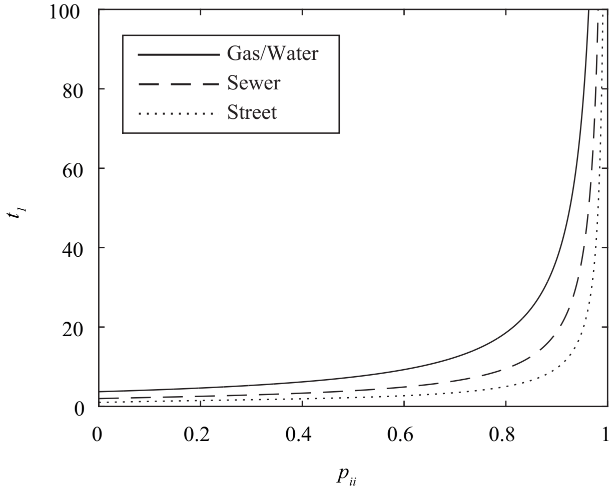


Figure 5.6: The expected number of steps t_1 before hitting s_5 when starting from s_1, as function of p_{ii}

5.5.2 Inspection costs and effect

Figure B.1 in appendix B shows the relation between prediction y and the number of Monte Carlo simulations. From this figure B.1, it can be concluded that 200 simulations are sufficient to obtain stable estimates for y. Figure 5.7 shows the distribution of the optima per infrastructure, together with the corresponding normal distribution. Based on a visual interpretation, it can be concluded the optimisation results approximate normality, and consequently, the sample mean is the best estimator as a basis for inspection costs. The sample means were 0.33, 0.33, 0.42 and 0.10 for gas, drinking water, sewer and street infrastructure respectively (see figure 5.7). Consequently, the corresponding inspection costs were set at 165, 165, 417 and 76.

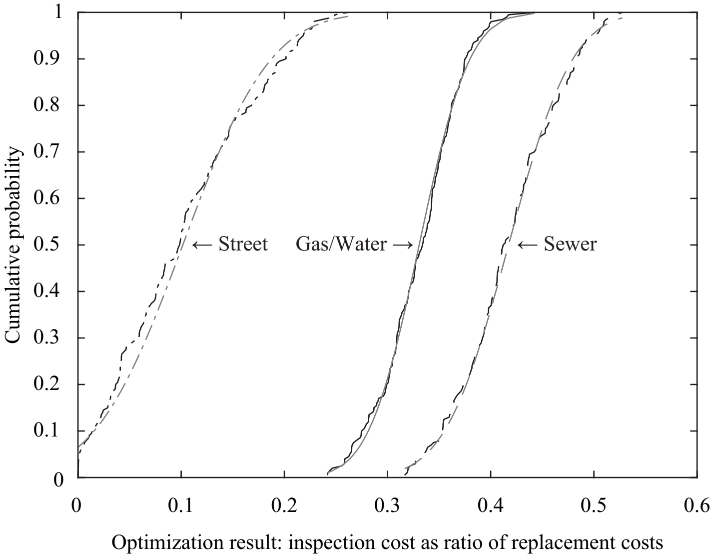


Figure 5.7: Cumulative probability distribution (black) with corresponding normal distribution (gray) of simulation annealing results from 200 Monte Carlo simulations

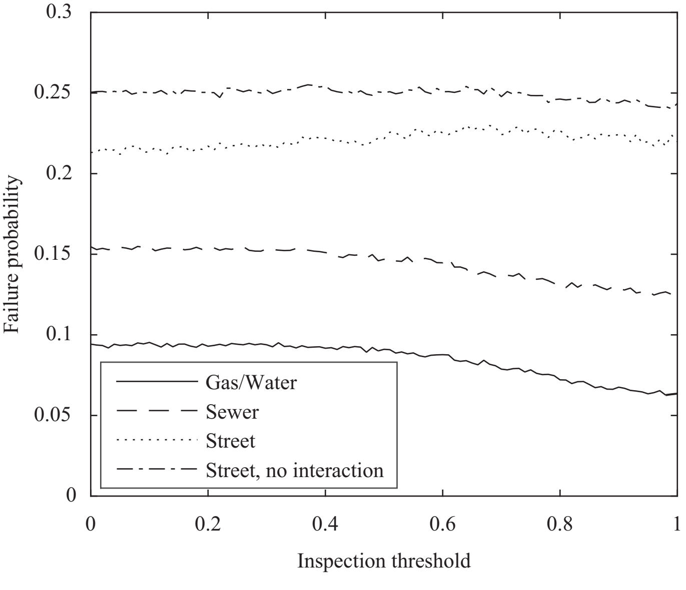


Figure 5.8: Mean failure probability over inspection threshold from 200 Monte Carlo simulations

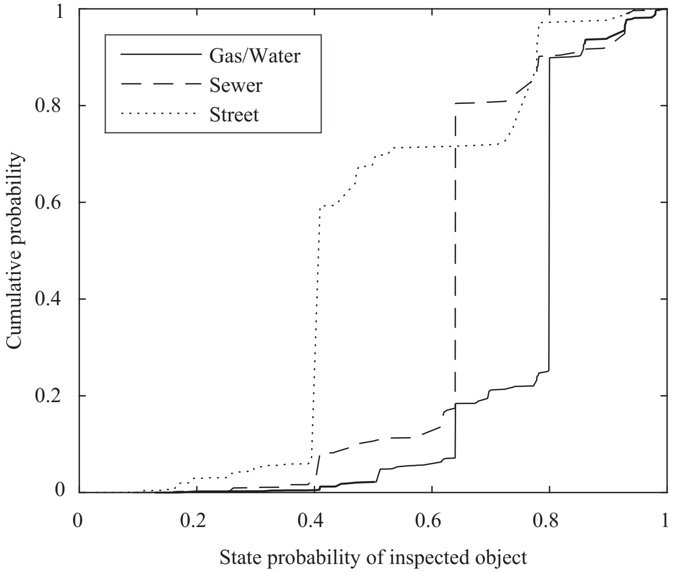


Figure 5.9: Cumulative state probability distribution of inspected objects from 200 Monte Carlo simulations

The results from figure 5.7 are further explained by figure 5.8, which shows the relation between the inspection threshold and an object's mean failure probability. Without physical interaction, the mean failure probability decreases with increasing inspection threshold. In other words, a player decreases the deterioration rate when inspecting objects, and consequently, increases inspection costs while decreasing replacement and collapse costs. An optimum for inspection costs exists, as shown in figure 5.7, where the total costs are independent from the inspection threshold. In fact, the overall failure probability for street objects is lower when interactions are included, implying that the failure probability for street objects is affected by replacement of sewer objects.

The decrease of failure probability with increasing inspection threshold can be clarified by the state probability distribution of inspected objects, shown in figure 5.9. The horizontal axis represents an object's probability of being in the discretised state. The sharp increases in figure 5.9 are caused by a relatively large portion (approximately 60 %) of state probabilities corresponding with replaced objects. A replaced object has state probability vector $\mathbf{u} = [1\ 0\ 0\ 0\ 0]$. After going through the Markov chain in equation (5.6), the first entry in $\mathbf{u}$ of a replaced object becomes approximately 0.80, 0.80, 0.65 and 0.40 for gas, drinking water, sewer and street infrastructure respectively. Consequently, given the applied discretisation procedure, the probability to remain in s_1 after inspection is 0.80, 0.80, 0.65 and 0.40 as well for the gas, drinking water, sewer and street object. This explains why the deterioration rate of gas, drinking water and sewer objects decreases with increasing inspection threshold. For street objects, the probability of going to any other state than s_1 is 0.60, indicating an increase in the deterioration rate due to inspection. On the other hand, the state probability of approximately 25 % of the inspected street objects was of 0.7 or higher. These objects have a 0.7 probability of remaining in s_1, resulting in a decrease in deterioration rate due to inspection. Overall, the effect of inspection on the failure probability for street objects is small compared with the other infrastructures.

5.5.3 Solution space for random replacement

Figure 5.10 shows the two dimensional solution space for the included infrastructures. Physical interactions cause the solution space of the street player to improve slightly, due to a lower mean failure probability, as also shown in figure 5.8. Future gaming results are to be compared with the solution spaces. All future players' scores located in the triangular region left of the confidence interval resemble a more cost-effective management strategy. All future scores located in or right of the confidence intervals resemble an equal or worse strategy than random replacement.

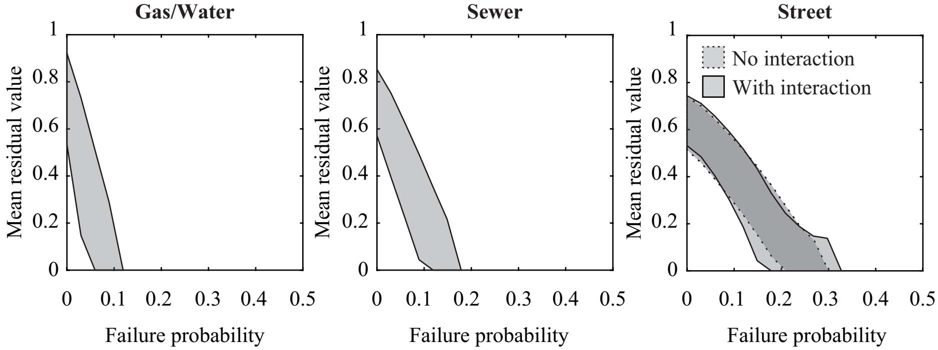


Figure 5.10: Solution space (95 % confidence interval) for random replacement, from 200 Monte Carlo simulations

Figure 5.11 shows the relation between the random replacement probability and a street object's mean failure probability for different w (see section 5.4.3). As logically expected, the failure probability increases with increasing w. The results of the sensitivity assessment show changes in w have a relatively small effect on the failure probability, i.e. an alternative solution space would largely overlap the current solution space ($w = 1$ in figure 5.11).

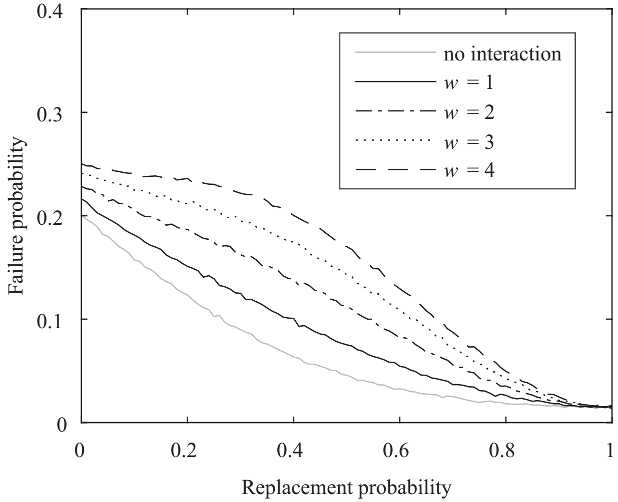


Figure 5.11: Street object mean failure probability over replacement probability, for random replacement, at different w from 200 Monte Carlo simulations

5.6 Lessons learned and future research

The article introduced the serious game Maintenance in Motion. This game intends to investigate the influence of information quality and cooperation between people on operational decision-making for urban infrastructure management. The game design process yielded two main lessons that model or game designers may consider useful.

Lesson 1: ‘strip to the bone’. Designing a research game or model calls for identifying most relevant processes needed to answer the research question. This forced the design team to simplify decision-making in reality without omitting its basic elements (information, uncertainty, choice and mutual interaction). This process proved to be challenging and time consuming, because for each element of decision-making in reality, its core functioning (in itself and in relation to other elements) needs to be understood, checked for relevancy and converted into a conceptual game element. Then it is decided to omit or include it in the game in an alternate manner, simplified even further and connected with the other game elements. As such, simplification of the game, while maintaining its functionality, proved more challenging than increasing complexity.

It is well understood that this particular game simulates an abstraction of reality in which various factors including personal attitude, policies, corporate strategy and budgets are explicitly omitted, in order to force the players to base their choices on presented information and cooperation. Of course, this decreased game realism hampers a player's ability to reflect his gaming experience to his day-to-day work. It is yet unknown whether the future players are willing to accept reality, as presented in the game, before playing according to their objective. Hence, future players require a sound game introduction before playing in order build trust, acceptance and engagement regarding the game's objective and level of abstraction. An indicator for successively achieving this is to what extent the gained results are explainable or random.

Lesson 2: 'motivate'. Relating to the previous paragraph, all choices for simplification and abstraction of reality should be motivated, because it creates transparency. This is important, because it allows to relate the reliability and validity of game results to the game design. Yet, a detailed game design description is usually neglected or hardly described in literature containing game development and results. Each game is unique in design and outcome generation due to a unique objective and variety of ways to achieve that objective. Thus, consensus about its applicability should not be taken for granted, calling for motivation of game setup.

Another aspect requiring motivation is parameter settings. Although it is inevitable to assume various parameter values based on experience and intuition, these values do not necessarily match game dynamics. Some game parameters partly lost their physical meaning, because they were tuned according to specific game dynamics. An example from this game is inspection costs. The relation between costs for goods/services in reality is controlled by other processes than it is in the game. Hence, the game requires a relation between costs that matches the dynamics of the game. Parameter calibration and model testing is relevant to foresee the game dynamics and outcome, in order to allow comparison with future results.

6 Individual and group decision-making: game results

6.1 Introduction

Urban networked infrastructures provide essential services to enhance transport of people and goods and for provision of telecommunication, water and energy. As such, management of these systems is a prerequisite to continue their functioning. The responsible entities strive to manage their infrastructure as cost-effectively as possible. This means: provide equal or better service levels, at lower costs (Katz and Kahn, 1978). Yet, it is difficult to assess this, because decision-making for urban infrastructures is embedded in a complex system (see section 1.2).

Adjacent networked infrastructures are typically preferred to be rehabilitated simultaneously, motivated by reduction of costs, nuisance to citizens and traffic disruption. Management responsibilities for these systems lie with multiple public or private entities, varying per country. Due to a collaborative rehabilitation preference and practice, the operational decision-making process is characterised as a multi-actor planning problem. Each infrastructure has its own technical, economic and functional lifetime, deterioration mechanisms and corresponding rehabilitation strategy in space and time. Yet, these infrastructures are located on top of or right next to each other. The combination of an overall preference for integrating public works and differences in spatial-temporal rehabilitation demands causes the involved decision-makers to make compromises about whether, where and when they rehabilitate simultaneously, in light of their organisational strategies and preferences. This implies decision-making is often based on negotiations between different stakehold-

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This chapter is based on: Van Riel, W., Langeveld, J., Herder, P., & Clemens, F. (2016). The influence of information quality on decision-making for networked infrastructure management. *Structure and Infrastructure Engineering.* in press.

ers in addition to available information about infrastructure condition (Allison, 1971; Lindblom and Woodhouse, 1993; Stone, 1988; Sylvan et al., 1990). This may be considered logical, because the best strategy per actor depends on the choices of others in multi-actor settings. Thus, maximising individual utility based on information about infrastructure condition becomes meaningless (Kraus, 1997; Parsons and Wooldridge, 2002; Sandholm, 1999).

Despite the difficulties in collaborative decision-making, literature points out multiple ways that may enhance its effectiveness. A distinction is made between technical and social aspects. Technical aids to enhance collaborative decision-making relate to collaborative decision support systems (CDSSs). The objective of a CDSS is to augment the effectiveness of decision-making groups through sharing of information between group members and a computer (Karacapilidis and Papadias, 2001), for example through reducing the complexity of a decision-making process by decreasing the cognitive workload of decision-makers (Jankowski and Nyerges, 2001). This implies relevant information (both tacit and explicit), decision-makers' preferences and potential solutions should be available to all decision-makers, allowing them to easily follow and participate in the associated processes. Yet, Jankowski and Nyerges (2001) indicated that using CDSS is advantageous in complex decision problems only; not in simple problems. A key element regarding social aspects in collaborative decision-making is leadership. Facilitative leadership is important for bringing actors together and getting them to engage each other in a collaborative manner. Leadership is crucial for setting and maintaining clear ground rules, building trust, facilitating dialogue, and exploring mutual gains (Ansell and Gash, 2008).

Collaborative decision-making can outperform individual decision-making, because groups have advantages in terms of information processing and elimination of individual errors (Chalos and Pickard, 1985; Kocher and Sutter, 2005). On the other hand, collaborative decision-making may suffer from 'groupthink', a psychological phenomenon triggering the players to seek for harmony in a collaborative decision process, although this harmony leads to irrational outcomes (Janis, 1972).

The system and process complexities reduce decision-making transparency, which is required to assess whether infrastructure management is cost-effective or not. Next to that, engineers typically believe that extensive and good quality information about structural condition leads to sound operational decision-making (e.g., Frangopol, 2011). As such, this chapter studies the question: Does better information about structural condition lead to other or improved decision-making, when compared to the situation encountered in present practice?

Serious gaming was chosen as approach to answer this question, because it allows to introduce real players who simulate part of the social system. In this way, the real actor or at least the actors' roles become part of the simulated system. Serious games are believed to be among the best methods for studying complex systems, because it is probably the only technique that can incorporate human players and social interactions, social and physical rules, mental and computer models, and individual and collective goals (Bekebrede and Mayer, 2006, p. 278). On the other hand, gaming has its drawbacks as well. One of them is the impossibility to reproduce the game, because of dependency on player availability and learning effect. Second, the number of possible simulation runs is limited because it takes longer to play a simulation game than it does for computers to run simulations. Other methods to assess effects of information attributes, for example its quality, on decision-making or system behaviour include agent based modelling (Bonabeau, 2002), choice experiments (Street and Burgess, 2007), game theory (Osborne and Rubinstein, 1994) and Markov Decision Processes (Ibe, 2013). Although widely applied, the drawback of these normative techniques is they assume self-interested rational decision-makers maximising utility. For example, increased quality of information about choice attributes increases decision outcome on an individual level (Chorus et al., 2007; Keller and Staelin, 1987), but this effect decreases as the quantity of available information increases (Keller and Staelin, 1987).

In this chapter results from the serious game 'Maintenance in Motion' are analysed and discussed. The game was specifically designed for this research to address two research questions. First, what is the influence of information quality on decision outcome? And second, what is the influence of collaboration between players on decision outcome? The game is a descriptive research instrument to simulate and analyse single and multi-actor decision-making for rehabilitation of multiple networked infrastructures, under conditions of perfect and imperfect information about structural condition. A detailed description of the game design and calibration was described in Van Riel et al. (2016a). This chapter further extends this research track by presenting the results obtained from actual infrastructure managers in practice.

6.2 Research approach

6.2.1 Sample selection

The players were selected in a snowball sampling procedure. The department heads of the organisations involved in the 'Urban Drainage Research Program' were contacted and asked to gather a minimum of four players. Additional organisations were included to further increase the sample size. The single requirement for the players was professional involvement in infrastructure management. This sampling procedure led to a selection of 56 players at 12 organisations, listed at the Acknowledgements. The included players were involved in infrastructure management at different hierarchal levels and at a variety of infrastructures, including sewers, drinking water, streets, flora and fauna, urban water and urban planning.

The game software was first tested in eleven gaming sessions (44 players at 9 organisations) to streamline gameplay, and to put the software to the test in real game situations. These sessions were evaluated after which minor improvements were applied to the game software.

The game sessions were played in a meeting room at each organisation. Each session's duration was set to three hours. The players were introduced to the game's background and operation. Emphasis was put on two aspects: their goal (see section 6.2.3) and the deterioration process. As such, the players were aware on how to play the game according to their goal. After the introduction, the four game types were played and followed by an evaluation of the results. Each player was handed out a single page fact sheet, presenting all relevant information about their objective, imperfect information, object states, costs of all actions, and physical and financial interactions (see section 5.3). The player roles (infrastructure type) and group configuration did not change during a gaming session.

6.2.2 Data collection and analysis

Four computers were connected to a server, on which the game ran. A database was filled during a gaming session that stored all data relevant for further analysis. This data is downloaded from the game in csv format. Each registered data record contains the item listed in section 5.3.2.2 on page 75.

The players' choices regarding inspection, replacement and no action were analysed to assess the relation between applied actions, object state and state probability. The rationale to do so, is to assess the validity of the game results. This analysis excludes collaborative choices, i.e. actions applied at the execution stage in the multi-player game types.

Chorus et al. (2007) found that increasing levels of uncertainty lead to information acquisition, considering individual travelling choices. For infrastructure management, the desire for information acquisition could be related to infrastructure lifetime. For example, if an infrastructure object would approach its end of lifetime, immediate replacement is likely to be preferred over inspection, despite the uncertainty about the current state of object.

The following hypotheses were tested:

1. choosing action 'inspect' occurs at lower state probabilities compared to choosing 'no action' or 'replace',
2. when choosing action 'inspect', the object state probability at action 'inspect' is related to the object state, and
3. choosing one of three actions is related to the object state, i.e. the object state distributions at the three different actions are mutually different.

The Mann-Whitney U test, a non-parametric test for equality of population medians of two independent samples, was used to test the hypotheses because of ordinal data in the dataset. The hypothesis of equal medians was rejected based a 95 % confidence interval (i.e. $\alpha = 0.05$). Confirmation of the hypotheses implies the game results are valid and the two main research questions can be answered. Individual player performance was assessed as the relation between expenditures and object failure (i.e. cost-effectiveness), where expenditures is the mean residual value rv of all replaced objects. $\overline{rv}$ at time (or game round) t is described as:

$$\overline{rv}(t) = \sum_{j=1}^{t} \frac{1}{t} \sum_{i=1}^{r} \frac{1}{r} rv_{i,s} \tag{6.1}$$

with $rv_{i,s}$ is the residual value of the replaced object i in state s, t is the number of rounds and r is the number of replaced objects. A linear residual value scheme per object state was assumed: state 1 1, state 2 2/3, state 3 1/3, state 4 and state 5 0. The number of object failures f were normalised as well over the number of objects m and number of rounds t, giving the failure rate λ.

$$\lambda(t) = \frac{f}{t \cdot m} \tag{6.2}$$

The failure rate, a term originating from reliability engineering (e.g. Rausand and Høyland, 2004), is the normalised failure frequency over the measured time for a given object. For infrastructures in practice, the failure rate is usually normalised with respect to measured time and infrastructure size, typically # km year. As such, the failure rate here deploys that concept as well. It should be noted that the generated failure rates in section 6.3.3 do not provide information for infrastructures in practice.

The mean residual value and failure rate scores were compared with a reference score space for random replacement. This reference score space, i.e. the 95 % confidence interval of two hundred million data points, includes the following strategies:

- inspect randomly,
- replace object when failed, and
- replace randomly when not failed.

Details of the underlying computation procedure were described in Van Riel et al. (2016a). Team utility was defined as the difference between individual planning and collaborative execution, in terms of costs C and mean infrastructure quality Q. Q was determined by a modified 'infrastructure value index (IVI)' (Alegre et al., 2014). The IVI is a measure, ranging from 0 to 1, to express the mean value of an infrastructure at some time, based on asset lifetime. Here, instead of object age, the residual value per object is used to obtain a mean infrastructure quality. C is described as:

$$C(t) = \sum_{j=1}^{t} \sum_{i=1}^{m} rc_i + rv_{i,s} \tag{6.3}$$

with rc_i being the replacement cost of object i. Q is described as:

$$Q(t) = \sum_{j=1}^{t} \frac{1}{t} \sum_{i=1}^{m} \frac{1}{m} rv_{i,s} \tag{6.4}$$

The difference between non-collaborative planning and collaborative execution was modelled as the relative change with the planning phase as reference.

$$C_{rel} = \frac{C_e - C_p}{C_p} \tag{6.5}$$

with C_{rel} being the relative change in costs, C_p is planned costs and C_e is collaboratively executed costs. The same approach was applied for mean infrastructure quality in equation (6.5).

$$Q_{rel} = \frac{Q_e - Q_p}{Q_p} \tag{6.6}$$

with Q_{rel} being the relative change in mean infrastructure quality, Q_e is the mean infrastructure quality after collaboration and Q_p is the mean infrastructure quality after non-collaborative planning.

Each player yields one data point per individual game. Each group yields one data point per multi-player game. The influence of information quality on individual performance was assessed as the difference in spatial distribution of data points between individual games with perfect and imperfect information (game type 1 and 2). Differences in spatial distribution of data points between multi-player games with perfect and imperfect information (game type 3 and 4) represented influence of information quality on team utility. The spatial distribution per data cluster was analysed through plotting the clusters' standard deviational ellipse. The standard deviational ellipse is typically used to illustrate three important data cluster features: the mean centre, its two-dimensional dispersion and the orientation of dispersion. The ellipse's axes rotation around its centre is the orientation for minimum (minor axis) and maximum (major axis) dispersion, where dispersion is measured as the standard deviation (Furfey, 1927; Lefever, 1926). The unequal variances two sample t-Test was used to assess significance of the difference between spatial distributions of two corresponding data clusters.

The difference in spatial distribution was qualified as follows. The difference, or shift, between two corresponding clusters was modelled as a vector. The direction of this vector represents the type of difference between the two clusters. Five vector directions were distinguished, including 'no shift', as illustrated in figure 6.1.

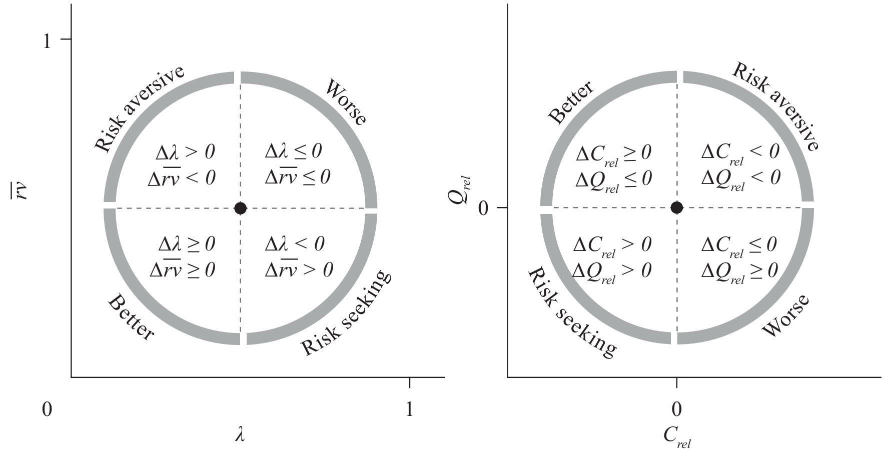

Figure 6.1: Analysis of differences in scores for single (left) and multi-player (right) simulations. Each quadrant resembles a type of difference with respect to the reference point in the centre.

A better management strategy is one with lower failure rate and lower mean residual value compared with its reference. In contrast, a worse management strategy is one with both higher failure rate and mean residual value. Risk aversion occurs when a player decides to replace an object before its expected end of functional lifetime, thereby reducing the probability of object failure. Risk seeking, on the other hand, occurs when a (group of) player(s) decide(s) to postpone object replacement to maximise functional lifetime, thereby increasing object failure probability.

Apart from cluster analysis, it is relevant to assess the score difference for individual players and individual groups. To this end, all shift directions were plotted as vectors, where the vector direction represents the qualitative difference (figure 6.1). The vector length represents the relative occurrence frequency of that vector direction. As such, each vector's length is the normalised occurrence frequency, ranging from 0 to 1. The cumulative vector length reflects 1.

Following Chorus et al. (2007) and Keller and Staelin (1987), a difference in game results is expected between simulations with perfect and imperfect information, for non-collaborative (single player) gaming simulations. The difference in game results between perfect and imperfect information for collaborative gaming simulations is expected to be absent (based on e.g. Allison, 1971; De Bruijn and Ten Heuvelhof, 2008; Lindblom and Woodhouse, 1993; Stone, 1988).

If a player would inspect all objects each round, he would always have perfect information about object state on which to base his replacement decisions on. Consequently, comparing results from perfect information and imperfect information would be meaningless in terms of the proposed cost-effectiveness (mean residual value versus failure rate). Therefore, the inspection rate per player is computed, i.e. equal to the approach in equation (6.2), to assess to what extent replacement decisions are based on perfect information.

6.2.3 Survey design and analysis

The players were asked to complete a survey after the game session to evaluate player experience considering game complexity, attractiveness and reflection of reality. These aspects indicate validity of the game results (Keller and Staelin, 1987; Sweller, 1988). A translation of the original survey is included in appendix E.

A five point Likert scale was used to measure to the respondents' game experiences on the following items: overall experience, game objective, game design, game complexity, game instructions, gaming time and waiting time. For each item, the Likert scale answer options were sorted from negative to positive experience. The distributions of Likert scores per item were visualised in a diverging stacked bar chart. This chart allows a relatively easy visual interpretation of the distribution of the given responses per item. All bars have an equal length. The frequency of given answers per survey question was normalised and depicted as different lengths within one bar.

6.3 Results and discussion

6.3.1 Action analysis

Figure 6.2 shows the cumulative distribution of state probabilities for the three available actions. The figure indicates at which given state probability an action was opted for. The horizontal axis, 'cumulative state probability', is the probability of the observed object to be in the visualised or a better state (examples in figure 5.2). As figure 6.2 shows, inspection was opted for at lower visualised state probabilities than replacement or no action. Results of the Mann Whitney U test show state

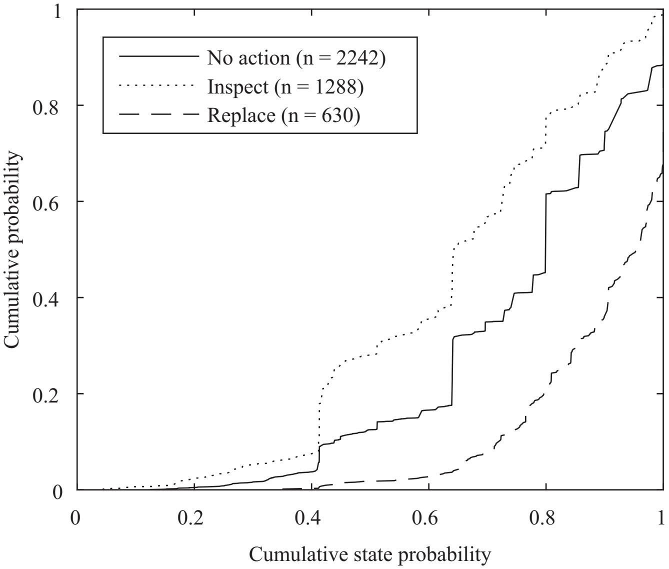

Figure 6.2: Cumulative state probability distribution for different actions

probability at action 'inspect' is significantly lower than at 'no action' or 'replace' ($p << 0.001$). These results mean that players opted for inspection, because of a reason instead of randomly: the visualised state probability was lower than they preferred and inspection was chosen to get perfect information about an object's state. This finding supports the work of Chorus et al. (2007), who found that increasing levels of uncertainty lead to information acquisition.

Figure 6.3 shows the cumulative distribution of cumulative state distributions of inspected objects, separated per object state. As figure 6.3 shows, the visualised cumulative state probability when inspection is opted for is related to the object state. Results of the Mann Whitney U test show the distributions of cumulative state probabilities significantly mutually differ ($p << 0.001$). These results mean that the likelihood an object is inspected decreases as the object goes to a worse condition state. The players preferred replacement to inspection when the object approaches s_5. This notion is further supported by the results in figure 6.4, which shows the object state distribution at various actions.

As expected and illustrated in figure 6.4, objects were more likely to be replaced when reaching the end of their functional lifetime. Vice versa, no action was generally opted for when objects were well before their functional lifetime. The conclusion from this visual interpretation is supported by results of the Mann Whitney U test, confirming the hypothesis that the state distribution for 'replace' is different from the state distribution for 'no action' ($p << 0.001$). These results mean that players opted for replacement or no action, motivated by the object's state, instead of randomly.

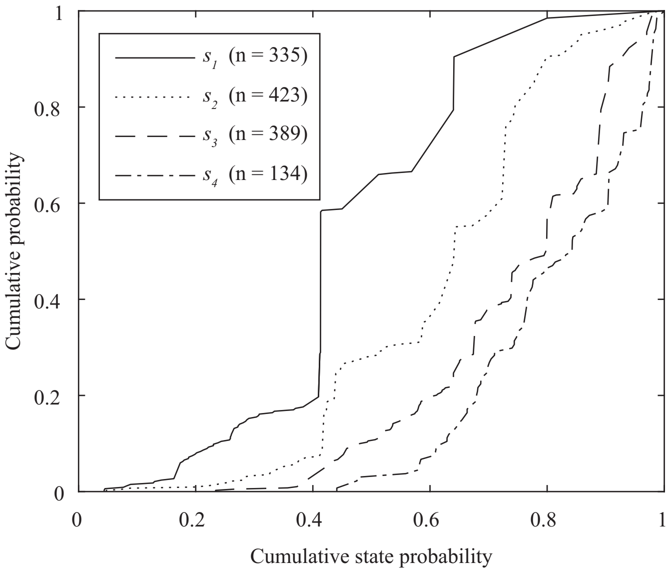

Figure 6.3: Cumulative state probability distribution of inspected object, separated per object state

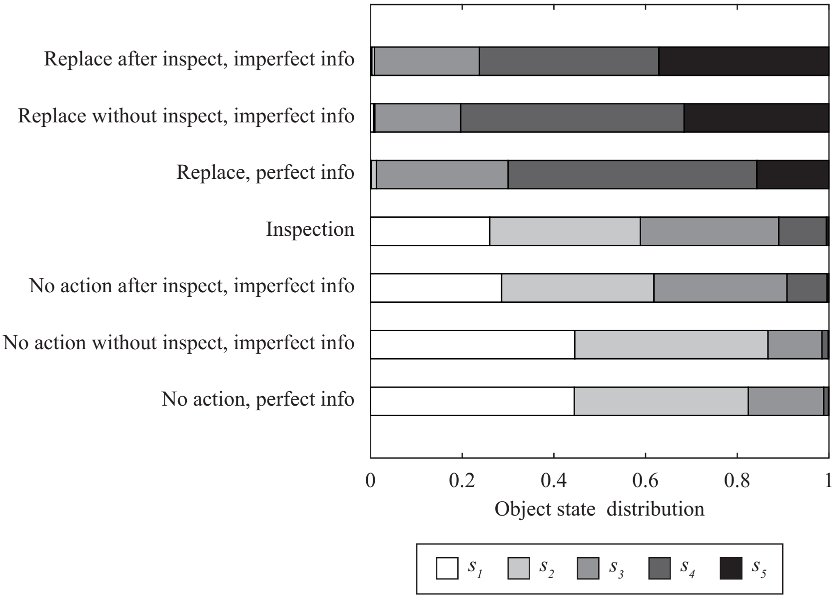

Figure 6.4: Object state distribution per action type

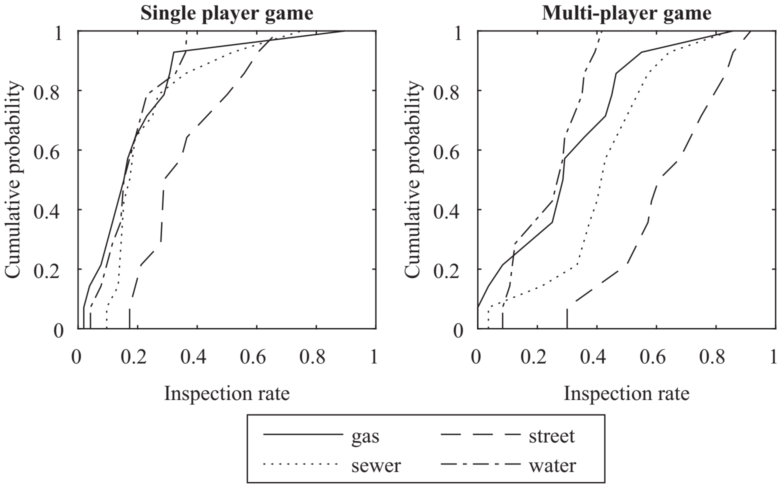

Figure 6.5: Cumulative inspection rate distribution of single player and multi-player games, separated per player

Figure 6.5 shows the cumulative distribution of inspection rates. An inspection rate of 0 implies a player did not inspect a single object during all rounds. An inspection rate of 1 implies a player inspected all his objects each round. It shows the inspection rate for all players is less than 1, because the cumulative probability of 1 (y-axis), for each line in both plots, corresponds with an inspection rate lower than 1 (x-axis). In other words, not a single player inspected all his objects in each round. This means a comparison between datasets of perfect and imperfect information is meaningful, because the results in terms of cost-effectiveness are not based on equal information quality.

Based on the presented results, it is concluded that the game results are valid and inferences can made from them. Section 6.3.2 further expands the validity evaluation by describing results from the distributed survey.

6.3.2 Survey results

Figure 6.6 shows the answer distribution per survey question. The answers obtained give information about their experiences and game result validity. Note that the survey results are based on the sample that included both the stages of game testing and actual playing.

The survey results show a relatively positive overall player experience, reflected by 99 % of the answer located at the two positive answers options. The responses to the other questions are primarily located in the positive answer options. This indicates they followed their game objective, leading to game results that are explainable with respect to the predefined analysis scheme. The majority of respondents indicated a ‘positive’ to ‘very positive’ conceptual game design, suggesting they could reflect upon it for their day-to-day practice, which increases game realism. The majority of responses on the items ‘complexity’ are also located at the most positive answer options. As a result, it suggests the players understood and comprehended the game functioning, indicating their choices were based on their objective and not made randomly. The scores for the item ‘rules’ are less profoundly positive compared to the other items. The responses for the item ‘playing time’ indicate players did not experience fatigue effects due to too long playing time. The responses at ‘waiting time’ indicate players felt involved, which positively affects game result validity. In general, the survey results support the validity claim from section 6.3.1, implying the game results can be considered valid, because of the positive responses on all presented items.

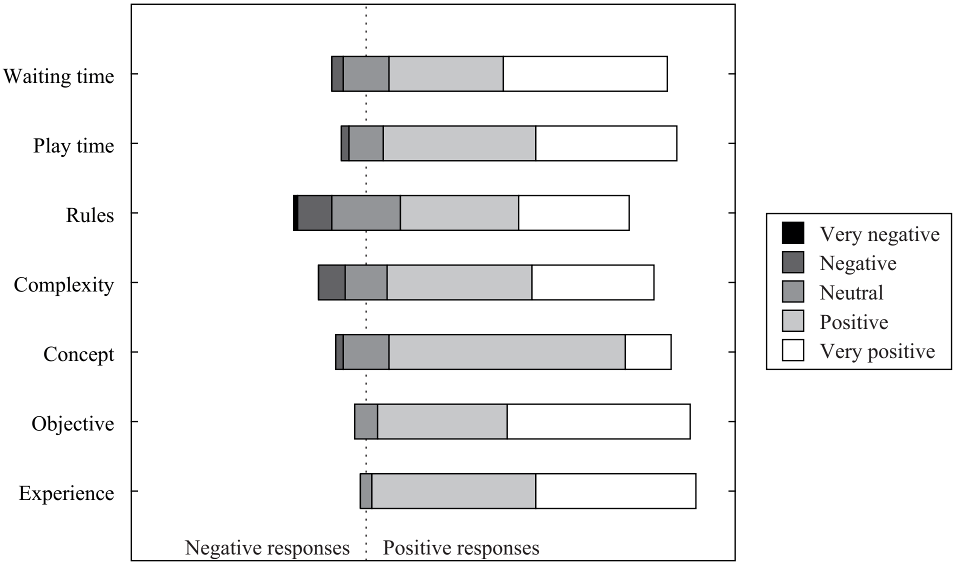

Figure 6.6: Answer distribution per survey question (n = 88)

6.3.3 Information quality and non-collaborative decision-making

Figure 6.7 shows the game results, in terms of two-dimensional cost-effectiveness, of the single player simulations. Each sub-plot contains 28 data points, two per player with a total of 14 players per infrastructure. The centroid per cluster is plotted as well, where each centroid is surrounded by its standard deviational ellipse. The visualised dispersion is based on one standard deviation. A reference score space, resembling random inspection and replacement (see section 5.4.3), is included as well.

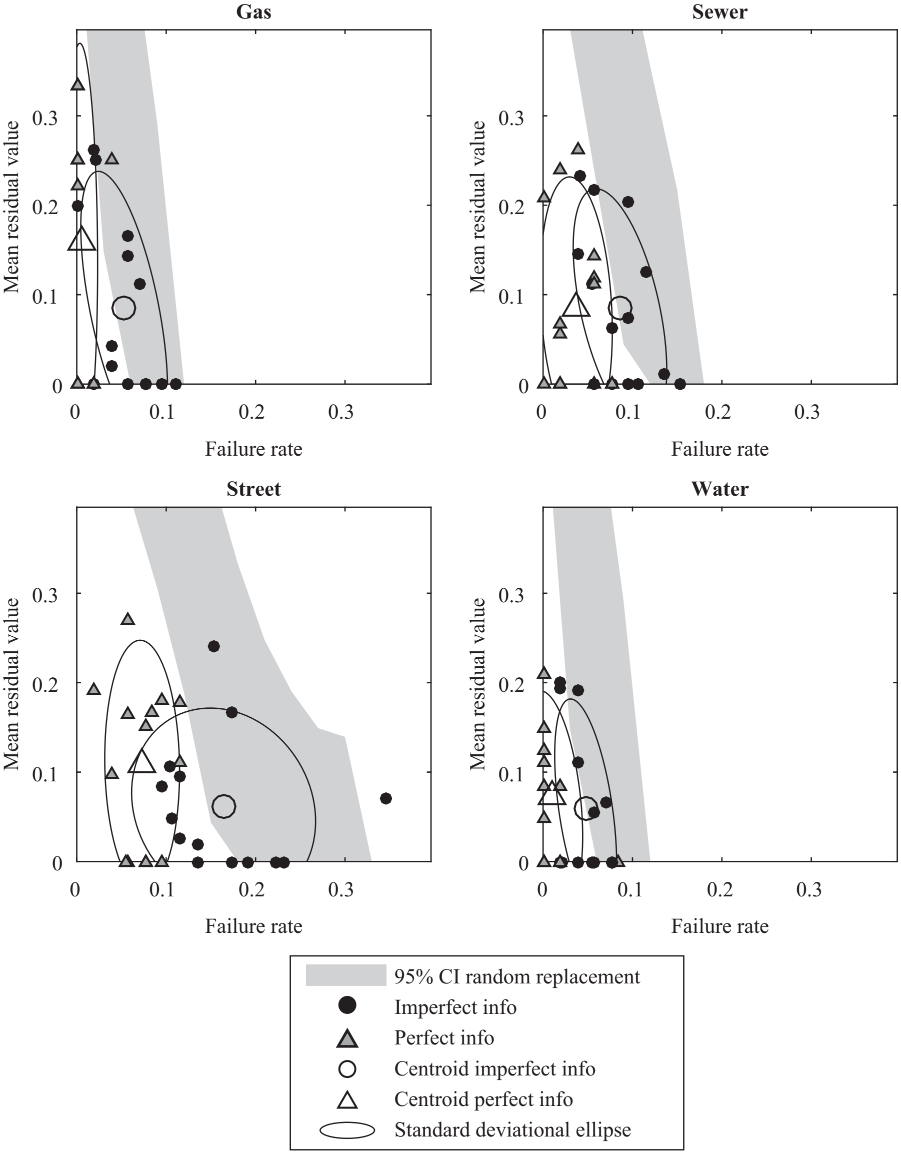

Figure 6.7: Game output of single player game

A first aspect that can be obtained from figure 6.7 is the mutual positioning of the two clusters per sub-plot, by comparing the two centroids and two-dimensional dispersion. Both clusters, for each infrastructure, are relatively separated in terms of failure rate, where results from perfect information simulations generally have a lower failure rate. Table 6.1 shows the results of the two sample *t*-Test to indicate whether two corresponding clusters differ significantly in their spatial distribution.

Table 6.1: p values from two sample t-Test regarding failure rate and mean residual value (n = 14)

Player	p for failure rate	p for mean residual value
Gas	$0.79 \cdot 10^{-4}$	0.14
Sewer	$0.31 \cdot 10^{-3}$	0.96
Street	$0.22 \cdot 10^{-3}$	0.15
Water	$0.18 \cdot 10^{-3}$	0.64

The results from table 6.1 show that the spatial distributions of two clusters per sub-plot differ significantly with respect to the failure rate. No significant difference was found regarding the mean residual value. Consequently, players scored significantly better, i.e. more cost-effectively, when presented with perfect information instead of imperfect information, applying the qualification scheme from figure 6.1. The results suggest that, overall, the players did not alter their replacement strategy when presented with perfect information, because there is no significant difference in mean residual value. On the other hand, the players encountered more object failure during the simulations with imperfect information, because of a significantly higher failure rate. A potential explanation for this is that the players expected the objects to deteriorate according to their believed rate, but these did not and failed sooner than anticipated. In other words, they had more bad luck.

When compared to a random replacement strategy, part of the game results stemming from the simulations with imperfect information showed to be equally cost-effective. The majority of game results from the simulations with perfect information showed to be more cost-effective than random replacement. One street player scored worse than random replacement. Additional analysis of the underlying data showed that the player did not always replace an object after it had failed. Hence, the player scored a higher failure rate than random replacement.

The shifts between two corresponding data points, i.e. two scores from the same player, are shown in figure 6.8. The relative occurrence frequency per direction is represented by relative vector length. Each shift resembles the difference with respect to the imperfect information data point. Figure 6.8 shows approximately 50 % of shifts were in the 'better' direction, reflecting a decrease in both failure rate and mean residual value. This means that players managed their infrastructure more cost-effectively when presented perfect information. The other 50 % were in the 'risk aversive' direction, reflecting a decrease in failure rate with an increase in mean residual value. It implies players replaced objects before their expected end of functional lifetime.

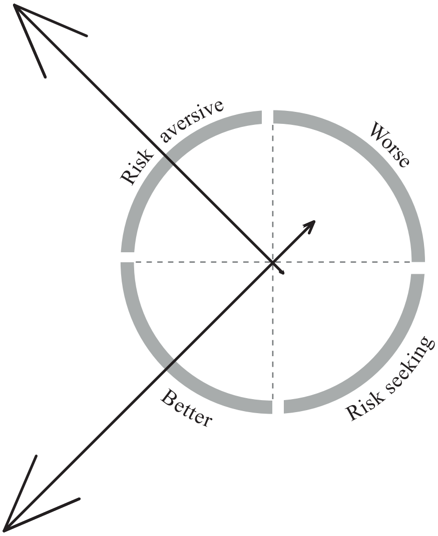

Figure 6.8: Shift directions and relative frequency of occurrence (n = 56)

6.3.4 Information quality and collaborative decision-making

Figure 6.9 shows the game results, in terms of two-dimensional cost-effectiveness, of the multi-player simulations. The plot contains 28 data points, equally divided over two clusters. The centroid is displayed for each cluster. Each centroid is surrounded by its standard deviational ellipse. The visualised dispersion is based on one standard deviation.

The data points of both simulation types in figure 6.9 share an approximately equal score space. The dispersion in both dimensions is approximately equal. Results from the two sample t-Test (sample size of 14) on both dimensions showed that the difference between game types for relative cost change is not significant ($p = 0.58$) but the difference for infrastructure quality is significant ($p = 0.20 \cdot 10^{-2}$). This is explained as follows. Application of the Mann-Whitney U test on the underlying infrastructure quality data (sample size of 356), of both game types, shows mean infrastructure quality at collaborative execution was significantly higher than at the non-collaborative planning stage ($p << 0.001$). Comparing mean infrastructure quality of the planning stages of both game types showed a significantly lower mean infrastructure quality at the game with perfect information ($p << 0.001$), implying fewer objects were planned for replacement in that game type. Hence, a higher relative change for mean infrastructure quality in figure 6.9 for the perfect information game type is logical.

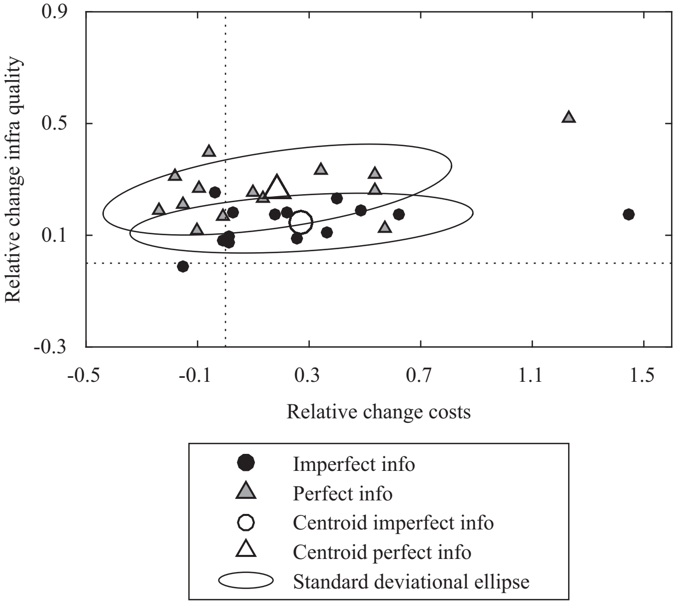

Figure 6.9: Game output of multi-player game

Comparing mean infrastructure quality between the collaborative execution stages of both game types showed no significant difference ($p = 0.10$). Although this latter p-value is close to the significance criterion of 0.05, it indicates infrastructure quality is approximately equal in both collaborative execution stages. These results suggest the quality of available information about current object state is primarily influential on an individual level (as in figure 6.7); not on group level. The results support the perspectives in decision-making theory (e.g. Allison, 1971; De Bruijn and Ten Heuvelhof, 2008; Lindblom and Woodhouse, 1993; Stone, 1988).

The shifts between two corresponding data points are depicted in figure 6.10. Again, each shift resembles the difference with respect to the imperfect information data point. Note that the qualitative classifications are located at different positions than in figure 6.8. Figure 6.10 shows an equal number of shifts in the 'better' and 'risk aversive' direction. Better equals a decrease in total costs and increase in mean infrastructure quality with respect to the imperfect information game type. Risk aversive equals an increase in both total costs and mean infrastructure quality with respect to the imperfect information game type.

Part of the collaborative game results were located in the left upper quadrant in figure 6.9 (10 of 28), resembling increase in mean infrastructure quality and decrease in costs with respect to the planning phase. Again, collaboration was shown to alter the players' judgments about the necessity of object replacement. Yet, they acted rationally by basing their collaborative decisions on team utility, i.e. lowest costs for acceptable infrastructure quality. Collaborative decisions in these groups were

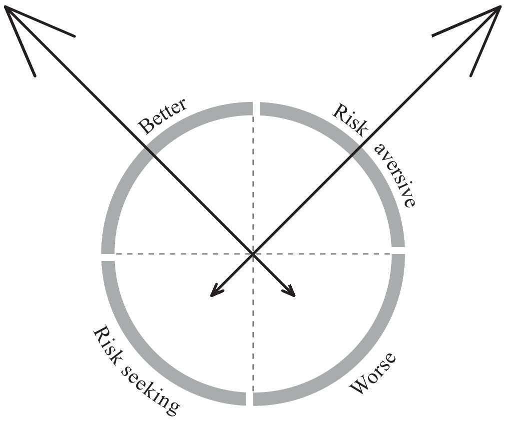

Figure 6.10: Shift directions and relative frequency of occurrence (n = 14)

typically guided by one or two players acting as 'leaders'. They closely monitored the effects on costs and object state and guided individual players to join simultaneous replacement or postpone their replacement for the next round. Yet, the results show that such rational collaborative decision-making is not common, which may be explained by the fact that these efforts put an additional cognitive workload on the players.

The majority of data points is located in the upper right quadrant (18 of 28), resembling more costs and better infrastructure quality in the execution phase than in the planning phase. This result has two implications. First, collaboration altered the players' judgments about the necessity of object replacement. Second, since the players knew their team utility score in the collaborative phase, simply because it was displayed, they had the possibility to act rationally accordingly, i.e. altering each individual choice and base their collaborative efforts on optimal team utility. Instead, the majority of groups saw that total costs increased while achieving a higher mean infrastructure quality. As such, the group's displayed behaviour was risk aversive. A typical verbal expression during these gaming sessions was "Ah, you are going to replace your object? Well, then I am going to replace mine as well to join you." In such cases, the players seemed to act opportunistically, because the actual rational argument of team utility was discarded and replacement was executed. The qualitative evaluation of the game sessions suggested that this could have been motivated by the idea that it would be cheaper this way and a failure in the next game round was likely to be avoided. It appears, at face value, that groupthink influenced the groups, hampering the search for a rational outcome. Yet, the underlying behaviours and motivations were not subject of our study, so would give ample room for further investigation. Heath and Gonzalez (1995) for example, concluded that interaction with others increases decision confidence, i.e. a person's belief about the correctness of a decision, while decreasing the quality of the decision. They reasoned that persons in groups are more inclined to seek areas of agreement than trying to motivate one's own position. When they work towards a consensual decision, the individuals in the group are more willing to modify their individual decisions based on the information they obtain from the others Heath and Gonzalez (1995, p. 323).

The collaborative decision-making process in the game could be improved by several options. First, a leader may be appointed upfront, who would be responsible for evaluating the management choices, and corresponding effects, during the gaming simulation. Second, group decision support may benefit decision-making by on screen presentation of 'optimal solutions'. Optimal may refer to lowest current costs or lowest expected life cycle costs, based on accurate forecasts of failure probability. As such, players are presented information about sound group choices, reducing the need to actively think about these and engage in discussions. Yet, it is quite unlikely perfect information about decision alternatives will be obtained in reality given the uncertainties in deterioration process and coincidental damages inflicted to the infrastructure by third parties. It is unknown whether incorporating both leadership and presentation of optimal solutions will yield different collaborative game results, because the effects of irrational human group behaviour seem relatively strong. Still, it is possible for group decisions to outperform individual decisions, as illustrated by the data points in the left upper quadrant in figure 6.9. The presented results were generated within a set of specific assumptions (e.g. information about current state only and absence of presentation of 'best' decision alternative) that conceptually mimic infrastructure management in current practice. Given the potential for improvements in collaborative decision-making, it is worthwhile to study the effects of the described ways to enhance collaborative decision-making on decision outcome.

6.4 Conclusions

The game simulates operational decision-making for networked infrastructure management, with the objective to assess whether changes in information quality affects players' choices. To this end, four gaming simulations were played: a single and multi-player game, both with perfect and imperfect information about infrastructure quality. The game appears to be a reliable and valid research instrument, because the results it generated were not random, but in line with the players' objective. Next to that, game complexity, attractiveness and reflection of reality were positively evaluated, benefiting result validity. The combination of these aspects allows for making inferences from the results.

It is found that information quality affects players' choices in non-collaborative gameplay. Yet, the influence is limited to one of two dimensions for cost-effectiveness performance: failure rate. The players scored significantly better regarding failure rate when presented perfect information instead of imperfect information. A significant difference in mean residual value was absent, suggesting the players did not alter their replacement strategy when presented perfect information, but encountered more object failures due to acceptance of imperfect information about object state. In other words, they had more bad luck. Moreover, the players' scores from the games with imperfect information are comparable with the computed solution space resembling random replacement.

A change in information quality hardly influences the collaborative game results. It means collaborative choices for team utility are primarily based on intuitive judgments leading to a compromise, instead of analytical reasoning as a group.

These conclusions suggest, within the limitations of the simplified reality in the game, efforts in increasing accuracy and reliability of information about infrastructure performance is only partially beneficial for increased cost-effective management. These efforts increase the quality of decision-making, but the added value is meaningful particularly in single actor decision-making environments. In multi-actor settings, however, increased quality of decision-making on individual level did not lead to increased quality of the outcome on group level. The outcome of the collaborative process is influenced most by negotiations and making compromises, probably triggered by groupthink effects.

This does not mean that efforts to increase accuracy and reliability of information about infrastructure performance, for example by improving inspection techniques and ageing models, are ineffective. Further research should focus on a cost-benefit analysis considering information quality improvement versus management benefit. Second, the underlying motivations of collaborative decisions should be thoroughly examined, in order to understand why certain collaborative choices are made. This aspect is currently largely neglected in decision support systems for infrastructure asset management. And third, effects of leadership and presentation of 'optimal' decision alternatives should be analysed in further research to identify options for increasing rationality in group decision-making.

7 Discussion and concluding remarks

The objective of this thesis is to describe the actual processes and use of information in decision-making for sewer replacement, in order to assess whether variations in information quality influence decision-making outcome. To this end, theoretical and empirical analyses were presented, combining qualitative and quantitative data collection and analysis techniques, including literature research, interviews with and a questionnaire for sewer asset managers, serious gaming, and extensive brainstorming and discussion meeting with experts from the urban drainage sector. This mixture of techniques was required to address the main objective. The provided insights into the actual decision-making for sewer replacement increased transparency and allowed to identify where improvements may be feasible.

The following sections present a discussion, four overall conclusions and five recommendations for further research and practitioners.

7.1 Discussion

Analysing decision-making in reality with little prior knowledge calls for a research approach that is able to grasp the complexity of all interacting variables. Consequently, a socio-technical systems approach was adopted, because it allows to consider human and organisational aspects, as well as technical aspects in the, in this case, management of a large infrastructure (Baxter and Sommerville, 2011; De Bruijn and Herder, 2009). Adopting this perspective proved to be worthwhile, because both the social and technical aspects showed to interact strongly.

Literature was reviewed regarding three main aspects: decision support models for sewer and other urban infrastructure asset management, decision-making theory and serious game development. Comparing decision support tools and decision-making theories showed large differences between the two, although decision support tools attempt to help decision-makers in practice. Details about this finding are presented at the conclusions (section 7.2). This research contributed to transparency in developing serious games for research purposes. The objective was to present the game design as transparent as possible, describing all design steps from the conceptual model to the detailed calibration. The game design guidelines in Duke (1980, 2014) provided a useful and comprehensive overview for all relevant design elements to take into account.

Interviewing was a logical first step in data collection because it is well suited for exploration of a topic and allows to create rich datasets. The analysis of decision-making in chapter 3 is obtained by interviews with sewer asset managers only. The analysis may have benefitted, at least in terms of validity, by interviewing the other involved infrastructure managers per project as well. This additional effort matches to the notion that each actor in a multi-actor decision-making process may have different interests and roles. The obtained interview data is considered generic for the sewer replacement in the Netherlands, based on feedback sessions with expert from the urban drainage sector.

The second part of the main objective, the influence of information quality, was chosen to be addressed by simulation. Interviewing would have been an alternative to simulation here, but it would have resulted in data from hypothetical situations, because each interviewee would be asked “what if you would have had better information?” Examples of applicable simulation methods for human behaviour are agent based modelling, game theory, stated choice experiments, path analysis, Markov decision processes and serious gaming. From these examples, serious gaming is essentially the only method that can incorporate interaction between persons. The interview results showed negotiation between infrastructure managers was an important aspect in decision-making upon sewer replacement. Hence, simulation by means of serious gaming would be closer to reality. Next to that, the other examples rely on predefined, usually rational, models of decision-making. This is not necessary for serious gaming, and hence, simulation would be closer to reality as no arbitrary assumptions about a decision-making model were needed.

The design considerations for the game led to a heavily simplified reality inside the game. Elements including citizens, traffic, nuisance, reputation, available budgets and effects of object failure other than costs were excluded from the game. The framework of reasoning for object replacement was reduced to object state and synergy from co-operation with other players. The advantage of this simplification is that it created a controlled experimental simulation environment, suitable for hypotheses testing. The downside of simplifying reality is that the game might become boring or even unrealistic, which in turn decreases the value of the obtained results. Several players noted this as a drawback of the game. Yet, the game proved to be a valid research instrument and the obtained results revealed a pattern that matches with decision-making theory (see chapter 3), both of which are satisfying considering research purposes. As such, the results are generalisable, although a larger sample size (fourteen currently) may have benefitted the applied statistical analysis.

Serious gaming is typically a method that aims at delivering a learning experience to the players (e.g. Harteveld et al., 2010; Martin et al., 2011; Mayer et al., 2005; Schulze et al., 2015; Speelman et al., 2014). Some players playing Maintenance in Motion might have expected a learning experience, because they had been curious about the functioning of 'a game' and their expectation it would help them in their professional daily practice. Yet, the learning experience was put on a conceptual level and not explicitly communicated to the players, because this was not the primary objective of the game. A successive game could therefore serve as a training instrument.

The game contained two information qualities on which players based their choices for object replacement: perfect or imperfect. Perfect information about object state showed to benefit decision outcome of individual players. It is yet unknown to what extent imperfect information should reach perfection, and the costs involved in reaching this through development of inspection techniques, in order for it to result in more cost-effective management. This is a challenge for future researchers.

7.2 Conclusions

The conclusions were drawn from observations of the urban drainage sector in practice and research, putting them into a specific context. This urban drainage sector has been a field of civil engineers, in which knowledge about fluid dynamics, pump performance, modelling and concrete pipe deterioration has been considered as a sound foundation for managing sewer systems and educating new sewer asset managers. Along with this technological orientation towards sewer asset management the belief that decision-making is rationalised as long as data about system performance is available was implcitely accepted. This is reflected in the urban drainage research field. Research about sewer asset management has mainly focussed on describing normative decision frameworks, i.e. decision support tools. Yet, the presence of the actual involved decision-maker(s) is virtually neglected in these tools.

Why is this relevant? The urban drainage sector has put extra attention to increasing the cost-effectiveness the last decade . Yet, the limited knowledge about actual operational decision-making impedes determining or improving cost-effectiveness of sewer asset management, because transparency is required to assess whether decision-making may be improved. The technical orientation towards sewer asset management hampers efforts to improve decision-making, because an additional socio-political perspective is required to take a step forward. For example, knowing the real condition states of individual sewer pipes in a city centre may be irrelevant when realising that the decision-making process for sewer replacement is probably triggered by activities of other infrastructure managers. Although the notion of multi-actor complexity may seem trivial to policy makers and political scientists, adopting this additional perspective to sewer asset management is new and yielded valuable results to the urban drainage sector.

The three main research questions are:

1. How does a sewer asset manager decide about sewer replacement?
2. How does a group of infrastructure managers decide upon joint public works?
3. How do variances in information quality influence decision outcome, both for individuals and groups?

Research question 1 is answered by conclusions 1, 2 and 3. Question 2 is answered by conclusion 4. Question 3 is answered by conclusions 3 and 4.

1. Intuitive reasoning is probably the main driver for decision-making for sewer replacement.

Intuition is a substantial factor in sewer replacement decisions to ensure continuity of the day-to-day practice (chapter 2). It is logical intuitive judgments are opted over analytical reasoning, because of two reasons. First, sufficient and accurate data and knowledge to predict structural condition is typically not available. Second, a sewer asset manager is faced with interests of other actors in or outside the organisation that he operates at, for example reputation issues towards citizens or political preferences for water management strategies. These two elements inevitably force a sewer asset manager to rely on his experiences and decide intuitively about sewer pipe replacement, because objective arguments alone do not suffice currently. It seems however, the use of intuition cannot be skilled, because the two conditions for intuition to be skilled (sufficient regularity and learning opportunity) are not met. Physical feedback of the sewer system to its manager is almost unobservable, because of the robustness of the sewer system and the relatively long time it takes before this feedback occurs. As such, chances for learning and gaining relevant experience are limited. Consequently, the already developed intuitions have a high chance of being incorrect. This notion of unskilled intuition contrasts with the perception of sewer asset managers in practice, who perceive their professional experience, or ‘gut-feeling’, as one of their most valuable assets to make sound decisions. It is not necessarily a problem that intuition is used, but it becomes a hurdle when one prefers to increase decision-making transparency and cost-effectiveness.

2. Decision support models for sewer asset management largely neglect the actual decision-making process.

Many studies related to the design or implementation of decision support models, for various infrastructures, propose normative decision frameworks or even claim to result in optimal maintenance strategies. Although these models attempt to assist decision-makers in practice, they neglect an important element: the real world containing the actual decision-making process (chapters 2 and 3). This decreases the effectiveness of the decision support tools, since they implicitly assume a technocratic attitude in the decision-making process. First, decision support tools require extensive and high quality data sets, which are usually not available in practice. Second, decision-making in practice is guided by a wide variety of information sources, a small portion of which are included in decision support models. Making decisions is an art of fine tuning, combining and negotiating about available information and interests of other infrastructure managers, mixed with a variety of specific local circumstances (chapters 3 and 4). Third, decision support tools portray decision-making in most cases as a single actor process, while decision-making in reality is a multi-actor process in many cases. Consequently, they are particularly useful in single actor decision-making settings, for example maintenance planning.

3. Individuals manage their infrastructure more cost-effectively when presented with perfect instead of imperfect information about current object state.

It was expected that individual decision-making benefits from increased information quality, based on the rational decision-making model and experiments described in literature. This was confirmed by the results of the serious gaming sessions, where the outcome of decision-making was measured in infrastructure failure rate and the mean residual value of replaced objects (a variable indicating the mean residual value of replaced objects, representing a player's replacement strategy). The results showed that the infrastructure failure rate is significantly lower when players are presented with perfect instead of imperfect information (chapter 6) about current object state. A significant difference in mean residual value was absent, suggesting the players did not alter their replacement strategy when presented imperfect information, but did encounter more object failures. Moreover, when compared to a random replacement strategy, part of the game results stemming from the simulations with imperfect information showed to be equally cost-effective.

4. Collaborative operational infrastructure management hardly benefits from increased information quality about current object state and typically leads to higher costs.

Collaboration among infrastructure managers to simultaneously replace adjacent infrastructures in practice is motivated by reduction of costs, nuisance to citizens and traffic disruption. While these motivations seem viable, collaboration in the gaming sessions typically (in approximately 65 % of the collaborative gaming sessions) led to increased costs (chapter 6). Players were willing to spend more money as a group than they had planned individually without collaboration, where the additional expenditures resulted in better infrastructure quality. Players knew their team utility score in the collaborative phase and had the possibility to act rationally accordingly. Instead, the majority of groups saw that total costs increased while achieving a higher mean infrastructure quality. The cost increase was 30 % on average. Comparing this with figures from reality, this is approximately 8 Euro/Dutch inhabitant/year (1.45 billion Euro/year on sewer asset management, 60 % for sewer replacement, 50 % of projects are multi-actor, 17 million inhabitants) sewer asset managers are willing to pay to work simultaneously instead of separately. This is approximately 10 % of the annual expenditure per inhabitant. Collaboration alters a manager's judgment about the necessity of replacement, because his frame of reasoning expands. Instead of judging infrastructure condition only, he may incorporate opportunity through joint actions with others, thereby potentially advancing or delaying his planned replacement action.

In approximately 35 % of the collaborative gaming sessions, collaboration led to cost reduction while increasing mean infrastructure quality, compared to non-collaborative planning. The cost reduction was 10 % on average, equalling to approximately 2.5 Euro/Dutch inhabitant/year when comparing this with reality, which is approximately 3 % of the annual expenditure per inhabitant. The group seemed to act rationally in most of their collaborative choices, because the players performed better as a group than they had planned without collaboration.

The quality of available information about current object state is primarily influential on an individual level; not on group level (chapter 6). This suggests group choices for team utility are primarily based on intuitive judgments leading to a compromise, instead of analytical reasoning as a group. This finding matches with decision-making theory (see chapter 3). The added value here is that it is analysed quantitatively. It suggests efforts in increasing accuracy and reliability of information about structural condition is only partially beneficial for increased cost-effective management. These efforts increase the quality of decision-making, but the added value is meaningful particularly in single actor decision-making environments. The outcome of the group process is influenced most by negotiations and making compromises. When considering that approximately half of the sewer replacement projects in the Netherlands are initiated through a multi-actor decision-making process (chapter 3), the current challenge for increased decision transparency and cost-effectiveness is unlikely to be solved by the current type of decision support tools for sewer asset management.

7.3 Recommendations

The following recommendations are provided, following from the discussion in section 7.1 and the conclusions in the previous section.

1. Decision support tools

Current decision support tools neglect how decisions are actually made, hampering their effectiveness in practice. Decision-making showed to be a process of incorporating and weighing multiple variables, some of which obtained from tacit knowledge. In order to close the gap between support tools and reality, model developers could pay more attention to multi-criteria decision support tools that can incorporate tacit next to explicit knowledge. Of course, the incorporated tacit knowledge needs to be properly motivated and evaluated frequently, because it should remain transparent for every user and insights may evolve over time.

The analysis framework presented in Van Riel et al. (2014a) could be expanded. In its current version, it focusses on the collaboration between a road and sewer asset manager, where the cost effect of shifting planned sewer works in time is analysed. Inclusion of additional infrastructures and more dynamic collaboration options develops insights into cost optimisation of collaborative infrastructure management.

2. Individual and group motivations

The underlying motivations of group decisions could be thoroughly examined, in order to understand why certain collaborative choices are made. If transparency is created in this respect, it allows for assessing whether and where decision-making may be improved.

Decision-making processes in sewer asset management could be analysed in relation to their context. As such, the presented analysis in chapter 3 should be expanded further by including relevant metadata for each executed renewal project, including deployed budget, structural condition assessment and involvement of other parties. Then, statistical analysis could provide insights into causal relations, or the absence of those, between decisions and their underlying motivations.

3. Serious game

A successive game could be developed with the primary function of delivering a learning experience relevant for sewer asset managers. To this end, the game could include various elements that were excluded from Maintenance in Motion, in order to provide the players with more realism they could relate to their daily work. Examples of elements to include are budget allocation, citizens, traffic and nuisance. It would provide an opportunity to test and evaluate management strategies. Preferably, alternative ways of budget deployment should be explored, because this currently seems to hamper improvement in municipal management strategies in the Netherlands.

4. Cost-benefit analysis

A cost-benefit analysis could be carried out considering information quality improvement versus management benefit. A first effort in this respect is presented in Rokstad et al. (2015), following a modelling approach. Another modelling option is to expand the Monte Carlo simulations provided in chapter 5 substituting perfect information (100 % certainty about current object state) with a range of uncertainties about current object state, combined with various replacement strategies.

5. Recommendations for current practice

Various sources of information are used today in sewer replacement decisions. It is important that sewer managers realise that neither every source is relevant at all times, nor do they give perfect information. This means that data should not be regarded as the 'truth', but as an indication of what might be the current status given specific circumstances in a particular point in time. People operate within bounded rationality, forcing them to use intuition to transfer information from multiple sources to judgments and decisions. Next to that, decision-making in multi-actor settings forces people to step away from their own preferences in order to make compromises. Sewer asset managers should be able to judge the impact of the uncertainties on the decisions they need to make on a day-to-day basis in order to motivate their choices properly, even in unpredictable decision-making processes.

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A List of information sources

Table A.1: List of information sources. The node degree was normalised by dividing by the number of nodes (26). The mean edge weight, excluding zero, was normalised by dividing by the maximum possible weight, the number of projects (150).

	Information source	Information category	Normalised degree	Mean normalised edge weight
a.	Camera inspections	System	0.885	0.040
b.	Pipe age	System	0.538	0.045
c.	Planning of urban redevelopment	Environment	0.654	0.029
d.	Planning of road works	Environment	0.615	0.034
e.	Citizens' complaints call data	Environment	0.423	0.047
f.	Settlement rate	Environment	0.269	0.055
g.	Storm water policies	Organisation	0.462	0.023
h.	Hydraulic model: Hydraulic performance	System	0.692	0.018
i.	Hydraulic model: Environmental performance	System	0.308	0.013
j.	Collapsed sewer pipe	Environment	0.346	0.009
k.	Maintenance reports	System	0.192	0.035
l.	Groundwater level	Environment	0.346	0.015
m.	Create manageable situation	Organisation	0.192	0.009
n.	Presence of trees	Environment	0.462	0.009
o.	Change in system layout	Organisation	0.192	0.009
p.	Soil settlement due to poor building preparations	Environment	0.154	0.007
q.	Quality of household connections	System	0.192	0.009
r.	Work already prepared	Organisation	0.231	0.007
s.	Limited ground cover	Environment	0.192	0.007
t.	Utility services activities	Environment	0.269	0.009
u.	Traffic density of road above sewer	Environment	0.231	0.008
v.	Budget	Organisation	0.154	0.007
w.	Time pressure	Organisation	0.077	0.007
x.	Parking issue	Environment	0.192	0.007
y.	Large construction project	Environment	0.077	0.007
z.	Influence of citizens' power	Environment	0.038	0.007
aa.	Observation during operational activities	System		
bb.	Damage to sewer inflicted by others	Environment		

B Costs as function of number of Monte Carlo simulations

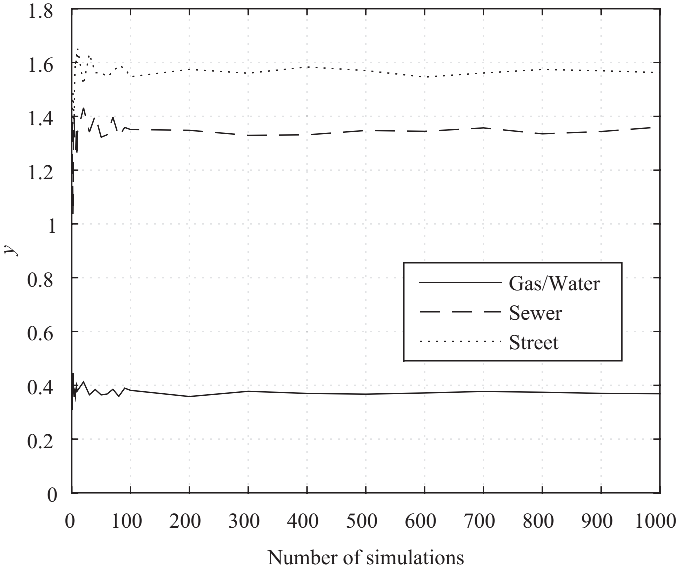

Figure B.1: Mean total costs y as function of number of Monte Carlo simulations

C Game flowcharts

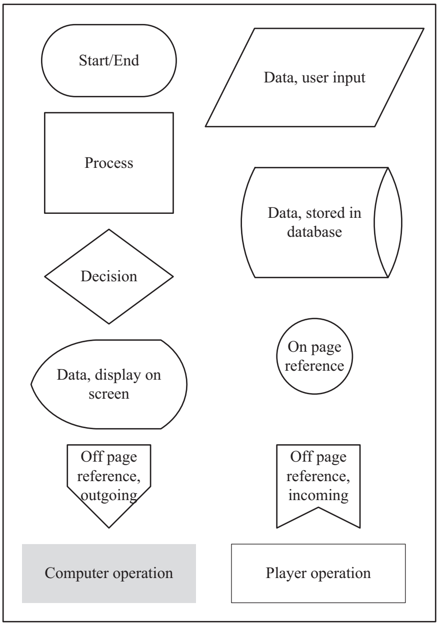

Figure C.1: Game flowchart: legend

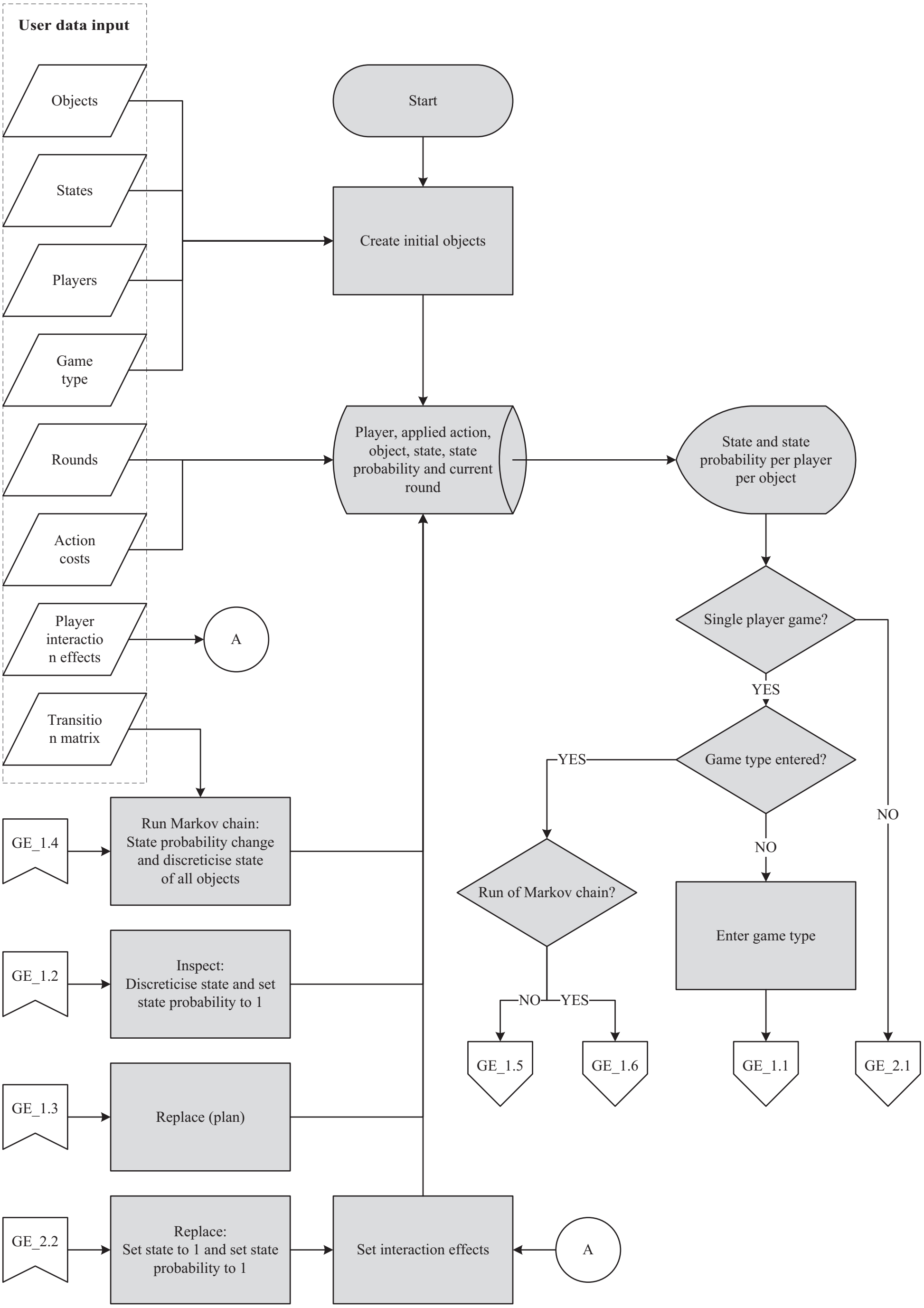

Figure C.2: Game flowchart: game engine, part 1

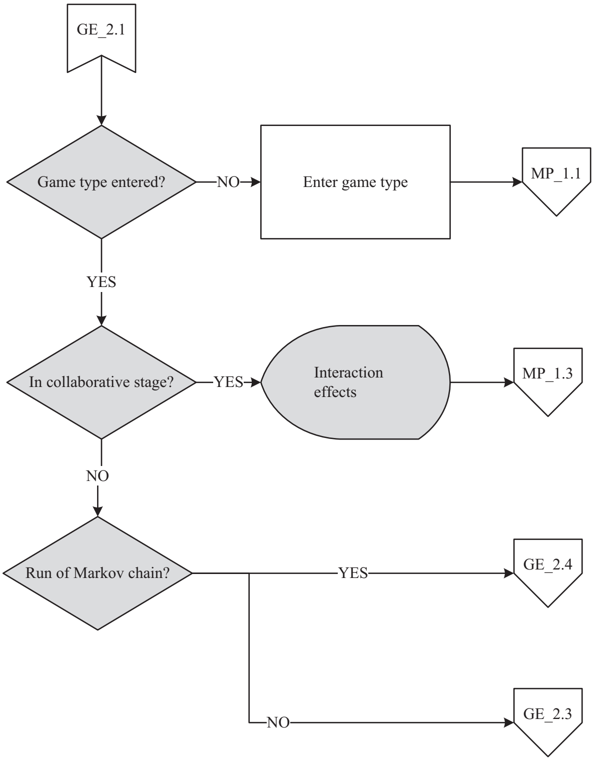

Figure C.3: Game flowchart: game engine, part 2

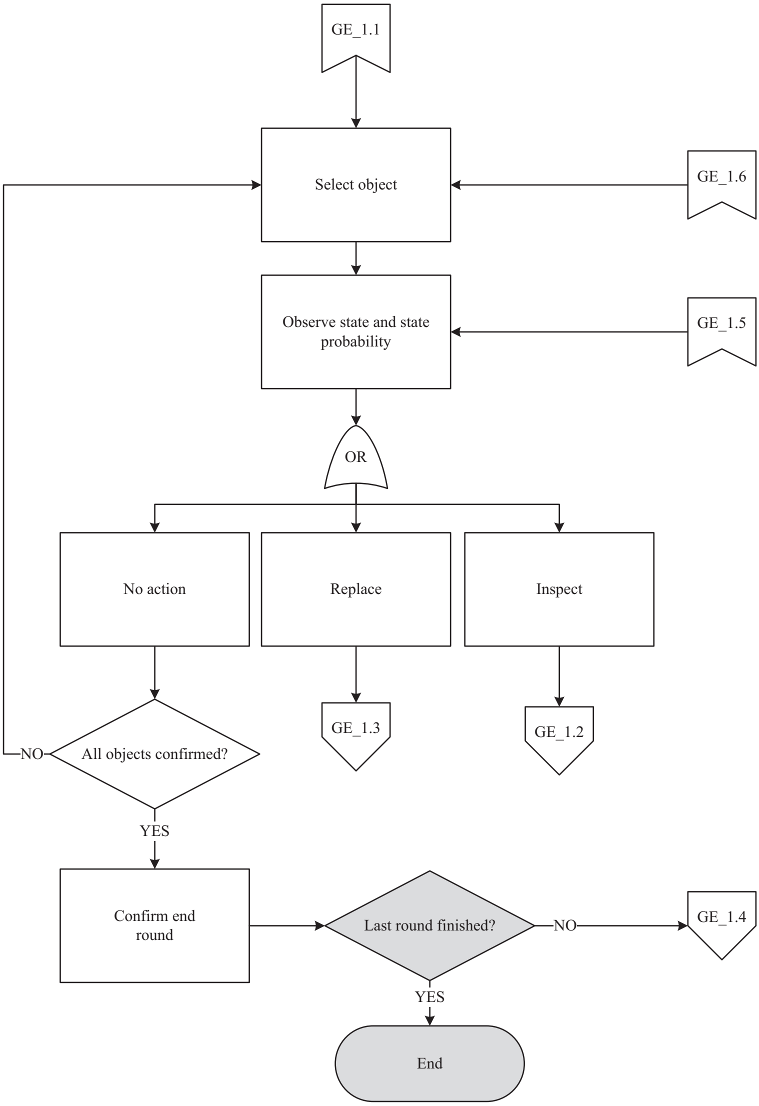

Figure C.4: Game flowchart: single player game

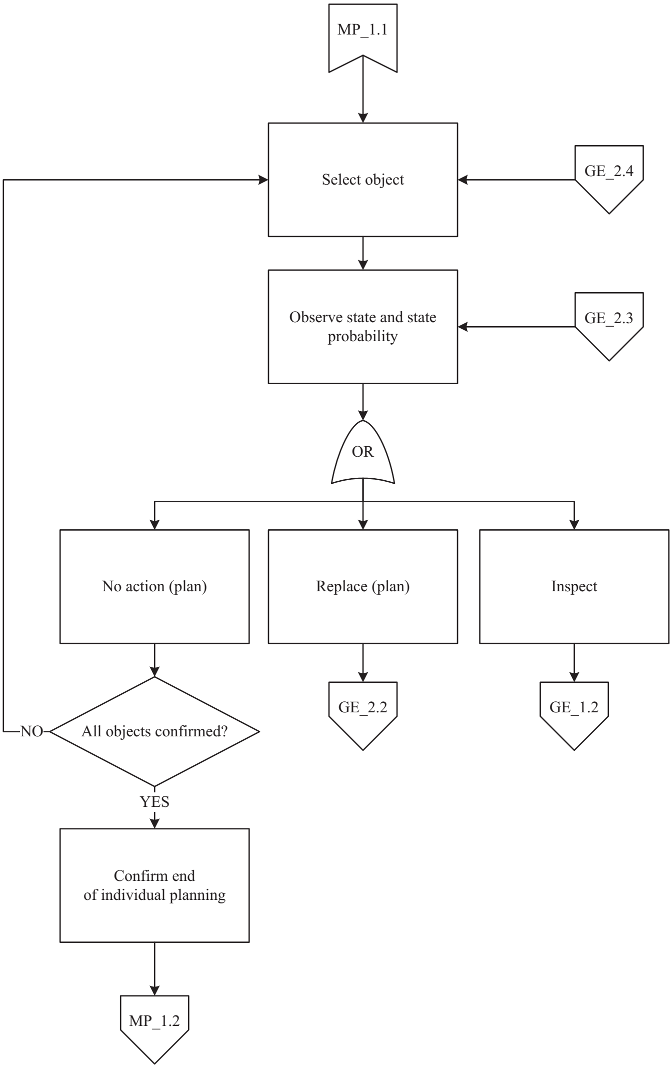

Figure C.5: Game flowchart: multi-player game, planning stage

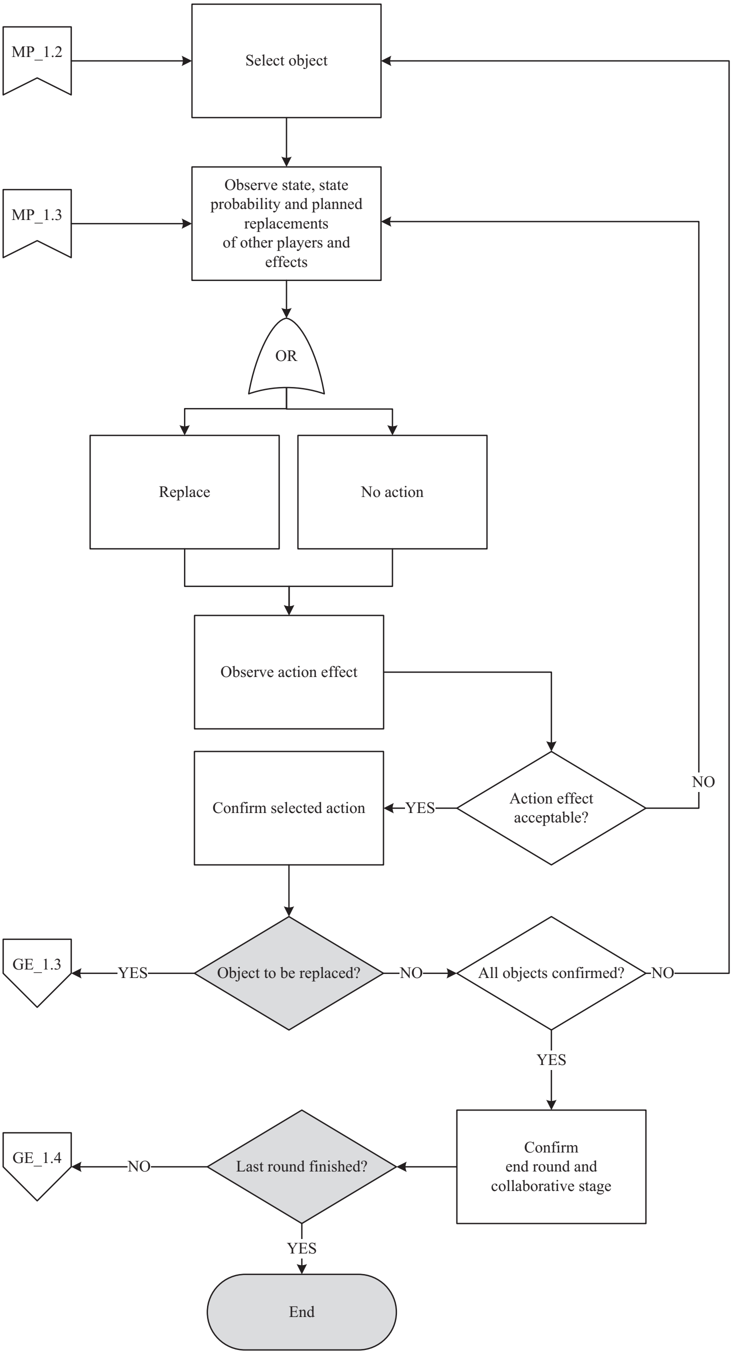

Figure C.6: Game flowchart: multi-player game, collaboration stage

D Matlab script game engine

```
% MATLAB SCRIPT OF THE GAME ENGINE 'MAINTENANCE IN MOTION'
%
% Written by Van Riel, W. & Clemens, F. (2015)
%
% Function to perform Monte Carlo simulations with game engine. The ...
    game engine is based on a discrete time discrete state Markov ...
    chain. Each player manages independent infrastructure  objects, ...
    which go through a deterioration process. Players can replace the ...
    object or do nothing to it. Inspection is a third action to ...
    apply, allowing to the object to go from a probabilistic to a ...
    discrete state.
%
% State discretisation is modelled by uniform sampling from the ...
    inverse cumulative state probability vector.
%
% The model contains a random replacement strategy. It replaces an ...
    object when failed and replaces randomly if not failed. ...
    Inspection is applied randomly as well.
%
% Four players are included (gas, drinking water, sewer and street), ...
    each with a different deterioration speed.
%
% Several physical infrastructure interactions are included:
% * replacement of sewer causes the street to go to state 1
% * replacement of gas causes the street to deteriorate faster, where ...
    faster means: the first entry in the state probability vector is ...
    equally divided over the other entries.
% * replacement of water cause the street to deteriorate faster, ...
    where faster means: the first entry in the state probability ...
    vector is equally divided over the other entries.
%
% [f,V] = GameEngine(P,v,T,pr,pi,R)
%
% Output:
% * V = mean residual value of replaced objects
% * f = failure rate
%
% Input:
% * P = transition matrix
% * v = relative speed vector for players (number of steps through chain)
% * T = time, number of rounds
% * R = residual value vector
```

```
% * pi = inspection probability
% * pr = replacement probability
%
% More details are presented in:
% Van Riel, W., Post, J., Langeveld, J.G., Herder, P.M., Clemens, ...
    F.H.L.R. (under review), A gaming approach to networked ...
    infrastructure management, Structure and Infrastructure Engineering

%% Model input parameters

n = 5;
v = [1 1 2 4];
m = length(v);
T = 100;
R = [1 2/3 1/3 0 0];    % residual value vector for 5 states
pii = 0 : 0.01 : 1;     % full range of pi
prr = 0 : 0.01 : 1;     % full range of pr
runs = 200;             % number of Monte Carlo simulations

%% Generate transition Matrix P

p = 0.8;                % manually chosen value that suits game speed

d = zeros(1,n-1);
for i = 1:n-1
    d(i) = 1/10^(i-1);
end

a(1) = (1 - p) / (d(1) + d(2) + d(3) + d(4));
a(2) = (1 - p) / (d(1) + d(2) + d(3));
a(3) = (1 - p) / (d(1) + d(2));
a(4) = (1 - p) / (d(1));

P(1,:) = [p , a(1) , a(1)/10 , a(1)/100 , a(1)/1000];
P(2,:) = [0 , p , a(2) , a(2)/10 , a(2)/100];
P(3,:) = [0 , 0 , p , a(3) , a(3)/10];
P(4,:) = [0 , 0 , 0 , p , a(4)];
P(5,:) = [0 , 0 , 0 , 0 , 1];

%% Monte Carlo Game Engine and register output

for k = 1:length(pii)
    pi = pii(k);
    for i = 1:length(prr)
        pr = prr(i);
        parfor j = 1:runs
            [x,y] = GameEngine(P,v,n,m,T,pr,pi,R);
            f(i,j,k,:) = x; % x is a 1x1x1x4 vector, each 4th ...
                dimension is a player
            V(i,j,k,:) = y; % y is a 1x1x1x4 vector, each 4th ...
                dimension is a player
        end
    end
end
```

```
function [f,V] = GameEngine(P,v,n,m,T,pr,pi,R)
```

```
%%
% Matrix S contains the following variables:
%
% S(1,:,:) is the state probability vector
% S(2,:,:) is the cumulative state probability vector
% S(3,:,:) is the discretized state

%% Preallocate memory

state = randi(n-1,1,m);             % create initial random states ...
    without failed states

S = zeros(3,5);                     % create initial matrix
S(1,:) = [0.25 0.25 0.25 0.25 0];   % initial state prob. vector
S = repmat(S,1,1,m);

temp_V = NaN(T,m);                  % residual value counter
r_count = zeros(T,m);               % Replacement counter
c_count = r_count;                  % Collapse counter

%% Loop all players m and all rounds T

for i = 1:T

    % set initial replacement switchboard
    replace = zeros(1,m);

    for j = 1:m
        S(1,:,j) = S(1,:,j) * P ^ v(j);
    end

    % cumulative state prob. vector
    S(2,:,:) = cumsum(S(1,:,:));

    % discretisation of state
    for j = 1:m

        a = rand();

        aa = [0 S(2,:,j)];
        [~,d_st] = histc(a,aa); % check index of interval
        if state(j) < n
            if d_st > state(j)
               S(3,:,j) = zeros(1,n); S(3,d_st,j) = 1;
               state(j) = find(S(3,:,j) == 1);
            else
               S(3,:,j) = zeros(1,n); S(3,state(j),j) = 1;
            end
        end

        a = rand();

        % Inspection and discretisation
        if pi > 0
            if S(2,state(j),j) < pi
                aa = [0 S(2,:,j)];
                [~,i_st] = histc(a,aa); % check index of interval

```

```
                S(1,:,j) = zeros(1,n); S(1,i_st,j) = 1;
                S(2,:,j) = cumsum(S(1,:,j));
                S(3,:,j) = zeros(1,n); S(3,i_st,j) = 1;

                state(j) = find(S(3,:,j) == 1);
                clear aa i_st
            end
        end

        % count failures
        if state(j) == n
            c_count(i,j) = 1;
        end

        % set replacement switchboard to 1 if failed
        replace(state == n) = 1;
    end

    % Replacement strategy and counter
    for j = 1:m

        a = rand();

        if a < pr
            replace(j) = 1;         % set replacement switch 'on'
            r_count(i,j) = 1;
            temp_V(i,j) = R(state(j));

            % Replace object
            state(j) = 1;
            S(1,:,j) = [1 0 0 0 0];
            S(2,:,j) = cumsum(S(1,:,j));
            S(3,:,j) = [1 0 0 0 0];
        end

        if state(j) == n
            r_count(i,j) = 1;
            temp_V(i,j) = R(state(j));

            % Replace object
            state(j) = 1;
            S(1,:,j) = [1 0 0 0 0];
            S(2,:,j) = cumsum(S(1,:,j));
            S(3,:,j) = [1 0 0 0 0];
        end
    end

    % set interactions and effects
    if replace(1) == 1 && replace(4) == 0
        b = sum(S(1,1,4)) / (n-1);
        S(1,1,4) = 0;
        S(1,2:end,4) = S(1,2:end,4) + b;
        S(2,:,4) = cumsum(S(1,:,4));
    end

    if replace(2) == 1 && replace(4) == 0
        b = sum(S(1,1,4)) / (n-1);
        S(1,1,4) = 0;
```

```
        S(1,2:end,4) = S(1,2:end,4) + b;
        S(2,:,4) = cumsum(S(1,:,4));
    end

    if replace(3) == 1 && replace(4) == 0
        state(4) = 1;
        S(1,:,4) = [1 0 0 0 0];
        S(2,:,4) = cumsum(S(1,:,4));
        S(3,:,4) = [1 0 0 0 0];
    end

end

%% Register output

V = nanmean(temp_V,1);              % V is a 1 by m vector
f = mean(c_count,1);                % V is a 1 by m vector
V = reshape(V,1,1,1,length(V));     % V is a 1-by-1-by-1-by-m vector
f = reshape(f,1,1,1,length(f));     % C is a 1-by-1-by-1-by-m vector
end
```

E Game evaluation questionnaire

Please mark the score that best represents your experience.

Overall experience

1-2-3-4-5
Very negative Very positive

I followed my game objective

1-2-3-4-5
Absolutely not Totally

Conceptual game design

1-2-3-4-5
Very negative Very positive

Complexity

1-2-3-4-5
Very negative (too simple or complicated) Exactly right

Game instructions

1-2-3-4-5
Very negative (too simple or complicated) Exactly right

Playing time

1-2-3-4-5
Very negative (too short or long) Exactly right

Waiting time

1-2-3-4-5
Very negative (too much or little) Exactly right

Additional comments: