Master Thesis

Identifying the Critical Public Infrastructure Objects

Anna Klamer
4075676
Graduation Thesis | CME 2001
MSc Construction Management and Engineering
Faculty of Civil Engineering and Geosciences
Delft University of Technology

Final Version | Oktober 2017

AUTHOR

Name	A. (Anna) Klamer
Student Number	4075676
Email	Annaklamer92@gmail.com
Telephone number	+31 6 19 706 938

GRADUATION THESIS

University	Delft University of Technology
Faculty	Civil Engineering and Geosciences (CiTG) Stevinweg 1 2628 CN Delft
Master	Construction Management and Engineering (CME)
Course	CME 2001 Master Thesis Preparation and CME 2000 Graduation Thesis

GRADUATION COMMITTEE

Chairman	Prof. Mr. dr. J.A. (Hans) de Bruijn Faculty of Technology, Policy and Management
Supervisor	Dr. R. (Rob) Schoenmaker Faculty of Civil Engineering and Geosciences
Supervisor	Dr. M.L.C. (Mark) de Bruijne Faculty of Technology, Policy and Management
External Supervisor	Dr. R. (Rogier) Licher Gemeente Amsterdam

Front Page Image: (Beautiful Views, n.d.)

PREFACE

Before conducting this research, I would have never thought that maintaining infrastructures can be as complex and as essential as they are. It is not only about maintaining a bridge from a technical point of view. It is about maintaining it from a social, environmental, safety and economic point of view as well. When infrastructure assets fail they can have an influence on an individual, a neighborhood, a city or even an entire country. This significance makes infrastructure asset management so complex, but interesting as well.

This research was a long learning path in which I had to face the many unknown aspects in infrastructure asset management. These unknowns are what this research made so challenging and also just as exciting. In truth, I could not have overcome these challenges by myself.

Therefore, I want to thank my graduation committee for their guidance and advice throughout the research process. Firstly, I would like to thank my first supervisor Mark de Bruijne for your patience and the willingness to frequently make time for me for the elaborative sparring sessions that helped organizing my sometimes disordered train of thoughts. Moreover, you were always helpful with structuring my research in a way that it makes sense in my thesis. Secondly, I want to thank my second supervisor Rob Schoenmaker, who I see as the expert in asset management who gave me the most valuable advice and guidelines when it came to the true content of asset management. My discussions with you helped me solve many complex issues and the uncertainties that I had to experience during my research. Then I would like to thank the chairman Hans de Bruijn for your sharp and clever comments. Especially thanks for giving that valuable and structured advice with my kick-off on how I should tackle my approach. And lastly, a special thanks to Rogier Licher, my supervisor at the municipality of Amsterdam. Thank you for supporting me in finding the right people for my interviews and workshops and your critical observations that always helped me reflect upon my findings. I appreciate our substantive discussions during our weekly meetings as well as your extensive feedback on my research.

Also, I would like to thank the asset department of the municipality of Amsterdam. I appreciated everybody's enthusiasm to participate in the interviews and workshops and to help me with valuable results. And additionally I am grateful for Jos Staal, the risk manager of the municipality of Amsterdam. As someone being new in the world of asset management, you were valuable for diminishing the complexity of my research and testing me by asking the exact right critical questions I did not think of before. The same goes for Martine van den Boomen, an expert in asset management who I could contact when I couldn't see the wood for the trees anymore. I am grateful for your substantive advice that always helped me become more certain about my research.

And last but not least, I would like to thank my family and my friends who were there during the entire graduation thesis of which especially my father and my sister in supporting my writing.

Anna Klamer
Amsterdam, October 9, 2017

EXECUTIVE SUMMARY

Introduction

Maintaining infrastructure asset systems can be challenging for public authorities since we are living in a time where there is an increasing rate of deterioration of infrastructure assets such as tunnels, bridges and streets. This is due to the ageing and the increased use of these assets. As a result, some assets need additional maintenance measures, besides the regular maintenance, to keep them from failing. However, there is a limited budget making it impossible to invest simultaneously in each aging asset. As a solution, the asset manager can prioritize the numerous assets in order to know in which asset needs to be invested first. The sophistication of this prioritization strategy ranges from 'observations' via extended asset maintenance logs and logical reasoning down to more complex prioritization strategies which make use of risk assessment. Asset managers can use risk assessments to prioritize investments in the maintenance of their assets by assessing the risks of the assets' failure. The risk of an asset failure can be defined as the probability of failure times the impact of failure. The higher the risk value attributed to the asset, the more critical the asset is assumed to be.

Problem Statement

In practice, however, risk assessments of assets don't always yield sufficient information to support a prioritization process and help decision makers to decide which investment in maintenance for which asset is necessary first. It appears that to be able to successfully conduct the risk assessment and prioritize maintenance, the asset manager must connect with two actor groups whose perspectives and interests have a big influence on the process which seeks to identify critical assets. One actor is the asset owner, whose interests towards assets are expressed at a strategic level and who speaks a non-technical, political language, has a long-term point of view and cares about social accountability. The service provider on the other hand speaks a technical, non-political language, has a short-term point of view and cares primarily about the functioning of the assets. So, these actor groups do not speak the same language, use different time perspectives and have diverging interests. Thus the asset manager has a challenging position and needs to translate content between these strategic and operational levels. This friction strongly affects the extent to which the asset manager can claim any degree of control over the process of identifying risks of all assets.

A literature review yielded many methods to identify the critical components of an object, which is necessary for determining the necessary maintenance measures to prevent risks. Nevertheless, no method in literature explains how asset managers can identify critical objects using risk assessments. However, such a method is required when an asset manager wants to prioritize objects of an infrastructure system in order to determine which object needs additional maintenance measures first to treat the current risks.

Objective and research questions

The objective of this research is to develop a systematic process model for the asset manager to identify the critical public infrastructure objects that simultaneously complies with the interests of the three management levels involved in the asset management process: the asset owner, the asset manager and the service provider. This model is presented in an IDEF0 model, a type of process model, which shows the necessary activities, inputs, outputs, mechanisms and controls underlying the risk assessment process. The research questions that guide the research are:

"What systematic model can describe the process that asset managers could use to identify the critical objects in a public infrastructure system, taking into account the interests of the asset owner, the asset manager and the service provider?"

1. *What systematic model can describe the process that enables asset managers to identify the critical objects in a public infrastructure system?*
2. *What key interests of the asset owner, the asset manager and the service provider need to be taken into account to identify the critical objects in a public infrastructure system?*
3. *How can the asset managers correspond with these interests during the execution of the process of identifying the critical objects?*
4. *How does the process to identify critical objects in a public infrastructure system work in practice?*

Approach

The first step is to fill in the research gap in the search for a model and a method to identify critical objects. As a result, the first IDEF0 model is developed, showing a systematic process for identifying the critical objects as well as the necessary inputs, mechanisms and controls. The subsequent purpose is to collect the interests of the asset owner, the asset manager and the service provider in the process of identifying the critical objects. This is necessary in order to validate and elaborate the problem statement that indicates that these interests are also opposing in the process of the identification of critical objects. The following step is to find out how the asset manager can comply with the interests of the three management levels during the execution of the IDEF0 model. This is done by collecting the requirements of the three management levels for making the IDEF0 model work in practice. These process requirements provide challenges that the asset manager must overcome during the execution of the model. Therefore, to assure that the IDEF0 model would work in practice and to find the solutions to these challenges, the last step is to test the IDEF0 model and execute it as much as possible. This results in an improved and extended IDEF0 model with additional requirements for it to work in practice.

Method

Using literature, first the suitable modeling technique is chosen for this research. Secondly a literature study is conducted on how critical assets, and specifically components, are identified in general, since literature does not explain how critical objects can be identified. Using the input of experts and logical reasoning a theoretical IDEF0 model is constructed to determine how critical objects can be identified with the necessary inputs, controls and mechanisms. Subsequently the empirical research began. The research took place at the asset department of the municipality of Amsterdam in the Netherlands. This is a municipality that owns numerous public infrastructure objects which show increasing rates of deterioration, whilst decreasing budgets decrease their ability to maintain. Through interviews with the three management levels of the municipality of Amsterdam the interests and process requirements were collected. This was done with the use of an ex-ante analysis. This analysis consists of making a prognosis on how the process of identifying critical objects would work in practice according to the three management levels. As a result, expected challenges can be predicted and the necessary process requirements to overcome some of these challenges can be derived. Next, the theoretical IDEF0 model with process requirements was tested in practice in order to improve the model and find the necessary solutions to the predicted challenges. This was done through workshops at the municipality of Amsterdam, resulting in the final IDEF0 model with additional activities and controls for making the model work in practice.

Results

As a result, an IDEF0 model has been developed for asset managers to identify the critical objects of an entire infrastructure system. Critical objects are identified by assessing the risks of the objects with a uniform risk matrix. This matrix must be uniform for all objects, because then the risks of all the different types of objects can be compared. The risk matrix is the tool for assessing risks of the failure modes of the object, where the risk is the product of the impact of the failure mode on the infrastructure system and the expected time until the failure mode will occur. The output of the risk matrix is the Risk Priority Number (RPN) of the object's failure mode, which will determine the criticality of an object. The higher the RPN, the more critical the object.

To make this risk assessment process comply with the defined controls, namely the standards of the International Organization of Standardizations (ISO) and the interests of the three management levels, additional activities are necessary. The common purpose of these controls are that the objects must add value to the organization. Therefore, the asset manager must define the risks of the objects in terms of the organizational goals and objectives, representing a top-down approach. Then the asset manager finds the critical objects considering the interests of the service providers, but also defends the critical objects back to the asset owner in terms of the organizational goals and objectives, which represents a bottom-up approach.

To make the top-down approach possible, the risk assessment process needs an input that defines the risk of an object for the organization. This input is created by the activity of translating the organizational goals and objectives into uniform Key Performance Indicators (KPI) and performance requirements for all objects, which supports defining the risks. For instance, the impact criteria can be determined by asking what would be the impact on the organization if an object does not fulfill a performance requirement. As a result, the risk matrix considers the impacts on the organizational goals and objectives, forming the top-down approach and correspondingly supporting a line-of-sight. Subsequently the risks of the objects are assessed providing the RPN of the object. However, this must be translated back to the strategic level, asking for that bottom-up approach. This can be done by clearly explaining where the high RPNs come from. However, an additional step would be expressing the RPNs per impact indicator. Then the asset manager can show the objects that are currently the most critical in terms of availability in a certain car network. This can provide new insights such as where the availability of a car network must be improved. So, aggregating the RPN of objects per impact criteria offer the asset manager new insights, satisfying the asset owner. As a result, the risk assessment takes on a top-down and bottom-up approach.

According to the interests of the three management levels the process of identifying critical objects must be uniform, simple and comprehensible in order to become feasible for the asset managers to execute. Therefore, an additional activity must be conducted. Since a public infrastructure system can consist of numerous objects and numerous failure modes, it is impossible to assess the risks of all failure modes of all objects. So, before being able to assess the risks of the objects, the objects with the expected highest impact during failure, such as the objects that are positioned in the busiest car networks, are filtered. Next only the significant failure modes of these objects are selected. As a result, the number of risks that have to be assessed can be diminished to a more feasible number.

Recommendations

The final IDEF0 model is not necessarily general and applicable to all public organizations. Therefore, a recommendation for further research is to test into what extent the model also works at public organizations that are similar, that own a small number of objects, or parties with a higher maturity level. Moreover, the final IDEF0 model shows the level on A0 however, it does not exactly tell in detail how each activity must be executed. Therefore, a valuable research would be to study the possible methods and tools for each activity considering the process requirements to decompose the IDEF0 model further into child diagrams. From comparing the results to the ISO 55000 standards it has become clear that the IDEF0 model does not cover all standards yet. Therefore, it would be valuable to fill in this gap. The IDEF0 model can be developed further by taking a long term point of view considering future risks, adding the Plan-Do-Check-Act cycle to the IDEF0 model, and develop a leadership strategy for the implementation of the IDEF0 model in practice.

Samenvatting

Introductie

Het onderhouden van infrastructuur assetsystemen kan uitdagend zijn voor publieke organisaties zeker nu het aantal verouderde assets zoals tunnels, bruggen en straten, sterk toeneemt. Daarnaast neemt het gebruik van assets toe waardoor het verouderingsproces sneller gaat. Sommige assets hebben daarom naast het huidige onderhoud extra onderhoudsmaatregelen nodig om te voorkomen dat ze falen. Echter, budgetten zijn beperkt zodat het onmogelijk wordt om tegelijkertijd te investeren in elke asset dat extra onderhoud nodig heeft. De asset manager zal dus de vele assets moeten prioriteren om te weten wat de optimale volgorde van investeringen dient te zijn. Een simpele methode van prioritering bestaat uit het observeren van assets en zo logisch mogelijk de risico's in te schatten dat een asset faalt. De risico van een falende asset kan gedefinieerd worden als de faalkans maal de impact van het falen. Hoe hoger het risico van de asset, hoe kritieker de asset is.

Probleemstelling

In de praktijk, echter, geven risicobeoordelingen van assets niet altijd bruikbare informatie voor het vinden van de kritieke assets en het maken van de juiste investeringsbeslissingen. Het blijkt dat om de beoordeling in de praktijk te verbeter, de asset manager twee actoren aan elkaar moet verbinden die veel invloed hebben op het proces van het identificeren van kritieke assets. Eén actor is de asseteigenaar, die een belang op het strategische managementniveau heeft, geen technische maar een politieke taal spreekt, een lang termijnperspectief heeft en veel geeft om de sociale verantwoordelijkheid van de organisatie. De serviceprovider, de andere actor, spreekt juist wel een technische taal, heeft een kort termijnperspectief en geeft vooral om het functioneren van de assets. Het probleem is dus dat beide actoren een andere taal spreken, een ander tijdsperspectief hebben en tegenstrijdige belangen behartigen. Dat maakt de positie van de assetmanager uitdagend; het gaat hem erom te bemiddelen tussen het strategische en operationele niveau. De frictie tussen beide lagen heeft invloed op de mate waarin de asset manager controle heeft over het identificeren van de kritieke assets.

Literatuuronderzoek bracht meerdere methodes naar voren voor het identificeren van kritieke componenten. Een methode is nodig voor het ontwikkelen van een onderhoudsplan om risico's te vermijden. De literatuur produceert evenwel geen methode om kritieke objecten te identificeren met risicobeoordelingen. Zo'n methode is nodig als de asset manager de objecten van een infrastructuursysteem wilt prioriteren om te bepalen welk object als eerste extra onderhoudsmaatregelen nodig heeft om de huidige risico's te vermijden.

Doelstelling en onderzoeksvragen

Het doel van dit onderzoek is om een systematisch procesmodel te ontwikkelen voor de assetmanager om de kritieke publieke infrastructuur objecten te identificeren. Het model houdt rekening met de belangen van de drie managementniveaus: de asset eigenaar, de assetmanager en de serviceprovider. Het model dat wordt gepresenteerd is een IDEF0 model dat laat zien wat noodzakelijk is aan invoeren, uitvoeren, besturen en ondersteunen voor de realisatie van het proces. De onderzoeksvragen van dit onderzoek zijn als volgt:

"Welk systematisch model beschrijft het proces dat de assetmanager kan gebruiken om de kritieke objecten in een publiek infrastructuursysteem te identificeren, meenemende wat de belangen zijn van de asseteigenaar, assetmanager en serviceprovider?"

1. *Welk systematisch model kan het proces beschrijven dat de assetmanager kan gebruiken om de kritieke objecten in een publiek infrastructuursysteem te identificeren?*
2. *Welke essentiële belangen van de asseteigenaar, assetmanager en serviceprovider dienen meegenomen te worden in het proces van het identificeren van de kritieke objecten?*
3. *Hoe kan de assetmanager deze belangen meenemen in het proces van het identificeren van de kritieke objecten?*
4. *Hoe werkt het proces van het identificeren van de kritieke objecten in de praktijk?*

Aanpak

De eerste stap is om te onderzoeken welk model en welke methode er nodig zijn om de kritieke objecten te identificeren. Zodoende komen we uit op het theoretische IDEF0 model dat het systematische proces van het identificeren van de kritieke objecten laat zien samen met het invoeren, uitvoeren, besturingen en ondersteuningen. Het volgende doel is om de belangen van de drie managementniveaus in het proces van het identificeren van kritieke objecten te verzamelen. Dit is nodig om de probleemstelling te valideren en uit te breiden om uitdrukking te geven aan de mogelijkheid dat belangen tegenstrijdig zijn bij het identificeren van de kritieke objecten. De volgende stap is om te onderzoeken hoe de assetmanager deze belangen kan meenemen in het toepassen van het IDEF0 model. Om dit te onderzoek worden de eisen van de drie managementniveaus voor het IDEF0 model verzameld. Deze eisen leiden naar nieuwe uitdagingen die de assetmanager aan moet gaan tijdens de uitvoering van het procesmodel. Om te verzekeren dat het IDEF0 model in de praktijk werkt en om concrete oplossingen te vinden voor deze uitdagingen, bestaat de laatste stap van het onderzoek uit het testen van het IDEF0 model in de praktijk. Dit heeft geresulteerd in een verbeterd en uitgebreid IDEF0 model met extra eisen om het in de praktijk te doen werken.

Methode

De literatuur produceert de eerste juiste modelleringstechniek. Verder onderzoek in de bestaande literatuur heeft duidelijk kunnen maken hoe kritieke assets, op componentniveau, in het algemeen worden geïdentificeerd. Met behulp van experts en door middel van logische beredenering is een theoretisch IDEF0 model ontwikkeld voor het identificeren van de kritieke objecten. Daarna begon het empirisch onderzoek. Dit onderzoek vond plaats in de assets afdeling van de gemeente Amsterdam. Dit is een gemeente dat in bezit is van vele verschillende publieke infrastructuurobjecten die steeds sneller ouder worden, terwijl het budget van de gemeente voor onderhoud beperkt is. Door interviews met de drie managementniveaus van deze gemeente zijn de belangen en de proceseisen verzameld. Dit is gedaan door middel van een ex-ante analyse. Met zo'n analyse wordt een prognose gemaakt voor hoe het IDEF0 model in de praktijk zal werken volgens de drie managementniveaus. Zodoende zijn de verwachte uitdagingen voorspeld en de noodzakelijke proceseisen om deze uitdagingen te overwinnen opgesteld. Daarna is het IDEF0 model met de proceseisen in de praktijk getest om het model te kunnen verbeteren en om oplossingen te vinden voor de verwachte uitdagingen. Dit was gedaan door middel van workshops bij de gemeente Amsterdam. Dit alles resulteerde in een verbeterd IDEF0 model met extra activiteiten en besturingen om het proces te doen werken in de praktijk.

Resultaten

Het resultaat is een IDEF0 model voor de assetmanagers om kritieke objecten van een infrastructuursysteem te identificeren. Kritieke objecten kunnen geïdentificeerd worden door het beoordelen van de risico's van objecten met een generieke risicomatrix. Deze matrix moet generiek zijn voor alle verschillende objecten, omdat dan de verschillende risico's vergeleken kunnen worden. De risicomatrix is een tool om risico's van faalwijzen van een object te beoordelen. Het risico is hier gedefinieerd als het product van de impact van de faalwijze en de verwachtte tijd totdat de faalwijze optreedt. De uitvoer van de risicomatrix is de “Risk Priority Number” (RPN) van de faalwijze, dat aangeeft hoe kritiek het object is. Des te hoger de RPN, des te kritieker het object.

Om de risicobeoordeling aan de ISO 55000 standaarden te voldoen en om rekening te houden met de belangen van de drie managementniveaus, heeft het risicobeoordeling proces extra activiteiten nodig. Een gemeenschappelijk doel van deze besturingen is dat het object waarde moet creëren voor de organisatie. Daarom moet de assetmanager de risico’s van het object voor de organisatie definiëren, wat staat voor een top-down benadering. Dan identificeert de asset manager de kritieke objecten, meenemende wat de belangen zijn van de serviceprovider, maar verdedigt dan ook waarom de geprioriteerde objecten kritiek zijn tegenover de asseteigenaar met betrekking tot de organisatiedoelstellingen. Dit staat voor een bottom-up benadering.

Om de top-down benadering mogelijk te maken, heeft de risicobeoordeling een invoer nodig dat het risico van het object voor de organisatie definieert. Deze invoer is gecreëerd door de activiteit van het vertalen van de organisatiedoelstellingen in generieke KPI’s en generieke prestatie-eisen voor alle objecten. Dit helpt het definiëren van de risico’s en het ontwikkelen van de risicomatrix. Bijvoorbeeld, impactcriteria kunnen bepaald worden door af te vragen wat de impact op de organisatie zal zijn als objecten niet voldoen aan de prestatie-eisen. Zo zal de risicomatrix de impacts op de organisatie meenemen en de line-of-sight voortzetten. Vervolgens worden de risico’s beoordeeld wat leidt naar het RPN van het object. Echter, deze RPN moet weer vertaald worden naar het strategische niveau, wat vraagt om een bottom-up benadering. Dit kan gedaan worden door toe te lichten waar deze RPN’s vandaan komen. Een extra activiteit kan zijn om de RPN van het object te aggregeren per impactcriterium. Dan kan de assetmanager laten zien welke objecten op het moment alleen kritiek zijn aan de hand van de beschikbaarheid van het autonetwerk van de stad. Dit levert nieuwe inzichten op zoals waar het autonetwerk verbeterd dient te worden om de beschikbaarheid van het systeem te verbeteren. Kortom, het aggregeren van de RPN van het object per impactcriterium geeft de assetmanager nieuwe inzichten waarmee hij de asseteigenaar tevreden kan maken. Het resultaat is een risicobeoordelingsproces met zowel een top-down als een bottom-up benadering.

De belangen van de drie managementniveaus in het proces van het identificeren van de kritieke objecten dicteren dat het proces generiek, simpel en begrijpelijk dient te zijn om het IDEFOmodel praktisch uitvoerbaar te maken voor de assetmanagers. Daarom dient er een extra activiteit uitgevoerd te worden. Omdat een publieke infrastructuur systeem kan bestaan uit vele objecten met vele faalwijzen, is het onmogelijk om de risico’s van al die faalwijzen te beoordelen. Dus voordat de risicobeoordeling begint, dienen de objecten met de hoogste impact tijdens het falen gefilterd te worden, zoals de objecten die in de drukte autonetwerken gepositioneerd zijn. Dan worden van deze objecten alleen de meest significante faalwijzen geselecteerd. Dit resulteert in een kleiner aantal risico’s dat beoordeeld dient te worden, wat de risicobeoordeling haalbaarder maakt in de praktijk.

Aanbevelingen

Het uiteindelijke IDEF0 model is niet generiek in de zin dat het toegepast kan worden binnen alle soorten publieke organisaties. Daarom is het belangrijk om verder onderzoek te doen door te testen in hoeverre het model werkt bij publieke organisaties die kleiner zijn, een kleiner aantal objecten bezit of partijen met een hoger maturiteitsniveau in assetmanagement. Ook is het IDEF0 model ontwikkeld op A-0 niveau, dus het laat niet precies zien hoe elke activiteit uitgevoerd dient te worden. Daarom is het waardevol om mogelijke methodes te vinden voor elke activiteit. Na het vergelijken van de resultaten met de ISO 55000 standaarden werd het duidelijk dat het uiteindelijke IDEF0 model niet alle standaarden meeneemt. Daarom zou het interessant zijn om onderzoek te doen naar hoe het IDEF0 model een lang termijnperspectief en toekomstige risico’s kan meenemen. Daarnaast is het van belang het Plan-Do-Check-Act principe toe te voegen en het verder ontwikkelen van een leiderschap strategie voor het implementeren van het IDEF0 model in de praktijk.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF DEFINITIONS

Asset failure	If an asset does not perform according to the performance requirements or objectives (Smith, 2006)
Asset management	Coordination of activities to realize value from assets. This value is realized for the organization by creating a balance between costs, risks and performance, whilst pursuing the organizational objectives. (ISO 55002, 2014; Mitchell, 2002)
Component	“An item, thing or entity that has potential or actual value to an organization” (ISO 55000, 2014). In this research a component is that what builds up an object. Where an object is a bridge, the components are the pillars, beams and deck.
Criticality of an Asset	“A relative measure of the risk of asset failure that hamper the organizational goals and objectives, where the risk is determined by the probability of failure, the impacts of the risk and its weighting factors” (Smith, 2006).
Element	A group of components, such as the entire foundation which consists of multiple components (Velde, Klatter, & Bakker, 2012).
Ex-ante analysis	An approach to forecast future events in order to gather unforeseen useful information (Bernstein & Freeman, 1975).
Failure mode	A manner in which something can fail (Hydro-Engineering Institute Sarajevo (HEIS) Project, 2014).
Functional asset decomposition	A functional break down of an asset. This decomposition looks at the items functional, referring to the functions of an asset (Haider, 2013).
IDEF0 Model	“A modelling technique used for developing structural graphical representations of processes or complex systems as enterprises”(Aguilar-Savén, 2004).
Impact Criteria	Types of impacts of the asset failure, which can be technical, such as the reliability and availability impacts, or non-technical, like economic and environmental impacts. (Lützkendorf, Speer, Szigeti, & Davis, 2005)
Infrastructure asset	“An item, thing or entity that has potential or actual value to an organization” (ISO 55000, 2014). Can be an object (tunnel), a component (the foundation of a tunnel) or anything else that builds up an infrastructure that can add or remove value to the organization.
Infrastructure asset system	An integrated set of infrastructure assets, working together in a network to add value to the user (Wasson, 2006).

Key Performance Indicator (KPI)	"A KPI embodies a strategic objective and measures performance against a goal." (Eckerson, 2009)
Mean Time Between Failure (MTBF)	"The time of the average period between failures" (Breemer, Veenvliet, & Heijmans, 2009).
Object	"An item, thing or entity that has potential or actual value to an organization" (ISO 55000, 2014). In this research an object is an asset that lies in the decomposition level under the infrastructure system, referring to assets such as a bridge and a tunnel.
Performance	"For the purposes of asset management, performance can relate to assets in their ability to fulfill requirements or objectives" (ISO 55000, 2014).
Performance requirements	Description of how well functional requirements must be performed to satisfy the organizational goals and objectives (K. M. Adams, 2015).
Physical asset decomposition	A physical break down of an asset system. This decomposition looks at the items physically, referring to the bridge and its components, such as the beams and pillars of the bridge (Haider, 2013).
Probability of Failure	The chance that an asset fails, which can also be expressed in the mean time between failures (Lützkendorf et al., 2005).
Process	"Relationships between inputs and outputs, where inputs are transformed into outputs using a series of activities, which add value to the inputs" (Aguilar-Savén, 2004).
Risk acceptance level	A level of risk that is acceptable to the organization (Duijm, 2015).
Risk Matrix	A matrix that provides a mapping of impact and probability of failure to risk. This is a tool that is used to assess risks (Duijm, 2015).
Risk Priority Number (RPN)	The number that represents the size of the risk, reflecting the priority of the assessed failure modes (W. Wang, 2009).
Subsystem	A group of objects based representing a network consisting of objects, or a group consisting of one type of objects (Velde et al., 2012).
Weighting Factors	A factor allocated to an impact criterion, which refers to how much an organization values that impact criteria compared to the other impact criteria. (Lützkendorf et al., 2005)

1 | INTRODUCTION

This chapter introduces the problem and its context of the research. Section 1.1 describes the research context. Section 1.2 analyzes the problem of the research and thus motivates the succeeding research; it is followed by the problem statement in section 1.3, and ends with the literature review explaining the research gap in section 1.4.

1.1 | The Research Context

The second half of the twentieth century show large investments in building infrastructures due to the destructive impacts of World War II. These infrastructures usually have long life spans, which can reach up to 50 to sometimes even 100 years (Neves & Frangopol, 2005). As a result, the focus now in the twenty-first century has shifted from building to maintaining infrastructure assets.

According to ISO 55000 (2014), assets are "an item, thing or entity that has potential or actual value to an organization." In a public infrastructure system, which can be the entire public space of a city, the assets are public works such as roads and tunnels that provide value to the organization that owns these public works. Maintaining these public infrastructure assets is challenging because there is an increasing rate of deteriorating assets. This increasing rate of deterioration is related to the ageing of assets and an increasing use of these assets. As a result, some assets need besides the regular maintenance, additional maintenance measures to keep them from failing. Such measures can be major maintenance, replacement or an adjusted maintenance plan (El-Diraby, Kinawy, & Piryonesi, 2017; Lei, Herder, & Wijnia, 2012).

The civil engineering asset manager of the municipality of Amsterdam, for instance, manages various quay walls in the city. Many of these show disturbing signs of deterioration, such as missing stones and structural cracks, and need additional measures that are not described in the current maintenance plan. Some quay walls need to be repaired, whilst others might need to be replaced even. However, there is a limited budget. So the asset manager does not have enough money to invest in additional maintenance measures for each quay wall. Besides these quay walls there are other assets in Amsterdam showing signs of deterioration as well. To determine which assets need to be invested in first, the asset manager can prioritize the numerous assets.

To know which asset needs to be prioritized, an asset manager can look at the assets that are performing the lowest. Yet, it can be discussed whether this is a proper method. For instance, when two bridges in a city are performing equally low, do you then know enough to say you can invest the same amount of money in both assets? No, for all we know one bridge is situated on the busiest street of the city and has a high probability of failure whereas the other one is positioned in a park and is hardly ever used. The more frequently used bridge would have a higher impact when it fails. And the higher the impact and the higher the probability of failure, the higher the risk of an asset, and thus the more critical the asset is (Parlikad & Jafari, 2016). Determining the criticality of an asset is the same as prioritizing assets based on risks, and can therefore support the asset manager in determining the most urgent investments and maintenance measures.

Nevertheless, risk assessments of assets are not always successful in practice. A reason for this is the challenging position of the asset manager between the asset owner and the service provider. This challenge is caused by the varying interests of the three parties involved. (David, 1989; Purdy, 2010). So, there is a need for a way to find the critical infrastructure asset that takes into account all interests from the asset owner, the asset manager and the service provider (Y. C. Wijnia & Herder, 2007).

1.2 | Problem Analysis

For a better understanding of the problem, the following section defines the most important terms that constitute the problem statement.

1.2.1 | Asset Management

Because of the change in focus from building to the maintenance of infrastructure assets, the term asset management came about. According to ISO 55002 (2014), the International Organization for Standardization, asset management denotes the coordination of activities to realize value from assets for the organization that owns these assets. This value is realized by creating a balance between costs, risks and performance, whilst pursuing the organizational objectives (Mitchell, 2002). It is up to the asset manager to find the best balance between these three factors, as can be seen in figure 1. An Increase in one factor can lead to a deterioration in the other (IAM, 2011).

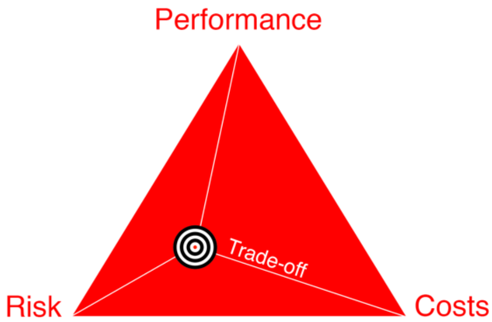


Figure 1 | Asset Management (own illustration)

According to ISO 5500 (2014) an asset is defined as "an item, thing or entity that has potential or actual value to an organization." A public infrastructure asset is then any item, thing or entity that builds up the infrastructure system. For instance, the infrastructure system of Amsterdam refers to the entire public space of Amsterdam, with a great variety of assets from the tunnels to the streets, the bridges and the traffic lights, all bound together in a system. It does not stop there as all these assets consist of other assets. For instance, the bridge consists of the columns, beams and the deck. These components can again be decomposed into smaller assets. So it doesn't matter in what detail you are looking at the infrastructure system as each item that builds up the system, from components to objects, that can have an effect on bringing value to the organization is called an asset (Velde et al., 2012).

1.2.2 | Risk Assessment

As explained before, the part of an infrastructure system that needs the most attention is the asset with the greatest risks to harm the organizational goals (Purdy, 2010). The size of the risk of the asset can then be used to determine how critical an asset is compared to the other assets' risks.

According to Smith (2006, p.12) criticality is defined as *"a relative measure of the impact of the loss of asset function on the objectives of the organization from the viewpoint of operations and maintenance."* However, this definition doesn't consider the complete risk of asset failure. We speak of asset failure when an asset does not perform according to its performance requirements or objectives. A simple definition for risk is the product of the probability and the impact of either a planned or unplanned event. The risk is then determined by the probability and the impact of a failing asset. The higher the risk, the more urgent is a maintenance measure to treat this risk (Crespo Márquez, Moreu de León, Gómez Fernández, Parra Márquez, & López Campos, 2009).

Not all types of impacts are equally important, though. The value of importance is determined by the weighting factors of the impact criteria. The impact criteria describe the types of impacts of the asset failure which can be technical, such as the reliability and availability impacts, or non-technical, like economic and environmental impacts. The weighing factors refer to an organization valuing one impact criteria more than the other. For instance, an organization can value the environment over the economy. In that case the impact of an environmental risk weighs more than the impact on the economy. The weighting factors are therefore a useful mean for reflecting the values set by an organization in the chosen impact criteria (Lützkendorf et al., 2005).

Another critique of Smith's definition concerns the viewpoint of operations and maintenance. But criticality can play an important role throughout the entire lifecycle of an asset. Therefore, a more accurate definition would be: *"a relative measure of the risk of asset failure that hampers the organizational goals and objectives, where the risk is determined by the probability of failure, the impacts and its weighting factors."* So, the risk must be defined in terms of the organizational goals and objectives. Taking all this into account it can be concluded that the way in which the risks of assets are assessed, making it possible to prioritize assets, is dependent on the organizational goals and objectives.

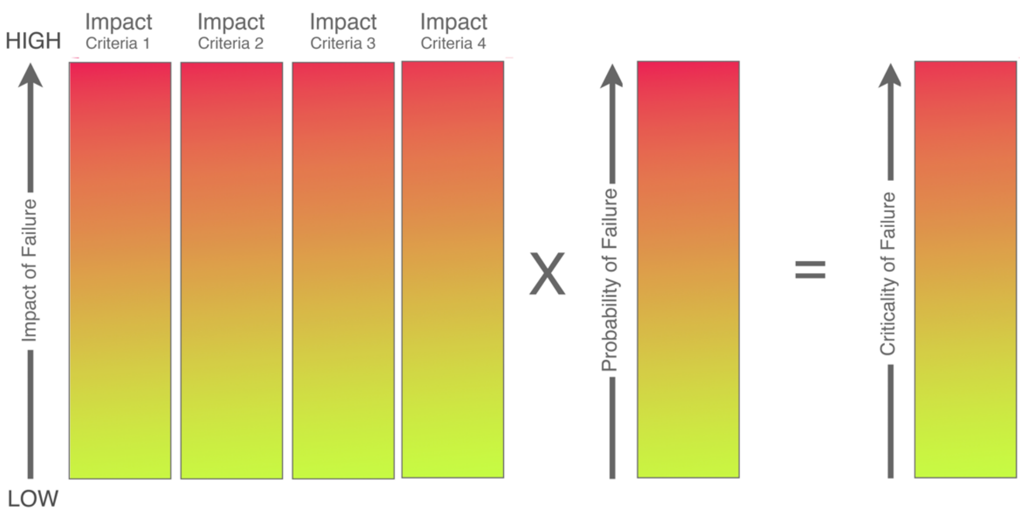


Figure 2 | Risk Assessment (own illustration)

To determine the criticality of an asset, the risks of the asset can be assessed using the risk assessment variables as visualized in figure 2. This shows 1) the different impact criteria, which are defined in the columns with the corresponding scale in the vertical direction. 2) The weighting factors of each impact criteria weigh the importance of each impact criteria. 3) The scale of the probability of failure. The probability of failure is the chance that an asset fails, however, this can also be expressed in the expected time between failures. The resulting product of the risk assessment variables is the size of the risk. The higher the impact and the probability of a failure, the higher the risk. The resulting risk of an asset compared to the resulting risk of other risk assessments, determines the criticality of that asset (Lützkendorf et al., 2005).

1.2.3 | The Asset Decomposition

Assets can be decomposed into different ways (Tan, Weijnen, Lee, & Ype, 2012). Usually this decomposition is done physically or functionally. A physical decomposition looks at the items physically, referring to the bridge that can be decomposed in its components, such as the beams and pillars of the bridge. Whereas a functional decomposition looks at the functions of the bridge, such as that the primary function of a bridge can be to connect point A to B. And where the bridge can be divided into components, the primary function of a bridge be divided into secondary functions. For instance, the primary function of a bridge can be divided into secondary functions such as carrying vehicles, bikes and pedestrians and preserving safety of the users (Haider, 2013; Tan et al., 2012).

A simpler way to envision this is with the physical decomposition. This is visualized in figure 3. This decomposition is like a hierarchy where the infrastructure system is positioned on top and the components at the near bottom. This hierarchy visualizes how objects, such as bridges, are grouped together in subsystems where a subsystem refers to a group of objects based on the type of object or based on a network that the assets are positioned in. A subsystem can be a cluster of all movable bridges, or a subsystem is a car network and contains varying types of objects such as bridges, tunnels and roads. The level below the objects are the elements that are groups of components. If the components are foundation footings, the element above is the foundation of a bridge. So, both the objects and components are physical assets, where the subsystems are clusters of objects, and the elements are clusters of components.

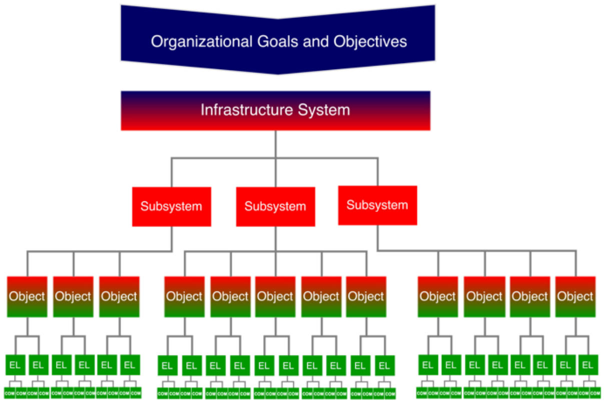


Figure 3 | Physical Asset Decomposition (own illustration)

1.2.4 | Prioritizing Assets based on Risks

Assets can be prioritized on the object and the component level. If an asset manager wants to make a decision on a maintenance measure that is necessary to treat the risks of an object failing, the asset manager can look at the component level (Haiany, 2016). It is the component failure that can lead to object failure; a bridge has failed if a column collapses.

However, not every component has the same risk. So, not every component has to be maintained equally to treat its risk. Some components can fail and will not lead to object failure. Such components will need less attention. For instance, if a lamppost of the bridge fails this doesn't automatically mean that the bridge has failed. One can still cross the bridge, so it still functions. Therefore, the columns have a larger impact on the functioning of the object. If it also appears that the columns have a larger probability of failure, the columns need more maintenance than the lamppost as it is a more critical component. Knowing which components are critical, contributes to the development of an efficient and effective maintenance plan. Such a plan describes the repetitive maintenance that must be executed to maintain the components to keep the risks of object failure as low as possible within the available budget (Mitchell, 2002). In conclusion, the risks of the components of an object must be assessed in order to determine the right maintenance measures.

A lot of methods have been developed for the identification of the critical components and the right maintenance measures, such as the well-known Reliability Centered Maintenance cycle (RCM cycle). This is a process used to determine the maintenance measures based on the causes of the risks (Davis, 2013; Moubrai, 1997). The output of this cycle is a risk-based maintenance plan that explains the repetitive maintenance that is necessary to prevent risks of failing objects from occurring.

Nevertheless, some objects must be seen as an exception to these generalized maintenance plans. This is because many objects will need additional maintenance because these objects have a different impact during failure or some objects are nearly failing due to deterioration. Such objects are currently a large risk for the organization and will urgently need an adjusted maintenance plan, major maintenance or these objects even need to be replaced, necessitating a large investment. Accordingly, prioritizing components gives an indication of *what* measures are necessary. Whereas prioritizing objects determines *where* currently additional measures are necessary.

This research is focusing on the problem that there is currently an increasing rate of deteriorating objects and therefore an increasing number of risks. Asset managers need to know on which object they have to focus on first in order to treat this number of risks. As a result, the asset managers must prioritize objects based on the current risks which is the main topic of this research.

1.2.4 | Asset Management Levels

The way the risks of assets are assessed is highly influenced by each of the three management levels that build up the infrastructure management hierarchy: the strategic, tactical and operational levels (Schoenmaker & Verlaan, 2013). Each level consists of another stakeholder with a view on another section of the decomposition of the infrastructure system. This shows all levels of assets in such a system and is visualized in figure 4. (Velde et al., 2012).

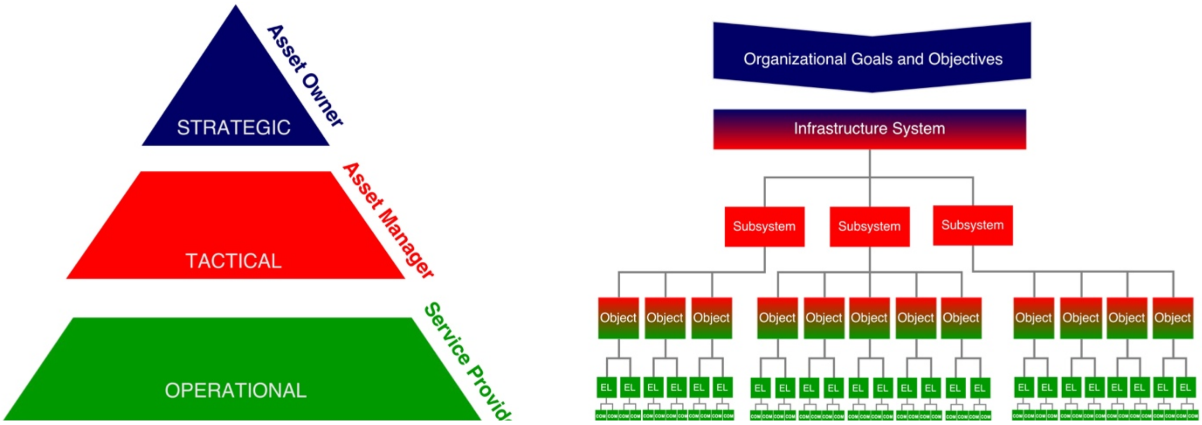


Figure 4 | Management Levels and Decomposition (own illustration)

Asset owner

The strategic level is the level of the asset owner. This is the level where the organizational goals and objectives are defined. Public asset owners in particular make strategic choices on the basis of a broad societal perspective due to their social accountability. Because of that they have a long-term perspective.

Further, asset owners have the final responsibility for the organization, for which the entire asset system creates value. Therefore, they expect substantiated information from the asset managers explaining the necessary investments for treating the risks of assets. This information must include a reflection on the organizational goals and objectives (Velde, Klatter, & Bakker, 2012; PAS 55-2:2008, 2008). It enables asset owners to ascertain that these investments realize the most value from its assets for the organization. If an asset owner accepts the recommendations from the asset manager, the asset owner provides the necessary budget (Mitchell, 2002).

Asset Manager

Below this is the tactical level, which is the level of the asset manager. The asset manager's perspective in the asset decomposition is on the level of the infrastructure system, the subsystem, and the objects. The asset manager has the overview of all objects, but does not know the details of every single object.
Asset managers defend what they think are the necessary decisions to maintain the assets in order to satisfy the organizational goals and objectives, realizing the most value from the assets (Mitchell, 2002).
In order to find out which assets are the most critical, they need two important inputs: one from the strategic and one from the operational level. Firstly, the asset managers need the organizational goals and

objectives to translate these into an asset management policy, providing the objectives for the assets. Secondly, they need information from the service provider on the current condition of their assets. The condition of the assets must satisfy the asset management policy. If not, risks occur and decisions must be made on taking the right measures to treat these risks. But the risks of assets must show the risks to the organization, and so the content of the risk assessment variables must be traceable to the asset management policy. In this way the risk assessment of assets can contribute to realizing value from the assets for the asset owner's organization (IAM, 2011; Mitchell, 2002).

When the asset managers can convince the asset owner that their assets are in need of additional measures, they receive a budget to execute these measures. Such a measure could be an expensive maintenance measure where the construction of a bridge has to be repaired to treat any high risks. So it can be concluded that the asset manager is positioned between the asset owner and the service provider, tying both parties together (Velde, Klatter, & Bakker, 2012; PAS 55-2:2008, 2008).

Service Provider
The bottom level of the hierarchy is the operational level. This is the level that consists of the components on the bottom, containing the beams and pillars, clustered together in elements, such as the entire foundation. On the operational level it is the service providers who are responsible for monitoring and inspection to determine the current condition of the object and its components, and the operational maintenance such as the replacements of components. In general, they are only busy with their tasks that concern the technical condition of their assets, which causes them to have a short-term perspective (Velde, Klatter, & Bakker, 2012; PAS 55-2:2008, 2008).

The service providers must be able to explain the asset manager stating the current condition of the asset. They must notify any defect, from the deterioration of components such as corrosion to the malfunctioning of the object like a movable bridge not opening anymore. In other words, they notify the asset manager on any signs that might indicate the occurrence of a possible cause of a risk. For instance, corrosion can lead to a weaker support structure which in the worst case could mean a collapsing structure resulting in many negative impacts, such as injuries or even fatalities. So, the service providers will notify if any corrosion shows up. In conclusion, the service providers provide the most essential input for the asset managers to assess the risks of assets to determine the assets' criticality.

1.3 | Problem Statement
Unfortunately, in practice the methods of identifying the critical assets are often insufficient for them to reach the strategic level (Wijnia & Herder, 2007). The asset owner expects the asset manager to justify why certain assets are critical, showing a clear connection between the risks and the organizational goals and objectives. For instance, the asset owner insists that the risks must be assessed on non-technical criteria also, like the asset's impact on the environment and on the reputation of the authority. In the end this seems obvious, since the aim of asset management is to realize value from an asset for the organization (Mitchell, 2002). However, asset managers don't always provide this required information, because they do not know how to do this in a systematic way (Zeb & Nasir, 2016).

At the same time, the asset manager is dependent on the service providers from the operational level as they provide the necessary information in order to assess the risks of assets. However, the quality of this information does not always meet the asset manager's expectations. Accordingly, unreliable information from the service providers can result in inaccurate risk assessments and therefore an insufficient justification of risks which means no convinced asset owner and therefore no budgets for treating the current risks of object failure (Balzer & Schorn, 2015; Woodhouse, 2007).

It appears that the asset manager must tie together two parties, the asset owner and the service provider, who do not speak the same language, have other time perspectives and differing interests in identifying the critical objects. Thus the asset manager has a challenging position with the responsibility to translate content between the strategic and operational level. This friction strongly affects the asset manager in the task to identify the critical objects.

1.4 | Literature Review

The International Organization for Standardizations (ISO) and the Institute of Asset Management (IAM) provide definitions and guidelines for applying asset management in practice. This is helpful for understanding asset management in general and developing a common language in asset management. However, they do not provide the necessary information on how to apply asset management exactly in practice (IAM, 2011; ISO 55000, 2014; ISO 55001, 2014; ISO 55002, 2014).

There is a lack of methods explaining how to apply asset management in practice, because the concept of asset management is new as the first standards were only published in 2008 (PAS 55-2:2008, 2008). Additionally, the practical translation of asset management depends on the context. Most outcomes from research on how to apply asset management are only applicable in a certain specific sector, such as a water distribution system (Hall, Masurier, Taylor, Baker-Langman, & Davis, 2004) or a nuclear plant industry (Marhavilas & Koulouriotis, 2008). But there is little relevant literature on the context of public authorities dealing with numerous and diverse infrastructure assets. Though Zeb & Nasir (2016) have developed a process for implementing asset management in case of a variety of assets, taking into account the asset managers' interests. Also, they focused on both the private and public asset owners but they did not research the interests from the point of view of the asset owner and the service provider. Moreover, they did not mention how to find the critical objects.

Most research on risk assessments of assets focuses on prioritizing the components and maintenance measures to develop risk-based maintenance plans. The literature presents many methods and tools on identifying the critical components of an object, such as the RCM cycle and the Failure Mode Effects and Criticality Analysis (FMECA) (Moubrai, 1997; Rausand, 1998). However, there is a lack in literature on prioritizing infrastructure objects to know where the current threats of risks are. The objective here is to remedy this shortcoming and thus provide fundamental practical information to asset owners and managers.

Further, some people have written about the three management levels and asset management (Radim & Soares, 2009; Woodhouse, 2007). But these articles focus more on the three levels and their responsibilities and tasks, and not about their interests in asset management. So literature does not yet explain the interests of the three management levels in asset management.

So, there appears to be no literature explaining how to find critical objects, and there is nothing on the challenges that the asset manager is facing in public authorities, such as the large number and varying types of assets and the various interests of all management levels. In brief, there is a need for a systematic process of identifying the critical objects owned by public authorities that reaches both the strategic and the operational level in order for it to work in practice.

2 | RESEARCH DESIGN

The current chapter elaborates the design for this graduation thesis. This design provides a structured outline for how the stated problem will be tackled. In section 2.1 the problem is translated into the objective of the research, followed by the research questions and the approach in section 2.2 and the scope in section 2.3. Section 2.4 explains the method of the research and introduces the organization where the research takes place. Finally, the reading guide is provided in section 2.5.

2.1 | Objective

The objective of this research is to develop a systematic process model in order to identify the critical public infrastructure objects that simultaneously comply with the interests of the three management levels: the asset owner, the asset manager and the service provider. As a result, an IDEF0 model is developed which clearly visualizes the necessary beginning and ending of the process, includes sequenced activities with the in- and outputs, and shows the relations between the activities, which is according to Zeb & Nasir (2016) important for processes to work in asset management. Moreover, this IDEF0 model leaves space for the asset manager to find the right balance between the various interests. Ultimately, the purpose of this process is that the asset manager will be able to convince the asset owner which objects need additional investments while at the same time addressing the needs and capabilities of the service providers.

This research could contribute to the awareness and consideration of the different interests of the three management levels in identifying the critical objects. As a result, it could support the asset manager in translating the strategic objectives into tactical activities using the operational outputs, and translating the outputs of these activities back to the strategic level. More specific, this contributes to the asset manager having an overview of the possible risks and therefore the asset manager will receive more control over the risks of all objects. Besides a better control, the asset manager could understand the asset owner better, resulting in a larger chance of convincing them. And by understanding the needs of the service provider, the quality of the information they provide can improve leading to more reliable risk assessment outputs. Conclusively, this process should be valuable in a time like this where asset management is being implemented by various public authorities for the first time, and the level of deteriorating assets is higher than ever. This means that asset managers are facing an increasing need of additional maintenance measures to keep the objects from failing while having unchanged budgets.

2.2 | Research Questions and Approach

For reaching the objective, the following research question and supporting sub-questions are researched:

"What systematic model can describe the process that asset managers could use to identify the critical objects in a public infrastructure system, taking into account the interests of the asset owner, the asset manager and the service provider?"

1. *What systematic model can describe the process that enables asset managers to identify the critical objects in a public infrastructure system?*
2. *What key interests of the asset owner, the asset manager and the service provider need to be taken into account to identify the critical objects in a public infrastructure system?*
3. *How can the asset managers correspond with these interests during the execution of the process of identifying the critical objects?*
4. *How does the process to identify critical objects in a public infrastructure system work in practice?*

First, a modeling technology is found that would be suitable for developing a systematic process model for the given problem statement. Next, the research gap is filled on a method to identify the critical objects of a public infrastructure system. As a result, the first theoretical IDEF0 model is developed showing a systematic process that enables the asset manager to identify the critical objects. Subsequently, the statement that the interests of the three management levels are also opposing in the process of identifying critical objects is validated. After validating the problem statement, research is conducted on ways the asset manager can comply with the interests of the three management levels while applying the theoretical IDEF0 model in practice. This is done by collecting the requirements of the three management levels for the IDEF0 model to work in practice. These requirements are additional controls to the theoretical IDEF0 model. However, these new controls provide new challenges for the asset manager in practice. Therefore, to assure that the theoretical IDEF0 model would work in practice and to overcome these challenges, the model has been tested in practice by executing it as much as possible. This has resulted in an improved and final IDEF0 model with additional requirements and activities for it to work in practice.

2.3 | Scope

The objective of developing a systematic process model to identify the critical infrastructure objects only focuses on the infrastructure objects that are visible with the public eye such as tunnels, roads and bridges. So public infrastructure systems like sewerage and electrical infrastructure systems are left out of the scope. Moreover, it only focuses on collecting requirements from the asset owner, the asset manager and the service provider. These are only the internal stakeholders that are part of the organization.

Moreover, the risks that are taken into account are the current risks during the maintenance and operation phase of objects. This does not include risks in general. Furthermore, the output of the to be developed IDEF0 model is supposed to be a list of prioritized objects based on the current risks. This serves as the input for the process of decision-making where possible maintenance measures that mitigate these discovered risks will be determined and analyzed. This decision-making process, however, is excluded from the scope. This is clarified in figure 5.

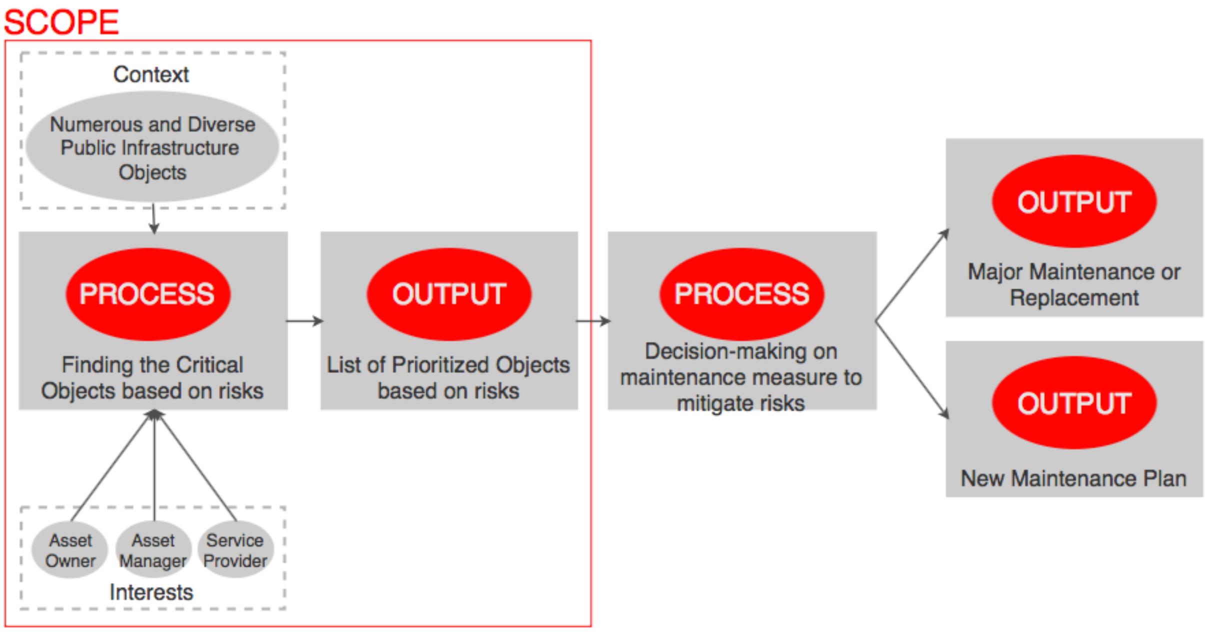


Figure 5 | Scope (own illustration)

Models can take on different levels of abstraction (Li & Chen, 2009). Since this research is determined to include the activities indicating what has to be done to identify the critical objects from beginning to end, the final model is developed on an abstract level. Therefore, the final activities do not explain how exactly these are executed. In other words, the activities are not described in detail explaining each action within the activity.

2.4 | Methodology

In the following section the methodology is explained in order to clarify how the solution to the given problem statement is found. This methodology is visualized in figure 6 below. This diagram shows that the research consists of three parts. In the first part a literature study is conducted to develop the theoretical IDEF0 model. Second, an empirical research is conducted to facilitate the IDEF0 model by defining additional controls, based on the process requirements of the three management levels. And the third part consists of testing the theoretical IDEF0 model in practice in order to improve and extend the model into the final IDEF0 model. Before going deeper into the methodology, the organization where the empirical research and the workshops took place, part 2 and 3, is introduced. This is the municipality of Amsterdam.

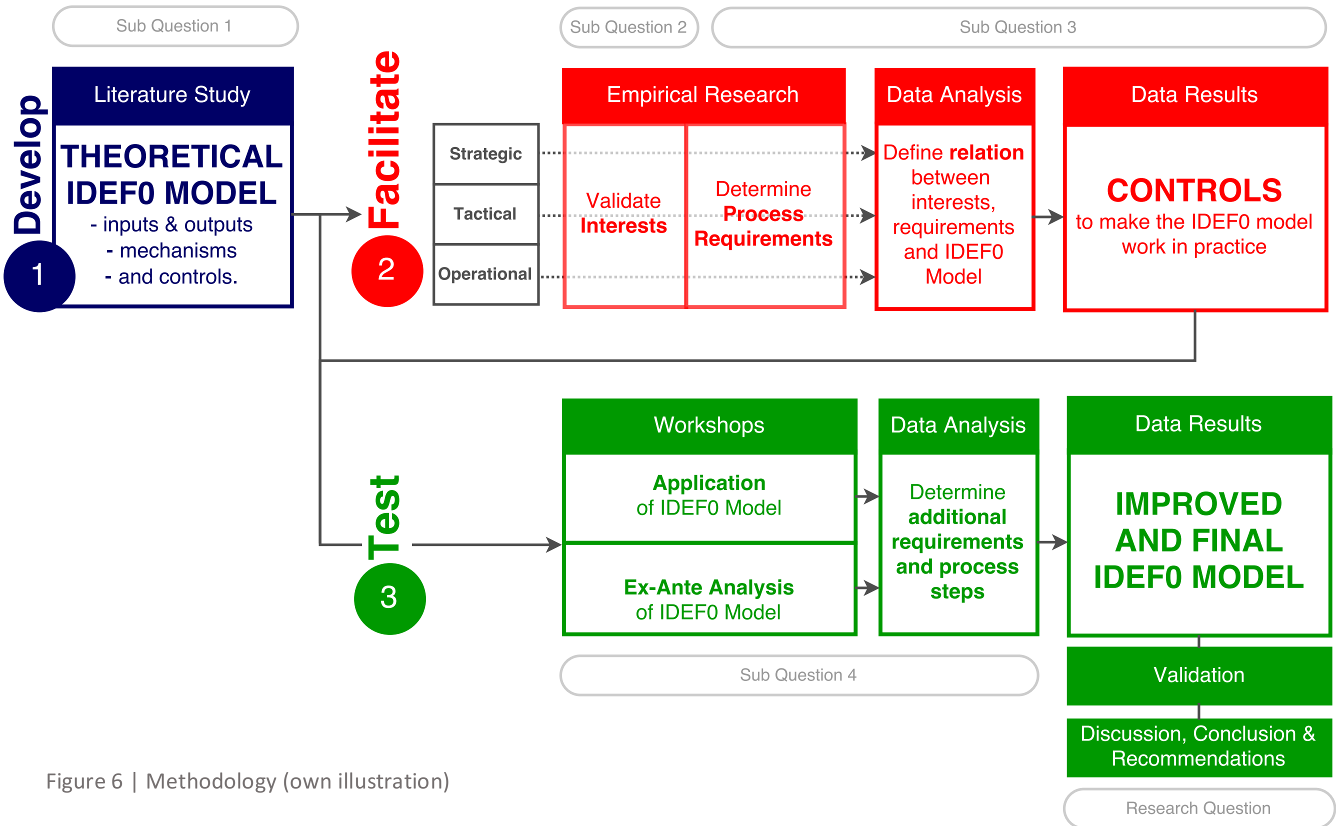


Figure 6 | Methodology (own illustration)

2.4.1 | Municipality of Amsterdam

Currently the municipality of Amsterdam is facing a reorganization of the asset department, which manages all assets building up the public area of Amsterdam. The reason for this reorganization is that the asset owner has chosen to cut back on its budgets for these assets and wants to improve the quality of the assets by centralizing the management of the assets from one department. The goal of the reorganization is therefore to implement asset management according to the standards of ISO 55000 and manage the assets by finding the right balance between performance, costs and risks.

The municipality of Amsterdam manages hundreds of thousands of differing objects with an increasing rate of deterioration. This is especially in Amsterdam a large problem due to the large number of old objects such as the bridges and quay walls. The expectation is that that this rate of deterioration will increase even faster due to the increase in tourism and economy. So, there is a clear need to control the increasing number of risks and specifically to treat the large risks that can harm the organization.

For now, they have maintenance plans for their assets that are currently executed. However, these plans are mainly based on the basic preventive maintenance and corrective maintenance when a failure occurs. But the maintenance plans do not take the objects' risks for the organization into account, while according to the ISO 55000 standards this is necessary for managing assets based on risks (ISO 55002, 2014). Moreover, the current repetitive maintenance is based on prescribed plans set up by the NEN organization. This organization develops generalized maintenance plans for all types of physical assets, from various types of bridges to streets. These plans try to deal with risks of object failure. However, according to numerous asset managers this is done implicitly. This means that these NEN plans do not support them in having a feeling of control of the risks of their objects. Also, these risks are general, meaning that these risks do not consider the impact on the organization. But most of all, these current plans do not deal with the problem of the current risks of the increasing number of deteriorating objects. As it turns out, the asset managers of Amsterdam are in a need of control of their objects' current risks in an explicit way, considering the impacts on the organization.

Currently they have a complete object inventory. It is a good thing that the asset managers have a list of all the objects they manage, since according to Zeb, Froese, and Vanier (2013) this is the first thing you need to do when you want to implement asset management. The asset managers are busy with assessing the performance of these objects. The next step for them is to map the risks. Before developing an indication of the future possible risks, the asset managers first want to have an overview of their current risks since these are the challenges that they are facing now and need to overcome.

Fortunately, the municipality of Amsterdam is well positioned to take these steps further as it has people on all three management levels with experience in asset management to do the necessary research.

2.4.1 | PART 1: Literature Study

Developing the Theoretical IDEF0 model

The first step is to do research on the most suitable modeling technique to map the process of identifying the critical objects. Hence, the requirements for the process model, such as that it had to be systematic and structural, are derived from the problem statement. Then various modeling techniques are compared according to these requirements. As a result, the modeling technique that fits these requirements best is selected.

Since there is no literature available in identifying critical objects, first a literature study is conducted to develop an understanding in how critical assets, and in specific components, are identified. Given this information, using advice from experts in asset management at the municipality of Amsterdam and using logical reasoning, a method is developed for how critical objects could be found. This method asks for a new mindset, making it complex to understand. Therefore, it is chosen to first present the context of identifying the critical objects in a simple relation diagram. Next, using the chosen modeling technique this relation diagram is transformed in a theoretical process model, namely the IDEF0 model.

2.4.2 | PART 2: Empirical Research

Facilitating the IDEF0 model

Since the IDEF0 model is partly based on literature and partly based on presumptions, the purpose of part 2 is to facilitate the initial IDEF0 model by making sure it complies with the interests of the three management levels. As a result, requirements are collected from the three management levels for making the theoretical IDEF0 model also work in practice.

First, the interests of the three management levels in identifying the critical objects are collected. From literature it is known, as explained in the problem statement, that the interests of the three management levels are opposing in assessing the risks of assets to develop maintenance plans. However, the method of assessing risks of objects as presented in the theoretical IDEF0 model is new. Therefore, it has to be validated whether the interests of the three management levels are also opposing in this method presented by the theoretical IDEF0 model.

The next purpose is to determine how the IDEF0 model can comply with the interests of the three management levels. Therefore, the requirements of the three management levels in the IDEF0 model are collected. These requirements stand for the relation between the interests and the IDEF0 model. Then the requirements are analyzed to discover useful information for executing the theoretical IDEF0 model in practice.

Interviews

The interests and process requirements are collected together through 21 interviews with people from the strategical, tactical and operational level of the asset management department of the municipality of Amsterdam and experts in asset management. An overview of the interviewees can be found in appendix C. The people stay anonymous, so in the rest of the research they will be referred to by their function; the asset owner, the asset manager, the service provider or expert. Most interviewees are from the tactical level because they have the most knowledge on the subject, can give additional important information, and ultimately, they are responsible for implementing the process of identifying the critical objects. Moreover, they are able to easily adjust their perspective to that of the asset owner and the service provider. As a result, the interviews with the asset managers dug deeper into the content.

The interviews are semi-structured interviews. These are more like conversations in which it becomes clear what you eventually want to find out, but the way in which you will find this out may vary per person. So, it is a conversation that is free to go into any direction. This is done by answering open questions instead of closed ones. An advantage of this way of interviewing is that it is suitable for complicated research with unfamiliar content. On the other hand, since the interviews can go into any direction the outcomes of the interviews can go into diverse directions as well, making it difficult to compare the outcomes and draw valid conclusions. Therefore, it is important to assure that each direction of the interview goes into the direction of achieving the purpose of the interview (Fylan, 2005).

As a preparation for the interviews, a stakeholder analysis is made, questions are prepared and a brief explanation on the method to identify critical objects is sent to the interviewees. The stakeholder analysis is done by analyzing the interviewees' position within the organization of the municipality of Amsterdam in order to understand how they are positioned according to the asset management hierarchy. Then the interview questions are designed, which can be found in appendix A and B (in Dutch). It is not an obligation to strictly ask every single question during the interview, as it is a semi-structured interview. Since there are various terms sharing the same definition in asset management, the interviewees are sent a brief overview of the outcome of the process explained by the IDEF0 model to assure that a common language is used during the interviews. As a supportive means of communication the simple relation diagram from part 1 is used, because this makes the complex process of identifying critical objects more comprehensible.

Then the interviews are conducted. First, the interests of the three management levels in the process of identifying the critical objects are collected. The second part of the interviews is meant to determine how this process can comply with the interests of the three management levels. This is done by collecting their requirements for the process, and therefore the IDEF0 model, to work in practice.

These interests and requirements are collected through an ex-ante analysis. An ex-ante analysis is conducted to try to forecast future events, which is in this case the process of identifying the critical objects in practice (Bernstein & Freeman, 1975). The challenge here is that the interviewees have to forecast events during the execution of a complex process that they are not familiar with. To make this ex-ante analysis easier, it is decided to repeat at the start of each interview how the simple relation diagram works which is developed in part 1. As a result, the diagram is used as means of communication to obtain their opinions on the purpose of identifying the critical objects and their stake in this process in order to shape their interests. Subsequently, it is possible to ask them what challenges they expect or what is necessary to do when the critical objects are identified in practice. This resulted in the process requirements for the theoretical IDEF0 model to work in practice.

Requirements Analysis

The requirements are analyzed to define the effects of the requirements on the IDEF0 model. This is done by allocating the requirements to each activity in the IDEF0 model. The requirements are listed from most important to least important. This ranking is determined according to the outcome of a prioritizations analysis. The priority of a requirement is determined by the number of times a requirement is mentioned by a different interviewee. After, the requirements from the three management levels are compared in order to determine how these requirements can work together in practice. As a result, conclusions can be drawn and challenges can be detected that the asset manager must overcome when the theoretical IDEF0 model is applied in practice.

2.4.3 | PART 3: Workshops

Testing and improving the IDEF0 model

To assure that the theoretical IDEF0 model works in practice and to find the solutions to the challenges that are found in part 2, the IDEF0 model is tested in practice. This is done by organizing three workshops at the municipality of Amsterdam. One workshop is to conduct the first activity of the IDEF0 model in practice. However, it takes too much time to conduct all activities in the given time period of this research. Therefore, the other two workshops are ex-ante analyses trying to forecast all challenges and requirements for the other activities to work in practice. The results lead to an improved and final IDEF0 model with additional requirements for it to work in practice.

One strategy in this research is to use the knowledge of a large number of people at the municipality of Amsterdam in order to gather as much as knowledge as possible, and to compare the various inputs from the participants to tests the input’s validity. As a result, 21 people are interviewed, and three workshops with every time around ten participants are organized. In other words, there are approximately 50 formal face-to-face contact moments to collect the input for this research. An advantage of this strategy of choosing a large sample size leads to more accurate results, as it avoids weighting the outlying opinions too heavy and the range of inputs is enlarged (Patel, 2003).

The final IDEF0 model is validated with two asset managers who also have experience managing infrastructure assets that are owned by public parties. One is the asset manager of the civil engineering assets of the municipality of Rotterdam, and the other one is an advisor in asset management at ProRail. ProRail is a public organization that manages and maintains the assets of the Dutch train network.

2.5 | Reading Guide

PART I - DEVELOP
Chapter 3 | Theoretical IDEF0 model

PART II - FACILITATE
Chapter 5 | Interests
Chapter 6 | Process Requirements
Chapter 7 | Requirements Analysis

PART III - TEST
Chapter 9 | Testing the IDEF0 model
Chapter 10 | Final IDEF0 model

Chapter 11 | Validation
Chapter 12 | Discussion
Chapter 13 | Conclusion
Chapter 14 | Recommendations

PART I

Literature Study

The first IDEF0 Model

3 | Theoretical IDEF0 Model

The purpose of this chapter, and also part 1 of this research, is to develop a process model that presents a method of the asset manager to identify the critical objects in a public infrastructure system. However, this research contains one large challenge. A method of identifying the critical objects is not mentioned in literature, as literature is mostly focused on identifying the critical assets in general. And when they go into detail, they focus on identifying the critical components of objects. Therefore, to develop this process model the method of identifying critical objects has to be developed first.

This chapter starts off with conducting a research in finding the most suitable modeling technique for developing the process model for identifying critical objects while considering the differing interests of the three management levels. Then a literature study is conducted to understand what methods are used to identify critical components. Using this understanding, a method is developed for identifying critical objects in a public infrastructure system. And last, using the suitable modeling technique this developed method is transformed into a theoretical process model. This theoretical process model provides the answer to the following question:

> “*What model enables the asset managers to identify the critical objects in a public infrastructure system?*”

3.1 | Process Model

According to Aguilar-Savén (2004, p.133) a process can be defined as “relationships between inputs and outputs, where inputs are transformed into outputs using a series of activities, which add value to the inputs.” So in this research the process is about transforming information on the collection of objects, the object inventory, into a list presenting the prioritized objects based on risks. The process that consists of the activities that turn the input into the useful output can then be presented in a model to improve the understanding in this process (Shen, Wall, Zaremba, Chen, & Browne, 2004). Yet, there are numerous types of process models that can be chosen from to use for this research (Li & Chen, 2009).

No modelling technique is better than the other. It is all about choosing the model that suits the given situation the best (Tangkawarow & Waworuntu, 2016). According to this situation, there is a need for a systematic process model that enables the asset manager to identify the critical objects, whilst taking into account the interests of the three management levels. Since the asset manager is also dependent on various inputs coming from the asset owner and the service provider, the process model should present the in- and outputs of each activity. Furthermore, the process model should present a structured representation of the process with the necessary sequenced activities from start to the end. So, the process should describe activities, such as assessing the risks, rather than each and single action that has to be made during the risk assessment. In other words, the process model should show “what” has to be done, rather than “how” exactly what has to be done. In conclusion, the process model must systematically present the rather abstract and sequenced activities from beginning to end, and it must include the interests of the three management levels.

This complies with the requirements of Zeb & Nasir (2016) for a process model in asset management. According to them you need holistic, systematic and integrated process models for the model to work in practice. With holistic they mean that the methodology must include all the necessary steps from beginning to end, and systematically refers to a method with inputs, outputs and activities clearly visualized in a simple diagram, and with integrated they mean that all steps are sequenced and logically interrelated and interdependent.

There are numerous types of process models. For instance, you have the Flow Chart which is a graphic representation of actions. However, Flow Charts describe actions instead of activities, do not show inputs and outputs and are more focused on decision-making (Aguilar-Savén, 2004). The Data Flow Diagram (DFD) does show inputs and outputs in the form of data, and is focused on information flow transforming among activities (Shen et al., 2004). However, DFD's models cannot present the inclusion of the necessary interests of the three management levels. A process model that does suit the given situation is the IDEF0 model. The IDEF0 model presents a structural graphical presentation of activities with the necessary inputs, outputs, the controls and mechanisms (Tangkawarow & Waworuntu, 2016). Here the controls can stand for the interests of the three management levels that have an influence on the activities of the process model. And the mechanisms represent the human resources: the three management levels. According to Shen et al. (2004) one disadvantage of the IDEF0 model is, however, that the model poorly expresses the sequences between activities. However, considering the rest of the requirements that the IDEF0 model does comply with, this model can be chosen to be good enough for the given situation of this research.

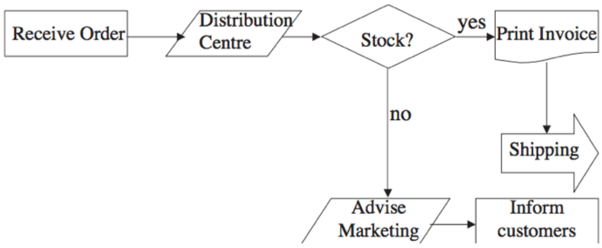


Figure 7 | Flow Chart (Aguilar-Savén, 2004)

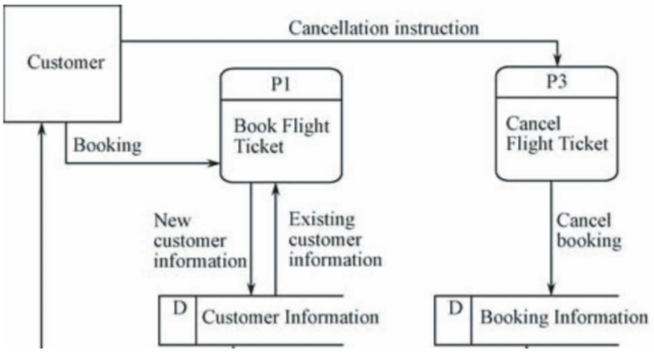


Figure 9 | Data Flow Diagram (Shen et al., 2004)

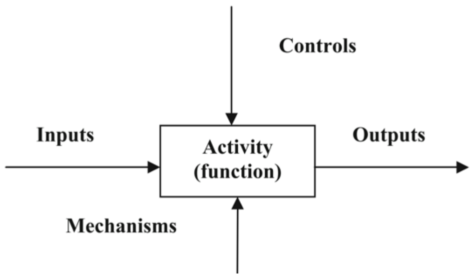


Figure 8 | IDEF0 model (Amadi-Echendu, Brown, Willett, & Mathew, 2012)

3.1.1 | IDEF0 model

IDEF0 is a function modeling method, which presents an order of activities in a structural way (Li & Chen, 2009). In figure 10 an incomplete IDEF0 model for the objective of this research is visualized. The box in the middle, A0, represents the main function: Identify the critical objects. As mentioned before, the model presents the function's inputs, controls, mechanisms and outputs (Hull, Jackson, & Dick, 2006; Zeb & Nasir, 2016):

Inputs:	That what is transformed by the activity into useful outputs, which is in this case the object inventory.
Controls:	The constraints or restrictions that govern the activity, such as guidelines and requirements like the ISO 55000 standards.
Mechanisms:	The resources that enable the inputs to be transformed into useful outputs, such as human resources which in this situation are the three management levels.

Outputs: That what is produced by the activity as a result of the input transformation. In this situation that is the list of prioritized objects.

In part 1 of this research the objective is to determine all the inputs, the mechanisms, the controls and the activities that must be executed to identify critical objects. As a result, this parent diagram on the level A-0 in figure 10 will be decomposed into child diagrams on the level A0, which will then show additional requirements, inputs and mechanisms per activity. This will be the theoretical IDEF0 model. The objective of part 2 of this research is then to determine the impact of the interests of the mechanisms, the three management levels, on the function of identifying the critical objects. As a result, additional requirements, and thus controls, for the theoretical IDEF0 model are developed. Then in part 3, the theoretical IDEF0 model is tested and improved with additional activities and controls for it to work in practice. As a result, the objective of this result is achieved as the final IDEF0 model is delivered.

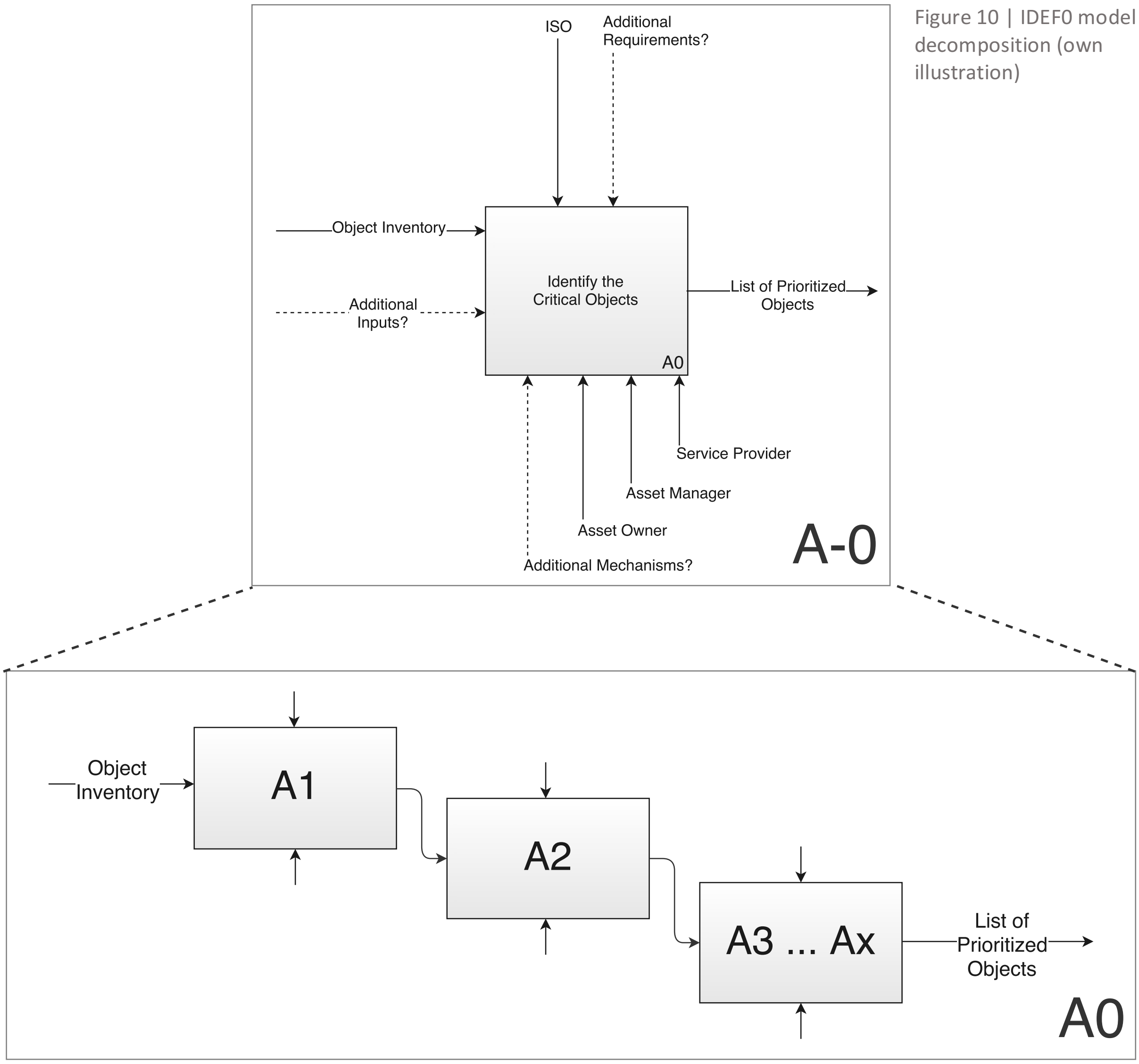


Figure 10 | IDEF0 model decomposition (own illustration)

3.2 | Identifying the Critical Assets

Before the method to identify critical objects of a public infrastructure system can be developed and presented in an IDEF0 model, a literature study is conducted. The purpose of this literature study is to create an understanding in what makes an asset critical, considering any type of asset, and in how to identify critical components of a public infrastructure system.

Let's start with the beginning. An asset, whether it is a component or an object or a system, is critical when it has high risks during asset failure. The definition of the risk in this situation is the product of:

- The probability of asset failure,
- and the impact that this asset has when it fails.

In order to understand more in detail what critical assets are in general and how the critical components can be identified, the following questions had to be answered with the use of a literature study:

1. How to determine asset failure?
2. What is the probability of failure?
3. What is the impact if an asset fails?
4. How to identify critical components?

3.2.1 | Asset failure

An asset is failing if it doesn't fulfill what it is required to do. There are various types of requirements for what an asset must do. One type of requirement is the functional requirement of an asset. For instance, for a bridge a functional requirement can be: A connection between A and B that can take on X number of cars. Hence, if this bridge isn't able to fulfill this function, this bridge has failed (CCPS, 2017). However, besides the fact that an asset can be required to fulfill its function, an asset can also be required to perform in a certain way.

According to ISO 55002 (2014) asset management is about managing assets in a way so that these assets add value to the organization in order to create a line of sight. According to Davis (2013), whose work was recommended by the Institute of Asset Management, the line of sight is an approach to align the activities and risks of maintaining assets with the goals of the organization. Therefore, it isn't only about managing the function of an object, but also about managing how an object performs to add value to the organization.

Therefore, assets are required to perform in a certain way to add this value. An object can for instance perform in a way that it is safe, reliable or sustainable. Such criteria tell more about the values that are important to the organization (Theoharidou, Kotzanikolaou, & Gritza-Lis, 2009). For instance, if the safety fence of a bridge has failed, you can still cross the bridge to come from point A to B, so the bridge still functions. Though the bridge's performance has been degraded, as the bridge is not safe anymore. So, functional requirements show what the object is supposed to do in the form of its function, and performance requirements explain how the object functions, as visualized in figure 11. In conclusion, when the object does not fulfill either its functional or performance requirement, the object has failed.

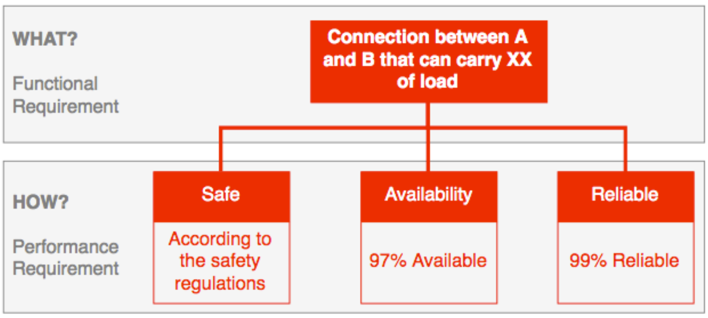


Figure 11 | Functional and performance requirements (own illustration)

KPIs and Performance Requirements

Performance requirements consist of a norm and an indicator. The most important indicators are called the key performance indicators, or KPIs. According to Eckerson (2009) “a KPI embodies a strategic objective and measures performance against a goal.” So, it has to be measurable in order to see to what extent the performance achieves the organizational objectives. For instance, the KPI can be the extent into which a bridge complies with the safety regulations. A norm can 100%, meaning that the bridge has to fully comply with the regulations. A performance requirement is therefore that the bridge has to comply to the safety regulations for 100%.

KPIs can be leading or lagging. A leading KPI is predictive. Such KPIs drive the performance of an object and can therefore inform beforehand about the extent into which the object complies to the performance requirement. For instance, the condition of an asset is a leading indicator. Such a KPI can give an indication if additional measures are necessary to improve the condition of the asset. A lagging KPI determines the outcome and therefore looks at the past. For instance, the total of times in a year that a movable bridge was not available for its users. (Kobbacy, 2008). According to Eckerson (2009) and the research of Arthur, Hodkiewicz, Schoenmaker, & Muruvan (2014) the number of leading and lagging KPIs must be balanced to be able to act both correctively and preventively.

In the situation of public infrastructure asset management, the performance requirements must be derived from the asset owner. Since the asset owner has a social accountability, the users of public infrastructure assets have a lot of influence on the performance of assets. In conclusion, the performance requirements for objects must be derived according to the organizational goals and objectives, which are mostly based on the social accountability of such an organization (ISO 55000, 2014; ISO 55001, 2014; ISO 55002, 2014).

Failure Modes

There are various failure modes, or types of failures, in which an asset cannot fulfill its requirements. For instance, when a bridge doesn’t fulfill the safety requirements (asset failure), this can be caused by the construction collapsing (failure mode) or a broken safety fence (failure mode). However, you don’t know what to do about this failure mode if you do not know how it has originated. For this the causes are detected.

Causes of Asset Failure

There are various types of causes, explained below (Mil, Dijkzeul, & Pennen, 2006):

INTERNAL CAUSES:	*Causes that come from the object itself*
Physical/technical:	*Causes of physical or technical failures, such as deterioration or corrosion. This happens in the physical level from the asset decomposition.*
Operational:	
Organization	*Causes related to the organization that manages the bridge, such as an under capacity of people.*
Human	*Causes related to human failure, such as maintenance measures executed poorly or inspections done wrong. These human failures can be either conscious or non-conscious.*
EXTERNAL CAUSES:	*Causes that come from outside the object*
Human (external):	*External human failures relate to causes that come from the user of the object, for instance a collision by a boat or a car.*
Nature:	*And not to forget, causes can also be natural, such as large windblasts or floods.*

3.2.2 | Probability of failure

So far, it has been explained when an asset fails and how it can fail. For understanding the probability of asset failure, or the likelihood that an asset fails, it is helpful to present the bathtub curve as shown in figure 12. Here the failure rate stands for the probability of failure. The lifespan of an asset can be divided over three phases. The first phase is the debugging phase. This is the phase in which the asset has just been build or installed. Here the probability of failure is initially high due to debugs, such as design or installation errors. After these debugs have been repaired, the probability of failure becomes fairly constant. This is the chance failure phase, where external sudden causes such as heavy weather can lead to failure. And finally the asset enters the wear-out phase, where the asset fails due to aging. Note that these failures can mature gradually or these can happen suddenly. (Adams, 2015; Rausand, 1998).

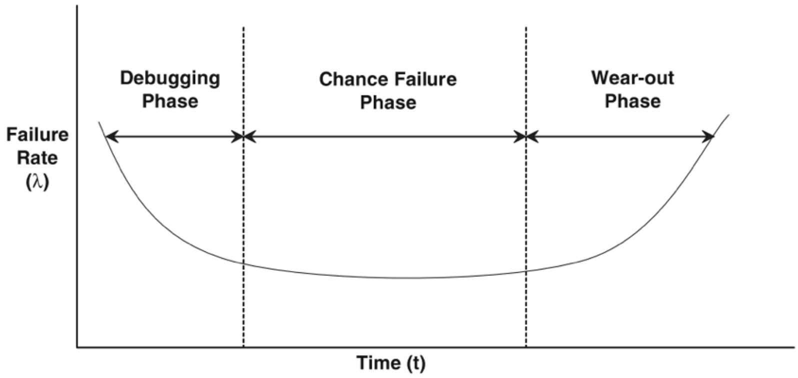


Figure 12 | Bathtub Curve (K. M. Adams, 2015)

The probability of failure is usually referred as being the frequency of an asset failing. This can be expressed in the mean time between failure (MTBF), which is the average time between failures occurring. The MTBF can be found based on historical data and experience, such as records on the number of times a movable bridge couldn't open, or data from the building contractor of the predicted life cycle of the bridge (Fernández & Márquez, 2012; Mitchell, 2002). However, ultimately it is difficult to determine the accurate probability of failure because of many uncertainties, such as dynamic factors that affect the probability of failure, and lack of data (Parlikad & Jafari, 2016).

3.2.3 | Impact of failure

According to the ISO 55000 standards, impacts of asset failure during risk assessment is about determining the impacts on the organization (ISO 55000, 2014). Therefore, such impacts are usually expressed in impacts on the environment, the safety, or the reputation of the organization. As explained before, a public authority has a social accountability and therefore tries to, among other things, represent the user's requirements. So when assessing risks, the impacts of asset failure must take into account impacts on the users also. Where corporate organizations might find impacts in the form of damage costs very important, do public authorities value impacts on society (Tan et al., 2012).

3.2.4 | Process for identifying critical components

The method of identifying critical components is situated in the process of the Reliability-Centered Maintenance (RCM). This is a process used to determine the maintenance measures for the components. With the use of the FMECA tool, which stands for Failure Mode Effect and Criticality Analysis, the critical components that need these maintenance measures the most are identified (Davis, 2013; Moubrai, 1997). Literature mentions numerous of types of RCM-cycles. Comparing the various RCM-cycles, a simple and generic diagram was developed as shown in figure 13 showing the steps taken by the asset manager, followed by a clarification of these steps (Cheng, Jia, Gao, Wu, & Wang, 2008; Crespo Márquez et al., 2009; Moubrai, 1997; Nowlan & Heap, 1978; Wei, 1991).

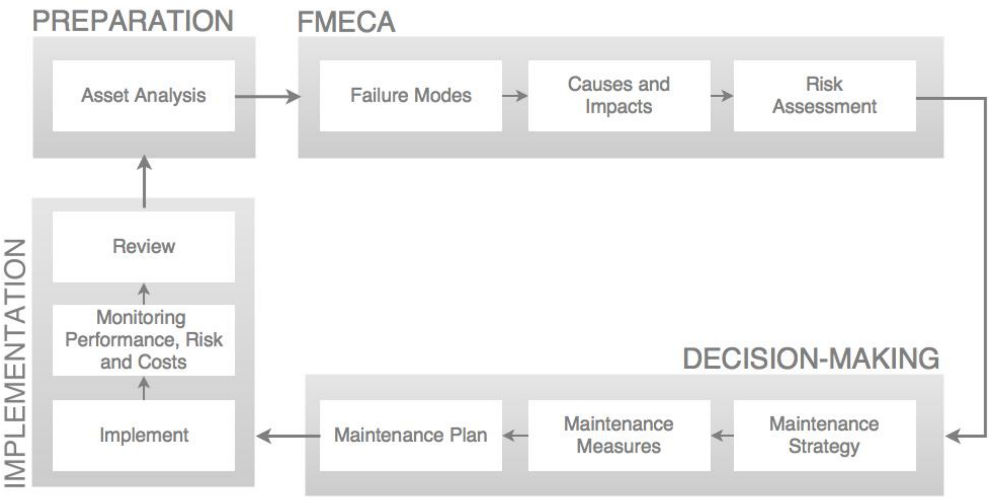


Figure 13 | RCM-Cycle (own illustration)

Preparation:	First define the objectives and the scope of the asset for which the maintenance measures must be determined. Here the asset can be any asset. It can be a car network (system), but it can also be a bridge (object), or an element of a bridge. Then define the asset's physical decomposition, functional decomposition and performance requirements.
FMECA Phase:	Find the critical failure modes by first defining from the analyzed asset all failure modes, its causes and effects (impacts, but also positive effects). Then the risks of the failure modes are assessed with the use of a risk matrix. Subsequently, the failure modes are ranked based on its criticality that is determined by its risk. The causes that make the failure modes critical indicate what components are critical and are therefore in need of maintenance measures. For instance, a malfunctioning motor (cause) that leads to a movable bridge that cannot open (a critical failure mode), shows that the motor is a critical component. The FMECA phase is explained further below.
Decision Phase:	By developing a maintenance strategy and knowing the critical failure modes, the right maintenance measures for the components can be chosen that treat the risks of the failure modes. As a result, these measures form the maintenance plan.
Implementation Phase:	Implement the maintenance plan, monitor and review the outcome: the performance, risks and costs of the assets. If people are not content with the outcome of the maintenance plan, it can be decided after the review to adjust the maintenance plan.

FMECA

The FMECA is an essential part for identifying critical failure modes. FMECA is an analysis procedure which analyzes the asset to determine the failure modes and relating causes and effects. Subsequently, it ranks the critical failure modes by assessing its risks. This supports decision-making on the right maintenance measures (Wei, 1991).

Assessing the risks of the failure mode and determining the criticality of the failure mode is done with the risk matrix, as illustrated in figure 14. A risk matrix combines the risk assessment variables: The impact criteria, in the figure named consequences, with its weighting factors and impact indicators and the probability of failure. The colors in the resulting matrix determine whether the resulting risk is acceptable or not (Mitchell, 2002).

A risk matrix has to be applied per failure mode. The reason for this is that each failure mode can have a different probability of failure and different type of impact. One failure mode can result in different damage costs compared to other failure modes. (Kobbacy, 2008) The risk can be found using various formulas, which all translate the ratings of the impacts and the probability of failure into a quantitative output. A simple example of such a formula is:

$$Risk\ Priority\ Number\ (RPN) = \ (Impact_1 \times wf_1 + \ Impact_2 \times wf_2) \times Probability\ of\ Failure$$

Here the "*wf*" stands for the weighing factor of the relating impact criteria. The output is the Risk Priority Number (RPN), which shows the level of priority or the criticality of the failure mode that is being assessed (Mitchell, 2002; Tan et al., 2012). Both the impact criteria and the weighing factors can represent the organizational goals and objectives.

Risk Matrix									
Potential Consequence of the Incident					Increasing Probability				
Rating	Health and Safety	Environment	Production	Reputation	A Never heard of in drilling	B Heard of in drilling	C Happened before in our company	D Reported < 3x/yr in our company	E Reported > 3x/yr in our company
0	No injury	Zero effect	Zero damage	No impact					
1	Slight injury	Slight effect	Slight damage < US$ 10k	Slight impact					
2	Minor injury	Minor effect	Minor damage < US$ 100k	Limited impact					
3	Major injury	Local effect	Local damage < US$ 1 MM	Considerable impact					
4	Single fatality	Major effect	Major damage < US$ 10MM	National impact					
5	Multiple fatality	Massive effect	Extensive damage > US$ 10MM	International impact					

Figure 14 | Risk Matrix (Duijm, 2015)

After identifying and assessing the risks of the failure modes, the failure modes can be prioritized according to the RPN. So, the higher the RPN the more critical the failure mode is. The following step in the RCM-cycle is to determine the correct maintenance measure to treat the risks. For this you can decide to (The University of Adelaide, 2009):

- Avoid the risk by taking measures that completely eliminate the risk
- Reduce the risk by reducing the probability or the impact of failure
- Transfer the risk to someone else such as an insurer
- Accept the risk and do nothing

3.4 | ISO 55000 standards

As explained before, the ISO 55000 standards are developed by the International Organization of Standards. The ISO 55000 standards provide an international norm for how to implement, develop, maintain and improve assets. The overarching fundamentals of the ISO 55000 standards are to 1) recognize the *value* of the assets to the organization, 2) *assure* the assets create this value, 3) realize this value with good *leadership* and 4) to *align* the objectives of the organization by translating the organizational goals and objectives into operational and tactical decisions. Looking at the inputs that determine critical assets, so far the KPIs and therefore the performance requirements of assets, the failure modes and the impact criteria of the risk matrix can reflect the organizational goals and objectives.

3.5 | From critical components to critical objects

The FMECA is the common method where risk assessments take place to identify the critical components. However, many uncertainties arise when the FMECA would be used to identify the critical objects. The purpose of identifying the critical objects is to develop a list with prioritized objects based on the current risks. Moreover, according to the ISO 55000 standards it is important to include the organizational goals and objectives. However, the FMECA does not comply with this, leading to several implications that have been deducted with logic reasoning and the help of asset management experts.

Purpose

First, the purpose of the RCM-cycle is to determine the right maintenance measures, which is left out of the scope of this research. And the purpose of the FMECA tool is to identify the critical failure modes in order to determine which components are critical and need maintenance measures. However, the purpose of the FMECA is not to identify and prioritize the critical objects.

Risk Assessment

Second, the risk assessment must be done differently when the purpose is to identify the critical objects. This is because when the risks of objects are assessed, one has to look at a different level of the asset decomposition.

An object fails when a component fails, which can be caused by various things. For instance, a bridge has failed (object failure) if the column has collapsed (component failure) which causes the construction of the bridge to collapse (failure mode). This was the result of a boat collision (cause). This relation is illustrated in figure 15.

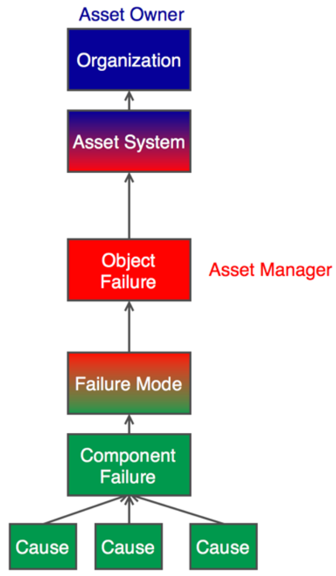


Figure 15 | From causes of failure to organization

When assessing the risk of a failure mode, caused by a component failure, it is logical to look at the impact of the failure on the object. However, when assessing the risks of an object, the risk matrix must consider a larger scale that focusses on the impact on the system and on the organization. This is convenient for creating an alignment between an object and the organizational goals and objectives, which is easier than creating a link between one component and the organizational goals and objectives. How would you define the impact of a failing beam of a bridge on the organization? You would first need to know the impact on the bridge, the object, to determine that link.

Moreover, when assessing the risks of objects, it is also important to consider that each single object can have different impacts. Impacts are said to be location dependent (Balzer & Schorn, 2015). Think for instance of the difference between the impact of a bridge failing on the busiest street of Amsterdam compared to a similar type of bridge failing in the countryside. Accordingly, the risks of each individual object must be assessed taking into account the object's location in the system. However, it can be assumed that this is extra time-consuming during risk assessments.

In conclusion, the risks of an object are assessed to determine its criticality with a risk matrix. However, the risk matrix will be developed differently compared to the one used on the component level. In the situation of identifying the current critical objects, one must consider the current risks in a larger scale.

Therefore, the risk matrix must consider the current expected time until failure, instead of the MTBF, and the impact of an object on the system and organization.

However, what to assess exactly? A risk matrix assesses failure modes, not a physical object, because a failure mode gives an indication on what the probability of failure and the impact of failure is and a single object does not. As one expert mentioned: "The asset manager cannot know the probability of failure of an object, if you do not know the condition of the components." This means that the asset manager must know the failure modes that are caused by component failures, to determine the probability of failure of an object. Moreover, determining the exact impact of an object's risk cannot be known without knowing where the risk has originated from; the failure modes and its causes. The FMECA identifies the failure modes and its causes. Hence, how the FMECA determines an object's failure modes is also necessary to identify and assess the risks of an object correctly. However, then a different risk matrix must be used. The differences between finding critical failure modes, referring to the component level, and critical objects is shown in table 1.

	Component Level		Object Level
Purpose is to determine:	To identify the ***critical failure modes*** to determine ***what maintenance measures*** are necessary …		To identify the ***critical objects*** to determine ***where maintenance measures*** are necessary
	… for making a maintenance plan	… for treating the current risks	
Types of risks:	Risks in general	Current risks	Current risks
Probability of failure:	Mean time between failure	Expected time until failure	Expected time until failure
Impact of failure:	Impact on object, and on organization if possible	Impact on object, and on organization if possible	Impact on system and organization

Table 1 | Comparing critical components and critical objects

However, the question still remains how to come from the RPN of an object's failure mode, to the RPN of the object. Yet, it can be assumed that the more critical failure modes an object contains, the more critical the object is.

ISO 55000 standards
And third, the FMECA does not comply with the ISO 55000 standards. It does not consider making an alignment with the organizational goals and objectives. Moreover, the FMECA, and the RCM-cycle either, does not explain how the asset manager can defend the risks back to the asset owner.

In conclusion, to identify the critical objects the FMECA must be used to identify and assess the risks of the object's failure modes. Yet, there is a need for a different type of risk matrix. And a challenge is to aggregate the RPNs of the object's failure modes to the RPN of the object. And to make the method to identify critical objects comply with the standards of ISO 55000, the method needs an input and an output that creates the alignment with the organizational goals and objectives.

3.4 | Conceptual Relation Diagram of Critical Assets

During conversations with asset management experts there were still misunderstandings because identifying critical objects asks for a different and new mind set. There was a need for a holistic overview that visualizes all aspects that have an influence on identifying the critical objects. Therefore, before developing the theoretical IDEF0 model, based on the information so far it was decided to first develop a simple relation diagram that visualizes the relation between the three physical levels of decomposition (system, object and components) and the mechanisms: the three management levels (strategic, tactical and operational) and the inputs when identifying the critical objects. This diagram is shown in figure 16 and clarified in the following paragraph.

3.4.2 | The Conceptual Relation Diagram

It is concluded that to prioritize the objects, an asset manager wants to find the objects with the highest probability of failure and the highest impact during failure; the critical objects. Think of a bridge that is nearly failing due to ageing (high probability of failure), or a bridge that is part of the busiest street of a city (high impact during failure). To be able to do this, the asset manager must assess the risks of the object's failure modes with the risk matrix. The output of the risk assessment indicates how critical an object is showing there is a need for action. When the critical objects are identified and prioritized, the next step is to apply the RCM-cycle to assess the risks on component level to find the required maintenance measures.

The relation diagram explains the necessary inputs for identifying the critical objects. As can be seen in the relation diagram, there are two types of inputs: one coming from the operational level and one coming from the strategic level. The input from the operational level is the input determining the failure modes of an object, the probabilities of failure and the impacts of failure. According to the experts, the service providers know the objects and its components the best. Even though experts are usually included when determining the possible failure modes, the service providers know best which failure modes occur the most and cause large impacts per object. The input from the strategic level is necessary to align the risk assessment with the organizational goals and objectives. Therefore, this input consists of the performance requirements, and therefore the definition of asset failure and the risk acceptance, and the impact criteria that are derived from the organizational goals and objectives. In conclusion, the strategic level determines the risk definition, and the operational level determines the risk assessment.

The middle part shows the impact of a component on an object, system and organizational goals in terms of risks. This show that the probability of component failure, affects the probability of object failure and then the probability of failure of the asset system. This then will have an impact on the core values of the organization of the asset owner. An example of where this knock-of effect occurs constantly is an important tunnel of Amsterdam, the IJtunnel, which connects the north with the centre of Amsterdam. This tunnel fails a couple times a year due to for instance a technical malfunction or a car collission. Since the importance of this tunnel, these failures are immediately published in the media harming the municipality's reputation, which is a core value of the municipality. Also, it has a large impact on the availability of the entire infrastructure system of the city, which is another core value of the municipality. As a result, the causes of failure lead to component failure, determining the probability of failure of this tunnel and the infrastructure system, which then determines the probability of the organization meeting its objectives. (Sun, Fidge, & Ma, 2014).

This aggregation from the probability of component failure to the probability of the organization meeting its goals and objectives, is the same when explaining the aggregation of the impact. It can be said that the components have an impact on the performance of the object. Subsequently, the performance of the object has an impact on the performance of the system and so also on the performance of the organization (Houten & Zhang, 2010).

On the following page the conceptual relation diagram can be found. This shows how the three management levels (or the mechanisms), the asset decomposition, asset risks, and the necessary inputs are related to each other.

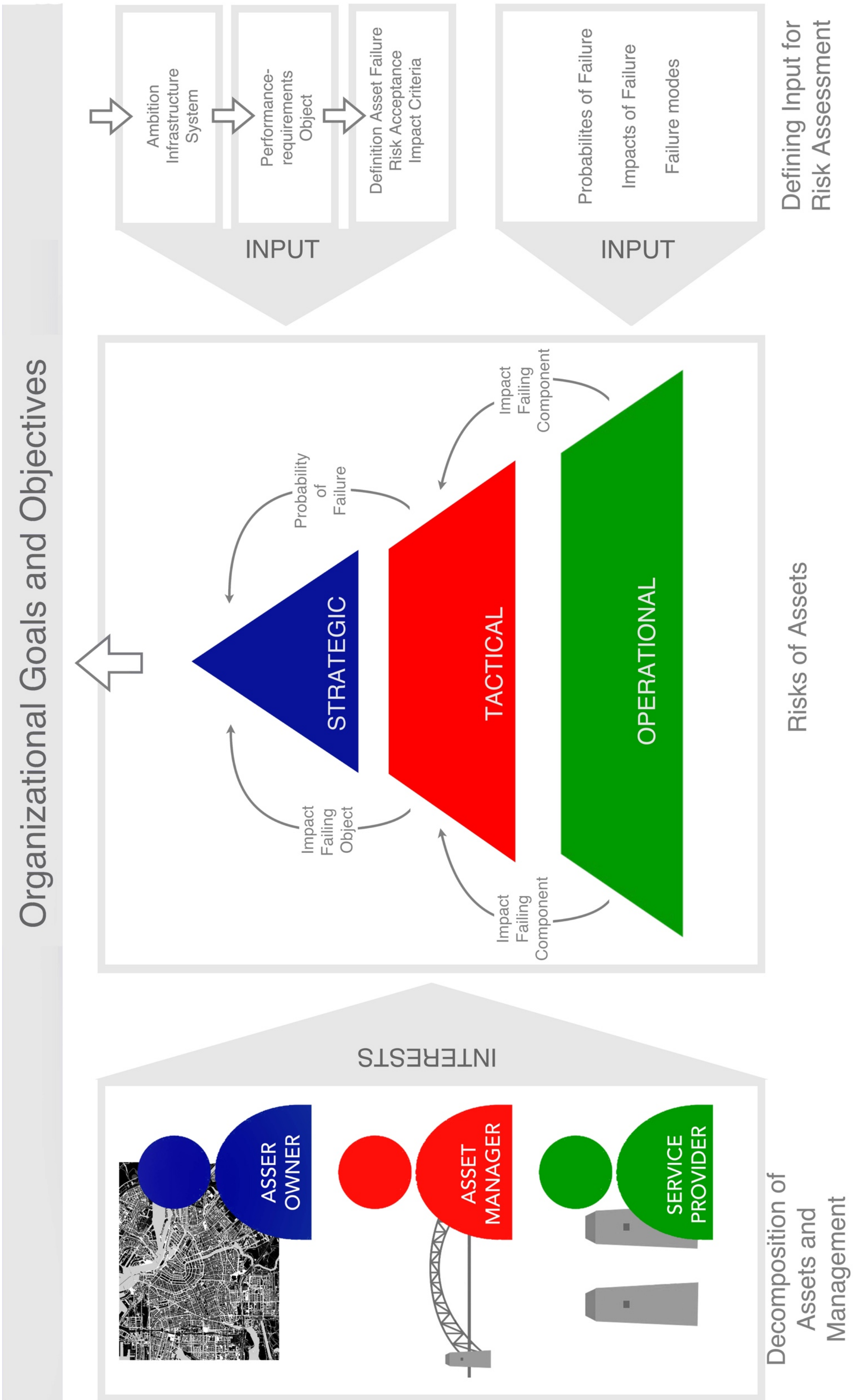


Figure 16 | Conceptual Relation Diagram (own illustration)

3.5 | Theoretical IDEF0 Model

Using the relation diagram the theoretical IDEF0 model can be developed. This is explained in this section.

3.5.1 | Activities

Analyzing the relation diagram, it became clear that the activities could be clearly derived, showing a clear sequence in activities. This is shown in figure 17. As a result, the following activities were derived:

Figure 17 | From relation diagram to activities (own illustration)

1) Translate organizational goals into the performance requirements of the objects

Risks of object failure cannot be identified without knowing when an object has failed and when an object failure is a risk for the organization. An object has failed when it does not fulfill its requirements anymore. So, the first activity should be defining the performance-requirements of the objects. These performance-requirements should be derived from the organizational goals and objectives. This was validated by the ISO 55000 standards explaining that the organizational goals and objectives must be incorporated into the asset management processes to develop a line-of-sight (ISO 55000, 2014; ISO 55002, 2014).

2) Identify the failure modes and causes of the object

After defining the performance requirements, the failure modes can be defined. To find these you have to ask yourself: In what ways does the object not fulfill its requirements anymore? Such as a bridge's structural collapse. Subsequently, the possible causes for each failure mode must be identified. So, what can cause the structure of the bridge to collapse? Knowing the causes supports assessing the risks. It helps determining the impacts of the failure mode, such as the economic impact expressed in the costs for repairing the failure, or the probability of failure, by for instance analyzing how many times these causes have occurred before (Healy, 2006).

3) Assess the risks of the failure modes of the object

I. Defining the Risk Acceptance

Before the failure modes' risks can be assessed, a risk matrix must be designed. The risk matrix consists of the risk assessment variables, which are the impact criteria and its weighting factors, the impact indicators along the scale, the probability of failure scale and the resulting risk acceptance levels. The risk matrix must show when a risk is acceptable or not for the organization. To continue the line-of-sight, it is important that the impact indicators describe the impacts of the risks for the organization (Duijm, 2015; ISO 55000, 2014).

II. **Determine the probability and impact of failure**
The probability and the impact of failure modes of objects is that what must be assessed with the risk matrix. The asset manager uses this information to assess the risks of the failure modes and to determine if an additional preventive measure must be executed to diminish the probability or impact of failure (Guerrero, Guillen, & Gomez, 2013). However, determining impacts and probabilities of failure come along with many uncertainties, since it can depend on subjective reasoning and guestimates (ISO 31000, 2015).

III. **Assess the risks to determine the RPN of the failure mode**
If it is known what the failure modes and its probability of failure and impacts are, and the risk matrix has been designed, the risks of the failure modes can be assessed. The output of this assessment is then the Risk Priority Number of the failure mode. (Wei, 1991)

4) Aggregate the RPN of the failure modes to the object and system levels

The purpose of this activity is for the asset manager to translate the assessed risks back to the strategic level in order for the asset manager to be able to justify the RPN of the failure modes towards the asset owner. To make it more comprehensible for the asset owner, the RPN of the failure mode must be aggregated to the RPN of the object. Then the risks of the objects can additionally be presented together in a system. This can be useful because if multiple objects fail together, the collective impact can be bigger. Therefore, it is better to not see all objects separately, but to see them perform together, which is the idea of system's engineering. As Wasson (2006) concluded: If one asset fails, this has an influence on the performance of other assets.

Even though literature mentions that RPNs or risks must be aggregated to a manageable level, no literature mentions how this is done in a situation where RPNs of failure modes must be aggregated to the object or system level. As seen in appendix G, multiple attempts were made to search for any similar research outcomes.

3.4.2 | Theoretical IDEF0 Model

The theoretical model is presented in figure 18. Here the defined activities are presented in the four boxes. The input consists besides the object inventory also out of the organizational goals and objectives, the impact of object failure modes and the probability of object failure modes. Moreover, notice that the performance requirements are both an input for A2 and A3, since this is necessary for both defining object failure and supporting the determination of the risk acceptance level. The service provider and asset owner are linked with the activities where they either provide the input or support the activity, such as that the service provider supports identifying the failure modes of an object. The asset manager and the ISO 55000 standards are linked to each activity, since the asset manager executes each activity and each activity must comply with the ISO standards.

However, still there are uncertainties about how this IDEF0 model would work out in practice. For instance, into what extent is it possible to identify all failure modes of all objects considering the available time? As this diagram shows, additional process requirements are necessary to make the theoretical IDEF0 model work in practice. These requirements are derived in the following part of this research.

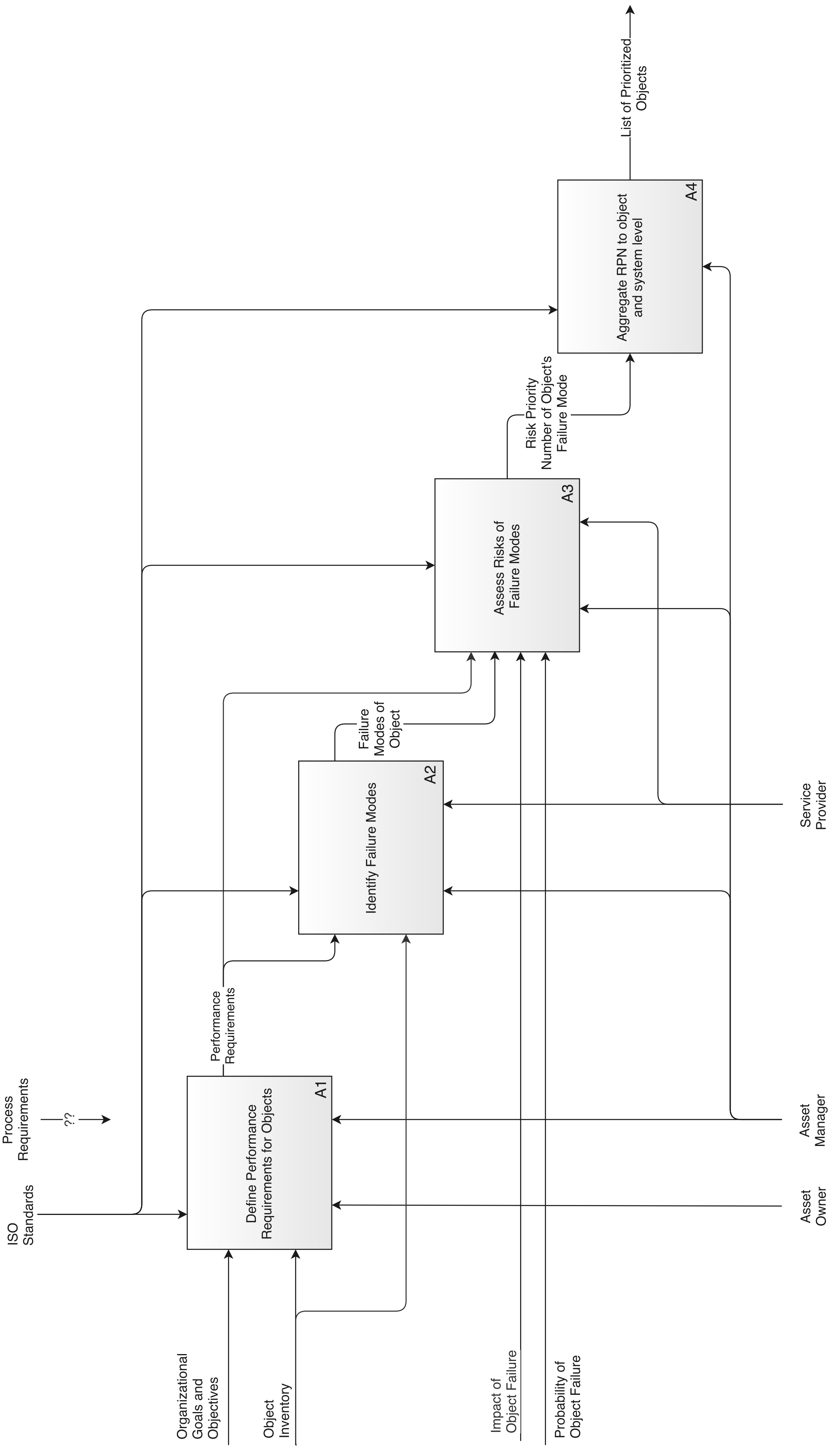


Figure 18 | Theoretical IDEF0 model

PART II

Empirical Research at the Municipality of Amsterdam:

Development of the IDEF0 model

4 | INTERESTS

The problem of this research states that the interests of the three management levels are opposing in the assessment of risks of assets. It can therefore be assumed that the interests would also be opposing when the critical objects are identified, consisting of a risk assessment process as well. To validate this problem statement in the context of this research and to develop an understanding in the interests, an empirical research has been conducted.

This empirical research has taken place at the asset department of the municipality of Amsterdam. As a preparation, a stakeholder analysis of the people to be interviewed is made. Then an interview has been designed and conducted, which resulted in an outcome explaining the interests in identifying the critical objects from the three management levels in depth. Analyzing this outcome has led to a substantiated reasoning behind the interests. This has provided the answer to the following sub-question:

> *"What key interests of the asset owner, the asset manager and the service provider need to be taken into account to identify the critical objects in a public infrastructure system?"*

4.1 | Municipality of Amsterdam

The interviews have been conducted at the public asset department of the municipality of Amsterdam in the Netherlands. This municipality is the largest municipality from the country. The municipality's asset department manages the following objects building up the public space of Amsterdam (Gemeente Amsterdam Verkeer en Openbare Ruimte, 2016):

- 1602 bridges
- 35 navigation locks
- 4 tunnels
- 28 million m^2 of pavement
- 125.000 lampposts
- 384 signalized 4-way intersections (traffic regulation system)
- 309.000 trees
- 26.500.000 m^2 vegetation

4.1.1 | Project Organization

As can be seen the municipality owns a huge number of diversed objects. The project organization evolving around the management of all of these public objects is illustrated in figure 19. This figure shows a segment of the project organization from which the interviewees were selected for this research, represented by the black boxes. This segment is focused on the civil construction assets. This is because the IDEF0 model was later partly tested in this segment.

As can be seen in the project organization, the asset department of the municipality of Amsterdam has an asset manager for each of the following group of objects: pavements, tunnels, traffic regulation system, green and public lighting. These are the objects that build up the public space of Amsterdam. The infrastructure of this public space is then the system. Above the asset managers there are the head of the assets and the people responsible for the program and reorganization of the asset department. They are positioned between the strategic and tactical level. They have an overview of what happens in the tactical level, but they also speak the language of the asset owner; they know the asset owner's perspective.

Below the asset manager there are the advisors in managing, monitoring and inspecting the civil construction assets. They support the asset manager in planning, making tactical decisions and dividing the work load. There are two advisors who focus on the dry civil constructions, which are the fixed and movable bridges and the viaducts, and there are two other advisors who focus on the wet civil constructions, referring to the navigation locks and quay walls. Parallel to them is an advisor who is specialized in monitoring and inspecting the civil constructions.

Between the tactical and the operational level are the daily managers, who know a lot about translating between the operational and tactical level. One of them focusses on the movable constructions, such as the navigation locks, and the other one focusses on the fixed constructions, such as the fixed bridges. They maintain the overview of the daily activities on object level and communicate with the service providers who monitor the assets. Parallel to these service providers is the advisor of planning and control, who supports the service providers in planning the inspections and small maintenance.

It is agreed upon keeping the interviewees anonymous in this research, since this motivated the interviewees to give more honest and critical answers, even though this would mean that they had to talk negative about the organization. Therefore, no names are mentioned. In the rest of the research people from the strategic level, also the program and reorganization, are referred to as the asset owner, those on the tactical level as the asset manager, and those on the operational level, including the daily manager, as the service provider.

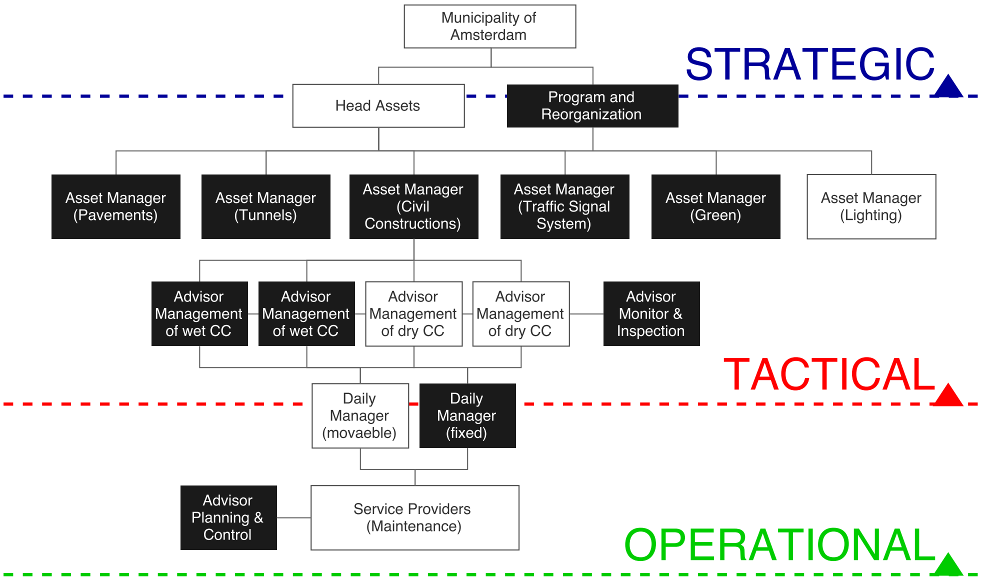


Figure 19 | Organization Structure of the Asset Department, Municipality of Amsterdam (own illustration

4.1.2 | Maturity Level

When it comes to implementing asset management, the municipality of Amsterdam has an intermediate level of maturity. Zeb, Froese, & Vanier (2013) have developed a method of assessing the maturity level of asset management of organizations. They have concluded that there are five stages that describe the maturity progress in asset management:

1. No awareness of asset management
2. Asset management is not being performed

3. Asset management is performed in an ad hoc way (each actor develops their own approach)
4. Asset management is formally defined, documented, and performed in a consistent way
5. Asset management is actively managed, with process control, feedback, and continuous improvement (Zeb et al., 2013, p.5)

As their research pointed out, infrastructure organizations regularly start with an asset inventory and a condition assessment of all their assets, and later move on to risk management and decision analysis. The municipality of Amsterdam does the same; they have an asset inventory that is as good as complete and now they are busy with assessing all objects' conditions.

Considering the three drivers of asset management, costs, performance and risks, the asset managers are currently assessing the performance of assets in their own way and they are trying to map the costs of the current maintenance and the bigger projects to come. You could say this is done in an ad hoc way (level 3), because this is done per object type in their own way. However, when it comes to other activity processes, such as risk management, they score between 2 and 3. Some asset managers are making attempts of conducting FMECA's to develop risk-based maintenance plans, whereas other asset managers don't. However, these FMECA's are executed by external parties that do not create an alignment with the organizational goals and objectives. Hence, the asset managers are certainly aware that it is important to manage the objects based on risks, and here and there some attempts are made on executing FMECA's, but it is not yet done in a consistent way. Accordingly, the municipality of Amsterdam is mostly in the beginning of stage 3. Therefore, the outcomes of the following empirical research are from a sample's perspective that does not have a lot of experience in managing assets based on risks.

4.2 | Interviews

The municipality of Amsterdam just started implementing asset management according to the ISO 5500 standards. Many asset managers at the municipality know ISO 5500. However, as explained before, the ISO 5500 indicates what has to be done with clear definitions, concepts and a few guidelines, but it doesn't say how asset management must be implemented. And this is something many asset managers at the municipality of Amsterdam do not know either. Partly the reason for this is that the asset department is currently busy with reorganizing the management system. Their purpose is to centralize the control over all assets at one department and to implement asset management according to ISO 55000. So the asset managers are with this complex reorganization as well. Moreover, the asset managers are not yet fully educated in the new standards of ISO 55000.

During the interviews with all the asset managers their knowledge on managing assets based on risks is tested by for instance asking them the definition of risk in the context of asset management. Next, the relation diagram from part 1 is used as a means of communication to explain what critical objects are and how these can be identified.

However, most of the times asset managers were confused about the difference between risks and performance. Many asset managers thought that when you measure the current impact of an object on the availability of the system, that you measure the impact of the risk. But this isn't true. It is better to think of measuring the extent into which an object is currently complying with the availability requirements that determines the performance of an object. Only when you measure the impact on the availability during the failure of an object, you measure the impact of the risk (Y. Wijnia & Croon, 2015). Therefore, additional visualizations have been made which can be found in appendix D (in Dutch).

As explained before, it is difficult for people to define their interests in something they do not know; namely the process of identifying the critical objects. Therefore, aspects of this process has been found that they do know. These aspects are mainly the information inputs of identifying the critical objects as presented in the relation diagram, the design and application of risk matrices and their experience with the collaboration between the three management levels. Asking about these aspects and using the relation diagram has led to the interviewees' interests.

However, for the interviews with the operational and the strategic level it wasn't always necessary to dig deep into the content of identifying the critical objects. They know everything about their interphase with the asset manager, such as the input they provide to the asset manager. The interviews with them therefore mainly focused on their expectations, challenges and how they expect to be dependent on the asset manager during the process of identifying critical objects. So, the asset owner was asked for instance what their interests were in the type of risks and what they expect from the asset manager in identifying the critical objects. Whereas the questions for determining the interests from the service providers considered mainly the current and expected challenges they have with communicating with the asset manager and the information that they have to provide. As a result, an elaborated understanding in their interests was developed, as explained in the following section.

4.3 | Interests

This section contains the results of the empirical research explaining the differing interests of the three management levels with reasoning, which therefore forms a substantiated answer to the posed sub-question.

Asset Owner

The asset owner finds four aspects important when it comes to identifying the critical objects. The first aspect is as expected and that is that they find it important that all decisions that are made in the organization reflect the organization's policy, and therefore the corresponding goals and objectives. Therefore, the risks of object failure must be expressed in risks for the organization. This corresponds with the ISO 55000 standards. Secondly, they expect that the asset manager can justify the critical objects in a way that the asset owner understands. The asset owner doesn't understand all technological explanations on decisions that have to be made on the operational level. This means that they need the asset managers to speak a non-technical and comprehensive language. Thirdly, they expect substantiated information. So, the asset manager must be capable of defending the posed options and be transparent about everything. And lastly, they have a long-term perspective which is also translated into their policy. For example, the municipality of Amsterdam looks at time periods from 5 to 25 years. Only to achieve any long-term ambitions, they need means that support such long-term ambitions. Therefore, they find it important that the plans for the way assets must be managed take into account this long-term perspective.

All of their interests relate to their expectations for the asset manager, because they are fully dependent on the asset manager in this process. Moreover, their interests come from their social accountability, leading to the involvement of their physical, social and political environment in decision-making. Thompson (1997) sees the social accountability of the asset owner one of the biggest challenges for the asset manager to comply with, because asset owners constantly have to adapt to the changing requirements from the users of the public objects and to the changing regulations. This environment is dynamic and as is the city council which can change every four years. This means that the asset manager also constantly has to adapt to these changes. Accordingly, the social accountability of the asset owner must be translated into the organization's goals and objectives, as Aditya & Kumar (2010) makes clear in their research on strategic issues in asset management. Thus, as Woodhouse (2007) concludes, the asset owner wants to know 'why' things are done instead of 'how' or 'what' things are done.

Unfortunately, it was not possible to interview the actual asset owner, which is the city council. It is possible that people from the city council would provide other answers, since they probably do not have an expertise in asset management. As a substitution, the people from the program and reorganization department were interviewed to obtain the interests of the asset owner. However, these interviewees can have more of a management point of view rather than a political one, which could influence their stance in all this. Yet, the objective of the program and reorganization department is to develop an alignment with the asset owner's interests and therefore were these interviewees a good substitution for the asset owner.

Asset Manager

The interests from the asset managers can be seen in two ways: the one coming from the relation with the asset owner, and the relation with the service provider. Looking at the relation with the asset owner, the interest from the asset managers is to provide a clear connection between the decisions they want to make and the organizational goals and objectives. Currently this isn't properly done at the municipality of Amsterdam, as an asset manager mentioned: "when it comes to the large investments, it is common that our plans are rejected due to a lack of convincing information". They say the asset managers should make decisions and develop plans based on the organizational goals and objectives. Then the asset manager would be capable to convince the asset owner. However, at the municipality of Amsterdam it is unclear for the asset managers how to do this.

Regarding the relation of the asset manager with the service provider, the interest of the asset manager is related to the need for information of high quality from the service providers that enable the proper management of the objects on the tactical level. For asset managers, high quality of information means reliable, usable and consistent information. Information that provides a clear overview. They expect advice from the service providers because they have the most knowledge about the objects. So, it is valuable to use their craftsmanship, which complies with Woodhouse (2007) who concluded in a research that asset managers can derive most improvements for their assets from the advice of their service providers.

Even so, some asset managers have trouble trusting the information from the service providers. A current problem in the municipality of Amsterdam is that the service providers hand in the information too late, incomplete or in the form of extensive long lists making it impossible for the asset manager to rely on in order to actually manage the assets and make the right decisions. An asset manager told that he once asked an external service provider to make an FMECA on a certain bridge type, and received a list of risks that could fill up an entire room without any links to the organization's core values. Such information output was unusable. Also, asset managers may have trouble understanding the service providers, because they aren't always capable of explaining situations comprehensibly and they frequently use different terms in asset management. In conclusion, the asset managers need usable and reliable information from the service providers to manage their objects in a feasible way in order to meet the expectations from the asset owner.

The reasons for the asset managers' interests can also be derived from their responsibility and dependence. Where the asset owner has a responsibility to their environment, referring to an environment also outside of the organization, the asset managers have a responsibility towards the asset owner. However, an asset manager is dependent on the service provider, showing their needs towards the information provided by the service providers. It is therefore up to asset managers to translate the information between the operational and strategical level. So they focus on how the tasks that are executed by the service providers can contribute to an outcome that satisfies the asset owner. They think about 'what' things must be done (Woodhouse, 2007).

The asset managers were mostly consistent in explaining their interests coming from the responsibility towards the asset owner. The reason for this consistency can be the reorganization and the implementation of asset management according to ISO 5500. Now they are expected and they feel the need to manage their objects in a way to produce value towards the asset owner, rather than managing their objects on their gut feeling. However, the asset managers are not completely sure how to do this yet.

However, there were different stances towards the service providers. The relations between the tactical and the operational level is different per type of object. Some asset managers have various service providers, whereas others had one internal service provider that is part of the municipality of Amsterdam. These internal service providers have good relations with the tactical level but also the entire organization of the municipality, resulting in an increasing responsibility towards the asset manager. This is an advantage of such a contractor, as validated by a research from Marsh (2000). Even though the asset managers agree on the problems of collecting usable and reliable information from the service providers, the extent of the size of this problem was different based on their relation with the service providers.

Service Provider

The service providers that were interviewed were the ones that fall under the municipality of Amsterdam. These service providers mentioned the importance of that they want to work with what they know and understand, which is the technical content. One service provider asked me even: "How do I know when my bridge looks pretty enough for them?" It appears that the service providers do not feel a responsibility to comply with the organizational goals and objectives. They just want to stick to managing their objects in a technical way, and not in a political one.

Moreover, they need help with providing usable information and communicating their craftsmanship in a way that it becomes usable for the asset manager. For this it has to be kept in mind that the service providers have a short-term vision, and cannot help the asset managers with planning anything for the long run. So, they have to understand what the asset manager is expecting from them, but also why the asset manager expects this. Woodhouse (2007) indicates that the foundation to a successful bottom-up approach in asset management is to make the service providers understand what is happening on the tactical level. In conclusion, the service providers need clear and simple instructions on what to do and how to communicate their knowledge to the tactical level in combination with an understanding in what happens with their provided information. Though, some asset managers say that there is a certain level to which it is possible to make the service providers understand what the asset managers do with their information.

The interests from the service providers are also influenced by their position within the organization. They have a responsibility towards the asset managers. But, frankly, they do not feel a responsibility towards the asset owner, which might be caused by the large distance between them. As Laue, Brown, Scherrer, & Keast (2014) explain, this has to do with the fact that the operational level is very task oriented rather than outcome oriented, so they do not worry about how their tasks contribute to the bigger picture. They just do their tasks, they like to maintain their assets and do the daily routines, but they do not like to fill out long and complex forms. Such forms work demotivating and causes them to fill these in improperly. Moreover, the service providers usually have many people between them and the asset managers. Therefore, the people who inspect and monitor the objects do not communicate with the asset managers, which diminishes their feeling of responsibility. In conclusion, the interests from the service providers are somewhat caused by their responsibilities towards the asset manager, but they are mostly caused by their task orientation.

4.3 | Conclusion

As mentioned in the start of this research and validated by this empirical research, the interests of the three management levels are indeed differing, which is due to the fact of several reasons. Briefly, the asset owner's interest comes from the social accountability and therefore has a very wide-ranging point of view, whereas the service providers are focused on their day-to-day work and have a limited point of view. And then the asset managers' interests come from being able to optimally interact between both levels.

Overall it appears that the reasoning behind everyone's interests comes from their position within the organization. This clarifies their responsibilities to others and their dependence on others, as illustrated in figure 20. Also, it can be concluded that their interests come from the fact that the service provider is task oriented and the asset owner is outcome oriented, which is shown in figure 21. As the asset manager has to cope with both levels, the asset manager finds it important that the tasks deliver a successful outcome. For this the asset manager has to translate what the asset owner wants to the service provider, and has to translate the information that the service provider provides to understandable information back to the asset owner. This shows that there is a need for a top-down (from strategic to operational) and a bottom-up (from operational to strategic) approach for the identification of critical objects. So, the asset manager must constantly function as a translator between both levels. In conclusion, the interests of the three management levels come from their dependencies, responsibilities and orientations within the organization.

Figure 21 | Dependencies and Responsibilities (own illustration)

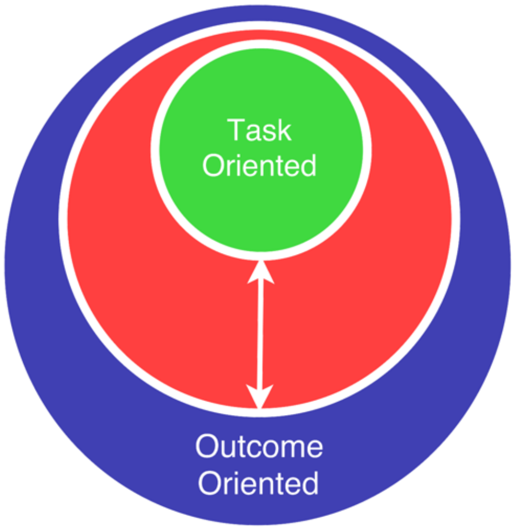


Figure 20 | Outcome and task oriented

5 | PROCESS REQUIREMENTS

So far, the problem statement has been validated and a theoretical IDEF0 model has been developed for the asset manager to identify the critical objects, including the relevant inputs, mechanisms, controls and output. However, this model is mostly based on literature, discussions with asset management experts and logical reasoning. Accordingly, it is not guaranteed that this model works in practice and corresponds with the interests of the three management levels. Therefore, the next step is to make this IDEF0 model correspond with the interests of the three management levels in order for it to work in practice. As a result, this forms the answer to the following sub-question:

> “*How can the asset managers correspond with these interests during the execution of the process of identifying the critical objects?*”

The IDEF0 model can correspond to these interests by collecting from the same interviewees from the municipality of Amsterdam their requirements for the IDEF0 model to work in practice. These requirements are called the process requirements and form additional controls for the IDEF0 model to work in practice.

5.1 | Process Requirements

The process requirements has been found through an ex-ante analysis. The purpose of an ex-ante analysis is to determine the requirements by predicting how the process would work in practice. For instance, what challenges can be expected? Can we foresee these challenges by incorporating any requirements into the process? And what are according to the asset owner, asset manager or service provider requirements for the IDEF0 model to work in practice? In this section the collected process requirements are structured per defined activity of the IDEF0 model.

Overall, the requirements were that the process of identifying the critical objects must be:

1) Feasible with the large number of varying objects,
2) Uniform for all objects,
3) Holistic and systematic,
4) Flexible to react on relevant changes,
5) Simple,
6) And reliable.

These requirements have a different effect on each activity. Therefore, this section describes the process requirements per activity. These requirements are ranked from most to least important. This importance was found by a prioritization analysis where the number of interviewees who mentioned the requirement determined the importance. So the more interviewees who mentioned a requirement, the more important the requirement was found. This prioritization analysis can be found in appendix G.

Step 1: Translate Organizational Goals and Objectives into Performance-Requirements

1. **The performance requirements must be the same for every object**
   From the asset owner perspective, this requirement comes from the fact that the municipality thinks it is the most ethical if every object in every part of the city is performing the same. So, if the city has to be sustainable and clean, all objects have to be sustainable and clean in the same extent. As a result, the performance requirements must be uniform for all objects. In the end, this is an ethical way of thinking and therefore complies with the social accountability of the public authority; the asset owner.

   From an asset manager's perspective, the performance requirements must be the same as much as possible for every object because this will provide a better and simpler overview, which makes the information more manageable. The asset managers do not think it is feasible if every single object has another performance requirement.

2. **The performance-requirements may not miss anything important**
   From an asset owner and asset manager perspective it is of great essence that the performance-requirements cover everything that is valuable. So, all types of performance-requirements that contribute to the objectives of the organization must be taken into account, leading to multiple performance requirements being different for each and single object.

3. **The performance requirements must be higher if the objects have higher impacts during failure**
   Multiple asset managers and a service provider have addressed that objects need a distinction in performance requirements because some objects have higher impacts during failure than other objects. For instance, a busy street that is used the most to enter and exit a city like Amsterdam might be required to be more available than a street in a calm neighborhood. This is because when a calm street like this fails, it would have a lower impact on the availability of the entire infrastructure system of Amsterdam. So, it is logical that a street in the busy car network needs a higher performance requirement than the street in a calmer car network.

4. **The performance requirements must be defined for the subsystems first**
   The previous requirement led in the following discussions to this additional requirement. Since the positioning of an object in a subsystem determines the object's impact during failure, it is simpler to take on a top-down approach and define the performance requirements first for the subsystem. For instance, for the car network you can determine three different availability performance requirements based on the impact of a failing object in that network on the availability of the entire city. So by defining performance requirements first for the subsystems, you create a better overview of the effect of performances of objects on the entire city.

5. **KPIs must be SMART**
   This requirement comes from the asset manager's interest for making information usable and manageable. Therefore, the information, such as the performance indicators, must be SMART which stands for Specific, Measurable, Applicable, Realistic and Timely (Verlaan & Schoenmaker, 2013). This also has to do with the fact that in a later stage these indicators must be communicated to the service providers.

Step 2: Identify Failure Modes and Causes

1. **Performance failure modes must be taken into account as well**
   Functional failure modes can be found by asking yourself what types of failures causes an object not to fulfil its functional requirement anymore? However, it is also important to look at performance failures, or non-technical failures, if an asset manager wants to take into account all ways in which an object can have an impact on the organization. For instance, a performance failure mode could be a littered sidewalk. This isn't a functional failure but it is important to take into account such a failure if it has a large impact that concerns the asset owner. So, the failures of an object must be analyzed by looking at performance failures as well.

2. **Non-technical causes must be taken into account**
   The probability of a construction of a bridge collapsing can be caused by technical or physical causes, such as deterioration or corrosion. However, as explained in paragraph 3.2.1, there are also other causes such as human, operational and natural causes. Some of these causes can have a large impact on a failure mode occurring and these causes can be foreseen in some situations. The asset managers made it therefore clear that they wish to have an overview of these causes as well.

Step 3: Assess the Risks of the Failure Modes

3A: Defining the Risk Acceptance

1. **Organizational goals must be reflected in the impact criteria, its indicators and its weighting factors**
   Not only through interviews it became clear, but also ISO 5500 and other literature pointed out that the best way of creating a line of sight in risk management is by translating the organizational goals into performance requirements into the risk acceptance level (Arthur, Hodkiewicz, Schoenmaker, & Muruvan, 2014b; Eckerson, 2009; Maia & Chaves, 2016). Also, the impact criteria and its weighting factors can reflect the organizational objectives. Plus, according to multiple asset managers, the impact indicators are simply KPIs but then with various norms, as shown in figure 21. In other words, they say the impact indicator of a risk is the same as a performance indicator.

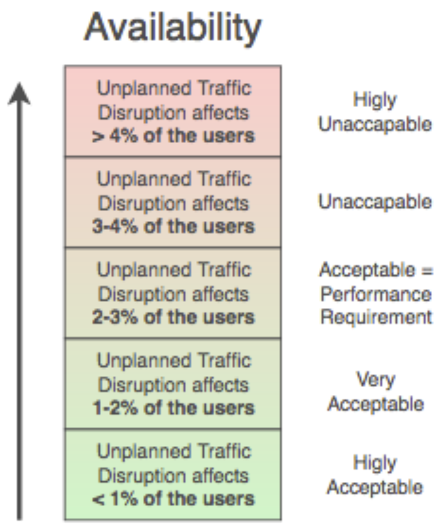


Figure 22 | Example SMART Impact Indicators (own illustration)

2. **Impact indicators must be SMART**
   Similar to the performance-requirements and the performance indicators, the impact indicators must be SMART as well. An expert said "if the indicators are not SMART, risk assessments will become long-winded discussions". Multiple experts have experienced that people misunderstood the impact indicators, causing unnecessary additional discussions when assessing the impacts of failure modes. Moreover, an asset manager pointed out the essence of considering the difference between impacts of failures taking place during the day and the night. Think off the impact of a fire in a tunnel that happens by day compared to when it happens by night. The impact of the fire during the day will be bigger. Many impact indicators for availability are expressed in a certain percentage of availability. So, tunnels of Amsterdam must be 98% available. However, this doesn't take the impact differences between

day and night into account. According to that asset manager is figure 21 an example of how to take this into account by referring to the users that are affected.

3. **The weighing factors and impact indicators must be easily adjusted to reflect changes in impacts**
   According to experts it doesn't happen often that organizational goals and requirements change. However, some asset managers made it clear that they notice that municipalities can change their visions every four years due to the elections. They notice that some core values can become more important than others, just like the fact that sustainability has gained more attention in the last couple of years. Therefore, the impact indicators should be adaptable to these changes, which can be done with the weighting factors. Something that is common to do in asset management (J. Wang, Attwater, Parlikad, & Russell, 2014).

4. **The risk matrix must be uniform for all objects**
   Many asset managers are having doubts to what extent they think it is possible in practice to compare assessed risks between different types of objects. How to compare apples and oranges? Therefore, a couple of asset managers with experience in risk assessments required that all objects' risks are expressed in similar terms and the risks must be assessed in similar ways. If the calories of an apple are counted with a simple method A and the orange's calories are counted with an extensive method B, it would not be reliable enough to compare these outputs. In other words, it would be best if the risks of all differing objects are assessed similarly with the same method and the same type of output, and therefore with the same risk matrix.

   This solution is validated with Mil et al. (2006). In some ways you can compare different items by expressing them into similar units. Such as that apples and oranges can both be expressed in a number of calories, can all kinds of impacts of risks be expressed in monetary units. By expressing all impacts into monetary units all impacts of the object failures become comparable. However, this appears to be easier said than done as it is a matter of many calculations and a lot of guesswork when it comes to translating societal effects into monetary effects. Consequently, such results can be somewhat inaccurate.

3B: Determining the probability and the impact of failure modes

1. **Do not assess all risks of all objects**
   The asset managers and experts know from experience how complex it is to determine all failure modes with all possible causes. So assessing the risks of all failure modes is too much work. "In reality this will never be done", an asset manager said. This complies with what is mentioned in various literature on why asset managers filter objects in large-scale asset systems before assessing the risks (Houten & Zhang, 2010; Kobbacy, 2008).

2. **Take into account the capabilities of the service providers**
   According to the service providers it soon became clear that in some cases they are expected to do more than what they are capable of doing. For instance, it appears that service providers have the feeling that they usually have a lack of time to be able to deliver enough and qualitative information to the asset manager. Also, they find it very difficult to write down their expertise on paper. Therefore, asset managers must be aware of the capabilities of the service providers in order to obtain valuable inputs from them.

3. **Monitor large changes that affect the risks of object failure**
   Many things can happen in a city that can result in a change in the risk of an object failure. According to the policy department “every 115.000 additional houses in Amsterdam equals 40% more movement in the city”. More movement means that the objects will be used more, meaning that they expect that the probability and impact of failure of some objects will increase. This is because more usage equals more load and a quicker deterioration process. And more usage means that more users will be affected during the object’s failure, which means a larger impact. So such large changes must be monitored to keep the risks up-to-date.

   This requirement can be validated by the research that has been executed by Adams, Srinivasan, Parlikad, González-Prida, & Crespo (2016). They proved that dynamic risk assessment is essential for avoiding high unexpected or unnecessary costs.

4. **Use knowledge and experience from service providers as advice**
   “They know more about our objects than we do”, an asset manager pointed out during the conversation about the translation between the operational and tactical level. He was talking about the service providers, such as the people who monitor and inspect the objects. They know the objects inside out and can recognize any deformations quicker than we can imagine. The asset manager has to manage over 100’s if not 1000’s of objects, and has simply no time to know the objects that well. Therefore, they have to rely on the expertise of the service providers. According to an expert it is therefore important that we take their advice seriously. This requirement was expected to be mentioned, validated with Woodhouse's (2007) paper.

3C: Assess the risks to determine the RPN of the failure more

5. **The RPNs must be comparable between objects**
   Many asset managers think that this is highly important, whilst they are also having doubts into what extent this is possible in practice to compare assessed risks between different objects. As explained before, how to reliably compare apples and oranges? So far the solution for this is using a similar risk matrix.

Step 4: Aggregate the RPN to Object and System level

1. **The RPN must also be aggregated to subsystem level**
   Some asset managers request an overview of the critical objects per subsystem, for instance the car network or a region, as well. This is important if the car network has to be improved in terms of availability or if a neighborhood has to be improved in terms of social safety. If the asset manager can see which objects are currently the most critical in terms of those categories, it is easier for the asset manager to decide where to invest in what kind of measures.

2. **The output of the aggregated information must be comparable and reliable**
   A system of objects or a network of objects are different types of objects put together. Accordingly, when the RPN of objects are aggregated to the subsystem or system level, the RPN of different types of objects must be comparable. So, the RPN must keep an accurate representation of the organizational goals even though when it is aggregated to another level. So, this quantitative way of assessing the risks must be very accurate and reliable.

3. **The output of the aggregated information must be able to be explained in terms of strategic language (so no technical related explanations)**

An RPN doesn't tell the asset owner something they understand. So, the final output of this process step should be a clear representation of the organizational goals and objectives. So, if the asset manager is able to show why an object is critical in terms of the organization's core values, the asset owner should be able to understand the asset manager better. As a result, it would be easier for the asset manager to defend their measures and therefore receive the budget from the asset owner.

General IDEF0 model Requirements

Some requirements weren't specifically related to one activity, but were meant for the entire process of the IDEF0 model. These are enumerated below:

1. **The process must be able to be applied to every type of object as much as possible: A uniform process**
   One expert mentioned that Shell has defined the same risk acceptance for the entire company. So, no matter what fails, the risk of that failure is assessed similarly. In other words, it would be best if this method is applied to each object similarly. Moreover, ethically seen treating every object the same is important for the asset owner, as the asset owner wants each bridge to be equally clean.

2. **The process is feasible with the large number of components, objects and failure modes**
   The municipality of Amsterdam owns a large number of objects. For instance, the asset manager that manages the bridges currently has 1600 bridges to manage. All of these bridges have numerous of failure modes and numerous of components. One the one hand, experts point out that you need to know the risks of the components in order to determine the risk of the object, but on the other is it not feasible to assess all these components' risks of all of those 1600 bridges. So the IDEF0 model must cope with this challenge in order for it to be feasible.

3. **The process shows a holistic view, integrating all important aspects, serving as a clear overview of all the necessary steps and the relations between the important aspects in order to find the most critical objects**
   This requirement is strengthening what Zeb & Nasir (2016) concluded to be necessary and what the objective of this entire research is, namely designing a holistic, systematic and integrated IDEF0 model.

4. **It should be clear which activities are flexible and how changes can be made**
   Requirements have shown multiple times that asset managers show the need for a process that can react to changes, such as the impact weighting factors. But, the failure modes can also change. For instance, if it has been chosen to adjust the design of an object by adding a new component to it, this new component can add another failure mode to it as well. Also, probabilities of failures can change over time. Thus, there are multiple dynamic factors in the process of identifying the critical objects, which the asset manager has to consider when applying the process in practice.

5. **The process must be easy to understand**
   According to experience from multiple interviewees, miscommunication and misunderstanding of proposed processes is something that happens often. Asset managers repeated many times how important it is to keep the process comprehensible, otherwise the entire process will be useless. A complicated process is unmanageable and it will cause the service providers to deliver wrong

information. This complies with the results from the research conducted by Adesola & Baines (2013) on important criteria that business processes must comply to. Here they mention that a process must be usable, meaning that the process must be easy to apply and use for it to be successful.

Moreover, many people experienced at the municipality of Amsterdam that processes work the best if these are clearly visualized. As the researches from Akkermans & Gordijn (2003) and Osterwalder & Pigneur (2005) indicate, it is difficult for people to process complex information from only text. Visualizations help and preferably graphical visualizations.

6. **The outcome of the IDEF0 model must be reliable**
   The outcome of the IDEF0 model will become the input for a decision-making process. In this decision-process various maintenance measures are developed to treat the risks of the most critical objects. Treating large risks can mean in some occasions that the entire object needs major maintenance or it even needs to be replaced. Such measures are large investments. So, the asset manager and the asset owner want the outcome of the IDEF0 model to be reliable enough to assure that the identified critical objects are worth the investment.

5.2 | Conclusion

This chapter explains the requirements of the three management levels for the activities of identifying the critical objects to work in practice. Collecting the requirements for the process to work in practice has led to the conclusion that there are three large challenges for the asset manager. The first challenge is that the asset manager must compare oranges and apples. An infrastructure system not only contains a large amount of objects; it also contains a large amount of different types of objects. And each object has other types of failure modes and risks. These differing risks must be made comparable to prioritize them reliably. According to the interviewees, the solution for this is to make a uniform process as much as possible, meaning all risks of all types of objects are identified and assessed similarly.

Another challenge comes from the fact that people are only familiar with assessing the risks of the components of objects. The risks of the components must be known first to determine the exact risks of the objects. However, as explained before, assessing the risks of all components is not feasible. So, the risks of the objects must be assessed in some way without knowing the exact risks of all components. This idea made many asset managers confused, as they did not think about this like that before.

Third, the asset managers clearly agreed that you cannot assess the risks of all components of all objects when there are numerous objects. However, they soon emphasized the fact that you cannot assess all risks of all objects either. Even if the process is kept very quick and simple, assessing all risks of all objects would still take too much time for a situation where you need quick decision-making to treat risks. Most of the interviewees therefore provided the idea of clustering objects and then assess the risks of these objects together. This means you have to assess fewer risks. However, this refers to the frequent misunderstanding on the difference between determining maintenance plans and determining he current critical objects. For determining maintenance plans you can cluster objects. However, if you want to determine the current critical objects, you cannot cluster because you need to know each object's individual and current risk. So, there is a need for making the process feasible by not having to assess all objects, whilst considering the object's individual probability and impact of failure.

Analyzing these requirements can provide new important insights. This analysis is presented in the following chapter.

6 | REQUIREMENTS ANALYSIS

So far, the performance requirements are known. But how can the asset manager correspond with all of these performance requirements? The next step is therefore to analyze the requirements in order to develop a greater understanding by 1) defining the relation between the three management levels' interests and the process requirements, and 2) defining the relation between the process requirements and the theoretical IDEF0 model. As a result, this will contribute to a complete answer to the following sub-question:

> "*How can the asset managers correspond with these interests during the execution of the process of identifying the critical objects?*"

6.1 | Relation between Interests and Requirements

So far the requirements were explained and allocated to the relevant activity. Also, the requirements were prioritized based on the number of times these were mentioned by a different person. Next, the types of requirements between the different management levels are compared. This is made easier by allocating the requirements to simple terms, such as allocating requirements to the terms uniformity and flexibility. The results of this analysis is shown in appendix E and F.

Figure 23 shows the main interests of the three management levels with the corresponding requirements in the simplified terms. It can be noticed that all requirements are related to the interests of the corresponding management level.

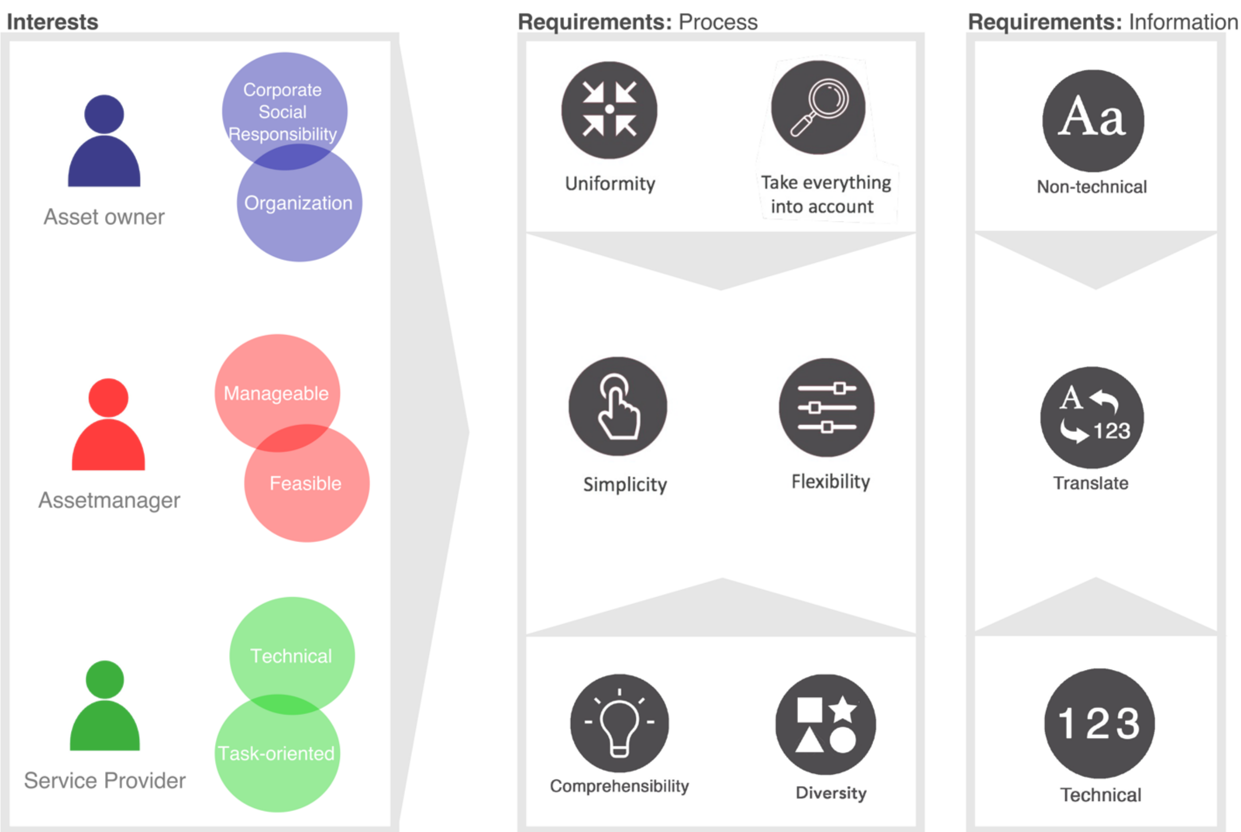


Figure 23 | Relation between interests and requirements (own illustration)

Asset Owner
Having a corporate social responsibility, the asset owner finds it important that all objects are treated equally, so that all users can experience and enjoy the objects similarly. Therefore, the asset owner insists on applying a uniform process where all objects are treated the same.

Moreover, the asset owner is responsible for the entire organization. Knowing that the objects have a large impact on the organization, it is very important that the investments which the asset managers present to the asset owner take everything into account. They cannot overlook anything, minimizing uncertainties as much as possible. Moreover, the asset manager must use non-technical language so that the asset owner understands everything and can be sure that providing the budget is the right decision.

Asset Manager
The asset manager must link the requirements from the service provider and the asset owner together, which leads to the asset managers' interests and therefore also the asset manager's requirements for the process. The asset manager finds it important that the process is manageable and feasible. This complies with the research from Adesola & Baines (2013) where it is mentioned that a business process must be feasible in order for it to be a success. Translating this into usable requirements for the IDEF0 model, it means that the process must be simple so that it is comprehensible for the service provider, and flexible so that it can adapt to changes coming from the requirements from the asset owner. When it comes to the requirements for the information, the asset manager requires the IDEF0 model to be capable of translating between the non-technical and technical information.

Service provider
The service provider is task-oriented and is only interested in the technical matters of the objects and the components. They find it difficult to translate their technical expertise into non-technical, or political, language. Therefore, they require the asset managers to respect that they only want to deal with technical information. Moreover, they expect the IDEF0 model to be comprehensible as they have trouble understanding and finding time to fill in the complex forms the asset managers provide. Also, the process must take the diversity between the objects into account. The service providers see every object differently, and therefore the objects need different attention. Consequently, they expect the IDEF0 model to take into account the differing necessities for all objects.

6.2 | Relation between Requirements and Process
The second step is to define the relation between the requirements and the IDEF0 model in order to see how the requirements could be processed into the IDEF0 model using logic reasoning. As a result, there are three ways in which this relation can be defined. First it is concluded that many requirements are opposing, which was expected since the interests are opposing as well. These opposing requirements are developed into a scale with one opposing requirement on each end; the scalable requirements. It is then up to the asset manager to choose a position on that scale between the two opposing requirements and apply that in practice. Section 6.3 goes deeper into the opposing requirements and the next chapter describes the resulting scalable requirements.

The second way in which the requirements have an influence on the theoretical IDEF0 model is that it can be processed into the design of the IDEF0 model. These requirements have an influence on the IDEF0 model because it determines the definition of an activity or it has an influence on the overall design of the diagram. First, the subsystems have to be taken into account in order to accurately define the performance requirements and impact and to be able to aggregate the RPN to the relevant levels. This therefore would has an influence on the activity of defining performance requirements and aggregating the RPN. And there are many requirements for a process model to look simple and comprehensible with visualizations in order to explain it to people. Unfortunately, the IDEF0 modeling technique does not consider such requirements. Therefore, a solution can be to develop an additional process model that can be used as a mean for communication. Then when people understand this simplified process model, the IDEF0 model can be used for additional information.

The last type of influence of a requirement on the IDEF0 model are the left overs. These aren't opposing to other requirements and these do not have an impact on the design of the IDEF0 model. These are simply requirements based on interviewees' experience for applying the activities of the IDEF0 model in practice. These requirements are also validated with literature and can therefore be seen as reliable and applicable to this research. These requirements are that performance requirements and impact indicators should be SMART, to use craftsmanship for obtaining advice, to present risks in visual ways, and to develop a line-of-sight. The overview of the simplified requirements per process step are allocated to the process steps below in table 2. Here the column ''application' refers to the three types of ways the requirements can be applied.

Process Step	Prioritization	Simplified requirement	Application
Process as a whole	1	Uniform	Scalable option
	2	Holistic	Process Model
	3	Flexible	Scalable option
	4	Take everything into account	Scalable option
	5	Simple	Scalable option
	6	Feasible	Scalable option
Step 1: Definition Performance Requirements	1	Line-of-sight	Requirement
	2	Uniform	Scalable option
	3	Take everything into account	Scalable option
	4	Reliable	Scalable option
	5	Simple	Scalable option
	6	Subsystem	Process Model
	7	SMART	Requirement
Step 2: Identification Failure Modes	1	Non-technical	Scalable option
	2	Take everything into account	Scalable option
Step 3: Risk Assessment	1	Feasible/ not too much	Scalable option
	2	Quantitative output	Requirement
	3	Line-of-sight	Requirement
	4	SMART	Requirement
	5	Simple	Scalable option
	6	Use craftmanship	Requirement
	7	Visual	Process Model
	8	Flexible	Scalable option
Step 4: Aggregation RPN	1	Comparable and reliable RPNs	Scalable option
	2	Visual	Process Model
	3	Line-of-sight (bottom-up)	Requirement
	4	Non-technical presentation	Scalable option
	5	Subsystem	Process Model

Table 2 | Application of requirements into IDEF0 model

6.3 | Opposing Requirements

Analyzing the relationships between the requirements and the management levels provides the pattern as visualized in figure 24. Here the red lines represent opposing requirements, whereas the green ones represent complying requirements. The red/green lines can be both opposing and complying, and the gray line represents no relevant relation.

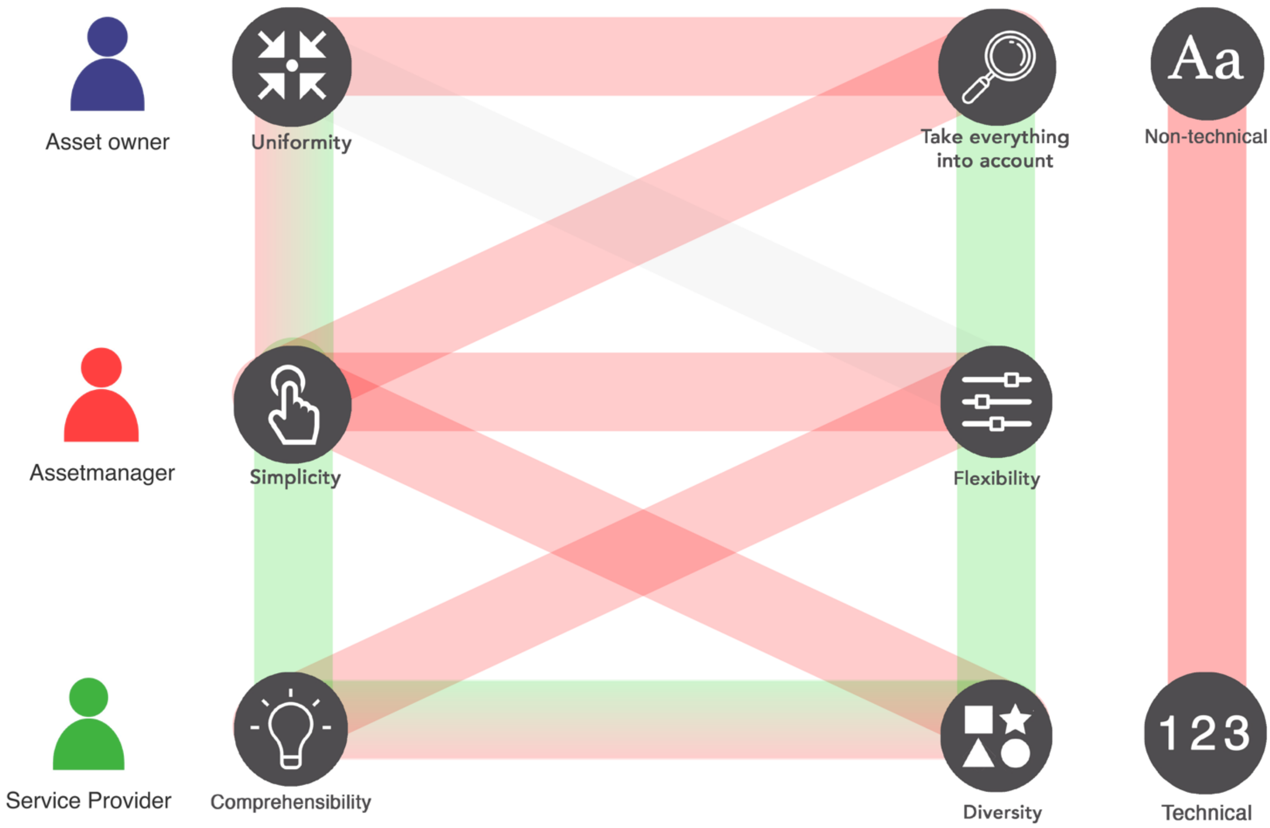


Figure 24 | Opposing Requirements (own illustration)

The figure's pattern shows four important conclusions that must be considered in the execution of the IDEF0 model:

1. The two main requirements per management level are opposing

Uniformity versus taking everything into account

A uniform process for all objects can come with the risk that something important is overlooked. This is opposing to the requirement that everything must be taken into account.

Simplicity versus flexibility

A process that is adaptable to changes makes it flexible. However, such dynamic features can make a process more complicated for the ones that must apply it. And therefore, flexibility and simplicity can be seen as opposing requirements.

Comprehensibility versus diversity

If there are different processes, or aspects such as different risk matrices, for every single object, the chance increases that processes become less comprehensible for the service provider and asset manager, since it is difficult to constantly adapt to another process. However, to the service provider it might be easier to understand if every object is treated differently. So, diversity can make it more and less comprehensible at the same time.

Knowing this, it turns out that the requirements on the left side comply with making the IDEF0 model feasible in practice. Whereas the ones on the right make the IDEF0 model more reliable in the sense that the outcome is more complete and up-to-date.

2. **Each requirement from the asset manager complies with one requirement from the other two management levels**

Uniformity – Simplicity – Comprehensibility
One simple process for all asset managers' types of objects can make the process more comprehensible for everyone. This can be achieved with developing a uniform process for all types of objects. However, looking at the opposing requirements, this leaves the risk that it doesn't take everything into account and that it doesn't respect that objects must be managed differently. Moreover, a uniform process doesn't necessarily only result in a simple process. A uniform process can be difficult to design, leaving with complex and possibly unusable results.

Take everything into account – Flexibility – Diversity
The asset owner wants the process to take everything into account, not overlooking anything. And the service provider wants the process to treat objects differently. Therefore, the asset manager requires the process to be flexible in order to adapt to changes so that it is capable of constantly keeping everything into account and to be flexible towards the differing objects. However, a flexible process is not simple and will ask for good change management.

3. **The process must translate from top to bottom and from the bottom to the top**

Non-technical versus technical
The asset manager constantly has to change the language from non-technical to technical and back. Like this, the asset manager must function as a translator between the service provider and the asset owner.

6.4 | Scalable Requirements

From the analysis, it becomes clear that there are multiple opposing requirements. It is the responsibility of the asset manager to determine how to incorporate these requirements into the execution of the IDEF0 model by deciding the right position on the scale. The following section describes the scalable requirements that are expected by the interviewees to be the largest challenge. Each scale describes the advantages and disadvantages for the process of the IDEF0 model per requirement on each end.

The asset manager is clearly conflicted between the requirement from the asset owner that everything must be taken into account, whereas the process has to be kept simple in a way keeping it usable and feasible. Asset managers know from experience that complex processes do not work well in practice, whereas they also want to defend their decisions to the asset owner by not missing anything important that the asset owner expects to be delivered. According to the prioritization analysis, the requirement for keeping it simple for the entire process was mentioned more than that everything has taken into account. Note that this requirement mostly comes from the asset managers who indicate that without such a requirement the entire process will not work.

For this scalable option the following opposing choices can be made:

Define a few Performance Requirements.
This will make the process simple and more manageable. One asset manager, as did Eckerson (2009), said that "less is more" when it comes to defining performance requirements or KPIs.

Define all possible performance requirements.
The asset manager will not overlook any important performance requirement that can contribute to the achievement of the organizational goals and objectives. However, this can be an overkill of information.

Determine only a few failure modes of a few objects.
Many asset managers are getting stressed with the idea if they have to think of all possible failure modes for 1600 bridges. By determining only a few failure modes of a couple of objects makes this process step easier and faster.

Determine all possible failure modes of all objects.
The advantage for finding all possible failure modes of all objects minimizes the chance of forgetting any important risk. Something that will satisfy the asset owner. However, it can lead to an information overload. Moreover, from interviews it became clear that it is impossible to define all failure modes because not all can be foreseen.

Include a few impact criteria.
Applying the risk matrix will be simpler, quicker and clearer.

Include all possible impact criteria.
In this situation no important impact criteria, and therefore relevant risks, will be overlooked.

Assess only a few risks of a few objects
Assessing everything is impossible with limited time and people.

Assess all risks of all objects
By assessing everything the most risks can be foreseen.

Simplicity and flexibility can be opposing. A flexible process refers to a process that can adapt to changes, such as changes in society, politics and requirements. As explained before, the municipality of Amsterdam can suddenly weight an impact of a risk on sustainability heavier. This means that the risk matrix must change. However, this isn't a simple task. It is simpler to have a static process where everybody can get used to.

Static Risk Matrices
The risk matrix is the same for all objects and stays the same. This will lead to no confusion between the different versions of risk matrices. Because if the risk matrixes are constantly changing, it can happen that some people are accidentally using older versions of the risk matrix, leading to incorrect results. Also, a static risk matrix leads to a better understanding, as everybody has time to grow their understanding in one risk matrix.

Dynamic Risk Matrices
The risk matrix can adapt to changes, such as changing risk acceptation levels or impact criteria. This results into the most feasible and up-to-date risk matrix that can constantly represent the organizational objectives. In other words, a dynamic process will lead to a more reliable and accurate outcome.

Opposing to a uniform process is a different process for each type of object. As explained before, objects must be treated differently if you want to keep the process feasible and avoid overlooking anything important. However, uniformity is a requirement makes it possible to compare the outcomes of a risk matrix. As a uniform process makes it more manageable and feasible for an asset manager, this turned out as being a requirement with the highest priority.

Similar Performance Requirements.
This leads to a more manageable and usable process, making it easier to keep the overview. Moreover, this is important for the asset owner to fulfill the social responsibility as this means the objects will be maintained similarly.

Different performance requirements per subsystem and every single object.
This takes into account that some objects need to be maintained differently to achieve the organizational goals and objectives.

Apply similar risk matrices to all objects
Applying similar risk matrices leads to similar outcomes. This makes it possible to compare the risks of different objects.

Apply customized risk matrices for every single object
Not all impact criteria are relevant for all types of objects and some objects might need additional impact criteria. Developing customized risk matrixes, however, does take more time.

From the analysis, it was concluded that the asset manager constantly has to act as a translator between the non-technical information from the asset owner and the technical information from the service provider. The diagram on below shows how the asset manager is in the IDEF0 model positioned between the asset owner and the service provider. First there is a translation from the top to the bottom, and then it is translated back from the bottom to the top.

Technical and quantitative information can be objective and comparable, which is necessary for determining the criticality of objects. However, non-technical information is also necessary because this is the strategic language necessary to explain the organizational goals. A list of challenges due to these opposing languages is presented below:

From organizational objectives … to performance requirements
The municipality of Amsterdam wants the city to be available. But how can the objects perform in order to contribute to an available city? And what norm will satisfy this objective? How to define an accurate performance requirement that satisfies the organizational objectives?

From organizational objectives … to risks assessment variables
The issue here is the accurate translation of political information into assessment variables, such as the impact criteria and the weighting factors. How can the weighting factor accurately be derived from a policy document of the organization? And how to be sure that such a number doesn't have too much and therefore an inaccurate effect on the output of the risk matrix?

To non-technical impacts … from technical failures
Or from non-technical failures … to technical impacts
If a bridge cannot open anymore because an important cogwheel doesn't function anymore, the impact of that bridge on the reputation must be estimated. However, this is complicated to determine accurately and this cannot simply be done by the service providers. Technical failures and impacts aren't new for the service providers. Non-technical ones are, also for many of the asset managers.

To strategic language … from risk priority numbers
Here the challenge is that the RPN must be both quantitative to be able to aggregate, compare and prioritize objects and it must provide a clear reflection of the organization's core values. So a number has to be translated into language that the asset owner can understand.

6.4 | Conclusion

This chapter analyzes the relation between the interests of the three management levels, their requirements and the IDEF0 model. As a result, this chapter explains how the asset manager can correspond with the varying interests of the three management levels in the execution of the IDEF0 model, forming additional controls for the IDEF0 model.

The relation between the interests and the requirements is clear, since the requirements form a logical representation of the management levels' interests. In brief, the asset owner prefers the process to be uniform but finds it essential that everything is taken into account so that the outcome of the process is reliable. The service provider wants the process to be comprehensible and wants it to consider the different features of objects, meaning that objects' risks need to be assessed differently. And the asset manager, as translator between the non-technical strategic level and the technical operational level, wants the process to be simple in order for it to be feasible, and wants it to be adaptable to changes and different assets in order for it to be reliable.

When analyzing the relation between the requirements and the three management levels it resulted into three types of ways that the requirements have an effect on the execution of the IDEF0 model. First, there are opposing requirements which the asset manager has to choose from to apply in practice. There are requirements that make the IDEF0 model feasible, but these requirements are opposing to the ones that make the IDEF0 model more reliable. As a result, the scalable options were established, showing what the advantages and disadvantages are of considering the opposing requirements in practice. And the second type of effect is the effect of the requirements on the design of the IDEF0 model. This has led to the requirement for having an additional simplified process model that can be used for communication purposes. And last are the requirements that have to be applied in practice anyhow, such as using SMART descriptions for the KPIs.

In conclusion, there are various challenges for the asset manager to apply this process. First, it is up to the asset manager to choose the right balance between the opposing requirements. Also, the asset manager has to compare oranges and apples and has to keep the process feasible by not having to assess all risks of all objects. Furthermore, the asset manager has to cope with the challenge of the uncertainties of the inputs for the risk assessment, such as that the probabilities of failure are never certain and cannot be predicted accurately and determining impacts is generally subjective.

Since this process is new to everybody from the municipality of Amsterdam, it can be expected that when it is applied in practice solutions to the opposing requirements or the other challenges will arise, but it can also be expected that new unforeseen challenges will arise. This certainly has appeared to be the case. Therefore, the IDEF0 model has been tested and improved. This testing is explained in the next part.

PART III

Testing the IDEF0 model in Practice

at the Municipality of Amsterdam

7 | TESTING THE IDEF0 MODEL

The next step was to test the IDEF0 model in practice at the municipality of Amsterdam in order to answer the following sub-question:

> *"How does the process to identify critical objects in a public infrastructure system work in practice?"*

The theoretical IDEF0 model has been developed based on literature, some experts and logical reasoning. So, it is likely that the process will turn out to work differently in practice. Also, additional controls are defined for making the IDEF0 model work in practice and expected challenges for the asset manager to execute the IDEF0 model in practice has emerged. Therefore, the purpose of testing the IDEF0 model is to see into what extent the IDEF0 model works in practice and to discover the solutions to the expected challenges. This has resulted in extended activities and additional requirements for the process to work in practice forming the improved and final IDEF0 model.

Since the entire IDEF0 model takes a lot of time to be completely applied in practice, it has been chosen to apply the first activity of the IDEF0 model in practice, and for the rest an ex-ante analysis has been conducted to predict how the process will take shape in practice. This is done by executing three workshops with the following purposes:

1. Translating the organizational goals into KPIs for all objects.
2. Defining KPIs and performance requirements, and designing a risk matrix for the civil construction objects.
3. Conducting an ex-ante analysis in order to:
    A. Determine how Amsterdam can filter failure modes and objects to keep the process feasible with the large number of objects.
    B. Further define the final and essential process step, which is aggregating the RPN to the object, subsystem and system level.

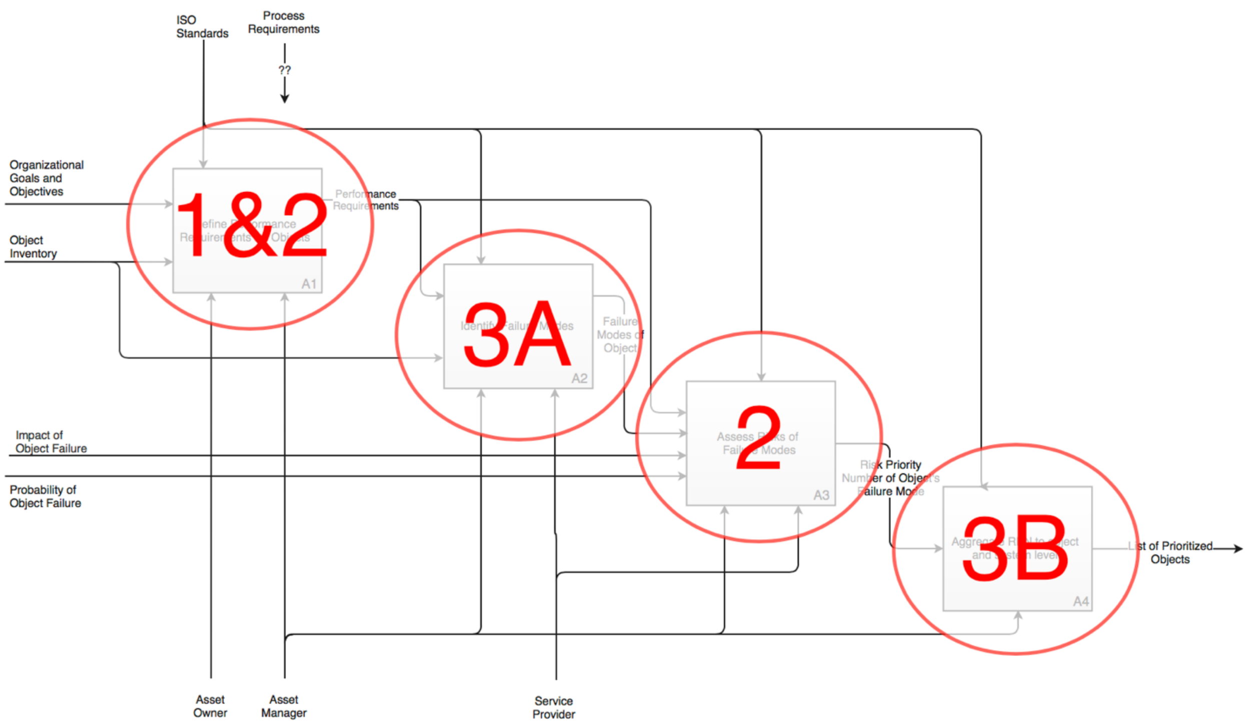


Figure 25 | Link between workshops and IDEF0 model

7.1 | Simplified Process Model

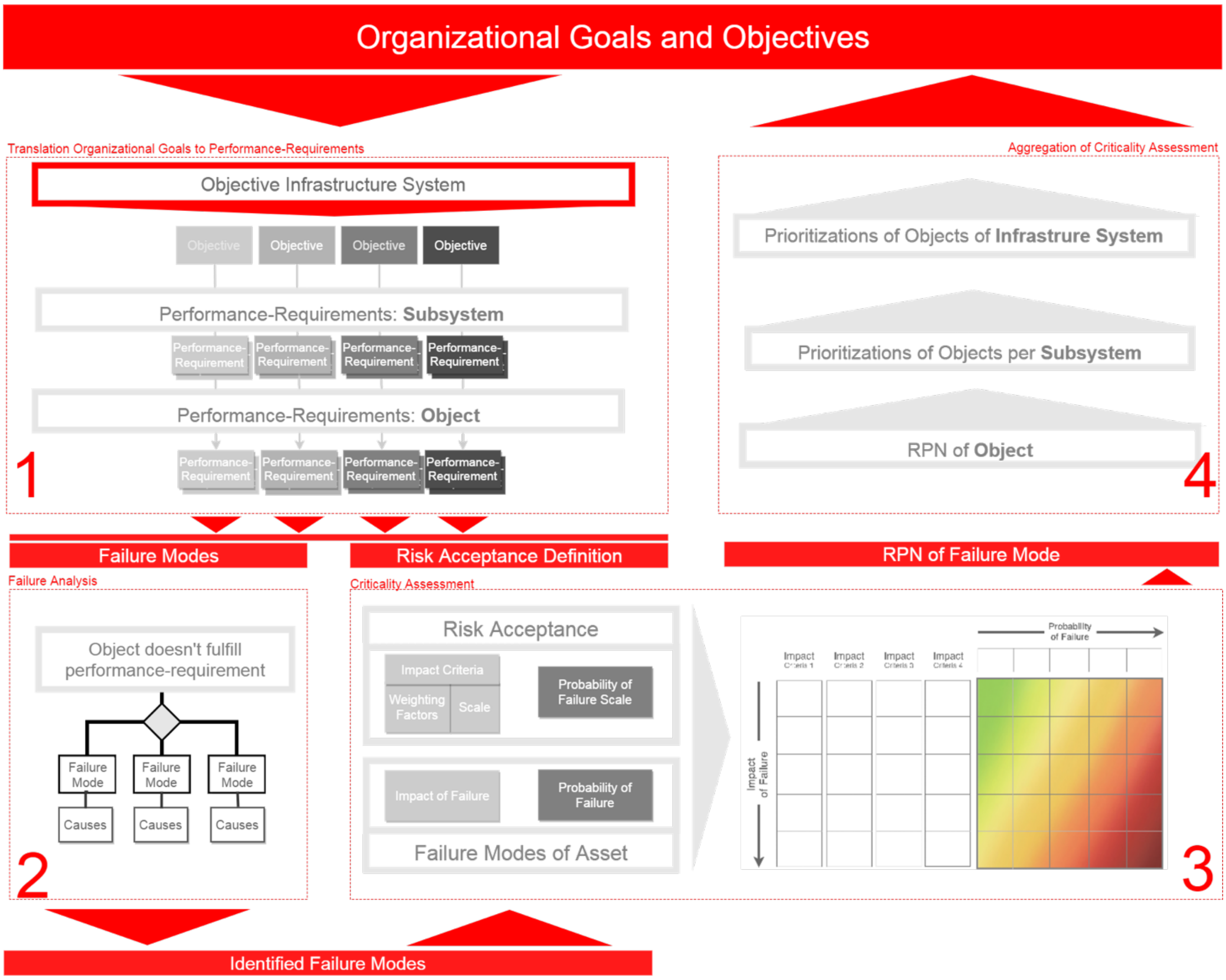


Figure 26 | Simplified process model

From the empirical research it has become clear that the asset managers were in need of a process model that would be easy to communicate. Also, the participants of the workshops should fully understand the process of identifying critical objects to deliver a valuable input during the ex-ante analysis. Therefore, it has been chosen to develop a means of communication by making a simplified IDEF0 model as shown in figure 26. This simplified model includes the two additional requirements for defining performance-requirements on the subsystem level and aggregating the RPNs to the subsystem level. The model corresponds for the most important part with the theoretical IDEF0 model. However, this one shows more visualizations and it shows more sub activities in the activities itself. In other words, this process model shows parent and child diagrams at the same time. This is something that the IDEF0 model cannot show simultaneously in the same model. However, the simplified process model does not show clearly all mechanisms, inputs, outputs and controls. Yet, it shows enough to explain visually how critical objects can be identified. This model has therefore been used as means of communication during the workshops.

As a result, the simplified process model can be used as means of communication to inform the necessary people in a visual way how the process works. Then when it is understood, the asset manager can use the IDEF0 model when the process is being executed because this shows more information that is important for understanding the execution, such as all inputs and outputs of each activity.

7.2 | Workshop 1 - *Translating the organizational goals into KPIs for all objects*

The purpose of this workshop was to define uniform objectives and KPIs for all types of objects. It was chosen to do this workshop, as when you look at the chronological sequence of the IDEF0 model, it would be the most logical to start with the first process step. Moreover, the municipality of Amsterdam was mostly interested in applying this step because they also want to measure all objects' performance for which they are highly dependent on having KPIs. And lastly, testing this step can be instructive for developing the line of sight, or in other words the top-down approach, that is necessary for good asset management according to ISO 55000.

This workshop was organized in cooperation with a program manager from the strategic level and an advisor in risk management. My responsibility in this workshop was to prepare the workshop, educate everyone on the matter and support the process of the workshop. The advisor would explain its context in risk management and also support the process of the workshop and the program manager would explain its larger context at the municipality of Amsterdam and the reorganization of the asset department.

It was organized for the tactical level of the asset department, some advisors and people from the policy department of the municipality of Amsterdam. The policy department of the municipality has written a document named "1 Amsterdam Heel & Schoon" (*English: undamaged and clean)* in which organizational goals and objectives have been translated into what this means for the maintenance of the public objects of Amsterdam according to multiple criteria.

A couple of performance criteria from 1 Amsterdam Heel & Schoon were found most important by the program manager and were therefore chosen as basis for developing the KPIs in the workshop:

Performance Criteria:	Objective Infrastructure System:
Availability & Safety	Maintaining our objects has our primary objective to guarantee an available and safe infrastructure system
Sustainability	We maintain the infrastructure system for the future and we contribute to the sustainability ambitions of Amsterdam
Attractiveness	We choose for a uniform city; everywhere in Amsterdam we strive for an infrastructure system in 2025 that complies with the predefined level "neat" as explained in 1 Amsterdam Heel & Schoon.

During the preparation it became clear that the first process step must be extended for being able to define the KPIs. This resulted in the following steps:

1) Define per performance criteria the objective for:
    a. The entire infrastructure system (e.g. the public space of Amsterdam)
    b. All objects building up this system (the streets, trees, traffic lights and bridges together)
2) Define per objective the KPIs for all objects
3) Define per KPI the norm, and therefore the performance requirement, per subsystem
4) Define per KPI the norm for all objects

Unfortunately, there was a lack of time to execute all activities. Since 1a) was already defined in the policy document "Heel & Schoon", the workshop consisted of two main steps: 1) defining uniform objectives for all objects and 2) defining uniform KPIs for all objects. This translation process was structured by filling in the blanks of the following:

What? – Objective Infrastructure System: *The infrastructure system is…*
How? – Objective Objects: *The objects contribute to this by…*
– KPIs Objects: *This contribution can be measured by…*

As can be seen is the step of defining the objectives for the objects added to the process. This appeared to be necessary for making the translation process easier. Therefore, the workshop started with translating the general "what" objectives from the document "Heel & Schoon" to uniform "how" objectives for the objects before determining the KPIs for the objects.

Defining the KPIs was chosen to be seen as a separate additional step instead of something that was done simultaneously with defining the performance requirements. According to an advisor it would be too complex to do this simultaneously, since defining only SMART KPIs can already be challenging and time-consuming, which complies with what Eckerson (2009) who says that you must first define the KPIs and then the requirements. And last, defining KPIs for the subsystems were left out during this workshop, because this intermediate step made it too complicated and time-consuming for now. Moreover, the subsystems can be useful when defining the performance requirements, but this was something for later.

7.2.1 | Results

The workshop started by splitting the group of nine people into a group of four and a group of five people. Each group must consist of people from different backgrounds to create more balanced answers. They had to give the answer to the following questions:

Which objectives for the objects contribute to…
… the availability of the infrastructure system?
…the safety of the infrastructure system?
…a sustainable infrastructure system?
…an attractive infrastructure system?

After the objectives per performance criteria were defined, the following step was to determine the relating key performance indicators that can and must be measured to control into what extent the objects comply to the previously defined objectives. The program of this workshop can be found in appendix I. And the final results of the workshop are visualized in the figure 27.

7.2.2 | Observations and Analysis

Overall, the purpose of defining uniform objectives for all objects was achieved. However, a clear disadvantage of defining the objectives uniformly, was that the objectives were vague and wide-ranging. Also, it is clearly easier and quicker said than done. The objectives for the performance criteria safety, attractiveness and sustainability were already defined in the policy document. However, an objective for availability was difficult to define for all objects uniformly. This is because some objects can become unavailable such as bridges, tunnels and roads. Whereas other objects cannot be unavailable themselves since such objects aren't accessible. Think of bridges that are accessible and can therefore become unavailable, however quay walls and public lightning are not accessible. These inaccessible objects only perform in a way that it has an impact on the availability of the area and the connected objects. Note that this impact does not refer to impact during failure, but the impact in terms of its performance. The objective defined in the workshop only refers to the objects that are available. Therefore, a more uniform objective could be that the objects must cause a minimum of planned and unplanned restrictions of the use of the infrastructure system.

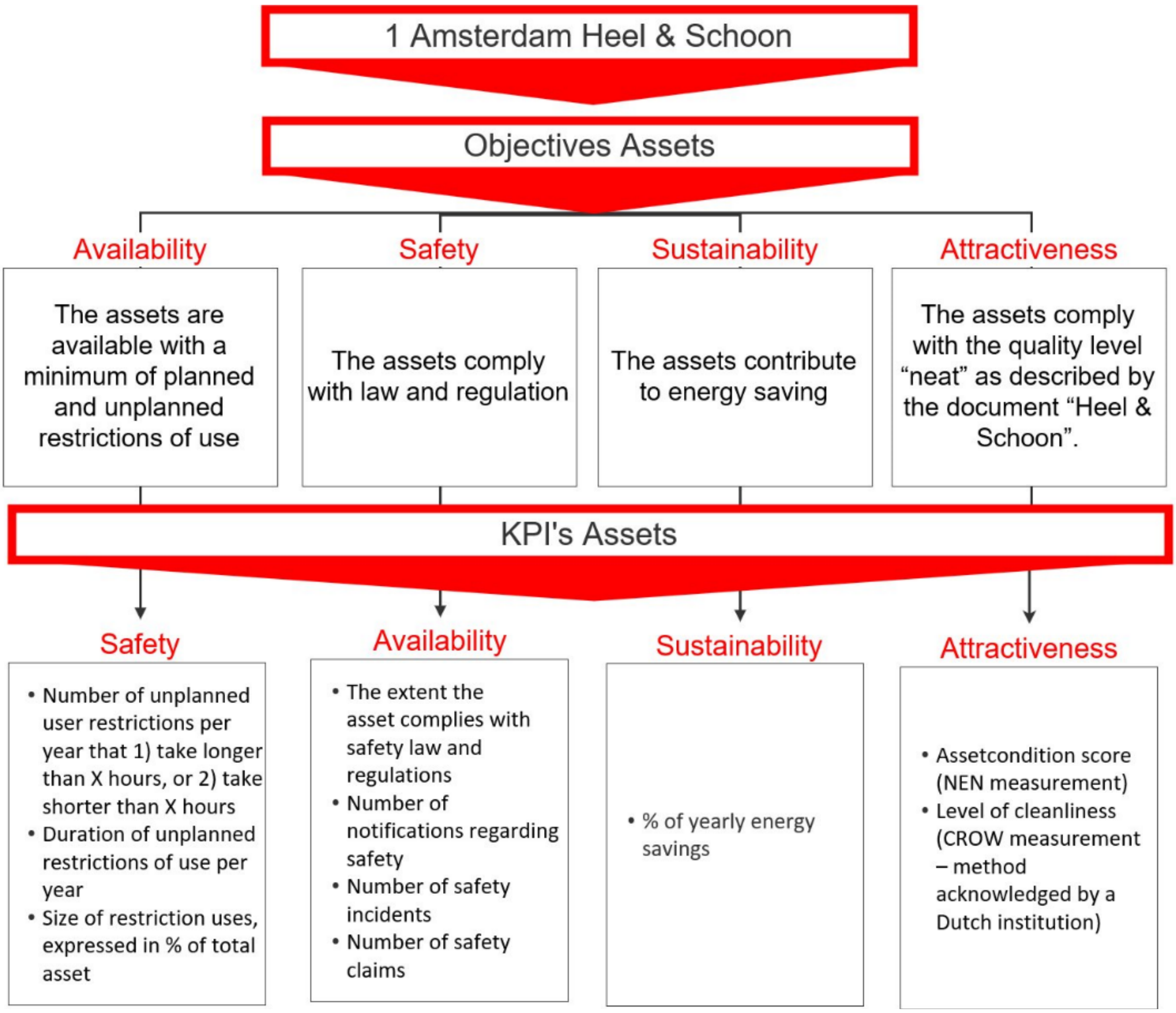


Figure 27 | Results objectives and KPIs

There was some confusion on the different types of objectives and KPIs. Due to the purpose of the workshop and the scope of the research, we had to focus on the KPIs determining the performance of an object only, however, people wanted to define other types of objectives and KPIs as well. This can be seen in the final safety objective that consists of two parts. The first part says that the objects must comply with law and regulations. Because if an object does not comply with this objective we need a maintenance measure to improve the object's performance. Anticipating on future safety risks is the second part of the defined safety objective, but this is not an objective that leads to measuring the performance of an object. If this objective is not achieved, we do not need a maintenance measure, but we need to improve our risk management approach. One objective determines the KPIs for measuring the performance of an object, the other objective determines the KPIs for measuring the asset management process. In other words, the objective consists of two types of objectives to measure two types of KPIs. These are two separate "lines of sight".

It was already expected that the different types of objectives and KPIs could lead to confusion as this was already the case during the preparation of the workshop. Therefore, a diagram was made as presented in appendix J explaining the different "line of sights" leading to different objectives and KPIs. This diagram only shows the type of objectives and KPIs (object performance, projects and asset management process) that are related to what the asset managers were concerned with during the workshop.

Ganesan & Paturi (2009) mention in their research that there are different types of KPIs because KPIs can be positioned differently in the management levels. Accordingly, the object KPIs will be measured in the operational level, whereas the asset management process KPIs will be measured in the tactical level. In other words, asset managers tended to think of other segments of the balanced score card as they looked from an internal business perspective as well. Especially the policy department considered other segments of the balanced score card to define objectives because they work in other departments of the municipality as well. So, they have a wider perspective. Since the people from the policy department have the least knowledge on asset management made the different types of objectives and KPIs for them the most confusing. Something that helped to diminish all this confusion was providing the diagram, but also emphasizing the purpose of finding the KPIs with this workshop. And this purpose was to be able to measure the performance of objects in order to determine if additional maintenance measures are necessary.

7.2.3 | Conclusion

So, this workshop led to an extended activity for being able to define the KPIs uniformly for all object types. However, during the workshop it became clear that uniform objectives and KPIs also result in more ambiguous descriptions. The more an objective must be shared by different types of objects, the less specific the objective becomes.

Moreover, an additional requirement was that it is important to educate the participants on the different types of KPIs to avoid misunderstanding. A KPI for a performing object is different than a KPI for the entire process of implementing asset management. This will lead to different risks. This distinction was very difficult for many participants to understand. As a solution, the participants of the workshop constantly had to be reminded of the purpose of defining these objectives and KPIs, referring to the performance of an object.

7.3 | Workshop 2 - *Defining KPIs and performance requirements, and designing a risk matrix*

The second workshop was organized by an external advisor in asset management for the tactical level of the civil construction asset department. My responsibility was to educate everyone on the process of identifying the critical objects, which all starts with defining performance requirements and designing a risk matrix. Therefore, the purpose of this workshop was to develop performance requirements and a risk matrix that weren't necessarily uniform for all objects, but more specific for civil construction assets.

The reason that this workshop was organized separately from the other objects and also time wise before workshop 1, was because the civil construction department is ahead of the other departments when it comes to implementing asset management. An advantage of this is that others can learn from them, however, a disadvantage is that all outputs such as performance requirements cannot be easily kept uniform. Though, this workshop was useful for my research to observe.

7.3.1 | Results

For defining the performance requirements, the performance criteria availability, safety and attractiveness were used. The following performance requirements were the outcome:

Availability:

KPI	*Norm*
The number of short-term (<4 hours) functional failure per civil construction object per year	< 2
The number of long-term (>4 hours) functional failure per civil construction object per year	< 0.2

Safety:

KPI	*Norm*
Comply with law and regulations	100%
The number of safety complaints (incidents and almost incidents)	< 20
The number of claims regarding constructive safety regulations (Arboveiligheid)	0

Attractiveness:

KPI	*Norm*
Object condition score (NEN)	> 4
Level of cleanliness (CROW)	> 4

Using these performance requirements, the risk matrix was developed, presented in appendix K. The chosen impact criteria and impact indicators were the following:

Impact criteria	Impact indicators
Availability	Duration of functional failure
Safety	Extent of safety incident
Attractiveness/ livability	Extent of media attention
Consequential Costs	Extent of costs for damage repair
Sustainability/ environment	Extent of damage of environment Extent of liability

7.3.2 | Observations and Analysis

Even though this workshop was challenging because the matter was new to everyone, it was also a success thanks to the organizer who clearly had experience with defining performance requirements and developing risk matrices. An observation during this workshop was there were many misunderstandings, which are possibly caused by the fact that most of the participants have no experience with risk matrices. One was that many participants didn't understand how to apply the risk matrix in practice. It was important to constantly remind them what the purpose was of applying the risk matrix. This is misleading, because there are multiple purposes for assessing risks of objects, such as identifying the critical objects or critical components. In this workshop the purpose was not completely clear. This led to the discussion of what purpose the tactical people from the civil engineering assets currently found more important. It took a long time to create an understanding between the different types of risks on the different decomposition levels with the different purposes. These differences are shown in the table 3.

Note that this table is similar to table 1, except that here the differences are given between what is being assessed with the risk matrix. This additional knowledge came out of the empirical research. Most participants from the workshop only understood the first column, which explains the type of risks that must be assessed to develop a risk-based maintenance plan. However, when they understood that if you want to control the current risks of the objects that are unacceptable, which is the scope of this research, you have to look at where the current risks of the objects are and therefore where the current additional maintenance measures are necessary. Then when you want to determine what maintenance measures are necessary to mitigate these current risks, you also have to look at what causes these current risks on component level. In other words, you can look at risks in general and you can look at the current risks that are object specific. Both types of risks are found for different purposes.

	Component Level		**Object level**
Purpose is to determine:	What maintenance measures are necessary…		Where maintenance measures are necessary
	… for making a risk-based maintenance plan for groups of objects	… for mitigating current risks of one object	
Types of risks:	Risks in general	Current risks	Current risks
To be assessed:	Failure modes of groups of objects	Failure modes of an individual object relating to the objects' functions/ components	Failure modes of an individual object
Probability of failure:	Mean time between failure	Expected time until failure	Expected time until failure
Impact:	Impact on object, and on organization if possible	Impact on object	Impact on system and organization

Table 3 | Difference between risks of components and objects

As soon as the participants gained this understanding, it led to the conclusion that they preferred to find the critical objects first, because they want to gain control over the current risks such as all the risks of the different deteriorating quay walls. But how then to assess the risks of all objects individually? These participants, for instance, are responsible for 1602 bridges. This struggle led to workshop 3A, where the purpose was to make the process of identifying the critical objects feasible in practice.

As there were many confusions during workshop 1 about the different types of KPIs, there were no confusions about this during this workshop. The reason for this can be that the civil construction department has more experience with defining KPIs and thinking of how to implement asset management. Moreover, some daily managers were present who represent the transition between tactical and operational. These people tend to have an operational perspective, so they wouldn’t have the knowledge to define KPIs for the tactical or strategic level.

The daily managers turned out to be very beneficial to invite during this workshop. They were helpful with determining which KPIs were measurable in practice. However, it could be noticed that they could only follow the discussions that involved their technical knowledge. For instance, when we assessed the risk of a bridge as example they could tell the necessary information about the failure modes and what could be expected if a certain bridge would fail. However, the right questions needed to be asked to collect the right information because they didn't understand how the risk matrix worked. Though, organizing a workshop per object type with the operational managers to check the feasibility of the resulting KPIs, performance requirements and impact indicators would be very useful.

Comparing these results to workshop 1, it can be concluded that the KPIs are nearly the same. The differences are mostly related to some definitions, such as that the KPIs from this workshop for availability only takes unplanned breakdowns into account. Also, they call it breakdown instead of user restrictions. The term "user restrictions" takes into account that some breakdowns do affect the car network, but it doesn't affect the water network. For instance, when a movable bridge fails to open for the passing ships, the bridge affects the users from the water network but it doesn't affect those from the car network. So, the term "user restrictions" is more specific.

Some impact criteria were given slightly different names compared to the performance criteria from "Heel & Schoon". However, it was interesting to include that both the performance indicators and impact indicators are related in order to extend the line of sight. This relation with the line of sight is illustrated in figure 28. The input is the performance objective determining the required performance, and the output is the resulting performance impact on the organizational goals and objectives. For instance, if the city is not attractive (performance criteria) it has an impact on the livability (impact criteria) of the city. And if the city is not sustainable (performance criteria), this has an impact on the environment (impact criteria). In conclusion, the performance criteria can be translated into impact criteria and the KPIs can be translated into impact indicators.

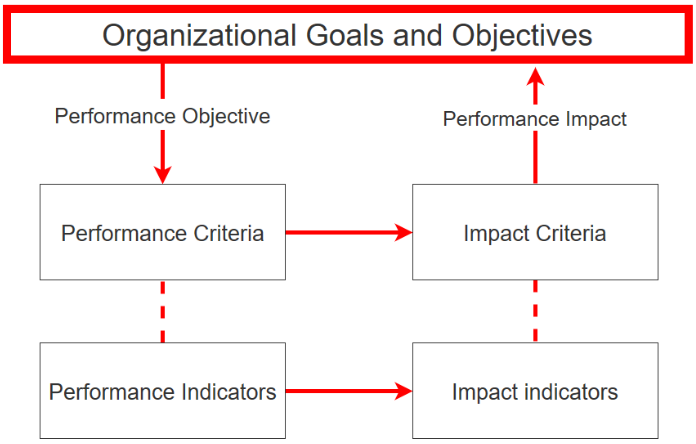


Figure 28 | Relation between performance and impact (own illustration)

7.3.3 | Conclusion

This workshop led to some interesting insights and additional requirements. First, this workshop made clear that it is very important to educate the participants on different types of purposes for applying a risk matrix as shown in table 3. So, during the development of a risk matrix, the purpose of the risk matrix must be clear to everyone. Otherwise you will obtain incorrect results. Second, including participants from the operational level in this workshop was highly useful for checking the feasibility of the performance and impact indicators. However, they had troubles following and adding value to the entire workshop, because a big part of the workshop was beyond their expertise. And third, an interesting conclusion was made on the relation between the performance and impacts of objects. It appears that if the relation between the performance criteria and indicators, and the impact criteria and indicators is defined as visualized in figure 27, a top-down and bottom-up approach can be established. However, in the end of the workshop everybody was struggling with the confusion of how the process of assessing the risks of all objects could be made feasible. Therefore, workshop 3 was introduced.

7.4 | Workshop 3

This workshop was entirely my responsibility. It was organized for the tactical level of the civil construction department, the same group as workshop 2. It consists of two parts, part 3A and 3B. The purpose of workshop 3A was to find out how the process can be made feasible in practice for the asset manager, considering the numerous objects. And the purpose of workshop 3B was to further define a new and so far an unknown activity: Aggregating RPNs in a way that the asset manager is able to justify the criticality of objects towards the asset owner. The program of this workshop, presented in a PowerPoint slideshow, can be found in appendix K.

7.4.1 | Workshop 3A – *Making the process feasible*

The reason for organizing this part of the workshop is that the demand for making the process of identifying the critical objects as feasible as possible was so big. Nobody thought that the initial IDEF0 model would work in practice if this one large problem wasn't solved.

Results

This workshop started with asking the question: How to feasibly assess the risks of all objects and all failure modes? Soon everybody agreed that it is impossible to assess the risks of all objects and let alone all objects' failure modes. There was a need for an activity of filtering first the objects that are potentially critical, leaving out the objects with no risks, in order to decrease the number of objects' risks that has to be assessed.

The brainstorm led to the development of a filter process, as visualized in figure 29. This filter filters the objects first by guesstimating objects that are potentially critical. As a result, some objects are left over. Then assessing the risks of all failure modes of these remaining objects is still not feasible. Therefore, the second filter filters out only the objects' significant failure modes. These are the failure modes that have the largest impact on the object not fulfilling its requirements only. Then the objects' significant failure modes enter the following step of the IDEF0 model, which is assessing the risks of these significant failure modes with the risk matrix. And this will then provide the criticality of the objects.

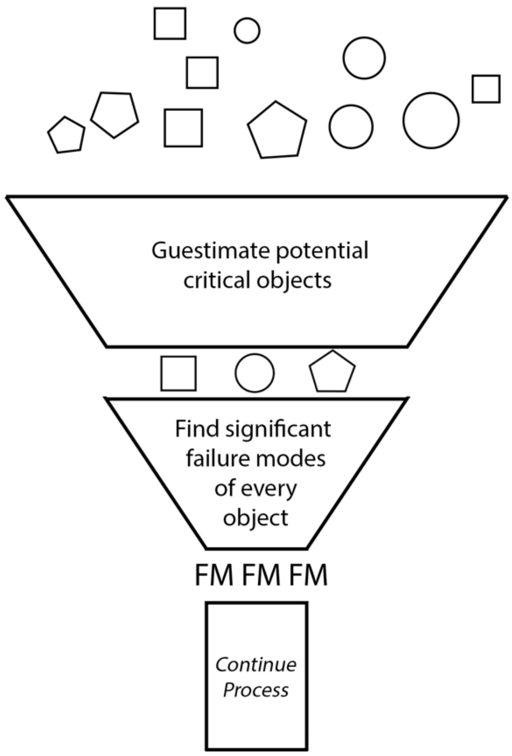


Figure 29 | Filtering Process (own illustration)

This concept forms the third activity of the new IDEF0 model. Therefore, the output of this filtering process forms the input of what has to be assessed with the risk matrix. This activity must be executed by the asset manager, but the asset manager will be reliable on the service provider.

However, it was still not clear how to execute these filter steps. How to guestimate potential critical objects? And how to identify the significant failure modes? To solve this, two brainstorm sessions were introduced.

First Filter: Guesstimating the Potential Critical Objects

The objective of this brainstorm was to first collect the following criteria that the first filter of "guesstimating potential critical objects" had to comply to:

- Consider objects that might need corrective and/or preventive measures;
- Only consider objects with high risks (impact and/or high probability of failure);
- Consider the different impacts that objects can have;

- The activity must be simple and not too long;
- The activity's outcome must be reliable.

As a result, different methods were determined to guestimate potential critical objects. The first method was by looking at the objects that are currently performing the lowest. This means that the objects that are showing the most malfunctions, attract the most complaints, or are the least neat will come out the first filter. The second method was by looking at the objects that would have the highest impact during failure. Then the objects with the highest impact on the availability of the system or the ones that attract the most complaints during failure will come out the filter. The third method was to look at the objects with the currently highest probability of failure, or in other words the shortest expected time until failure. Then objects with the most signs of deterioration and therefore the lowest conditions will then come out the filter. And the last method was to fully rely on the service providers and their craftsmanship, since they know the objects individually well. By assessing these methods with the predefined criteria, the following table came out:

	Corrective	Preventive	Risks	Impact	Probability of Failure	Easy and Quick	Reliable
Lowest Performance	X	X		X			X
Highest impacts	X	X	X	X			X
Lowest Condition	X	X	X		X		X
Craftsmanship	X	X	X	X	X	X	

Table 4 | Method comparison

As a result, all methods can find objects correctively and preventively, because all methods can show failing objects and all methods can give an indication that an object is nearly failing. However, all these methods do not automatically consider the extensive way of forecasting low probability of failures. Then the first method falls off because it does not consider risks. And the craftsmanship falls of, because in the participants' opinion the criteria that it has to be reliable was more important than that it would be easy and quick. Then the two last methods were filtering the objects with the highest impacts or the lowest condition (so the highest probability of failure).

During the discussion the participants of the workshop formed their preference for the method of filtering the objects based on the highest impact in the first filter, because they find objects with high impacts more important. These are the objects that cause the biggest problems during failure. For example, that one bridge that is hardly ever used somewhere in a park will not lead to many problems during failure. Such bridges with low impact should therefore not pass the first filter, even though when it has a high probability of failure. However, those bridges that are positioned in the busiest car network of Amsterdam should pass this first filter. These objects are the ones causing the big problems during failure. Whereas when you are looking only at the probability of failure during the first filter step, it is possible that such objects with high impacts do not make it through this first filter.

Second Filter: Identifying the Significant Failure Modes
From the workshop two main methods were established for finding the significant failure modes. The simple method was asking the service provider what failure modes of the concerning object have the largest impacts. The second method, which can take longer but can be more reliable than only asking the

service providers, was analyzing the failures of the object. This can be, for instance, by looking at the failure modes that cause the object not fulfilling its functional, availability and safety requirements. This method corresponds to how Cotaina et al. (2000) and Kobbacy (2008) explain it in their papers. Only Cotaina et al. (2000) would look at the functional failure modes. Assuming that this method only looks at the functions and not at the performances of an object, the performance failure modes will be over looked. A bridge can also fail when the entire bridge is covered in trash and graffiti, which can also lead to many complaints. This is a failure mode that is not taken into account when the asset manager only looks at functional failures. In conclusion, to find the most significant failure modes of an object the simplest way is to ask the service providers. Then a longer process would be to determine the failure modes having the largest impact. These failure modes can be a mode in which the object does not fulfill its functional or also its performance requirements.

Observations and Analysis

One additional feasibility issue that was expected to be challenging in this filtering process was guesstimating the potential critical objects with incomplete data which currently is the case at the municipality of Amsterdam. However, they cannot wait until they have sufficient data because they need to make large decisions soon. It was concluded that the asset managers must look at the current available information. For instance, the municipality of Amsterdam is now busy measuring the current conditions of all objects. The current condition can be used for determining an indication of the current probability of failure. Also, it appears that other departments of the municipality of Amsterdam have a lot of useful information available such as the number of users of the various networks of the city, like the car network. Knowing the number of users of each part of the network provides an indication on the impact of a failing object in each part of the network. So, first they need to look at the data they currently have to make the first indication of the current critical objects. Then later they can decide what additional data is necessary to improve the outcome of the risk assessment. Then plans can be made on how this data can be collected and how the service providers play a role in this. Better data can then lead to a better outcome of this process.

Another idea for making the process of risk assessment more feasible is to only take the most important impact criteria into account, which are the availability and safety at the municipality of Amsterdam. Then only the current impact on these criteria will have to be considered during risk assessment, leaving out the rest. This will save a lot of time. For instance, then you only have to assess the risks of the objects in the busiest car network that currently score the lowest on the safety laws and regulation.

Conclusion

In conclusion, to make the process of identifying the critical objects feasible, the asset manager must filter out the potential critical objects first. These potential critical objects come from predicting which objects have the highest impact on all impact criteria during failure. However, if this filtering phase takes too much time, only the most important impact criteria can be taken into account.

The second filter that will make the process more feasible, is filtering out the significant failure modes of the objects. The significant failure modes would have the highest impact on the organizational goals and objectives. These can be found by either asking the service providers or by conducting a failure analysis based on the functional and performance requirements. Then the following step of the IDEF0 model continues, which is assessing the risks of these significant failures determining the actual criticality of the object.

And if the asset manager is afraid that there is not enough data available, the asset manager must look at the current available data. Then in a later stage, the relevant data that is missing can be created to improve the outcome of the process.

8.4.2 | Workshop 3B - *Aggregating RPNs*
The last step of the IDEF0 model is how to aggregate the risk priority number in a way that the asset manager can justify towards the asset owner the risks and therefore the necessary investment of that object. No information could be found in literature on this process step, which is verified in appendix H. Therefore, it was decided to also conduct an ex-ante analysis on this aggregation process in order to find out if additional requirements would come out.

Requirements
In the end only one requirement for aggregating the RPNs to the right level was found. It turned out that it is important to consider that expressing the total risk priority number is not enough. They also require the risks per impact criteria to be presented. For instance, by only multiplying the probability of failure with the impact on availability provides a clear relation between the objects and the availability of the city. Such impact specific risk is called the impact RPN. An impact RPN can also give new insights. Such as that the municipality of Amsterdam might want to improve the availability of the city. Subsequently, the asset manager can then determine which objects are currently critical only in terms of availability. As a result, the output of the risk matrix must be expressed in the total RPN and the RPN per impact criteria.

Observations and Conclusion
It was obvious that the participants had difficulties with understanding this last step of aggregating RPNs to the system level. By defining the purpose of this step in the terms they were familiar, improved their understanding of the process step. However, it still took a lot of time to develop enough understanding. So, finally there was not a lot of time left to discuss the expected challenges and requirements for this process step. Also due to their lack of understanding it was impossible to collect a valuable outcome of this ex-ante analysis. Therefore, only one requirement was found. This is the requirement of expressing risks not only in total RPNs, but also in impact RPNs.

Since this activity is so new to everyone, it would have been better to invite asset managers that have more experience with asset management. Or this workshop must be repeated before executing this activity in practice. Yet, this activity is not necessary an obligation to make the IDEF0 model work out. It is more of an activity to improve the quality of the outcome of the IDEF0 model.

7.5 | Scalable Requirements in practice
Lastly, according to the test of the IDEF0 model in practice a clear preference has been set for the scalable requirements, which leads to the final requirements and therefore the controls for the IDEF0 model to work out in practice at the municipality of Amsterdam. The derived requirements per scalable requirement are as follows:

7.5.1 | Simplicity versus taking everything into account
According to the asset managers from Amsterdam it is important to start the process as simple as possible by choosing a small number of KPIs. Then using their experience with this first set of KPIs, they can decide to repeat the process to improve the current KPIs or add some KPIs. This way of thinking of starting simple, evaluating and then improving it complies to the plan, do, check and act cycle as described by the standards of ISO 55000. This cycle can be applied to the entire process, such as developing the risk matrix, filtering the potential critical objects and the risk assessments.

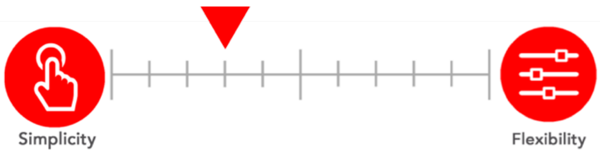
7.5.2 | Simplicity versus flexibility

As explained before, the requirement for the process being simple appeared to be the most important. However, it appears to be important also to be conscious of how to make the process flexible. From the workshops it can be concluded that there were two ways in which the process was required to be flexible. First, there was a clear consensus on the fact that the weighting factors for the impact criteria should be flexible. This would lead to a constant accurate representation of the organizational goals and objectives. Even though they expected that this is challenging and not simple, they do want to try this in the future.

And the second way of making the process flexible had to do with when the process must be applied in practice. The conclusion of that discussion was that there are two reasons for repeating the process in practice. First, you will do this in order to improve the process and the process outcome. For instance, the first time the KPIs are defined it can turn out that these KPIs do not give a complete representation of the performance of the objects. This means that the process was not entirely accurate and therefore the process must be repeated to improve the process and to define new KPIs.

And the second reason for repeating the process has to do with the need to repeat risk assessments. The risk assessment must be repeated when new unacceptable risks occur. This is dependent on changing probabilities and impacts of failure of objects. Probabilities of failure can increase due to an increase in load or aging. Therefore, it must be monitored when a probability of failure is entering the danger zone. And an impact of failure can increase when the area around an object changes. Think of a small car network that was hardly ever used before. However, with the introduction of a new residential area adjacent to this car network, the number of users of this car network will increase. As a result, the impact during the failure of objects on this car network increases as well leading to higher risks.

However, the risk assessment must also be repeated if the strategic level introduces changes in organizational goals and objectives. For instance, they could think that sustainability has become more important. Subsequently, the weighting factor for the impact on the environment has to increase to update the new representation of the organizational goals and objectives. So, the process must be flexible in the sense that it must be repeated to improve the process and the process outcome, and to keep the risks up-to-date.



7.5.3 | Uniformity versus diversity

This was an interesting scalable requirement, because this depended highly on the situation. According to them, the things that must be as uniform as possible are the KPIs, the performance requirements and the risk matrix. The reason for this is that if you apply the same method and tools for assessing the risks, it makes it more reliable to compare and aggregate the risks of the varying objects. This is the same as being able to compare apples to oranges by comparing similar features such as the calories of both fruits. However, this is under the condition that the methods for obtaining the number of calories is similar.

Diversity is important because there was still the requirement that the different types of impacts of all objects must be taken into account. However, the outcome of workshop 3A proves that this is still be possible in a uniform process. Also, if you apply the risk matrix per individual object, you still take the different impacts into account. Though, this process still leaves the risk of not seeing objects as something individually anymore. For instance, it is a risk to use similar performance requirements for all objects, if other objects could be in high need of exceptional requirements. Therefore, the asset managers and service providers must keep looking as an expert, and not blindly follow this process. The process is more a direction, but it does not define an exact path with clear boundaries.

7.5.4 | Non-technical versus technical

For the constant translation between the strategic and the operational level there were multiple requirements that came from the people attending the workshops. First, for defining the performance requirements it is of high essence to include people from the policy department who can help translating the organizational goals and objectives. This avoids the risk of misinterpreting the organizational objectives, which was the case during the workshop.

Second, when developing the risk matrix, it is important to ask the operational level for advice on whether it is realistic to determine certain impact indicators. The information must be available and reliable.

Third, for determining certain impacts and probabilities of failure of objects, it is convenient to take the advice from the service providers seriously. However, you cannot depend on this advice fully in case of large decisions.

And last, you need an additional role that is responsible for comparing the RPNs of the various types of objects. This is a person that has an overview of all objects together in the entire infrastructure system. However, when this person makes decisions on the necessary investments after comparing all objects of the entire system, this person must check these decisions with the asset managers.

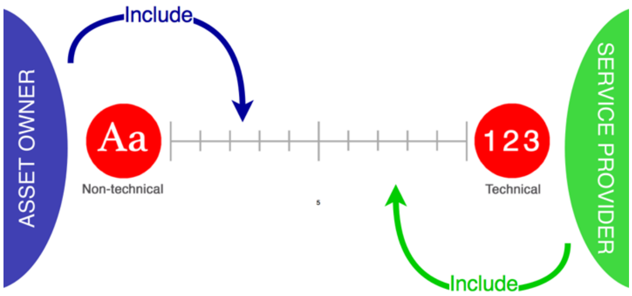


Figure 30 | Inclusion of strategic and operational level in translation process (own illustration)

7.6 | Conclusion

This chapter gives a clear indication on how the theoretical IDEF0 model would work in practice. The biggest conclusion is that if you want the IDEF0 model to work in practice with the large number of objects, you must filter the objects and failure modes first. As a result, you do not have to assess irrelevant risks of failure modes or objects that are far from being a risk.

The other findings from the workshops has led to additional requirements and preferences for the scalable requirements for applying the process of identifying the critical objects at the municipality of Amsterdam. An example of an additional requirement is that the asset managers must include more areas of expertise. The asset managers should include the strategic level in the interphase with the strategic level, such as when the performance requirements are defined, and the asset managers should include the operational level in the interphase with the operational level, so when the impact indicators are defined or when the failure modes are determined.

Also, in these workshops it appeared to be very important to make clear what the exact purpose and context of every workshop is, because you can define performance requirements for different reasons and you can develop risk matrices for different reasons. Moreover, the participants from the workshop found it the most important to have a simple process, and then a uniform process. Though, the disadvantages of a simple and uniform process are that it can easily overlook the importance of the differences between objects and the objectives and indicators become ambiguous. On the other hand, a simple process means that it will be executed, and uniform means that the different types of objects can be compared, meaning that the asset manager will obtain a reliable overview of the current risks.

8 | IMPROVED AND FINAL IDEF0 MODEL

The theoretical IDEF0 model has been tested in practice through various workshops. The outcome of these workshops has led to the conclusion that additional activities and requirements are necessary to make the theoretical IDEF0 model work in practice. As a result, an improved and final IDEF0 model was developed. This model is presented in section 8.1 together with the also improved simplified process model. In section 8.2 the main changes are enumerated, followed by the relation with the three management levels in section 8.3.

8.1 | Final Process models

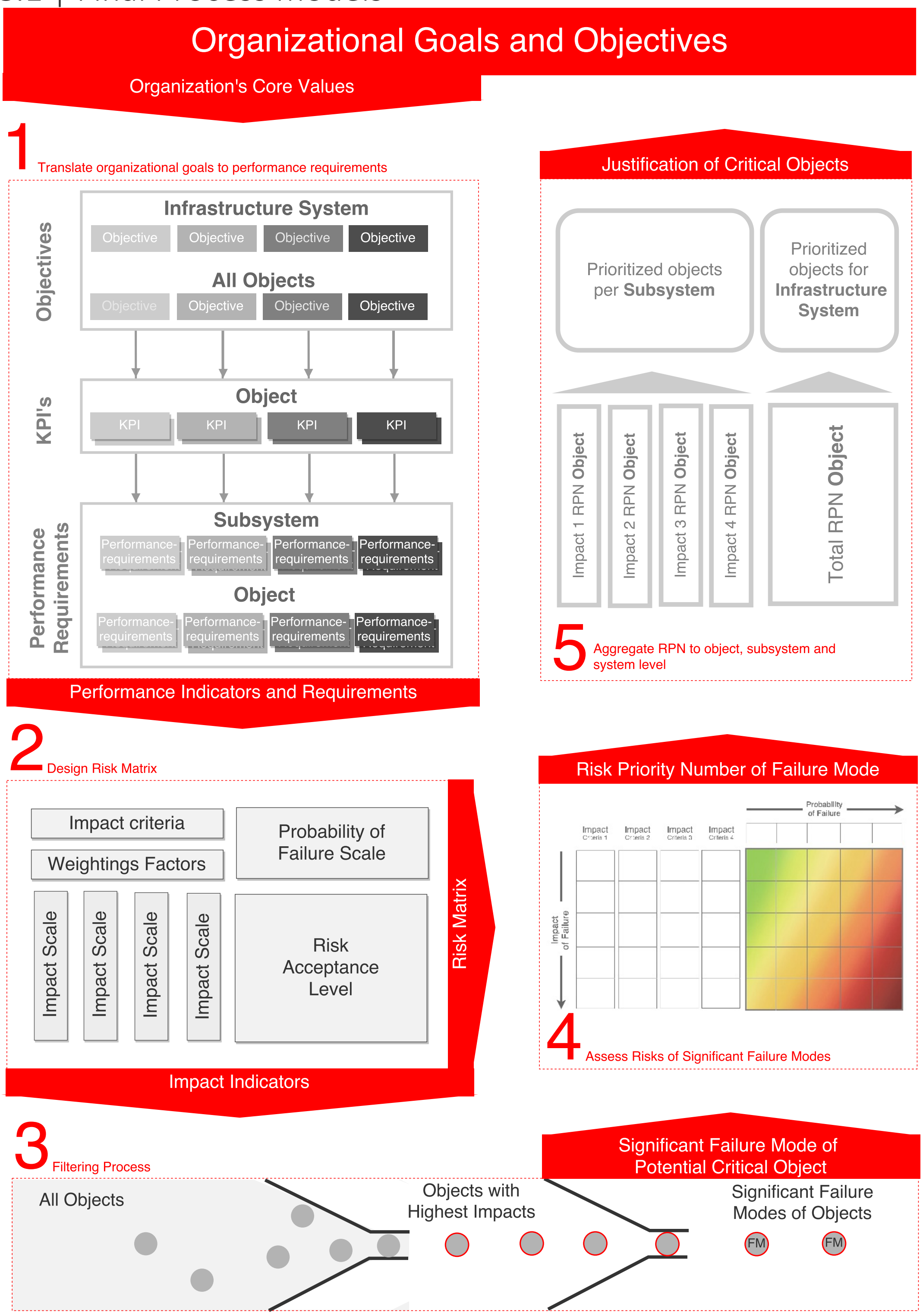


Figure 31 | Final simplified process model (own illustration)

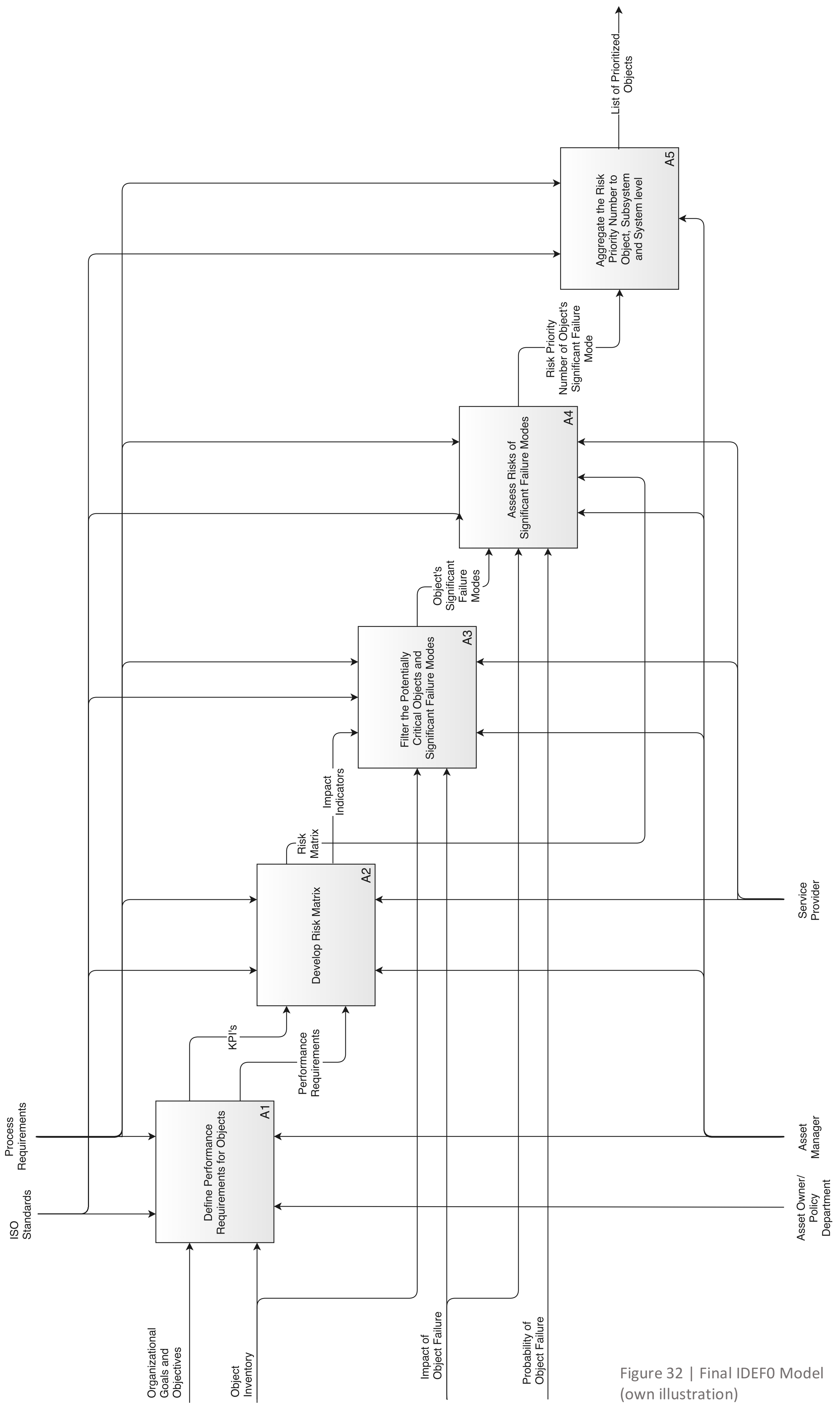


Figure 32 | Final IDEF0 Model (own illustration)

8.2 | Main changes

Besides the changes in requirements that were presented in the previous chapter, the workshop also led to changes in the activities. When comparing the final IDEF0 model with the theoretical IDEF0 model, it can be seen that activities are split up, added, or even removed from the diagram. And as the simplified model shows, some activities are extended and contain sub activities.

There are three large changes in the activities of the IDEF0 model. First, the activity of analyzing all failure modes and all causes has been removed, because this step was not feasible due to the numerous objects and failure modes. As a result, an activity was added to the diagram to make the risk assessment more feasible. This is activity A3, which represents the filtering process where the potential critical objects and its significant failure modes are filtered. And third, the activity of designing the risk matrix is seen as a separate step, because this is an activity that must be done separately from the risk assessment since this activity can take a long time.

Two process steps were extended as visualized in the simplified process model, which are the first and the last one. The purpose of the first activity is to define the performance requirements. First this was supposedly done by defining the objectives for the entire system, and then the performance requirements for the subsystems and the objects. Two additional activities were added to this. First, defining the objectives for all objects. And second, defining the KPIs must be seen as a separate step before defining the performance requirements. Both steps made the translation steps shorter and therefore the entire translation from the organizational goals and objectives into performance requirements simpler.

The last activity of aggregating the RPNs from the object to the level of the subsystem and system level, is extended in the sense that the RPNs must be expressed in the total RPN of an object and the RPN per impact criteria of an object. As a result, the asset manager can obtain a list of prioritized objects per impact criteria or per subsystem, and a list of prioritized objects for the entire infrastructure system.

8.3 | The Three Management Levels

The two figures on the following page show the relation between the IDEF0 model and the three management levels. For this it has been chosen to use the simplified process model as means of communication, because this model can show the concept behind the top-down and bottom-up approach in relation with the three management levels clearer. The figure on the left shows how the strategic (blue) and the operational level (green) are involved in the process. Overall, the process is executed by the asset manager. But the strategic level plays an important role in the first activity of the process, where the organizational goals and objectives are translated into the performance requirements of the objects, and in the last activity, where the risks must be justified according to the organizational goals and objectives to the asset owner. The strategic level knows the organizational goals and objectives the best, so such people should support the translation process and the justification of risks. For instance, like in the first workshop where the KPIs of the objects were defined based on the policy document representing the objectives of the municipality of Amsterdam, people from the policy department who wrote that document were also participating.

Then in the second, third and fourth activity the operational level plays an important role. In the second activity when the risk matrix is defined, the feasibility of the impact indicators must be checked with the service providers. When filtering the potential critical objects and its significant failure modes, it could be useful to ask the service providers what they think are critical objects and significant failure modes. And when applying the risk matrix, again the service providers can be asked what they think are the probability of failure or impacts of an object failure. As explained before, their advice is perceived as being useful, but they are also seen as not being fully reliable. So, the service providers are rather used as advisors, than determiners.

The figure on the right shows how the top-down and bottom-up approach is incorporated into the diagram. Basically, the organizational goals and objectives are translated downwards to the object level. This is used to find the current risks. And as a result, the risks are translated up, back to the strategic level.

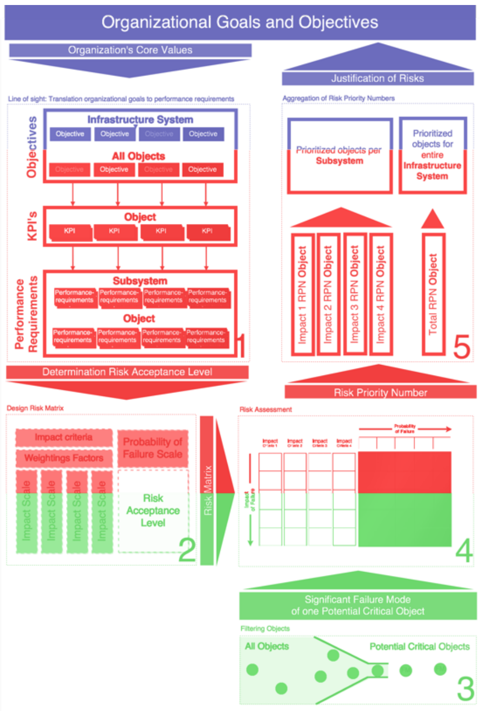


Figure 33 | Relation with the three management levels

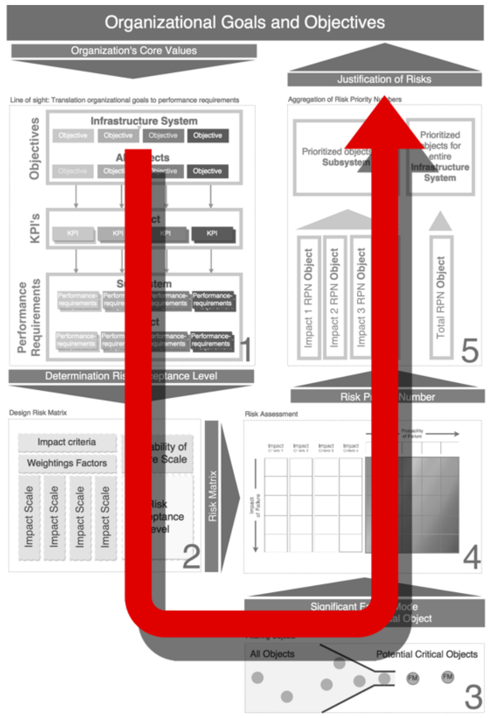


Figure 34 | Top-down and bottom-up approach

8.4 | Conclusions

This chapter provides the final IDEF0 model the final simplified process model and the changes compared to the theoretical IDEF0 model in chapter 3. It explains how the three management levels are related to the final IDEF0 model and how this and the top-down and bottom-up approach is clearly visualized in the simplified process model. As a result, the simplified process model functions as a means of communication, and the final IDEF0 model functions as a supporting tool for the asset manager when identifying the critical objects in practice. It is an IDEF0 model that “visualizes the necessary beginning and ending of the process, sequenced activities with the in- and outputs, and the relations between the activities”, as it was meant to be according to the objective of this research.

9 | VALIDATION

The final IDEF0 model, and in specific the activities and the controls that are necessary for identifying the critical objects, have been validated at two public parties. One party was the municipality of Rotterdam, which is another municipality that owns the same type and the large number of objects. Just like the municipality of Amsterdam, they are also busy implementing asset management. As a result, it can be expected that Rotterdam is also looking for ways to prioritize their objects to mitigate current risks. This validation was done with the asset manager of the civil engineering assets.

The other public party was ProRail, which is a government task organization that manages and maintains all the objects building up the Dutch national railway network. These objects are also infrastructure objects. It is known that they have implemented asset management a long time ago. Therefore, it could be expected that they already have a method of identifying the critical objects in order to prioritize them. For this validation the conversation took place with an advisor in asset management who had twenty years of experience.

The validation introduces the two parties by first comparing them with the municipality of Amsterdam in terms of types of infrastructure objects they own and their maturity level. Then it presents the discussions of the IDEF0 model with the two parties. With the asset managers the need behind identifying critical objects and its difference compared to identifying critical components was discussed. Then it was discussed what the activities are to identify the critical objects and what the necessary controls are to make it comply with the standards of ISO 55000 and to make it work in practice. As a result, they were asked whether they thought the IDEF0 model was correct and applicable in their organization as well. Therefore, it was tested whether the IDEF0 model was general enough. This was done by asking whether they agreed that the process and the found requirements of the three management levels were correct. And here correct refers to the extent the results were general enough and therefore also applicable on their objects. Also, would it be feasible in their opinion? And how would they experience this process in practice?

Next, it was asked how they currently identify their critical objects and why they do it like that. This was analyzed by comparing their method to the final IDEF0 model of this research and using the requirements from this research. Think of a requirement such as that the object's individual probability of failure and impact must be assessed to obtain a realistic current risk, and that the process must be simple and not too long if you want it to work in practice. The results of the two validations are explained below.

9.1 | Municipality of Rotterdam

The municipality of Rotterdam is the second largest city of the Netherlands, and also the second largest municipality. Therefore, they also own a large number of differing infrastructure objects. Yet, a difference compared to Amsterdam is that the infrastructure objects of Rotterdam aren't as old. This is because during the bombing after World War II, Rotterdam had to rebuild most of its infrastructure objects. Another difference is that the maturity level of the municipality of Rotterdam is higher than that of the municipality of Amsterdam. This is because currently they have conducted the first two activities and partly the third activity of the final IDEF0 model (Zeb et al., 2013). So, they have defined performance requirements, developed a risk matrix and have partly applied the risk matrix. However, they are currently more focused on assessing risks of objects in order to develop risk-based maintenance plans. This is because they do not currently have such a problem as Amsterdam in facing a large number of deteriorating objects, since the objects of Rotterdam are a lot newer. Therefore, they are more focused on preventing risks by identifying critical components, based on critical failure modes, to determine risk preventive maintenance measures. Moreover, they do not apply the ISO 55000 standards, because they think this is for now making the process too complicated. They believe that making all asset management related activities comply with these standards takes a lot of time to understand and to implement. They prefer a simple process using logic sense over being an ISO 55000 certified organization.

IDEF0 model

Overall, the asset manager found the final IDEF0 model and the requirements from this research as far as he knows correct. His largest concern, however, is that the last process step where the RPN is aggregated to the level of the infrastructure system could take too much time. According to them, this activity asks for a new expertise and could be a complex puzzle that must be solved before it will work in practice. Even though he thinks this is a valuable activity, such an activity should be applied in a later stage. A stage in which the rest of the process runs smoothly enough and is therefore under control. Based on what they currently do, it was also concluded that the way in which they want to find the currently critical objects is different compared to the IDEF0 model. Their way is simpler and quicker, however, using their way can cause the asset manager to overlook large risks.

Their method

First, they did the first activity exactly the same, which is defining the performance requirements for the objects. For developing the risk matrix, they also did it similarly by translating the strategic goals into the matrix by deriving the impact indicators from the performance indicators. However, the municipality of Rotterdam does most of the rest of the process in a different way, because they are more focused on identifying critical components than critical objects.

Second, they determine the general failure modes of groups of objects. They group the objects because this saves time compared to determining all failure modes of each object individually. These groups of objects are based on types of functions, which is for instance “an underpass” referring to a tunnel. And they choose to group the objects based on functions, because according to the asset manager of Rotterdam this makes it easier to identify the failure modes. This corresponds to what Cotaina (2007) does, as they analyze the ways in which these functions fail, leading to all possible failure modes. Then they analyze these failure modes to determine the most significant ones with a fault tree analysis. Then they assess the risks of the failure modes, using a risk matrix considering the impacts and the general probabilities of failure. So far, they have found the critical failure modes which can be used for developing the maintenance plan.

And last, they use these critical failure modes to identify the critical objects. They look at the same types of objects in the city and see where these significant failure modes are occurring the most. Then they have found the potentially critical objects. Then on these objects the risk matrix is applied again to determine the current level of risk. They do not aggregate the RPNs to the system level.

Analysis and Observations

Comparing this process to the final IDEF0 model it can be concluded that the big difference is that Rotterdam clusters the objects, determines from these clusters the general failure modes that are the most significant, and then looks at which object these significant failure modes occur the most. The IDEF0 model of this research explains that when you group objects and determine the general failure modes and risks, you can overlook the currently individual risks of an object. As many experts and asset managers say, it is a risk itself to generalize objects and to not look at objects separately during risk assessment.

Moreover, they do not define the performance requirements uniform for all objects. But they have different performance requirements per group of objects. They do this because they think this is important when they manage their objects fully based on performances. They find it more important to take everything into account, such as the different types of performances of objects, rather than a uniform process.

Because they have different performance requirements, they also have different impact indicators per cluster of object. Therefore, you could say that they cannot reliably compare the outcome of the risk matrixes between all groups of objects. However, they do express all the impacts in monetary units. And according to the asset manager of Rotterdam this is enough to be able to compare oranges with apples.

An observation was that the asset manager was in the beginning confused with the type of risks this research is focused on. In Rotterdam they are mainly busy with general risks to develop maintenance plans for groups of objects. And this process is then used to also determine critical objects. But they are not really focusing on finding the current critical objects systematically. Let alone that this is defined as a formal process. So, during the discussion a big part concerned distinguishing the differences between current and general risks as seen in table 3 in section 7.3.2.

9.2 | ProRail

ProRail owns also a large number of infrastructure objects. However, there are a few differences compared to the infrastructure objects of Amsterdam. Most of the objects of ProRail aren't like civil engineering objects difficult and expensive to replace. The objects of ProRail mostly consist of rail corridor, overhead wiring and level crossings, which are objects of which they have numerous data on the probability of failure. Therefore, they can predict when to replace their objects before these deteriorate. Yet, they also have some civil engineering objects, like bridges and tunnels, of which they do not have data on the probability of failure. But they do not yet face the problem that they have to prioritize these objects because these do not show a disturbing number of deterioration signs. Moreover, the asset manager of ProRail has the feeling that they so far receive enough budget to invest in the treatment of all the current risks, also those of the civil engineering ones, since the risks of their objects are so high; if there is any infrastructure system that nationally receives the most complaints, it is the national railroad of the Netherlands that is maintained by ProRail.

Moreover, ProRail has a high maturity level. Higher than that of the municipality of Rotterdam, since they have extensive risk-based maintenance plans, a current overview of the most important causes of the highest risks and performance requirements for non-technical criteria such as safety (Zeb et al., 2013). So looking at the IDEF0 model of this research, they have developed formal processes for all activities. However, just like Rotterdam, they do not feel the need to identify the critical objects. Therefore, ProRail focuses more on preventing risks by developing maintenance plans.

Furthermore, they do not implement ISO 55000, because also they prefer using their own expertise and common sense to develop methods for asset management. Therefore, they do not have clear systematic processes to develop a clear line-of-sight when defining the performance requirements or developing the risk matrices.

IDEF0 model

The asset manager from ProRail concluded that the final IDEF0 model of this research can be seen as correct. The question he raised is just to what extent such a process would work in practice even when the given requirements are taken into account. In his experience everybody dislikes risk management.

He agrees with the fact that a systematic approach for a process that reaches the strategic level would deliver better results such as risks that are actually important to the organization, but he is not sure into what extent it will work out if the process is too big and takes too much time. Therefore, he has some doubts about how sincere the entire process is executed and repeated when necessary.

Their method
When ProRail notices that objects currently have high risks, they either have enough money and invest in these risks right away, or for the big investments in the civil engineering object they look at the objects that are currently entering the wear-out phase, based on technical criteria, measured conditions and expected probabilities of failure. Since they do not own a large number of deteriorating civil engineer objects, only a few critical objects remain.

Then they organize meetings to discuss which objects are the most critical. During these meetings there is no systematic method in which they decide which object is the most critical. The asset managers that are capable of convincing the need of investing in their object the best, receive the additional budget. However, most of the times it is simple to compare the objects and determine the most critical one, because it is relatively obvious which one is the most critical. At the same time there is still enough money to invest in the most obvious critical objects, so this way of using discussions does not give any problems.

However, he expects a time will come that more objects become critical due to the increasing rate of deteriorating objects, and the differences between the critical objects aren't easy to distinguish anymore. Then it would be unacceptable that large investments are distributed based on such unsystematic discussions. This would therefore be a time where a systematic IDEF0 model like the one in this research comes in handy.

Analysis and Observations
ProRail's method of identifying the critical objects is just like the one of Rotterdam simple and quick. An advantage of this is that asset managers will not see these methods as a high threshold to implement and repeat. On the other hand, when a time is coming that the number of deteriorating objects is large and it is difficult to determine which object is more critical than the other, their methods might lead to investing in objects that do not contain the largest risks as they do not systematically assess the risks. Moreover, they do not first consider the objects that have a high impact, which is done in the filtering process of the final IDEF0 model. This was something according to the municipality of Amsterdam important since these cause the biggest problems.

A repetitive observation was that also during this meeting again confusions were arising between the different types of risks and the different purposes. The reason for this is that also ProRail is more focused on developing risk-based maintenance plans to prevent risks, based on grouping objects.

9.3 | Conclusion

Since the meetings with the two asset managers largely focused on how the IDEF0 model works and what the differences are between finding current risks and general risks, there was little time left to dig deeper into the IDEF0 model and discuss the validation of all the found requirements and challenges.

Overall, it can be concluded that just like during the workshops, there were again confusions about the different types of risks. The reason for this is because they might not make this distinction often because they don't have to (yet). Also, they do not systematically identify current risks to identify the critical objects. But they focus more on risk-based maintenance plans, and therefore risks in general.

For them it is not necessary to identify the current critical objects with the help of an extensive and systematic process at the moment. One reason for this is that so far they have enough money to invest in all critical objects, since they do not have such a large number of deteriorating objects. However, this is expected to change in the future, since they expect the rate of deteriorating objects to increase. This rate is already more noticeable in Amsterdam, because they have more objects that are older and therefore deteriorating, such as the quay walls and the bridges. Thus for now this process might not yet be very relevant for the municipality of Rotterdam and ProRail, however, when they notice that they do not have enough money to spend on all critical objects anymore, they could use the IDEF0 model of this research.

Nevertheless, when they tried to be critical about the IDEF0 model their main concerns were about the fact that the IDEF0 model can take too much time. The reason for this is because from experience they know that activities such as risk assessments are time-consuming and if the risks of individual objects are assessed it is assumed to be time consuming as well in a system containing numerous objects. Even though when the filtering process is applied, it can still be the case that the remaining number of objects is large. Rotterdam said that therefore the last activity of aggregating the RPN to the system level will eventually not be executed. And ProRail said that people do not like risk management, so he had doubts how carefully the entire process would be executed in practice.

10. DISCUSSION

This research filled the practical and research gap with how to identify critical objects of a public infrastructure system. The current chapter summarizes and discusses the main findings of this research in section 10.1 and 10.2 and the limitations of the findings in section 10.3. In section 10.4 the chapter closes with the limitations of the approach of this research.

10.1 | Summary of the Findings

Interests and process requirements

It was found and validated that the interests of the three management levels are opposing. As a result, the requirements for the process of identifying the critical objects were opposing too. Overall, the asset owner finds it important that the objects do not form risks for achieving the organization's goals and objectives which represent their social accountability. Therefore, an approach was needed to translate these goals into the definition of risks on object level. This refers to the need for a top-down approach. However, this information on the bottom also had to return to the strategic level because the strategic level expects substantiated and reliable reasoning from the asset manager for why objects are critical according to their goals and objectives. Also, this must be done in a language that the asset owner understands. Ultimately on the one hand the asset owner wants the IDEF0 model to be as uniform as possible as they want the objects to be treated similarly in a uniform process. This is because they find it important that every bridge is equally clean, no matter in which neighborhood the object is located. On the other hand, the IDEF0 model must also take all relevant factors into account, such as all organizational goals and objectives, in order to provide a reliable outcome.

The service providers are focused on their day-to-day work and have a short-term point of view. They expect a process that is comprehensible to them so that they understand what information they have to provide to the asset manager. They usually do not understand or have the time to deal with the strategic level. They don't necessarily know how to express their objects' condition in non-technical values, or will understand why the asset owner wants to treat all objects the same if they are clearly unique. In conclusion, the service providers want the process to be comprehensible to them so that they understand what is expected from them, and they want the process to take into account that objects are unique and therefore must be treated differently.

As a result, the asset manager is conflicted between the asset owner and the service provider. The asset manager wants to make the process uniform in order to compare the different types of objects and to keep the process simple. Making it simpler would lead to a better execution of the process on the tactical level, but it will also lead to a better comprehensibility on the operational level. The asset manager wants to keep the process's outcome reliable enough by taking all the important aspects into account. As a result, the asset manager must make the process flexible to adapt to changes, and consider the differences between the types of objects. However, all of these mentioned requirements can be opposing, such as a process that must be both uniform and diverse, and both simple and flexible. Moreover, the asset manager also must deal with translating the political language from the strategic level into technical language on the operational level, which then must be translated back into strategic language again. As a result, the asset manager finds himself in a challenging position between two differing parties with opposing interests and different languages. Overall, the three management levels preferred the IDEF0 model for identifying the critical objects to be:

1) Feasible considering the perceived complexity of the process by the asset managers and the large number of varying objects by keeping the process:
    a. Simple
    b. Holistic and systematic
    c. And uniform for all objects
2) Reliable by:
    a. Taking everything into account
    b. And flexible to react on relevant changes

Final IDEF0 model

The literature study led to a theoretical IDEF0 model that was subsequently tested in practice with the process requirements of the three management levels. An improved IDEF0 was the result showing in a more elaborative and feasible way what has to be done to identify the critical objects whilst complying with the interests of the three management levels.

Translate the organizational goals and objectives into the performance requirements for the object.

The first process step for the asset manager would be to translate the organizational goals and objectives into the performance requirements of the object. This would be the start of developing a line-of-sight. To avoid misinterpretations of the organizational goals and likewise to support this translation process, it appeared to be very useful to include somebody with the knowledge of these goals in this process step, such as the policy department of the organization. This step should be kept simple by choosing the smallest number of performance requirements as possible. Also, performance requirements should be tried to be made uniform for all types of objects. This is challenging because uniform KPIs can lead to more ambiguous KPI descriptions, while the KPIs must be SMART as well. To make the performance requirements uniform for all objects, all asset managers of all object types must be included in this process step.

Develop a risk matrix.

The uniform performance requirements for all object types form the input for the following step, which is developing a uniform risk matrix for all object types. The risk matrix is the tool for assessing the risks of the failure modes of the objects. The risk here is the impact of the failure mode on the system and the expected time until that failure occurs. The output of the risk matrix is the Risk Priority Number (RPN) of the failure mode, which will determine the criticality of an object. The higher the RPN of the failure mode, the more critical the object. This matrix must be uniform for all objects, because then all the risks of all the different types of objects can be compared. The impact indicators building up the risk matrix can be derived from the performance requirements by questioning what the impacts would be if an object does not fulfill a performance requirement. So what would the impact be if an object fails to meet the environmental performance requirements? As a result, the risk matrix considers the impacts on the organizational goals and objectives, continuing the line-of-sight. Yet, the impact indicators must be uniform and feasible, so all asset managers will develop the uniform risk matrix together, and then the feasibility of the impact indicators are checked with the available data in the organization and the service providers.

Filter the potentially critical objects and its significant failure modes.

Since a public infrastructure system can consist of numerous objects and numerous failure modes, it is impossible to assess the risks of all failure modes of all objects. So, before being able to assess the risks of the objects, the potentially critical objects and its significant failure modes must be filtered first in the filtering process. The filtering process starts with looking at the objects in the system that are expected to have the highest impact during failure. Think of the objects that are positioned in the busiest car networks or in the center of a city. These are the objects that are most likely to cause the biggest problems for the organization when they fail. To save time, not all impact indicators need to be included but only the most important ones. For Amsterdam the most important is the impact on the availability and the safety of the infrastructure system. After having filtered the objects with the highest impacts, the next step is to filter only the significant failure modes of these objects. These are the failure modes that have the largest impact on the object not fulfilling its requirements. These potentially critical objects and their significant failure modes form the input to the following step.

Assess the risks of the significant failure modes to determine the RPN.
The risk assessment takes place in the fourth process step. The risks of the significant failure modes of the objects are assessed with the uniform risk matrix. Then the higher the impacts during failure and the shorter the expected time until failure, the higher the RPN. This step can also be kept simpler by choosing to assess the risks only according to the most important impact indicators. The asset managers assess the risks of their own objects, since they know their objects best. Based on the impact indicator that is being assessed, people with a relevant expertise can be asked for advice. For instance, the service providers usually have an overview of the safety claims of an object and can help with assessing the impacts on safety, and the transportation department knows everything about the availability of the city and can provide information on the impacts on availability. Ultimately, the asset managers can rank the RPNs of all objects which provides a list of objects going from most to least critical.

Aggregate the RPN to the object, subsystem and system level.
It appeared there was an interest in an additional process step. This process step is at this moment a theory and needs extra research to figure out how it can work in practice. The idea of this step is that the asset managers can also express each risk of the object in one type of impact. For instance, the risks are then only expressed in terms of the impact on availability. Then the asset manager is able to show the objects that are currently the most critical in terms of availability in a certain car network; a subsystem. This can provide new insights such as where the availability of a car network must be improved first if the availability of an entire infrastructure system must be improved. In conclusion, aggregating the RPN of objects into subsystems per impact criteria can offer the asset manager new insights, satisfying the asset owner.

To overcome the expected challenges, there is a selection of main requirements for the final IDEF0 model to work in practice. First, the filtering process that filters the potentially critical objects and its significant failure modes is the most important to be executed. This step makes it feasible by not having to assess millions of risks. Moreover, the requirement for keeping the entire IDEF0 model simple and uniform came out as being the most essential requirement for making the IDEF0 model feasible. This is because the process needs to be uniform for the asset managers to be able to compare the risks of the differing objects, and it needs to be simple to keep the process useful and comprehensible. Therefore, besides the IDEF0 model also a simplified process model with visualizations was developed. And since the asset managers fully dependent on the strategic and operational level and obviously the tactical level, the last important requirement is that the asset managers must be aware of the interests and the capabilities of the three management levels.

10.2 | Discussing the Findings in its Context

The main aim of this research was to find a systematic way in which the process of identifying the critical objects can comply with the interests of the three management levels. As a result, the final simplified process model and the IDEF0 model with the defined inputs, mechanisms and controls serves as a solution to four main problems.

The research started with two basis problems. The first problem is that nowadays the asset managers are facing an increasing rate of deteriorating objects that apart from the regular maintenance need additional maintenance measures, whilst they are having the same size of budgets. Therefore, the asset managers are in need of a method for prioritizing their objects based on the risks of object failure, which supports them in knowing in which object needs the additional maintenance first. The other problem is that the asset manager is strangled between the asset owner and the service provider who have differing interests in the process of assessing the risks of the objects.

However, at the start of the research a large research gap was found. It was unknown how critical objects must be identified. This was unknown to the people of the municipality of Amsterdam, and it was unknown in literature. Literature was more focused on identifying critical assets in general, and when literature became more specific it was more about identifying critical failure modes to determine the critical components as can be found in the books written by Moubrai (1997) and Mitchell (2002), or the papers of Rausand (1998) and Wei (1991). As a result, this research contributes to filling op this large research gap.

And then during the empirical research one other problem came up which could make the IDEF0 model useless if this problem wouldn't be solved. That problem was that the entire IDEF0 model for finding critical objects would never be feasible if it has to be applied to every failure mode of every single object in an infrastructure system that contains thousands of objects. So a solution had to be found for how to assess all risks of all objects in a feasible way.

As a result, there appeared to be one main unknown which is how to identify the critical objects in general. Then two other unknowns had to be discovered. First, how to do this whilst complying with the interests of the three management levels, and second how to do this feasibly in a system containing numerous objects. Since this research made a first attempt on exposing these three unknowns, this research provides a solid basis for further research on this topic. Also, it fills in the great research gap concerning risks of objects. In conclusion, in the world of infrastructure asset management the findings of this research contributes to both literature and practice.

Overall, this IDEF0 model should contribute to developing an awareness of the possible risks of the objects. Even though this IDEF0 model will not lead to an overview of all possible risks, it does lead to certain risks. Knowing this creates certainty for the asset managers, which is better than the current feeling of the asset managers of the municipality of Amsterdam who have no idea what the risks of their objects are. In conclusion, this research is not so much about the determination of all possible risks, but about generating awareness of the current possible risks and thus to give asset owners more confidence in their difficult task.

Another positive outcome is that a systematic process that considers the risks to the strategic level and the capabilities and opportunities in the operational level will improve collaboration between the three management levels. At the municipality of Amsterdam managers do not know each other's interests and they do not find critical objects in a systematic way. As a result, the asset manager is not able to convince the asset owner, and the service providers do not understand what the asset managers are expecting from them. Therefore, the findings of this research show how it is not only about the outcome of the process, it is also about the process itself, improving the collaboration between the three management levels and adding value to the organization. This awareness contributes to elevating asset management to a higher level.

ISO 55000

The standards of ISO 55000 give a good indication on what makes good asset management. Since these standards were studied and used for developing the initial IDEF0 model, it turns out that the outcome of this research complies with the standards of ISO 55000, due to the following reasons that are considered to be important by the ISO 55000, ISO 55001 and ISO 55002 (2014):

- The IDEF0 model contributes to creating a line-of-sight; it considers a top-down approach
- The outcome of the risk assessments makes a clear link back to the organizational goals and objectives. This link even becomes clearer by applying the last process step of aggregating the RPN to the relevant system level. This corresponds to the bottom-up approach.
- The IDEF0 model considers non-technical performance and impact criteria, such as sustainability and safety.

As a result, this IDEF0 model contributes to bringing value to the organization and all stakeholders, to supporting alignment across the organization to create this value and to achieve a foundation in assuring that the current risks are in control.

Nonetheless, these findings do not cover all guidelines of the ISO series. Asset management finds the long-term point of view important as well. However, the IDEF0 model is for now mostly focusing on the current risks in the short term. The reason for this choice is that it seems more valuable to control the current situation first before you are looking at the future. Moreover, the findings of this research do not mention in detail how to apply the plan–do–check– act cycle, which is important for ISO 55000 as well. However, adding this cycle to the IDEF0 model would be valuable, especially since this IDEF0 model could be repeated to improve the process and its outcome. This is explained in the following section. And third, ISO 55000 emphasizes the importance of leadership for effective asset management. However, the relation between the findings and the leadership was not yet fully defined. In conclusion, the IDEF0 model can be developed further by taking a long term point of view considering future risks, adding the PDCA cycle to the IDEF0 model, and develop a leadership strategy for the implementation of the IDEF0 model in practice.

10.3 | Discussing the limitations of the findings

This research contributes to various needs such as filling up a large knowledge gap, creating awareness of the current possible risks of objects and knowing how to develop a line-of-sight in asset management. Also, the results should support the asset manager in finding these risks in a systematic way whilst complying with the interests of the three management levels and overcoming the expected challenges in practice. However, the true feasibility of the findings of this research is disputable. Possible limitations of the findings are that the IDEF0 model is too complex, will not automatically result in a smooth process with a valid outcome, takes too much time to be applied in practice, might not last and it contains various additional expected challenges.

10.3.1| Complexity

First of all, the main concern throughout this research was the complexity of identifying the critical objects. If the entire tactical level must understand such a complex process, would the method still be feasible in practice?

The complexity of the IDEF0 model stems from the fact that the entire topic was new to everyone who took part in this research; from the asset managers of the municipality of Amsterdam to the asset manager of ProRail. Besides the novelty of the process of identifying the critical objects, asset management in practice is fairly new as well. Moreover, the IDEF0 model suggests a new way of thinking that complies to ISO 55000, which is challenging for people to understand. It is not just a process that concerns identifying the critical objects, it is a process that considers three different perspectives; that of the asset owner, the asset manager and the service provider. As a result, the IDEF0 contains additional activities to comply with all perspectives, like the translation process from the strategic level to the performance requirements of objects, and a long list of requirements from all management levels. A brand new process that introduces unfamiliar activities, that considers all interests of all three management levels and that comes with a long list of requirements and challenges, has led to an IDEF0 model that is integrating so many aspects that it is indeed complex. As a result, the feasibility of this complex IDEF0 model can be called into question.

This constant concern of an infeasible IDEF0 model due to its complexity was mentioned by most interviewees. Therefore, numerous service providers, asset managers, asset owners and experts emphasized the importance of keeping the process as simple as possible. As a result, the requirements that lead to a simple process and decrease the complexity of the IDEF0 model, such as not going too much into detail and not taking everything into account, has become a ‘must’ for making this process feasible. Moreover, educating the interviewees to create understanding on how the process works worked out well during the research. So, complying with the process requirements and a good education on how the IDEF0 model works should diminish the perceived complexity of the IDEF0 model.

Moreover, this process is found complex because it concerns three fairly new additional activities. These are the first, third and the last activity. The first activity, which is defining the performance requirements, is besides the input for risk management also the input for measuring the performance of all objects. So, this step makes it more complex, yet knowing the performance of the assets is one of the important drivers to asset management according to ISO 55000, and so this activity has to be executed anyway. The third activity of filtering the potentially critical objects and significant failure modes is new since it was developed during the workshop. However, this activity is there with the purpose to simplify the execution of the IDEF0 model in practice and therefore make it more feasible. The last activity can be easily left out. This activity is not a requirement for the process to work in practice. It is an activity that has been developed because it was believed by the interviewees that this would provide interesting and useful new insights. However, if this activity is left out, and the RPNs of the objects are known, there is still enough output to justify the current critical objects to the asset owner. In conclusion, the first activity must be done anyway in asset management, the second and fourth activity are necessary for risk assessment, the third one is necessary for making it feasible and the fifth one can be left out, as can be seen in figure 35. Therefore, the activities do not necessarily have to be the main reason for making this IDEF0 model complex.

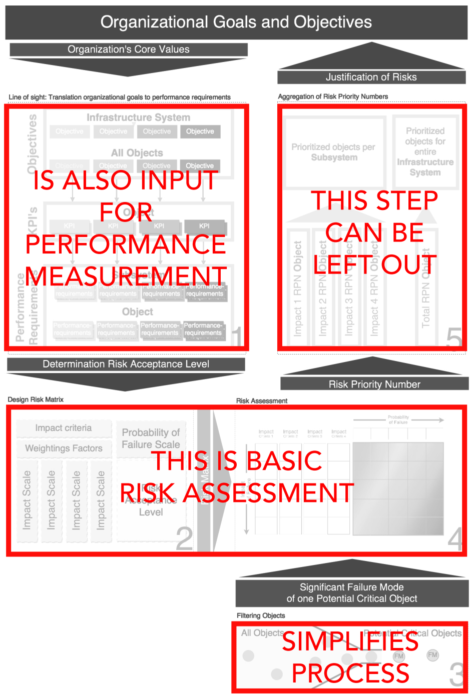


Figure 35 | Discussing the complexity of the activities (own illustration)

In conclusion, the IDEF0 is complex because the process is new to everyone, it contains various activities that can be complex and it comes along with numerous requirements. At second thought the various steps that appear to make the process complex aren’t necessarily making it as complex after all. In addition, the process can be simplified and fears of complexity can be overcome by educating people on the tactical level and by applying all defined requirements that will make the IDEF0 model simple.

10.3.2 | Completeness

The first time the IDEF0 model will be applied in practice it will not provide the most complete outcome. Furthermore, the process itself will most likely not run smoothly right away. Both effects were experienced when the first activity of the IDEF0 model was practiced during the workshop. The reason for an incomplete outcome is that the participants of the workshops clearly preferred the feasibility requirements over the reliability requirements. The reliability requirements consider taking everything into account in order to develop a more complete outcome. Moreover, risk assessments come along with uncertainties, as can be seen in figure 36, making it impossible to identify all risks and assess these risks without uncertainties (ISO 31000, 2009).

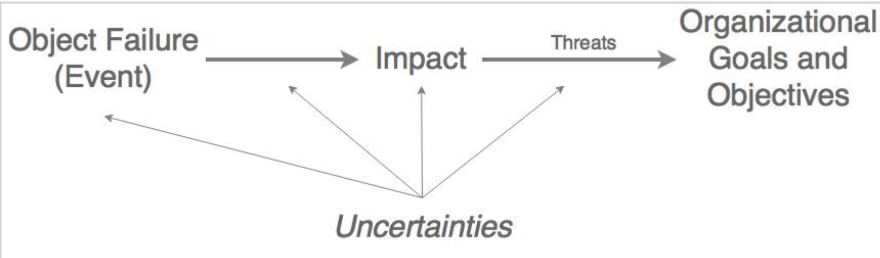


Figure 36 | Uncertainties according to ISO 31000 (2015)

The reasons that the IDEF0 model is expected not to run smoothly the first time is that the IDEF0 model is new. This was experienced in the first workshop when the model was actually applied in practice. Even though with the ex-anta analyses some methods can be found for making the process run smoothly in practice, possibly not everything will be foreseen. Therefore, the first time the rest of the activities will be applied in practice it is expected that the IDEF0 model will not provide all critical objects in the smoothest way. Yet, the idea is that the more times the IDEF0 model is applied, the better the process will be executed, the more complete the outcome will become as shown in figure 37.

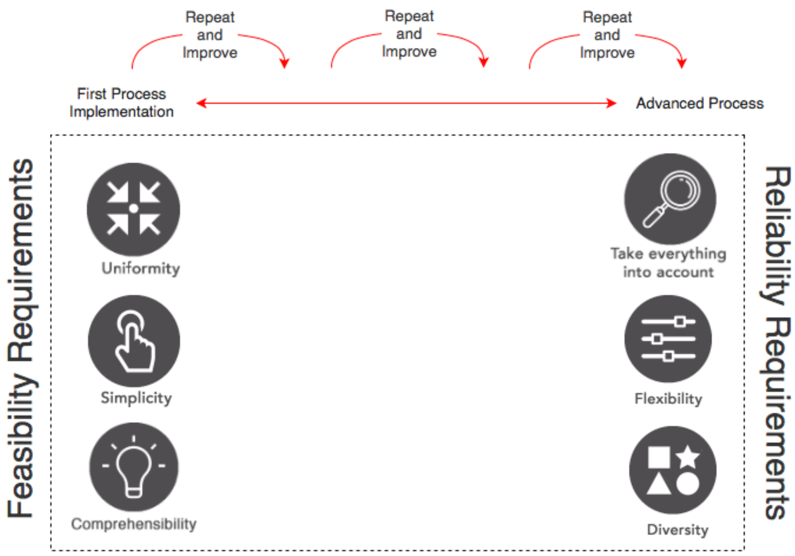


Figure 37 | Improving IDEF0 model's process and outcome

I want to stress some considerations for when to repeat the IDEF0 model to improve its process in order to improve its outcome. Applying it just once will lead to an incomplete and out-of-date outcome. However, applying it too many times is not feasible either because it takes a long time to execute the entire IDEF0 model, as explained in the next section. Improving the outcome of the IDEF0 model can be done in three different ways, as visualized in figure 38. The first activity of the IDEF0 model is to define the performance requirements. This step must be done and repeated to make sure the KPIs cover every possible performance that is necessary and to improve the norms.

Developing the risk matrix will be an iterative process in order to constantly improve the matrix. It is not possible to develop the perfect matrix in just one time. Also, the risk matrix will be adjusted when impact indicators must react to changing organizational goals and objectives. I advise to revise the risk matrix in times when large alterations occur in the organizational goals and objectives. For instance, at the municipality of Amsterdam this can be every four years when the city council changes. But in another organization this can be the case when a new policy document is developed. Then when the policy document states that the organization's attention for sustainability has increased, the weighting factor for the impact on the environment can increase as well.

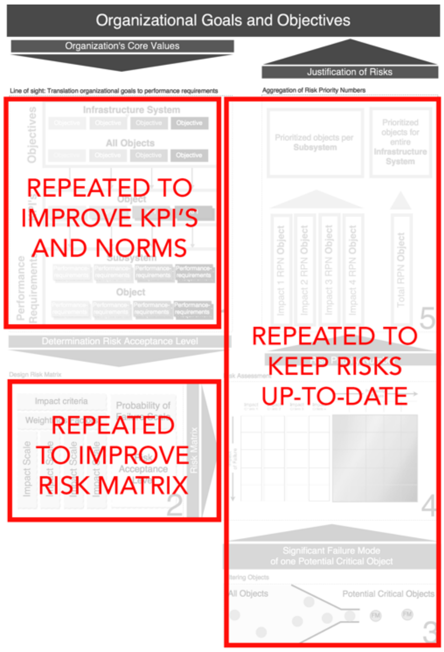


Figure 38 | Improving the IDEF0 model's outcome

Identifying the potential critical objects, assessing these objects' risks, and then aggregating the RPNs to the right level must be done sequentially. This is because when new potential critical objects arise, the risks of these objects must be assessed in order to keep the list of the current critical objects up-to-date. For instance, when a certain car network becomes busier over the years, the impacts during failure of the objects in this network will increase as well. These objects can then suddenly become potential critical objects. This asks for a new risk assessment and an aggregation of the resulting RPN. Also, the probability of failure of the potential critical objects must be monitored. If a probability of failure is entering the danger zone, the risk matrix should be applied again in order to check whether the resulting risk is still acceptable. In conclusion, the risk matrix must be applied again when new potential critical objects arise due to increases in impacts and probabilities of failures, followed by the activity of aggregating the RPNs.

In conclusion, the first time the IDEF0 model will be applied in practice will not go perfectly and it will not deliver the most reliable outcome. Executing the IDEF0 model in practice has led to more relevant insights than conducting the ex-ante analyses. Moreover, by knowing where to repeat the IDEF0 model, it will lead to improvements in the reliability of the process and the process outcome. Repeating the IDEF0 model can be done to either improve the KPIs and the norms, the risk matrix or the risks of the critical objects. The more times the IDEF0 model is repeated and improved, the more reliable the IDEF0 model can become.

10.3.3 | Time consuming

Additionally, it is expected that the IDEF0 model can take some time to be executed, especially the first time. The workshop for defining the KPIs took half a day, while this is only a portion of the first activity. The consequence of a time consuming process is that the level of motivation for repeating and improving the IDEF0 model will fall. Like this, the model will not last. Moreover, if the process takes too long some risks might have already occurred before the risks are identified, causing the asset manager to be too late to treat the risks.

However, in my opinion it is important to work from coarse to fine by first conducting the IDEF0 model in a course way, and then when it is repeated it can become finer every time. This will keep the process from taking too long. By keeping it coarse the first time, the activities do not have to be enhanced but are kept simple, causing the steps to be finished quicker. For instance, only a few performance requirements are defined and the risk matrix does not have to be faultless. The first time it is more about the idea, setting a basis and creating an understanding. Then the following times the process can be improved, working out the details. As a result, the first round of applying the IDEF0 model will not take too much time, and the following rounds will be about improving the process and its outcome step by step, as explained in the previous section.

Besides the idea that the more times the IDEF0 model is applied the better the process and the better the outcome will be, the execution will become quicker as well. The asset managers will get used to the process and will find out how to execute the activities more efficiently. This will result also in a less time-consuming process.

So yes, the IDEF0 model can be time consuming. However, by working from coarse to fine the asset manager should be able to control the time it takes to execute the entire process. Also, it can be expected that when the process is repeated, the process will be executed more efficiently and therefore quicker.

10.3.4 | Significant Failure Modes

From the start there were some doubts about how to go from the activity of assessing the risks of the failure modes of the object to determining the criticality of the object based on the RPN of the failure modes. So is it possible that one object has one significant failure mode and the other one has two. Then these failure modes' risks are assessed, and the asset manager faces the following:

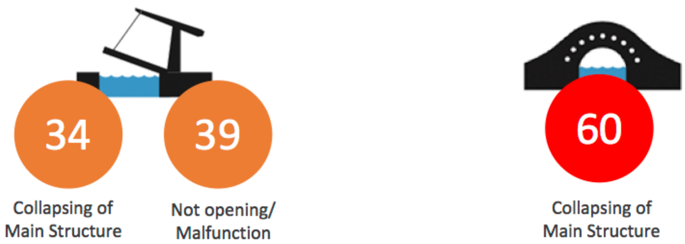


Figure 39 | Failure Modes of two bridges

One object, the movable bridge, has two significant failure modes that both have medium high risks. Individually seen these are almost unacceptable, but the total risk is 73. This is higher than the fixed bridge that has one significant failure mode with one unacceptable risk. Which object would you choose to invest in first?

When it is a matter of time and the failure mode of the fixed bridge has a higher probability of failure, you might want to invest first in the fixed bridge because the chance that it will fail is larger. But what then if all probabilities of failure are more or less the same? So far this was found to be a challenge. After some discussions with people still no solution was found. An idea is to look at the failure modes rather than the objects, and simply treat the failure mode with the highest RPN, because this still indicates that this is the highest risk.

10.3.5 | Relation between impact and subsystems

Two sub activities that were left out of the research that are expected to be challenging in practice are determining the norms for the performance requirements for subsystems and objects, and the aggregation of RPNs. A theory is that it helps to know the reasons behind the different sizes of impact, because this will determine the relevant type of subsystem per impact indicator.

For the impact criteria availability, one can look at the car network. For the reputational impact criteria, it is better to look at neighborhoods. The differences are visualized in figure 40. Here the car network consists of three different types of networks. The objects in the darkest network have the highest impact when it fails, and the lightest color refers to the lowest impact. This is explained by the number of users of that network. The darkest color can be, for instance, a provincial road that is critical for the in- and outflow of the entire city. So, if this busy network fails on availability, the impact will be higher on the entire car network's availability than when a light-colored network fails such as a quiet street in a residential area. Accordingly, for the availability criteria, the transportation networks must be considered as the relevant subsystems.

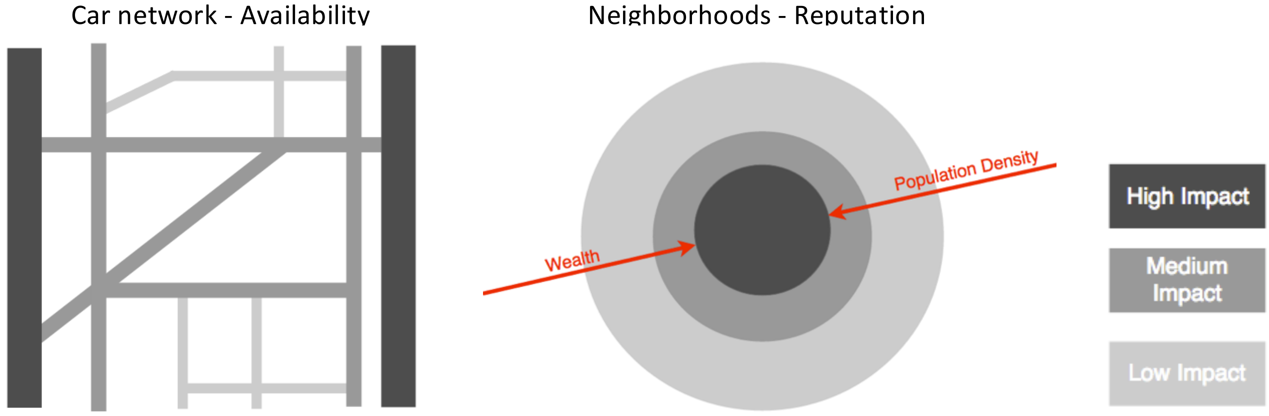


Figure 40 | Impacts and subsystems

The right image shows how the impacts on the asset owner's reputation are shown to be different per neighborhood. When an object is covered in graffiti, which can be an object not fulfilling its performance requirements, this will have a higher impact in a wealthy and highly populated neighborhood such as the center of Amsterdam, than in a less wealthy neighborhood with a lower population density. According to an asset manager of Amsterdam, people complain more in wealthy and highly populated neighborhoods of the city. These complaints can lead in some situations to negative publicity in the media, which can harm the reputation of Amsterdam and therefore the organizational goals and objectives of the municipality. Accordingly, for the reputation criteria the clusters of neighborhoods based on the population and wealth can be the relevant subsystems.

So, for creating the relevant subsystems per impact criteria the asset manager can think of what "X" is that determines the different sizes of that certain impact of object failure. But what does all this mean for the IDEF0 model? First, it becomes easier to determine performance requirements. After knowing what the determinants are per impact criteria, clusters of sizes of the impacts can be made. Such clusters can be the busiest street, the quietest street, and the street in between. Then you can allocate the required performance to each cluster. For instance, in the busiest car network the objects is required to have a maximum of 1 hour of impact on the availability of network per year, for the medium network this is 5 hours and for the lowest network this is 10 hours. Knowing this, the availability requirements for the objects must correspond with the norms of the network that the object is positioned in.

The same goes for aggregating the RPNs per impact RPN in the final activity. If the asset owner wants to know the current largest risks in terms of availability, you show the ones on the busiest car network with the highest probability of failure. And when the asset owner wants to know the objects with the greatest risk for reputational damage, you show the objects with the highest probability of failure in the wealthiest regions with the highest population density. As a result, knowing the relevant subsystems makes it easier to present each risk per impact criteria.

The more clusters are made, the more precise the performance requirements can be defined. However, this can make the process of defining requirements and aggregating the critical objects also more complex. This corresponds to the process requirement that it all has to be kept simple but that you also have to take everything into account if you want the process and its outcome to be as reliable as possible.

In other words, you are clustering the types of impacts to make it more feasible to determine norms for certain performance and impact criteria. This theory might work differently in practice, though. Therefore, it would be a recommendation to apply this theory in practice and see what the challenges are.

10.3.6 | Conclusion

Various doubts can rise about the extent into which the IDEF0 model and the process requirements will work in practice and will last in the future. These doubts come from the various limitations to the findings of the research. Even though an attempt can be made to remove these doubts, it is important to realize what the true essence of these results have appeared to be. The true essence is that the findings of this research can be used by an organization to learn how to systematically implement asset management with the idea that objects must add value to the organization. It is about reaching the strategic level and considering the capabilities and opportunities of the operational level as well. It will help asset managers with convincing the asset owner the necessity behind additional maintenance measures, and with supporting the service providers in providing the right input. Moreover, all the three management levels will grow awareness when it comes to the risks that are related to object failure. All this contributes to elevating asset management, according to ISO 55000, to a higher level. Indeed, the IDEF0 model and this new way of thinking about assets is complex and unreliable for now, but as soon as people become more used to asset management it will become simpler and the outcome will improve.

10.4 | Discussing the limitations of the approach

At the start of the research it was decided to choose a certain approach to find a valuable answer to the stated research question. However, the approach of this research can also be reflected on which leads to various limitations.

10.4.1 | Sample: Municipality of Amsterdam

It can be discussed that the results of this research aren't fully general. The initial IDEF0 model was based on literature, which means that this model can be seen as a general model. Yet, this model did not seem to work out in practice. The process requirements that had an influence on the development of the final IDEF0 model were derived from the municipality of Amsterdam only, meaning that the final IDEF0 model is not as general. Therefore, it could lead to implications if the model is applied at other public organizations that own infrastructure assets.

There are several dominant characteristics of the sample, the municipality of Amsterdam, that had a large influence on the development of the process requirements and the final IDEF0 model. These characteristics build up the assumptions for the final IDEF0 model. These characteristics of the municipality of Amsterdam is that the organization is large, owns a large number of varying objects, has a low maturity level in asset management, and it is an organization that notices an increasing rate of deteriorating objects whilst facing a constant budget. These assumptions are limitations of the IDEF0 model because when this model is applied at other public organizations that do not share these characteristics, the model might work out differently.

Size of organization
The municipality of Amsterdam is the biggest municipality of the Netherlands, and can therefore be considered as a large organization. A large organization contains more people and has larger budgets than a smaller organization. So, a small organization has less means to invest in the execution of this IDEF0 model. Accordingly, a small organization might require the IDEF0 diagram to also be feasible with a smaller number of means. This can have an effect on the feasibility of the current process IDEF0 at a smaller organization.

An organization with more people means also that there is a larger distance between the three management levels which can lead to a lack of understanding in each other's interests. For instance, an organization that only consists of five people can be expected to be more aware of each other's interests compared to an organization that consists of hundreds of people. As a result, identifying, understanding and complying with the opposing interests might not be such a big challenge in a smaller organization. Therefore, the execution of the IDEF0 model can be simpler for a smaller organization.

Another result of more people in an organization is that the tactical level is larger, meaning that more people should understand how the IDEF0 model works. The municipality of Amsterdam saw this as a large challenge and therefore emphasized the importance of keeping the process comprehensible to everybody that has to execute it in order for it to be feasible in practice. That is also the reason why besides the IDEF0 model a simplified process model was designed as means of communication. A small organization, however, has a smaller tactical level so also more control over how the model is being understood and executed. As a result, for them it is easier to require the process to be more complex by taking more into account, such as defining additional performance and impact indicators.

To sum up, the final IDEF0 model might be less feasible for an organization with a smaller number of means to execute the final IDEF0 model. Also, a smaller organization might find it less challenging to consider the opposing interests as well will they find it less necessarily to have a IDEF0 model that is as simple as possible because for them it could be easier to handle complexity.

Number of objects
To make the final IDEF0 model feasible with the large number of objects the activity of filtering only the potentially critical objects and its significant failure modes was added to the model. Yet, Amsterdam has to oversee the risks of 1600 bridges, whereas a small town might only have to oversee 2 bridges. So, this filtering process step could be unnecessary for a small infrastructure system containing a small number of objects.

Also, an organization that owns a large infrastructure system with many objects has to deal with a larger number of users as well. A larger number of users means a larger impact during object failure, which causes such an organization to find their social accountability more important. This is the case with municipality of Amsterdam, where the asset owner emphasizes the importance of expressing the impact of the risks in terms that matter to the user. This requirement for expressing impacts in these extensive ways might be overdone in a small town with a small infrastructure system where the impacts are small. Yet, this would not have a large impact on the IDEF0 model, because such an organization can then choose only two impact indicators for the development of the risk matrix.

So, organizations with a smaller number of objects do not need an elaborated process that considers additional process steps to make the process more feasible with a large number of objects. And smaller organizations might not need to express the risks in such an extensive political way but this does not necessarily have to make the IDEF0 model less applicable.

Maturity level
The municipality of Amsterdam does not score high when it comes to their maturity level in asset management (Zeb et al., 2013). This means that the data of this research comes from people with little to no experience in risk management of assets. An organization with a higher maturity level could have provided more data. For instance, during the ex-ante analyses additional challenges could have been predicted by the ones with more experience in the matter, leading to additional process requirements for the IDEF0 model to work in practice. Therefore, the lack of knowledge and experience of the sample, and the choice of using one sample only can be seen as a limitation of the collected data of this research.

Moreover, the municipality of Amsterdam requiring the IDEF0 model to be simple and comprehensible in order for it to be feasible is also due to the low maturity level of the organization. This would mean that organizations with higher maturity levels might not care so much about making it as simple as possible. They could prefer making the process and its outcome more reliable by taking more into account.

Yet, some organizations have such a high maturity level that they don't have to map the current risks with this IDEF0 model at all, because they have predicted the current risks beforehand already. Such an organization could be ProRail, an organization with a high maturity level in asset management. They can foresee when most of their objects need additional maintenance measures because they can forecast when an object is failing due to the large number of data they have collected over the years. So, organizations that have advanced methods to forecast risks accurately might not need an additional method of identifying the current risks.

In conclusion, a limitation to the data of this research is that it comes from only one organization with a low maturity level, which has limited the perspectives of experts that can be necessary for achieving valuable results. Moreover, an organization with a higher maturity level, like ProRail, might already have methods that they can forecast risks and therefore do not need to know the current risks.

Increasing rate of deteriorating objects and high impact
Not every infrastructure system is facing an increasing rate of deteriorating objects. The municipality of Rotterdam does not have many deteriorating objects in their infrastructure system, because Rotterdam has relatively new objects since everything was rebuilt after the bombing during World War II. ProRail already has a solution to the problem of an increasing rate of deteriorating objects. This is because this organization has data available to determine the probability of failure of their objects. Therefore, they know when the risks will occur and can likewise prevent the risks with their regular maintenance plan. As a result, this IDEF0 model is mostly relevant for public organizations that notice an increasing rate of deteriorating objects with a limited budget.

The sample
Due to the choice of conducting the empirical research at the municipality of Amsterdam only causes the finally developed IDEF0 model to come with various assumptions and therefore limitations. Besides these limitations, the municipality of Amsterdam was in the end a good sample for this research. First, they had many people who were easily willing to be interviewed and to participate in the workshops. Moreover, the municipality of Amsterdam is currently implementing asset management in order to be able to manage their assets based on the drivers: costs, performances and risks. Since they did not fully know

how to do this based on risks yet, the organization was flexible towards the research and stood open for new options. Furthermore, the problem of dealing with the increasing rate of deteriorating objects was a problem that is currently a large challenge that the municipality of Amsterdam wants to overcome. Moreover, the research became even more interesting thanks to an additional challenge for Amsterdam which was to assess risks of objects in a feasible way, considering that not all risks of all objects and all failure modes could be assessed in reality. So besides the various limitations, the people, the current maturity level in asset management and the additional challenges at the municipality of Amsterdam made the sample valuable for this research.

10.4.2 | Workshops

The workshop with the purpose of making the initial IDEF0 model more feasible and figuring out how to aggregate the risk priority number to object, subsystem and system level only consisted of participants coming from the civil engineering department. The reason for choosing the civil engineering department is because compared to the other departments these people are the most advanced when it comes to asset management. This was necessary because participants were needed who would easier understand the research and would come up with valuable ideas coming from their knowledge and experience. Yet, it still can be discussed that the outcome of this workshop is limited, because the range of knowledge could have been extended by including other asset departments. Though, the other workshop with defining the KPIs for all the objects did include participants coming from all object types. This choice of sample increased the range of knowledge, but this sample was also necessary for defining uniform KPIs for all object types.

10.4.3 | Requirements Analysis

The process requirements were prioritized based on the number of interviewees who mentioned the requirements. The more interviewees who mentioned a certain requirement, the more important that requirement became. However, this does not have to indicate that such a requirement is truly the most important. Some requirements might have been mentioned more because the conversation was subconsciously led into that direction. Or maybe some requirements were not mentioned because the interviewees didn't think of it themselves at the moment while they do find it an important requirement. Therefore, this is a clear limitation of this research. An improvement would've been to extend the requirement's analysis. Then after the interviews a list of all the mentioned requirements would be sent back to all interviewees. Then the interviewees can vote on the requirements they find the most important. Like this you obtain a more accurate prioritization of the process requirements. However, on the other hand, during the workshops it became clear what their real preferred process requirements were. And during a workshop with an ex-ante analysis it might be easier for them to determine their preference for the right requirements for the IDEF0 model to work in practice, than when being send a voting poll.

10.4.3 | Validation

When the organizations had to be chosen to validate the finalized IDEF0 model, the purpose was to find organizations that also own infrastructure objects and have a higher maturity level when it comes to managing assets based on risks. Then the context of the type of objects would be basically similar and it was assumed that with people with a lot of experience in asset management it would be easier to test the validity of the outcome of the research. As a result, ProRail and the municipality of Rotterdam seemed two perfect options.

Ultimately, both organizations could validate the outcome of the research. However, it appeared that the process was for both organizations not useful (yet). So do both organizations do not face the problem of such an increasing rate of deteriorating objects. So, a better organization for validating the findings of this research would have been also large municipalities such as The Hague or Utrecht, which are two municipalities that own the same type of old infrastructure objects that presumably also need to prioritize their objects due to the increasing rate of deteriorating objects.

10.4.4 | Conclusion

It can be concluded that the municipality of Amsterdam was a valuable sample for this research. However, this sample has also led to some limitations of this research. First, their lower maturity level in asset management might have caused a limited size of deliberated data. Also, choosing one single sample could have caused a narrower range of data, than when multiple samples would have been chosen. This narrow range has led to various assumptions for this final IDEF0 model to work at other public organizations. These assumptions are that the organization should be large, owns a large number of old objects, has a low maturity level and is facing an increasing rate of deteriorating objects while having a limited budget.

In figure 41 the relation between the characteristics of an organization and the expected preferred type of process requirements is visualized. The municipality of Amsterdam preferred the feasibility requirements over the reliability requirements, which had a large influence on the finalized IDEF0 model because they insisted that the process diagram had to be altered in a way to make it more feasible in practice. As a result, the filtering process was added. However, when another organization would have been used for the empirical research, another outcome could have been collected. For instance, another organization with a higher maturity level in asset management could have preferred the reliability requirements over the feasibility requirements. If this was the case, the final IDEF0 model might have had additional process requirements or steps to improve the reliability of the outcome.

Figure 41 | Expected process requirements for different types of organizations

Even though the final IDEF0 model and the process requirements have various assumptions, it does not mean that the final IDEF0 model is not applicable to other organizations. For some organizations, the theoretical IDEF0 model that is based on literature can be used, but another empirical research must be conducted to derive new requirements and the theoretical IDEF0 model must be tested at that organization to develop a more applicable final IDEF0 model for that organization. This is basically repeating part 2 and 3 of this research. Yet, the final IDEF0 model is still applicable to many other organizations, such as other municipalities that share the same characteristics which is presumably the municipalities of large cities like The Hague and Utrecht.

11 | CONCLUSION

The objective of this research was to develop a feasible IDEF0 model for the asset manager to identify the critical public infrastructure objects that complies with the interests of the three management levels: the asset owner, the asset manager and the service provider. As a result, this research formed the answer to the following research question:

"What systematic model can describe the process that asset managers could use to identify the critical objects in a public infrastructure system, taking into account the interests of the asset owner, the asset manager and the service provider?"

This chapter provides the answers to the sub-questions in section 11.1 and the answer to the main research question in section 11.2.

11.1 | Answering the sub-questions

1. ***What systematic model can describe the process that enables asset managers to identify the critical objects in a public infrastructure system?***

Given the problem statement, there was a need for a process model that can systematically present the rather abstract and sequenced activities of the process from beginning to end, including the interests of the three management levels. As a result, the IDEF0 model was selected as the right type of process model.

The critical objects are identified by assessing the risks of the failure modes of objects. This is done with the use of a risk matrix. The risk matrix provides a Risk Priority Number (RPN) based on the expected time until failure and the impact of this failure mode on the system level. The higher the RPN, the more critical the object. So the inputs for the risk assessment is the expected time until the failure mode occurs and the impact of this failure. For collecting this input the asset manager is dependent on the operational level.

The main difference between assessing the risks of objects and assessing the risks of components as explained in literature, is that on object level your purpose is to prioritize objects in order to find out where additional maintenance is necessary. Whereas on component level your purpose is to determine what maintenance is necessary to develop a maintenance plan. Also, on object level you mainly look at the object's individual impact, and you look at the current probability of failure (or expected time until failure). And on component level you look at the general probability of failure and general impacts. Therefore, assessing the risks of objects asks for a new mind set.

Considering the standards for asset management of the International Organization for Standardization (ISO), just assessing the risks of objects is not enough (ISO 55000, 2014; ISO 55001, 2014; ISO 55002, 2014). These ISO 55000 standards explain that asset management is about the object adding value to the organization; the strategical level. The object and its components are maintained and managed in the operational and tactical level, but its value should reach the strategic level. This means that before the risks of the objects are assessed, the asset manager should know when object failure is a risk for the organization. This can be done by first translating the organizational goals and objectives into the performance requirements per criteria, such as the criteria availability and safety. Then the question lies upon what the impact would be on the organization if an object does not perform according to these requirements. This way of thinking supports the development of the risk matrix and its impact indicators.

Also, the failure modes of an object can be defined by thinking of the ways in which an object does not fulfill its requirements. Therefore, for developing the risk matrix and determining the failure modes according to the standards of ISO, the asset manager is dependent on the organizational goals and objectives.

However, when the risks are assessed, the risks must also return to the strategic level which means that the risks must be defended towards the asset owner. So, the asset owner must understand why the objects are critical according to their organizational goals and objectives. This asks for presenting the RPN of the object and the system instead of the object's failure mode. This is easier to comprehend for the asset owner.

As a result, an IDEF0 can systematically present this process for identifying critical objects. Here the inputs are the object inventory, the probability and impact of failure coming from the operational level, and the organizational goals and objectives coming from the strategic level. And the mechanisms are the three management levels: the asset owner, the asset manager and the service provider. The activities of this IDEF0 model are the following:

Step 1: Translate the organizational goals and objectives into the performance requirements of the object.
Step 2: Identify the failure modes that lead to an object not fulfilling its performance requirements.
Step 3: Assess the risks of the failure modes with a risk matrix to determine the Risk Priority Number.
Step 4: Aggregate the RPN to object and system level.

2. ***What key interests of the asset owner, the asset manager and the service provider need to be taken into account to identify the critical objects in a public infrastructure system?***

Literature states that the asset manager faces challenges of the differing interests of the three management levels when assessing the risks of assets. This also appeared to be the case when assessing the risks of objects to identify the critical objects. So the asset owner's interests in identifying the critical objects come from the public organization's social accountability, having a long-term and ethical point of view. Whereas the service providers are focused on their day-to-day work and have a short-term point of view. The service providers only want to consider the object being an object, and not some political added value. As a result, the asset managers' interests come from being able to optimally interchange between both levels. The asset manager therefore wants to be able to manage the interfaces between the management levels. Thus, the service provider should understand what information they have to provide to the asset manager, and the asset manager should be able to translate this in comprehensible language to the asset owner.

3. ***How can the asset managers correspond with these interests during the execution of the process of identifying the critical objects?***

To make the initial IDEF0 model comply with the interests of the three management levels, the model must comply with the process requirements from the three management levels to make the model work in practice. These process requirements were divided into two types of requirements. First, there are the requirements to make the IDEF0 model feasible in practice, which is keeping the model uniform for all types of objects, keeping it simple and therefore comprehensible. Second, there are the requirements to make the IDEF0 model reliable, by taking everything into account that increases the reliability of the identification of the critical objects, by keeping the model flexible to adapt to changes and by considering each object as an individual object.

Some of these requirements are opposing. For instance, the asset owner wants the asset manager to take everything into account, from the possible performance requirements to all possible risks, in order to make the outcome of the process reliable. However, imposingly, they also want all objects to be treated equally, which means they demand a uniform process. Also, the service providers want on the one hand a process that respects the diversity between objects, but on the other hand, they demand a comprehensible process. So, a large challenge for the asset manager while applying the IDEF0 model in practice, is to comply with all these opposing requirements.

Additionally, some requirements had an impact on the activities of the theoretical IDEF0 model. So were the clear requirements on being able to defend the RPNs to the strategic level. As a result, many asset managers did not only want to be able to express the RPN of the failure modes on object level, the asset managers also wanted to aggregate the RPN of the object to the subsystem level, such as the car network or a neighborhood which is a level that is easier for the asset owner to comprehend than the entire system or just one object.

Another requirement also had an impact on the execution of the theoretical IDEF0 model in practice. So did literature and experts point out that you cannot know the risks of the object, without knowing the risks of all components of the objects. However, large infrastructure systems can consist of hundreds if not thousands of objects with numerous components. Identifying all failure modes of all objects and then also assessing all risks of all these failure modes were impossible according to the asset managers. So, the theoretical IDEF0 model was found unfeasible and was in need of an alteration to make it more feasible.

Furthermore, other challenges were arising with the theoretical IDEF0 model. First, the probabilities of failure are never certain and cannot be predicted accurately and determining impacts is generally subjective. This makes the risk assessment less reliable. Second, the asset managers found the process complex. In order to inform the necessary people in practice, there was a need for an additional process model that was simpler and supported with visualizations. And last, assessing the risks of different types of objects was found challenging, because this is the same as comparing oranges to apples.

4. ***How does the process to identify critical objects in a public infrastructure system work in practice?***

Testing the initial IDEF0 model in practice resulted in a change in activities and requirements for making the process work in practice to overcome the expected challenges. The biggest alteration was leaving out the activity of identifying all failure modes of all objects because this was not feasible in practice. In return another activity was added to the new IDEF0 model. The purpose of this activity was to make the IDEF0 model more feasible by decreasing the number of risks that must be assessed to find the critical objects. This step is a filter process that first filters out the objects with the highest impacts. Then the second filter filters out the significant failure modes of these objects. This then becomes the input for the risk assessment. Moreover, it has been chosen to see the activity of designing the risk matrix as an individual activity that is separated from applying the risk matrix, since these two activities take a lot of time in practice and cannot be done simultaneously. Considering the requirement of the asset managers to change the last activity into aggregating the RPN to subsystem level as well, the following activities make up the final IDEF0 model:

Step 1: Translate the organizational goals and objectives into the performance requirements of the object.
Step 2: Design the risk matrix.
Step 3: Filter the potential critical objects and its significant failure modes.
Step 4: Assess the risks of the significant failure modes to determine the RPN.
Step 5: Aggregate the RPN to object, subsystem and system level.

During the testing, also preferences were arising for the predefined opposing requirements to overcome the challenges in practice. It became clear that the most important requirements were the feasibility requirements. These requirements were that the IDEF0 model must be uniform for all object types because this would make it easier to compare oranges to apples. And by keeping it simple and comprehensible the asset managers believed that this IDEF0 model has a bigger chance of succession in practice. As a result, these requirements determined the most important controls of the final IDEF0 model to make it work in practice.

11.2 | Answering the main research question

When the asset manager wants to systematically identify the critical public infrastructure objects whilst complying with the interests of the asset owner, the asset manager and the service provider, it is best to apply the final IDEF0 model with the defined controls that was developed using this research. If the asset manager wants this process to be feasible, it is of essence to apply the filtering process and consider the feasibility process requirements.

Whilst applying the IDEF0 model, the asset manager must be aware of the relations between the activities and the requirements of the three management levels to understand which choices have which type of effects. These effects can be both positive and negative. And the effects of these requirements are what can make this process challenging for the asset manager. Such a challenge is that a uniform process for all types of objects makes it possible to compare the various types of risks more, however, uniformity can also result into ambiguous objectives and KPIs. Therefore, during the application of the IDEF0 model, the asset manager must understand such challenges in order to cope with them.

To obtain the most value of the three management levels, the asset manager must include the three management levels in the IDEF0 model the right way. Not every activity has to be done together, but when there is an interface between the tactical and the strategic level, the strategic level must be included. Such as when the organizational goals and objectives are translated into KPIs and performance requirements for the objects. The same goes for the interfaces between the tactical and the operational level. This is for instance the case when the asset manager must determine the impact indicators for the risk matrix. These indicators must be measurable. Since some of these indicators will be measured by the service providers, they should know when such an indicator is measurable. Involving the right people at the right moment will contribute to a simpler process and a better outcome.

However, the true essence of the findings of this research is about being aware of the risks for the organization, and being aware of how the service providers can contribute to identifying and assessing these risks. And this awareness does not only rise among the asset managers, but also among the asset owners and the service providers. As a result, the asset managers can gain confidence in controlling the current risks of their objects.

Also, the essence lies in building a foundation to the need of being able to identify critical objects that is unknown in literature and unknown in practice. Besides, an asset management process that is systematic and creates a feasible top-down and a bottom-up approach is new and therefore valuable in the world of asset management. As a result, the final IDEF0 model with the corresponding requirements that comply with the interests of the three management levels elevates asset management to a higher level according to the standards of ISO 55000, filling up a substantial knowledge gap.

Additionally, the findings of this research is a solution to a societal problem that is expected to enlarge in the future. Public infrastructures can have economic, cultural and social effects, as does it have an influence on every single person that uses and pays for it. This person can even be you while driving to work, walking to the grocery store or simply said: every time you leave your house. Therefore, these findings fill in both a relevant research gap in literature and a knowledge gap in practice that will have a noteworthy contribution to the entire society.

12. RECOMMENDATIONS

Since this research topic covers something that is new to literature and new to practice and because the research contains several limitations, it can be said that further research is worthwhile. This chapter begins with enumerating some recommendations for further research that is mainly followed from the limitations, and ends with the recommendations for the municipality of Amsterdam.

12.1 | Recommendations for further research

The main limitations come from the sample of the empirical research. The process requirements of the three management levels were only derived from the municipality of Amsterdam. So, the results do not stand for a generalized outcome that is automatically applicable to all public organizations. This outcome is applicable to public organizations that are large, own a large number of objects and have a high maturity level. Therefore, recommendations for further research is to test the IDEF0 model and adapt if necessary by testing the model at the following public organizations:

- Similar public organizations, like the municipalities of The Hague and Utrecht, to see if the final IDEF0 model is there applicable there as well. If so, the IDEF0 model can be seen as a model that is more generalized than that it is only applicable at the municipality of Amsterdam.
- Public organizations owning a small number of objects. Possibly, such organizations do not have the problem of having numerous objects so for them it is easier to apply the IDEF0 model to each object. Therefore, the IDEF0 model can be expected to adapt in a certain extent.
- Smaller organizations. Presumably, these organizations have less means, such as people, money and time, to execute the IDEF0 model. This means that the model has to become more efficient so that it takes less people to execute it. But probably other requirements arise as well, which will influence the IDEF0 model.
- Parties with a higher maturity level in order to test to see if these parties prefer the reliability requirements and how this would then have an influence on the final IDEF0 model.

Another limitation of this research is that the IDEF0 model was not applied in practice fully. From the workshops it became clear that the outcome from applying it in practice was more valuable than conducting the ex-ante analyses. Therefore, there are still some uncertainties about the level of feasibility of the IDEF0 model. There is a chance that some issues are not foreseen yet. Therefore, a recommendation on further research is to continue this research by testing the rest of the IDEF0 model in practice.

A third important limitation of this research is that according to the explanations on IDEF0 models this research's final IDEF0 model shows the level on A0, however, it does not exactly say in detail how each activity must be executed. For instance, it does not explain how a risk matrix must be developed. Nevertheless, there is a lot of literature on all types of tools and methods available for the first three activities. Therefore, a valuable research would be to study the possible methods and tools for each activity considering the process requirements.

From comparing the results to the standards of ISO 55000, it became clear that the IDEF0 model does not cover all guidelines and standards of the ISO standards yet. Therefore, it would be valuable to fill in this gap. Therefore, the IDEF0 model can be developed further by taking a long term point of view considering future risks, adding the PDCA cycle to the IDEF0 model, and develop a leadership strategy for the implementation of the IDEF0 model in practice.

And the last recommendation on further research is to focus on the challenging interfaces between the management levels. For instance, how to stimulate a good collaboration between the three management levels in applying the IDEF0 model in practice? So how can the asset manager include the service providers the most effective way in developing a risk matrix and determining risks? Or what exact information does the asset manager need to successfully convince the asset owner? Also, the translation process from strategic language to the operational language back to the strategic is expected to be a big challenge. A research on how to include the asset owner and the service provider and how to manage the various types of information by developing a DFD model would be valuable for the application of the IDEF0 model in practice.

12.2 | Recommendations for the municipality of Amsterdam

The following section is directed to the municipality of Amsterdam. This section sums up my recommendations on identifying the critical objects of the public infrastructure system of Amsterdam. These recommendations are based on my observations and numerous interviews and workshops, but also the informal conversations at the coffee machine so to speak.

Knowledge development

The basis of identifying the critical objects is understanding assessing the risks of assets. The asset managers from the municipality of Amsterdam know good asset management from an operational point of view. But they could improve their knowledge on asset management from a strategic point of view. Currently they are concerned with how their objects are functioning, rather than how their objects can perform to add value to the municipality of Amsterdam; the strategic level. In other words, their mindset stays in the operational level and is not reaching the strategic level.

The reason for the asset managers not reaching the strategic level and therefore not implementing asset management according to the standards of ISO 55000, is that this way of thinking is completely new to most asset managers. This is noticeable as multiple asset managers had trouble understanding the difference between the performance and risks of their objects. The performances and risks of an object are next to the costs the main drivers of asset management according the ISO 55000 standards. It is an ambition of the municipality of Amsterdam to manage their assets based on these three drivers and implement asset management according to ISO 55000. Understanding the differences between the three drivers is therefore the fundamental basis of accomplishing this ambition.

Another reason is that the asset managers do not have time to educate themselves thoroughly in asset management according to the standards of ISO 55000. Possibly they are too busy with the reorganization and everything that is happening on the operational level. Therefore, my first recommendation is to educate the asset managers on what asset management is about in general and from a strategic point of view, but also how they can achieve this. This will contribute to understanding how a top-down and a bottom-up approach can be applied, starting and ending at the strategic level.

Another valuable opportunity for the asset managers is to find out the current available data that is already being collected and could be relevant as input for the process of identifying critical objects. An advice is to communicate with the service providers, since they can offer more information than is currently known. Overall the asset managers know what the service providers can and do, but they have limited ideas on what the service providers can offer for assessing risks. Then during the workshop with the civil construction department, where two service providers were present, it became clear that the service providers register all sorts of safety issues. Also, they mentioned that there is another department at the municipality that receives all sorts of complaints. In other words, impacts of risks that have already occurred are being registered without the asset managers' knowledge. Moreover, the policy department mentioned during the workshop that the municipality saves data that can be useful for measuring current performance and estimating impacts of object failure. For instance, the municipality offers data on the availability of the entire infrastructure system of Amsterdam. In conclusion, it is extremely valuable for the asset managers to communicate with the service provider and other departments of the municipality in order to find out what useful data is available, which can be a relevant input to the IDEF0 model for identifying the critical objects.

Process manager

The most valuable results are obtained if one process manager is chosen to be fully responsible for the IDEF0 model to be applied in practice and who contributes to guiding all asset managers in finding their critical objects in a uniform and comprehensible way. If not, it can be expected that in practice the IDEF0 model will not work out as planned. Some asset managers will not understand some things of the IDEF0 model and do not know who to contact for help. And nobody feels the responsibility for executing the IDEF0 model uniformly for all object types, because the asset managers are only concerning about their own object type. So a process manager is necessary who keeps the overview, feels responsible for executing the IDEF0 model according to the requirements and understands the entire IDEF0 model.

This process manager must understand asset management, risk management and the IDEF0 model thoroughly and must invest one if not two days per week in the application of the IDEF0 model. From experience, the workshops take a lot of time, because the topic is very new to everybody. Hence, a process manager is necessary who has enough time to implement the process of identifying the critical objects. Moreover, this person can after defining the performance requirements, also develop a plan for measuring the performances of all objects according to the standards of ISO 55000.

However, an expected challenge for this process manager will be finding the balance between having the overall responsibility and being sure that the asset managers also keep feeling responsible for executing the IDEF0 model to their objects. It can be expected that the more responsibility is given to a process manager, the less responsibility the asset managers will feel. Moreover, keeping the IDEF0 model uniform is expected to be a large challenge, because this is very new for the municipality of Amsterdam.

In the organization of the municipality of Amsterdam, as presented in figure 19 in chapter 4, this process manager could be best positioned in the program and reorganization department. This is because this department currently keeps the overview of all asset departments and is responsible for implementing asset management according to the standards of ISO. Since the current reorganization comes along with the development of various new processes for implementing asset management, is important that the IDEF0 model finds its place in these existing processes.

Process

From the results of this research it can easily be concluded that when the IDEF0 model is applied in practice it is important to start as simple as possible. So do not consider all KPIs with the perfect definitions and requirements, and do not develop an extensive risk matrix that includes long and incomprehensible descriptions. For now, it is more about developing an awareness and feeling of control over the current risks of object failure, rather than finding and treating all possible current risks. Then later when the IDEF0 model is repeated in the future, aspects such as the number of KPIs and the risk matrix can be extended and improved.

For now, the subsequent step would be allocating norms to the defined KPIs in order to develop the performance requirements uniformly for all objects. This can be done according to the theory explained in paragraph 10.3.5, which explains that performance requirements could be determined according to subsystems per performance criteria. However, this is still only a theory and is anything but simple. My recommendation, therefore, is to start with defining one norm per KPI for all objects into the extent that is possible. This is the utmost simplest way of defining the performance requirements. Try doing this with the tactical level including at least one person of each object type. Only then it is possible to keep the requirements uniform for all objects.

And then after, an attempt can be made for developing a uniform risk matrix for all objects. My recommendation is to first do this with the tactical level only, because only their knowledge is necessary first for keeping the matrix uniform. The purpose would then be to make a start and see into what extent it would even be possible to develop uniform impact indicators. This can be done by taking each impact criteria, such as the environment, and define the relating impact indicator. So if an object fails in performing in terms of the environment, what are the expected impacts? Then choose preferably one dominating type of impact indicator that tells the most about all impacts and one that is measurable. When each impact indicator is defined, each asset manager should check after the workshop with their service providers or with the department that saves data the feasibility of the impact indicators. Then it will become clear into what extent the indicators are truly SMART. Note that the same can be done with the performance indicators. When this is done, the asset managers can come back together and develop the rest of the risk matrix preferably in collaboration with an expert in developing risk matrices.

For the rest of the process data must be available. During the filtering process, my recommendation is therefore to look at the currently available data. The asset managers can look first at the impact criteria availability. This is the most important criterion for the municipality of Amsterdam. This means that all the objects in the busiest biking, car and waterway network should be selected. Information showing this is currently available. Moreover, information is currently being developed on the safety conditions of all objects. The next step can therefore be to determine which objects are currently failing in terms of the safety conditions. Also, it can be determined which objects are currently failing according to the current inspections. As a result, the objects with the current highest probabilities of failure, in terms of safety and technical conditions, that have a high impact on the availability of Amsterdam can now be filtered out. Then the asset managers can together with the service providers determine the significant failure modes of these filtered objects. For this, there are multiple methods available such as the Fault Tree Analysis (Riplová, 2007).

For all process steps additional workshops with ex-ante analyses can be executed. My recommendation is to organize such workshops between the activities of the IDEF0 model. As a result, everybody can make a prognosis easier on how the next activity will go if they know the current output of the last activity. And it can especially be expected that participants need to be further in the process to make more accurate prognoses for the last activity of aggregating the RPN. So since not all challenges of the IDEF0 model in practice can be foreseen with the findings of this research, a workshop with an ex-ante analysis at the start of each activity can be useful.

Motivation

And the last thing I want to say, I noticed a remarkable eagerness from the tactical level of the asset department. My recommendation is to use this eagerness and make it grow into motivation. When I told them the possibilities of mapping the current risks, I could see the enthusiasm in their eyes as if I was selling them an astonishing product on the market. I can say that this motivation is very beneficial for applying the IDEF0 model in practice, because this process would not be going anywhere if it was not for the asset managers.

If anything I have learned in this project it is how important it is to pay attention to risks in infrastructure systems. Currently, many people are doing so. But I had to find out the many gaps in their knowledge. It struck me indeed that infrastructure can have high impacts ranging from being social, to economic to even cultural. I feel a great satisfaction to be able to contribute with this research project to a much-needed knowledge that has such societal significance.

13. BIBLIOGRAPHY

Adams, J., Srinivasan, R., Parlikad, A. K., González-Prida, V., & Crespo, A. M. (2016). Towards Dynamic Criticality-Based Maintenance Strategy for Industrial Assets. *IFAC-PapersOnLine*, *49*(28), 103–107. https://doi.org/10.1016/j.ifacol.2016.11.018

Adams, K. M. (2015). *Non-functional Requirements in Systems Analysis and Design*. https://doi.org/10.1007/978-3-319-18344-2

Adesola, S., & Baines, T. (2013). Developing and evaluating a methodology for business process improvement. *Journal of Chemical Information and Modeling*, *53*(9), 1689–1699. https://doi.org/10.1017/CBO9781107415324.004

Aditya, P., & Kumar, U. (2010). Strategic issues in engineering asset performance measurement, (May).

Aguilar-Savén, R. S. (2004). Business process modelling: Review and framework. *International Journal of Production Economics*, *90*(2), 129–149. https://doi.org/10.1016/S0925-5273(03)00102-6

Akkermans, J. M., & Gordijn, J. (2003). Value-based requirements engineering: exploring innovative e-commerce ideas. *Requirements Engineering*, *8*(2), 114–134. https://doi.org/10.1007/s00766-003-0169-x

Amadi-Echendu, J., Brown, K., Willett, R., & Mathew, J. (2012). *Asset condition, information systems and decision models.* New York: Springer Science & Business Medi. Retrieved from http://download.springer.com/static/pdf/852/bok%253A978-1-4471-2924-0.pdf?originUrl=http%3A%2F%2Flink.springer.com%2Fbook%2F10.1007%2F978-1-4471-2924-0&token2=exp=1487607508~acl=%2Fstatic%2Fpdf%2F852%2Fbok%25253A978-1-4471-2924-0.pdf%3ForiginUrl%3Dhttp%25

Arthur, D., Hodkiewicz, M., Schoenmaker, R., & Muruvan, S. (2014a). Asset Planning Performance Measurement Framework, 73–78. https://doi.org/10.13140/2.1.3158.9128

Arthur, D., Hodkiewicz, M., Schoenmaker, R., & Muruvan, S. (2014b). Asset Planning Performance Measurement Framework. *Ceed.Uwa.Edu.Au*, (October), 73–78. https://doi.org/10.13140/2.1.3158.9128

Balzer, G., & Schorn, C. (2015). *Asset Management for Infrastructure Systems*. https://doi.org/10.1007/978-3-319-17879-0

Beautiful Views. (n.d.). Bridge, canal, Boats, Netherlands, autumn, Amsterdam.

Bernstein, I. N., & Freeman, H. E. (1975). *Academic and entrepreneurial research: Consequences of diversity in federal evaluation studies.* Russell Sage Foundation.

Breemer, J. J. a Van Den, Veenvliet, K. T., & Heijmans, H. W. N. (2009). RAMS and LCC in the design process of infrastructural construction projects : an implementation case.

CCPS. (2017). *Guidelines for Asset Integrity Management*. Hoboken, New Jersey: John Wiley & Sons.

Cheng, Z., Jia, X., Gao, P., Wu, S., & Wang, J. (2008). A framework for intelligent reliability centered maintenance analysis. *Reliability Engineering and System Safety*, *93*(6), 806–814. https://doi.org/10.1016/j.ress.2007.03.037

Cotaina, N., Carretero, J., Matos, F., Chabrol, J., Djeapragache, D., Prete.P, … Perez, J. (2000). Study of Existing Reliability Centered Maintenance (Rcm). Approaches used in Different Industries. *Universidad Politecnica de Madrid*, 1–97.

Crespo Márquez, A., Moreu de León, P., Gómez Fernández, J. F., Parra Márquez, C., & López Campos, M. (2009). The maintenance management framework. *Journal of Quality in Maintenance Engineering*, *15*(2), 167–178. https://doi.org/10.1108/13552510910961110

David, F. R. (1989). How companies define their mission. *Long Range Planning*, *22*(1), 90–97. https://doi.org/10.1016/0024-6301(89)90055-1

Davis, R. (2013). *An introduction to asset management*. Retrieved from www.eatechnology.com

Duijm, N. J. (2015). Recommendations on the use and design of risk matrices. *Safety Science*, *76*, 21–31. https://doi.org/10.1016/j.ssci.2015.02.014

Eckerson, W. W. (2009). Performance Management Strategies. *Business Intelligence Journal*, *14*(1), 24–27.

El-Diraby, T., Kinawy, S. N., & Piryonesi, M. (2017). *A Comprehensive Review of Approaches Used by Ontario Municipalities to Develop Road Asset Management Plans*.

Fernández, J., & Márquez, A. (2012). *Maintenance Management in Network Utilities*. (H. Pham, Ed.), *Springer*. London: Springer. https://doi.org/10.1007/978-1-4471-2757-4

Fylan, F. (2005). Semi-structured interviewing. A handbook of research methods for clinical and health psychology (pp. 65–78).

Ganesan, E., & Paturi, R. (2009). Key Performance Indicators Framework - A Method to Track Business Objectives, Link Business Strategy to Processes and Detail Importance of Key Performance Indicators in Enterprise Business Architecture. *15th Americas Conference on Information Systems (AMCIS) 2009*, 1–10. Retrieved from http://aisel.aisnet.org/amcis2009/736

Gemeente Amsterdam Verkeer en Openbare Ruimte. (2016). *Heel & Schoon*.

Guerrero, A. C., Guillen, A. J., & Gomez, J. F. (2013). A process to develop a quantitative FMECA analysis of critical systems in an offshore wind turbine. *Proceedings of 2013 International Conference on Renewable Energy Research and Applications, ICRERA 2013*, (October), 590–594. https://doi.org/10.1109/ICRERA.2013.6749824

Haiany, H. Al. (2016). *Reliability centered maintenance*. Luleå University of Technology. https://doi.org/doi:10.1201/9781420031843.ch6

Haider, A. (2013). *Information Systems for Engineering and Infrastructure Asset Management*. Springer Gabler. https://doi.org/10.1007/978-3-8349-4234-0

Hall, J. W., Masurier, J. Le, Taylor, C., Baker-Langman, E. A., & Davis, J. P. (2004). A decision-support methodology for performance-based asset management. *Civil Engineering and Environmental Systems*, *0*, 1–25. https://doi.org/10.1080/1028660031000135086

Healy, J. A. (2006). Criticality in asset management. *Work*, 1–15.

Houten, T. P. Van, & Zhang, L. L. (2010). Managing Assets in The Infrastructure Sector, *2*(2), 55–60. https://doi.org/10.5772/9722

Hull, E., Jackson, K., & Dick, J. (2006). *Requirements Engineering*. *Requirements Engineering*. Springer. https://doi.org/10.1007/978-1-84996-405-0

Hydro-Engineering Institute Sarajevo (HEIS) Project. (2014). Municipal Asset Management Toolkit (Guidelines for Local Decision Makers).

IAM. (2011). Asset Management – An Anatomy 3, (1.1), 1–84. https://doi.org/978-1-908891-00-6

ISO 31000. (2009). *Risk management–principles and guidelines*.

ISO 31000. (2015). *Risk* (Vol. 22). https://doi.org/10.1093/rpd/ncr142

ISO 55000. (2014). *Overzicht, principes en terminologie*.

ISO 55001. (2014). *Assetmanagement - Managementsystemen - Eisen*.

ISO 55002. (2014). *Richtlijnen voor het toepassen van ISO 55001*.

Kobbacy, K. A. H. (2008). *Complex System Maintenance Handbook*. (D. N. P. Murthy, Ed.). London: Springer. https://doi.org/10.1007/978-1-84800-011-7

Laue, M., Brown, K., Scherrer, P., & Keast, R. (2014). Integrated Strategic Asset Management: Frameworks and Dimensions. In *Infranomics* (Vol. 24, pp. 75–87). Springer. https://doi.org/10.1007/978-3-319-02493-6

Lei, T. van der, Herder, P., & Wijnia, Y. (2012). *Asset Management, The State of the Art in Europe from a Life Cycle Perspective*. Springer Netherlands. https://doi.org/10.1007/978-94-007-2724-3

Li, Q., & Chen, Y.-L. (2009). *Modeling and Analysis of Enterprise and Information Systems*.

https://doi.org/10.1007/978-3-540-89556-5

Lützkendorf, T., Speer, T., Szigeti, F., & Davis, G. (2005). A comparison of international classifications for performance requirements and building performance categories used in evaluation methods. *Proceedings of 11th Joint CIB International Symposium. Helsinki, Finland.*, 1–19.

Maia, I. R. D., & Chaves, G. M. M. (2016). Integration of Risk Management into Strategic Planning: A New Comprehensive Approach. *Enterprise Risk Management Symposium*, (April).

Marhavilas, P. K., & Koulouriotis, D. E. (2008). A risk-estimation methodological framework using quantitative assessment techniques and real accidents' data: Application in an aluminum extrusion industry. *Journal of Loss Prevention in the Process Industries*, *21*(6), 596–603. https://doi.org/10.1016/j.jlp.2008.04.009

Marsh, P. D. V. (2000). *Contracting for engineering and construction projects*. Gower Publishing, Ltd.

Mil, B. P. A. van, Dijkzeul, A. E., & Pennen, R. M. A. van der. (2006). *Risk Modelling Handbook*. Utrecht.

Mitchell, J. S. (2002). *Physical Asset Management*. Retrieved from http://www.maintenancebenchmarking.com/best_practice_maintenance.htm

Moubrai, J. (1997). *Reliability Centered Maintenance*. Oxford: Butterworth-Heineman.

Neves, L. C., & Frangopol, D. M. (2005). Condition, safety and cost profiles for deteriorating structures with emphasis on bridges. *Reliability Engineering and System Safety*, *89*(2), 185–198. https://doi.org/10.1016/j.ress.2004.08.018

Nowlan, F. S., & Heap, H. F. (1978). Reliability-Centered Maintenance. Springfield, Virginia, US.: National Technical Information Service, U.S. Department of Commerce.

Osterwalder, A., & Pigneur, Y. (2005). Clarifying Business Models : Origins , Present , and Future of the Concept Clarifying Business Models : Origins , Present , and Future of the Concept. *Communications of Association for Information Systems*, *15*(May).

Parlikad, A. K., & Jafari, M. (2016). Challenges in infrastructure asset management. *IFAC-PapersOnLine*, *49*(28), 185–190. https://doi.org/10.1016/j.ifacol.2016.11.032

PAS 55-2:2008. (2008). *Asset Management. Guidelines for Aapplication of PAS 55-1.*

Patel, M. X. (2003). Challenges in recruitment of research participants. *Advances in Psychiatric Treatment*, *9*(3), 229–238. https://doi.org/10.1192/apt.9.3.229

Purdy, G. (2010). ISO 31000:2009 - Setting a new standard for risk management: Perspective. *Risk Analysis*, *30*(6), 881–886. https://doi.org/10.1111/j.1539-6924.2010.01442.x

Radim, B., & Soares, C. G. (2009). *Reliability, Risk, and Safety: Three Volume Set: Theory and Applications*. (S. Martorell, Ed.) (Vol. 2). CRC Press.

Rausand, M. (1998). Reliability centered maintenance. *Reliability Engineering and System Safety*, *60*, 121–132. https://doi.org/10.1007/978-1-84882-472-0_16

Riplová, K. (2007). Tool of Risk Management : Failure Mode and Effects Analysis and Failure Modes , Effects and Criticality Analysis, *5*(1), 111–120.

Schoenmaker, R., & Verlaan, J. (2013). Analysing Outsourcing Policies In An Asset Management Context : A Six-Stage Model. *Institute of Public Works Engineering Australasia*, (August).

Shen, H., Wall, B., Zaremba, M., Chen, Y., & Browne, J. (2004). Integration of business modelling methods for enterprise information system analysis and user requirements gathering. *Computers in Industry*, *54*(3), 307–323. https://doi.org/10.1016/j.compind.2003.07.009

Smith, P. (2006). Towards an Assessment Tool for the Strategic Management of Asset. *Engineering*, 1–11.

Sun, Y., Fidge, C., & Ma, L. (2014). A Generic Split Process Model for Asset Management Decision-Making. *Engineering*, (March).

Tan, A., Weijnen, M., Lee, J., & Ype, W. (2012). *Engineering Asset Management and Infrastructure Sustainability*. *Engineering Asset Management and Infrastructure Sustainability SE - 71*. London: Springer. https://doi.org/10.1007/978-0-85729-493-7_71

Tangkawarow, I. R. H. T., & Waworuntu, J. (2016). A Comparative of business process modelling techniques. *Materials Science and Engineering*, *128*. https://doi.org/10.1088/1757-899X/128/1/012010

The University of Adelaide. (2009). Risk Management Handbook. *Annals of Physics*, *54*, 258. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:No+Title+Avail#0

Theoharidou, M., Kotzanikolaou, P., & Gritza-Lis, D. (2009). Risk-based criticality analysis. *IFIP Advances in Information and Communication Technology*, *311*, 35–49. https://doi.org/10.1007/978-3-642-04798-5_3

Thompson, J. L. (1997). *Lead with Vision: manage the strategic challenge*. London: International Thompson Business Press.

Velde, J. van der, Klatter, L., & Bakker, J. (2012). A holistic approach to asset management in the Netherlands. *Structure and Infrastructure Engineering*, 1–9.

Verlaan, J. G., & Schoenmaker, R. (2013). Infrastructure Management: dynamic control of assets. *Institute of Public Works Engineering Australasia 2013 Conference*, (August 2013), 1–9.

Wang, J., Attwater, A., Parlikad, A., & Russell, P. (2014). Measuring the performance of asset management systems. https://doi.org/10.1049/cp.2014.1046

Wang, W. (2009). Handbook of Maintenance Management and Engineering. *Handbook of Maintenance Management and Engineering*, (January 2009), 479–498. https://doi.org/10.1007/978-1-84882-472-0

Wasson, C. S. (2006). *System engineering analysis, design, and development : concepts, principles, and practices*.

Wei, B. C. (1991). A unified approach to failure mode, effects and criticality analysis (FMECA). *Reliability and Maintainability Symposium, 1991. Proceedings., Annual*, 260–271. https://doi.org/10.1109/ARMS.1991.154445

Wijnia, Y. C., & Herder, P. M. (2007). The State of Asset Management in the Netherlands. *Next Generation Infrastructure Foundati*, (1812), 1–9.

Wijnia, Y., & Croon, J. De. (2015). The Asset Management Process Reference Model for Infrastructures, 1–11.

Woodhouse, J. (2007). Asset Management : Joining up the jigsaw puzzle –. *ME Plant & Maintenance*, *Sept/Oct*, 12–15.

Zeb, J., Froese, T., & Vanier, D. (2013). Infrastructure Management Process Maturity Model : Development and Testing. *Journal of Sustainable Development*, *6*(September), 16. https://doi.org/10.5539/jsd.v6n11p1

Zeb, J., & Nasir, H. (2016). Introduction to an Asset Management Program Development Methodology (p. 12).

Appendix A - Interview Design (Experts)

Doel: Inhoudelijkere kennis en ervaring verzamelen en objectievere eisen van experts verzamelen

Algemeen:

1. In wat geef jij precies **advies** aan gemeente A'dam?
2. Hoeveel **ervaring** heb jij met het beoordelen van risico's van assets?
3. Wat is het **doel** van assets sturen op risico's?
4. Heb jij enig idee wat de **huidige situatie** is wat betreft het beoordelen van risico's? Zo ja, ben jij het hiermee eens?
5. Op welk **niveau** van de decompositie (deelsystemen, objecten, componenten) moeten de kritieke assets gevonden worden en door wie?
6. Wat denk jij dat de **eisen** van elk niveau zijn voor het proces van het vinden van kritieke assets?
7. Welke **informatie** is voor dit proces nodig en waar komt de informatie vandaag?

Inhoudelijk:

1. Hoe zouden de prestatie-eisen gedefinieerd moeten worden? Waarom?
2. Hoe wordt de faalkans bepaald?
3. Hoe worden de impact criteria en wegingsfactoren bepaald?
4. Hoe bepaal je de faalwijzen en oorzaken?
5. Wat zijn de grote uitdagingen hiervan?
6. Hoe vaak moeten risico's beoordeeld worden? Waarvan is dit afhankelijk?
7. Voor het vinden van risico's, wat zijn de voor en nadelen van:
    a. Alleen technische faalmechanismen beoordelen?
    b. Alleen kritieke faalmechanismen van object beoordelen?
    c. Alleen technische impactcriteria kiezen?

Appendix B - Interview Design (Organization)

Doel: Bewustzijn creëren en eisen verzamelen voor het proces van het vinden van de kritieke assets

1. Wat is de **huidige situatie**? Hoe worden nu risico's beoordeeld? Welke informatie om dit te doen is al aanwezig/compleet?
2. Wat is voor jouw organisatieonderdeel het **doel** van het bepalen van kritieke assets? Wat maakt een asset nou echt kritiek?
3. Op welk **niveau** van de decompositie (deelsystemen, objecten, componenten) moeten de kritieke assets gevonden worden en door wie?
4. Hoe komen we aan de **informatie** voor het vinden van kritieke assets? Van wie komt de benodigde informatie? Wanneer krijg je deze informatie?
5. Hoe **gebruik** je deze informatie om de kritieke assets te bepalen?
6. Wat zijn de verwachte **uitdagingen** voor jouw organisatieonderdeel voor het proces van het vinden van de kritieke assets?
7. Wat zijn de **eisen** vanuit jouw organisatieonderdeel voor dit proces?

Appendix C - Overview Interviewees

Experts	
Expert Asset Management	April 18 June 2
Expert Asset Management	April 26
Expert Asset and Risk Management	May 2
Expert Process and Asset Management	May 4
Expert Asset Management	May 17

Program/asset managers (strategic)	
Head of Program and Reorganization	March 22
Program Manager from Program and Reorganization	April 26
Asset Manager Civil Constructions	May 9

Service providers (operational)	
Manager of bridges	May 15
Monitoring and Inspections from Civil Constructions	May 18
Monitoring and Inspections from Civil Constructions	May 24

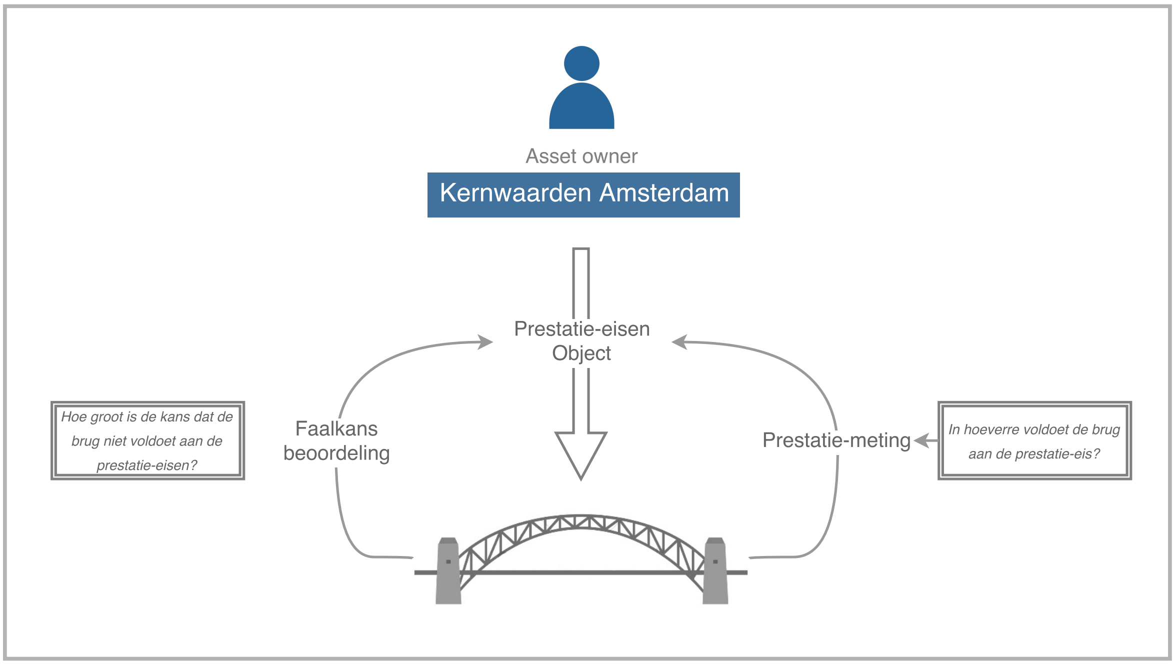
Asset managers (tactical)	
Asset Manager Pavement	May 9
Asset Manager Civil Constructions	May 9 May 17
Asset Manager Traffic Signal System	May 9
Asset Manager Tunnels	May 10
Asset Manager Green	May 10
All asset and program managers from civil construction	May 11
Program manager from Civil Constructions	May 17
Program manager from Civil Constructions	May 18

Validation	
Expert Risk Management	June 12
Policy Department (Municipality of Amsterdam)	June 12
Project Risk Manager (IBA)	June 13
Expert Asset Management (RWS)	June 13

Table 5 | Overview interviewees

Appendix D – Additional visualizations

Monitoring & Inspectie:



Definitie: Falen & Risico Asset

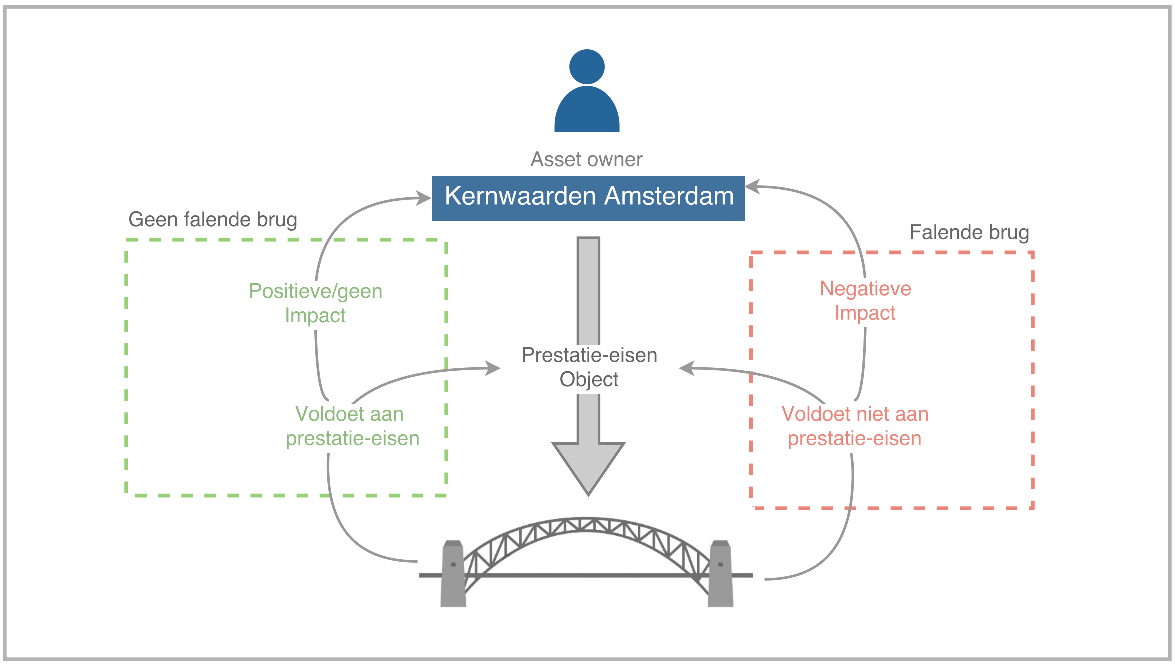


Figure 42 | Difference between performance and risk

Appendix E – Interests

	Asset Owner	Asset Manager	Service Provider
Line of Sight (Goals & Objectives Allignment)	Decisions must reflect organizational goals and objectives which are non-technical	Asset manager must provide any connection between decisions and organizational goals and objectives	Want to keep working with what they know and understand, which is the technical content. So, 1) they do not understand the organizational goals and objectives, and 2) they cannot assess non-technical criteria (such as political requirements)
Language	Wants a non-technical explanation	Must translate technical into non-technical information	
Usable information	Expect substantiated information (transparant and traceable risks)	Need reliable information Need a clear overview of information Need advice from the service providers	They need a simple form of registration Need help with not providing an overload of unusable information Need help in communicating their knowledge in a strategic/AM language
Time vision	Long-term vision	Medium-term vision	Short-term vision

Table 6 | Overview interests

Appendix F – Requirements

	Asset Owner		Asset Manager		Service Provider	
Organizational Goals	Asset management decisions reflect organization's goal and policy	3	Considering impact on **organizational goals**	6	-	
Unifor	Urban **uniformity**	3	**Uniformal** method	4	-	
Information	**Understandable information** from asset manager	1	Need a **complete, quick and easy** overview of all risks	3	-	
	Risks must be **transparant and traceable; Information must be substantiated**	2	Clearly translated through all management/asset **levels**	1		
			A clear translation between the information provided by the **service providers** and the possible **maintenance measures**	1		
	The output for assessing the object's risks need to be **comparable**	3	The output for assessing the object's risks need to be able to be translated to the entire **system's** and **areas'** criticality	5		
Proce	-		The process must be **dynamic/flexible**	2	-	
			Need a **clear, easy and realistic** process for determining critical objects	3		
			Performance requirements must represent the necessary performance of an asset **correctly**	4		
			Failure modes must look at failure modes besides the technical/internal causes	3		
Informatio	-		Know how to deal with **unavailable information**	3	-	
			Use **historic data** to determine the most likely probability of failure	3		
			Need **usable information** from service providers to make decisions (objective, reliable, on time)	4	Need **enough time** to execute assignments	1
					The guidelines for inspection must **clear and easy**	2
					Cannot report **non-technical** criteria	3
			There is a need for **filtering** the focus on assets/ failure modes because of the great amount	5	Need to provide only information on **selected elements** of object that is necessary	3

Table 7 | Structuring requirements based on type of requirements

Appendix G – Prioritization Analysis

	Asset Owner		Asset Manager		Service Provider		Service Provider		# TOTAL
Process as a	applied to every type of asset as much as possible: A uniform process	3	applied to every type of asset as much as possible: A uniform process	4					7
			The process shows a holistic view, integrating all important aspects	4			The process shows a holistic view, integrating all important aspects	2	6
			flexible and how changes can be made	3			flexible and how changes can be made	1	4
			The process steps must be easy to understand	3					3
Step 1: Definition P Requirem	The performance requirements must be the same for every asset: Uniform process	3	The performance requirements must be the same/not too many for every asset	3			Do not define too many performance requirements	2	8
	Performance-requirements should be derived from the organizational goals and objectives	3	Performance-requirements should be derived from the organizational goals and objectives	6					9
			The performance requirements must be higher if the assets have higher impacts during failure	3					3
	The performance-requirements may not miss anything important	2	The performance-requirements may not miss anything important	4			The performance-requirements may not miss anything important	2	6
			Performance-requirements and - indicators must be measurable (SMART)	2			Performance-requirements and - indicators must be measurable (SMART)	1	3
Step 2: Identification F			Non-functional failure modes must be taken into account	3					3
			Non-technical causes must be taken into account	3					3
Step 3: Criticality A			Organizational goals must be reflected in the impact criteria and its scale and its weighting factors	6					6
			Take into account the capabilities of the service providers	4	Need enough time to execute their tasks	1			5
			The weighing factors and impact scales must be easily adjusted to reflect changes in impacts	2			The weighing factors and impact scales must be easily adjusted to reflect changes in impacts	1	3
			Do not monitor everything all the time (focus only on that which is critical/will become critical)	5	Want to provide only information on selected elements of object that is necessary	3			8
			Descriptions of the scale of impact criteria must be SMART	4	Guidelines for monitoring and inspection must be comprehensible, do not ask for non-technical inspections	2	Descriptions of the scale of impact criteria must be SMART		6
			Use knowledge and experience from service providers as advice	3			Use knowledge and experience from service providers as advice	1	4
			The output determining the criticality must be quantitative and	5			The output determining the criticality must be quantitative and	2	7
			Need a complete, clear and easy overview of all risks	4					4
			Monitor changes that affect the probability or impact of failure	2			Monitor changes that affect the probability or impact of failure	2	4
Step 4: Aggre Critica			Need an overview of the critical assets of a system and a region	5			Need an overview of the critical assets of a system and a region	2	7
			The increased impact of assets failing together must be taken into	2			The increased impact of assets failing together must be taken into	2	4
	The output of the aggregated information must be comparable and reliable	3	The output of the aggregated information must be comparable and reliable	5					8
	The output of the aggregated information must be able to be explained in terms of strategic language (so no technical related explanations)	2	The output of the aggregated information must be able to be explained in terms of strategic language (so no technical related explanations)	5					7

Table 8 | Prioritization of Requirements

Appendix H – Literature Gap for RPN Aggregation

Purpose: To find out how far research is when it comes to aggregating RPN from failure modes of an object to relevant subsystems to the entire asset system.

Requirements for literature:

- Must take into account the same type of physical assets
- Must take into account the same type of sub systems (networks and regions)
- Must take into account non-technical impacts

Research gate

Used word:	Outcome:
Risk aggregation	Publications describe the wrong contexts, such as risks of financial assets
Risk aggregation assets	Nothing relevant
Risk aggregation infrastructure	Nothing relevant
Risk priority number aggregation	Publications with the context of technical engineering on component level. Not really focused on aggregation.
Risk priority number aggregation infrastructure	Same results as previous search
Criticality number aggregation	Nothing relevant
Criticality number aggregation infrastructure	Results are more focused on system's engineering, which would be relevant by aggregating availability risks. However, this is too complex for now.
Total risk number infrastructure system	Nothing relevant
Total risk number assets	Nothing relevant
Total risk number asset management	A new book called: **Integrated Asset Management for Corridor Infrastructure : A Wider Asset Management Perspective for an Enhanced Level of Service.** Requested full text.
Aggregation societal risks	No system context
Aggregation societal risks infrastructure system	No aggregation
Risk evaluation infrastructure	Nothing relevant
infrastructure assets car network	**Integrated Asset Management for Corridor Infrastructure : A Wider Asset Management Perspective for an Enhanced Level of Service.**
Infrastructure assets car network region	Same as previous

Scholar Google and Books

Used word:	Outcome:
Risk aggregation	Nothing relevant
Risk aggregation assets	Financial assets
Risk aggregation infrastructure	System's engineering (no focus on aggregation)
Risk priority number aggregation	No focus on aggregation
Risk priority number aggregation infrastructure	Nothing relevant
Criticality number aggregation	Nothing relevant
Criticality number aggregation infrastructure	Nothing relevant
Total risk number infrastructure system	Nothing relevant
Total risk number assets	Nothing relevant

Total risk number asset management	Nothing relevant
Aggregation societal social risks	Nothing relevant
Aggregation societal social risks infrastructure system	Nothing relevant
infrastructure assets car network region	Nothing relevant

Appendix I – Program Workshop 1

Workshop Prestaties 17-09-2017

Aanwezig:
Kennis en Kaders
Adviseur Tunnels
IHP-trekker Groen
Controller Assets (financieel 1 A H&S)
IHP-trekker
Secretaris Programmeren
Adviseur AM Civiele Constructies (IHP-trekker)
Procesbegeleider van programmering van gebieden en IHP's
Adviseur AM Civiele Constructies (extern)

Wat moeten we doen?

- Uitgangspunt: SMART doorvertalen van **Functionaliteit, duurzaamheid en aantrekkelijkheid** naar de prestatie eisen van een opererende asset
- Uniforme ambities en KPIs definiëren

---- gebruik voorbeelden, o.a. Rotterdam -----

Opdracht 1: Definiëren Ambitie Assets

1. Brainstorm in groepen van 2

- Welke ambities voor alle assets dragen bij aan.....
  .... De veiligheid van de openbare ruimte? *(Functionaliteit)*
  .... De beschikbaarheid van de openbare ruimte? *(Functionaliteit)*
  .... Een duurzame openbare ruimte? *(Duurzaamheid)*
  .... Een leefbare openbare ruimte? (*Aantrekkelijkheid)*
- Zijn er nog specifieke ambities voor bepaalde asset groepen of afwijkingen?

2. Gezamenlijk doornemen en kijken naar de passende ambities
3. Ambities beter definiëren indien nodig

Opdracht 2: Definiëren Prestatie-indicatoren

1. Brainstorm

- Welke prestatie-indicatoren dienen gemeten te worden om te controleren of jouw assets voldoen aan de voorop gedefinieerde ambities voor de assets in de openbare ruimte?
- Welke prestatie-eis hoort hier kwantitatief bij? (wat is de norm als we het goed doen?)
  Gebruik verschillende brillen o.a.: (1) Technisch, (2) wetgeving, (3) gebruikers/ omgeving, (4) prestaties m.b.t. tevredenheid, wat haalde onlangs de krant?

Vragen:

- ✓ Draagt de indicator bij aan de gewenste prestaties en eisen voor alle assets in de openbare ruimte?
- ✓ Zijn er conflicterende prestaties of eisen?

2. Gezamenlijk doornemen opbrengst indicatoren

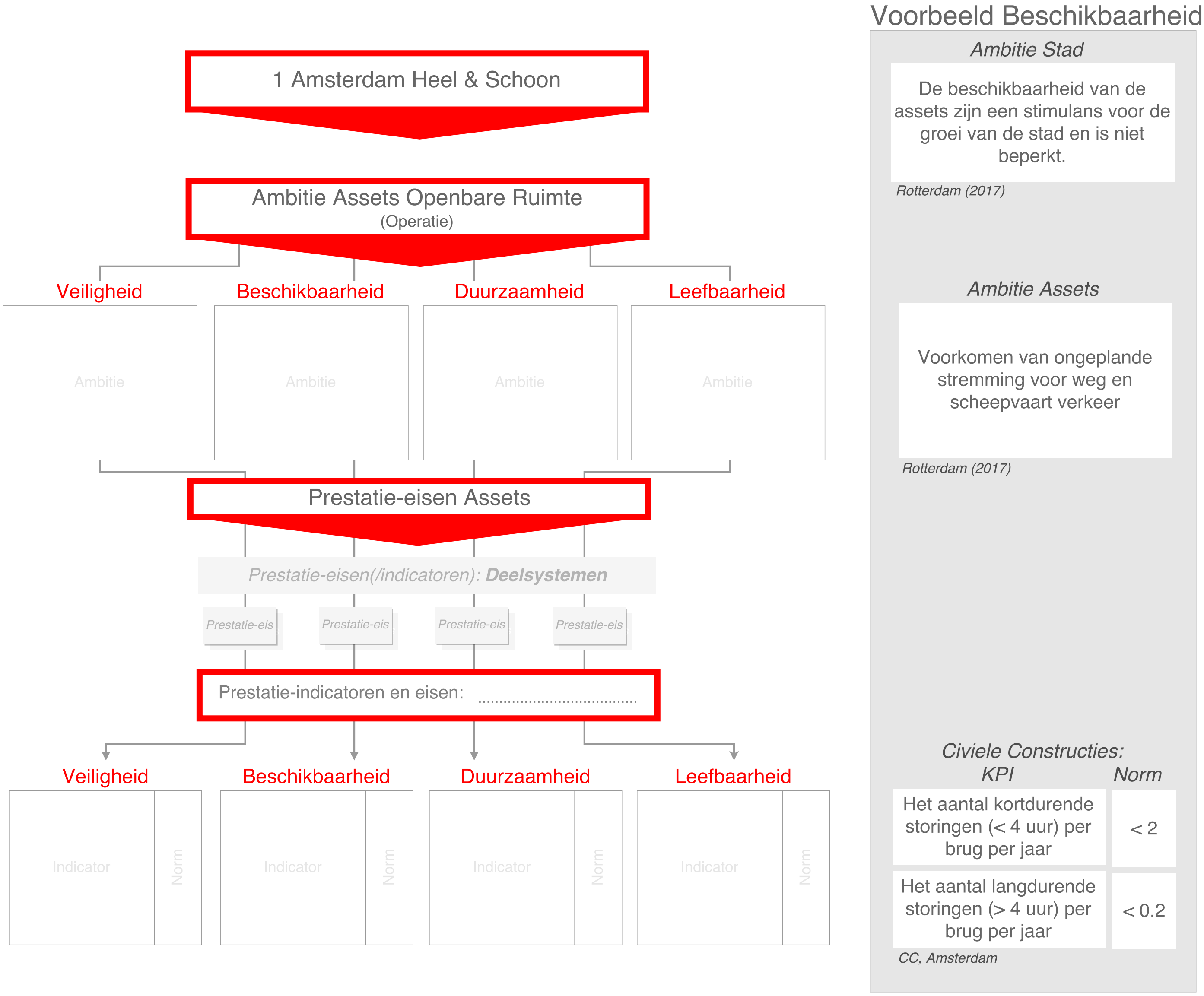


Figure 43 | Workshop form

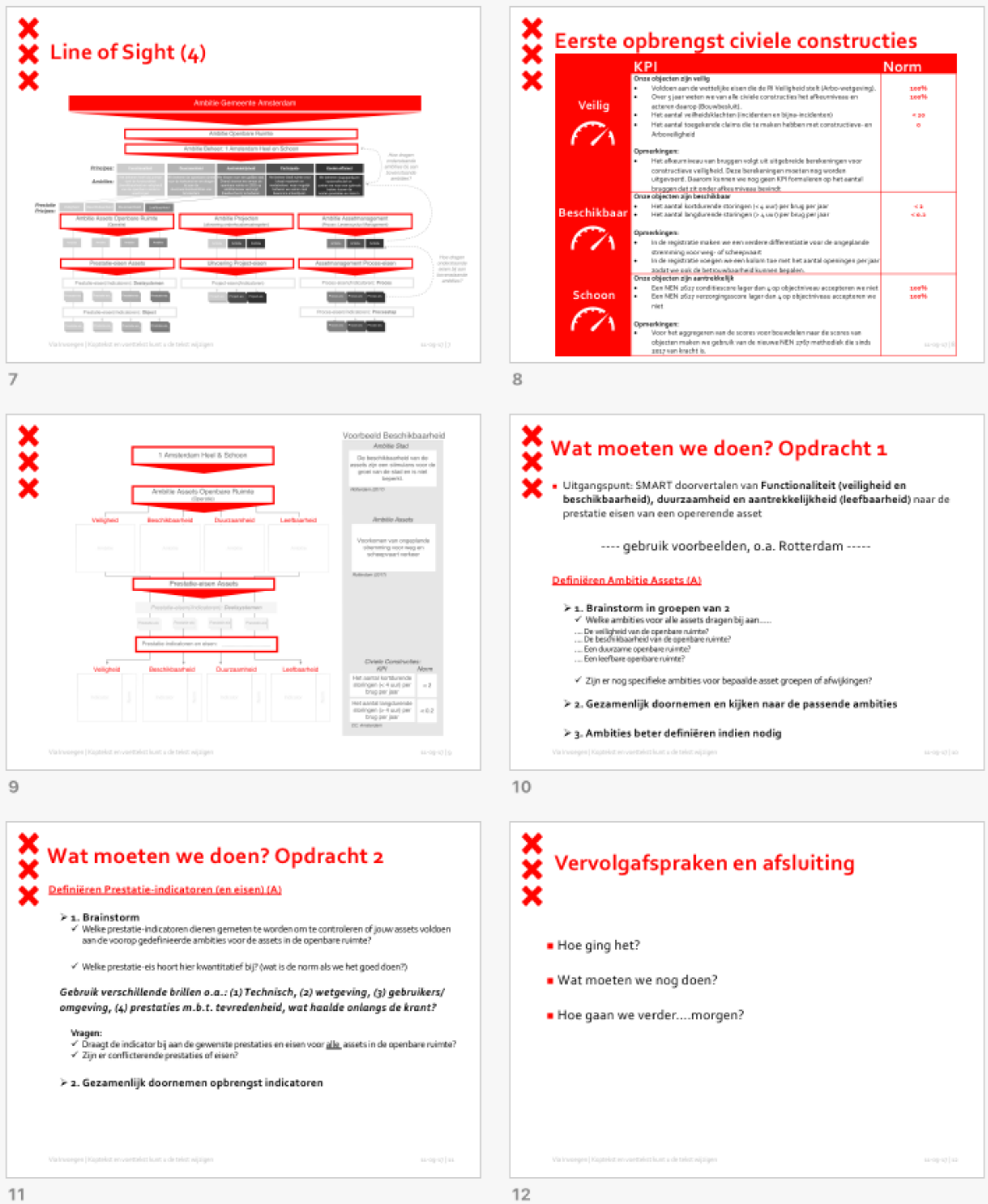


Figure 44 | Powerpoint workshop 1

Appendix J – Different types of objectives and KPIs

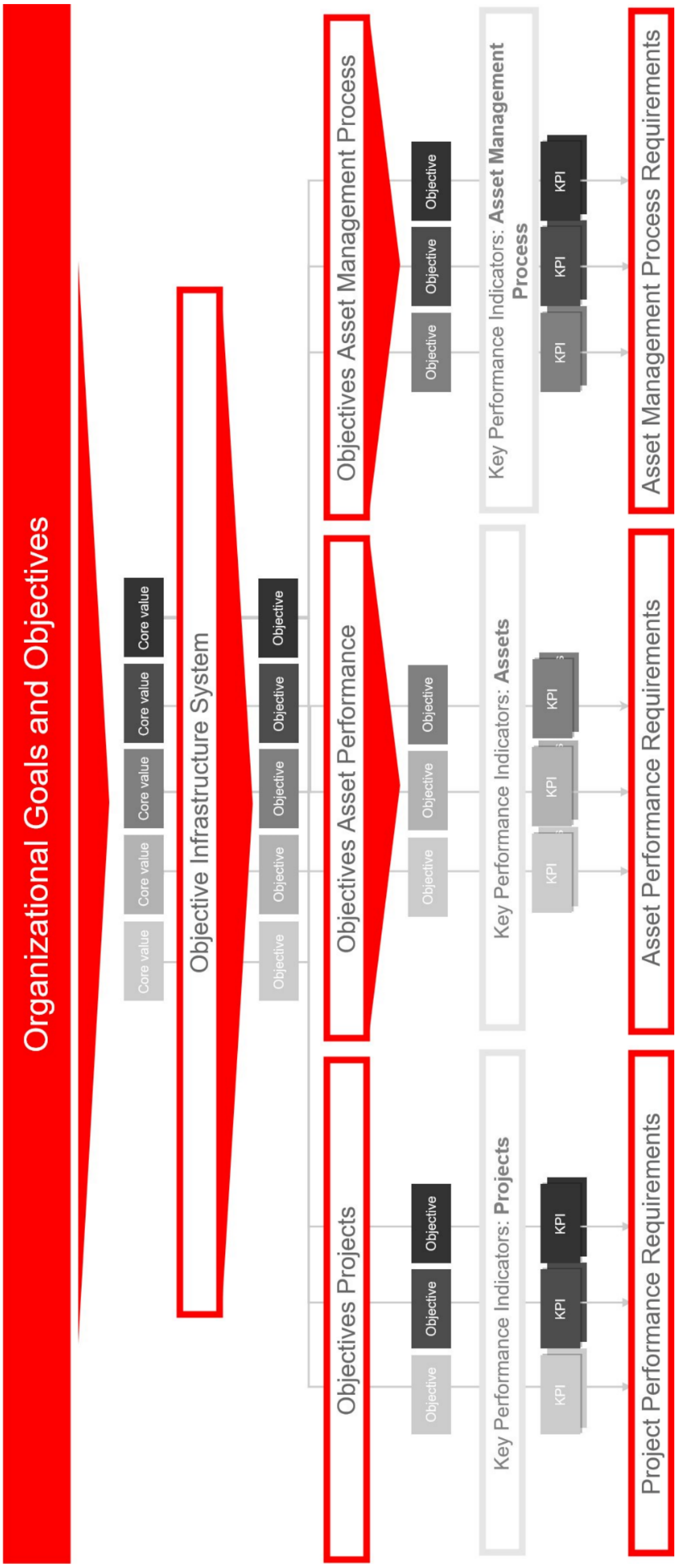


Figure 45 | Different types of objectives and KPIs in asset management

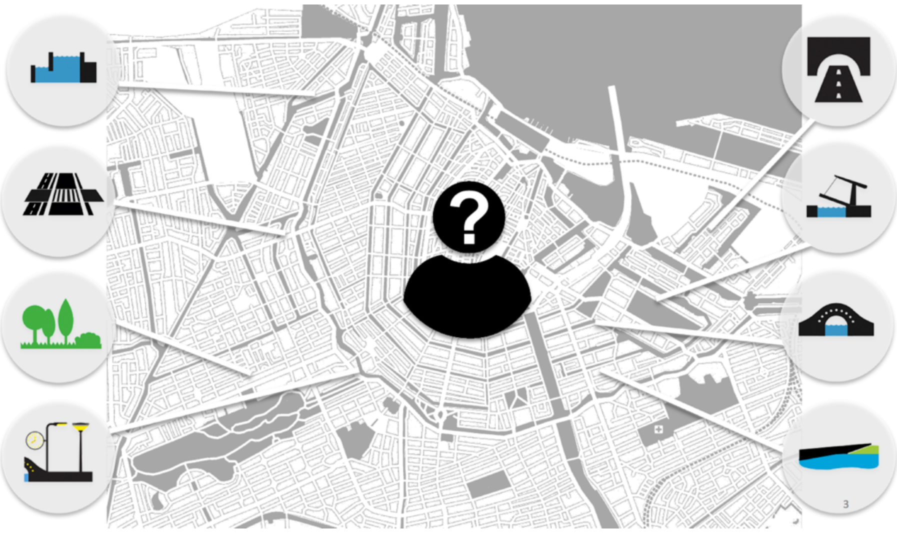
Appendix K – Risk Matrix Civil Construction

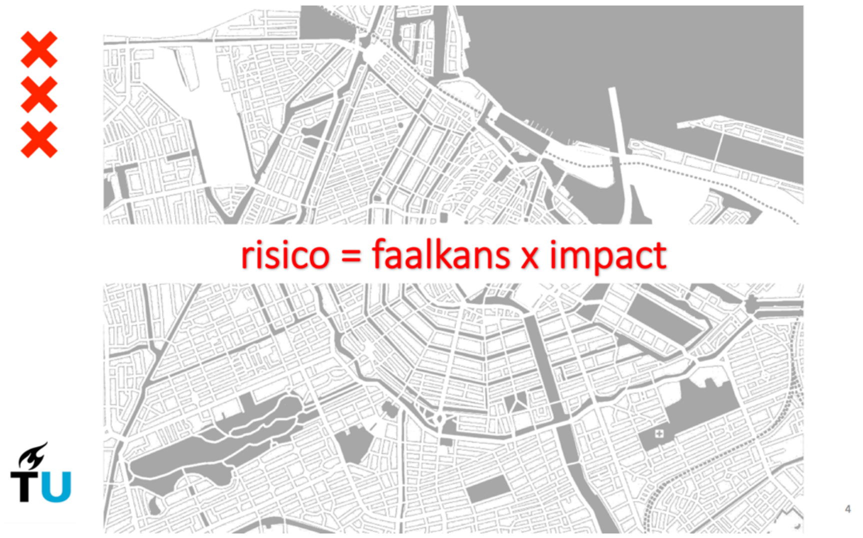
ERNST					FAALKANS					
Functioneel		Aantrekkelijk	Efficiency	Duurzaam						
Veiligheid	Niet-beschikbaar	Leefbaarheid	Gevolgkosten	Milieu	> 30 jaar	10 jaar - 30 jaar	3 jaar - 10 jaar	1 jaar - 3 jaar	Maandelijks	Wekelijks
Geen veiligheids-incident	< 1 uur	Geen negatieve aandacht Geen gevolgen voor de reiziger	<€ 5.000,-	Incidentele klacht Geen effect op milieu						
Ongeval/incident zonder letsel	> 1 uur < 4 uur	Negatieve aandacht in plaatselijke pers Beperkte (<1 dag) hinder voor reizigers en of bewoners	> € 5.000 < € 20.000,-	Meerdere klachten Gevolgen voor milieu beperkt, lokaal en beheersbaar.						
Ongeval met middelmatig letsel	> 4 uur < 1 dag	Negatieve aandacht in regionale pers Kortdurige (< 1 week) hinder voor reizigers en of bewoners	> € 20.000,- < € 100.000,-	Stucturele aanhoudende klachten Gevolgen voor milieu lokaal, lichte verontreiniging						
Ongeval met niet blijvend zwaar letsel	> 1 dag < 1 week	Korte negatieve aandacht in nationale pers Ernstige maar kortdurende (< 1 maand) hinder voor reizigers of bewoners	> € 100.000,- < € 500.000,-	Gevolgen voor milieu lokaal, verontreiniging die sanering behoeft Aansprakelijk.						
Ongeval met blijvend letsel	> 1 week < 1 maand	Negatieve aandacht in nationale pers. Langdurige (< 1 jaar) ernstige hinder voor reizigers of bewoners	> € 500.000,- < € 1000.000,-	Grootschalige verontreiniging bodem/water, maatregelen nodig Aansprakelijkheid en aanhoudende klachten, juridisch geschil.						
Dodelijk ongeval	> 1 maand	Langdurige negatieve aandacht in (inter)nationale pers Zeer langdurige (> 1 jaar) ernstige hinder voor reizigers of bewoners	> € 1.000.000,-	Ernstige milieuschade. Ingrijpende herstelmaatregelen nodig met blijvende schade Langdurige juridische nasleep						

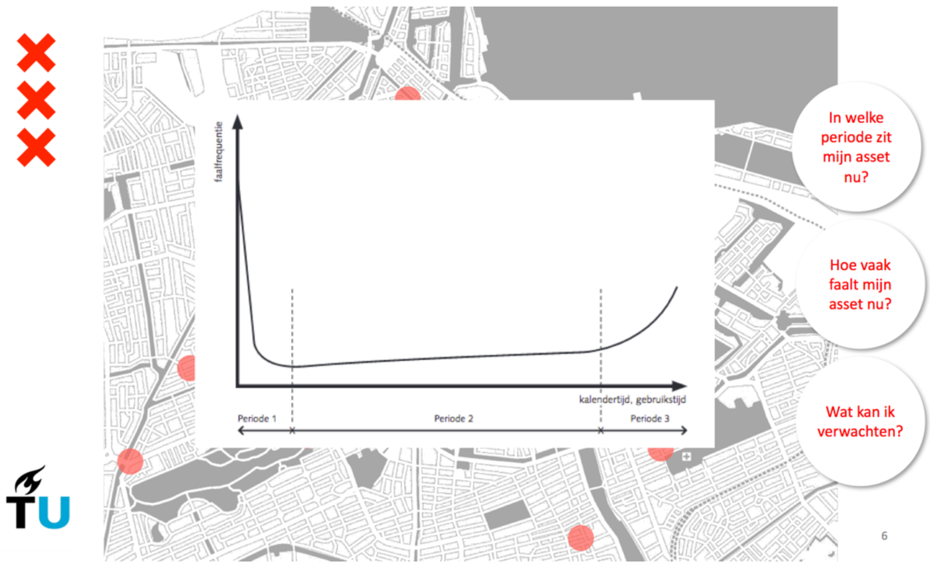
Table 9 | Risk matrix civil construction assets

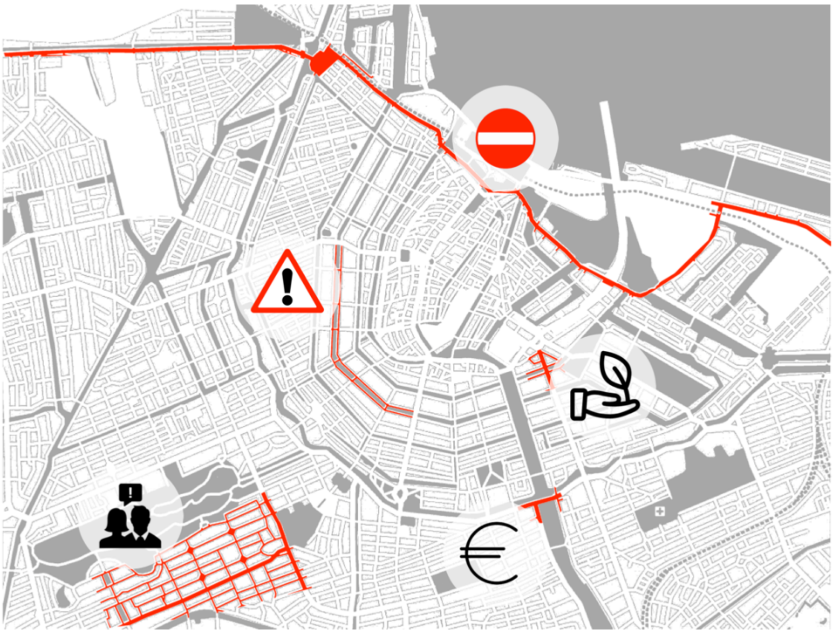
Appendix L – Program Workshop 3

Figure 46 | Powerpoints workshop 3


3

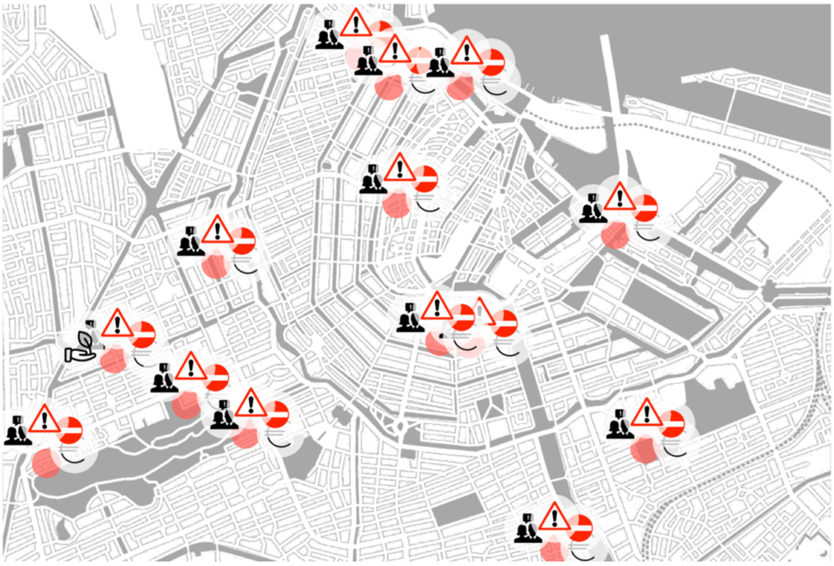

risico = faalkans x impact
4


faalfrequentie
kalendertijd, gebruikstijd
Periode 1
Periode 2
Periode 3
In welke periode zit mijn asset nu?
Hoe vaak faalt mijn asset nu?
Wat kan ik verwachten?
6



8

Risico = Faalkans x Impact



9

ERNST					FAALKANS					
Functioneel		Aantrekkelijk	Efficiency	Duurzaam						
Veiligheid	Niet-beschikbaar	Leefbaarheid	Gevolgkosten	Milieu	> 30 jaar	10 jaar - 30 jaar	3 jaar - 10 jaar	1 jaar - 3 jaar	Maandelijks	Wekelijks
Ongeval/incident zonder letsel	> 1 uur < 4 uur	Negatieve aandacht in plaatselijke pers Beperkte (<1 dag) hinder voor reizigers en of bewoners	> € 5.000 < € 20.000,-	Meerdere klachten Gevolgen voor milieu beperkt, lokaal en beheersbaar.						
Ongeval met middelmatig letsel	> 4 uur < 1 dag	Negatieve aandacht in regionale pers Kortdurige (< 1 week) hinder voor reizigers en of bewoners	> € 20.000,- < € 100.000,-	Stucturele aanhoudende klachten Gevolgen voor milieu lokaal, lichte verontreiniging						
Ongeval met niet blijvend zwaar letsel	> 1 dag < 1 week	Korte negatieve aandacht in nationale pers Ernstige maar kortdurende (< 1 maand) hinder voor reizigers of bewoners	> € 100.000,- < € 500.000,-	Gevolgen voor milieu lokaal, verontreiniging die sanering behoeft Aansprakelijk.						
Ongeval met blijvend letsel	> 1 week < 1 maand	Negatieve aandacht in nationale pers. Langdurige (< 1 jaar) ernstige hinder voor reizigers of bewoners	> € 500.000,- < € 1000.000,-	Grootschalige verontreiniging bodem/water, maatregelen nodig Aansprakelijkheid en aanhoudende klachten, juridisch geschil.						
Dodelijk ongeval	> 1 maand	Langdurige negatieve aandacht in (inter)nationale pers Zeer langdurige (> 1 jaar) ernstige hinder voor reizigers of bewoners	> € 1.000.000,-	Ernstige milieuschade. Ingrijpende herstelmaatregelen nodig met blijvende schade Langdurige juridische nasleep						

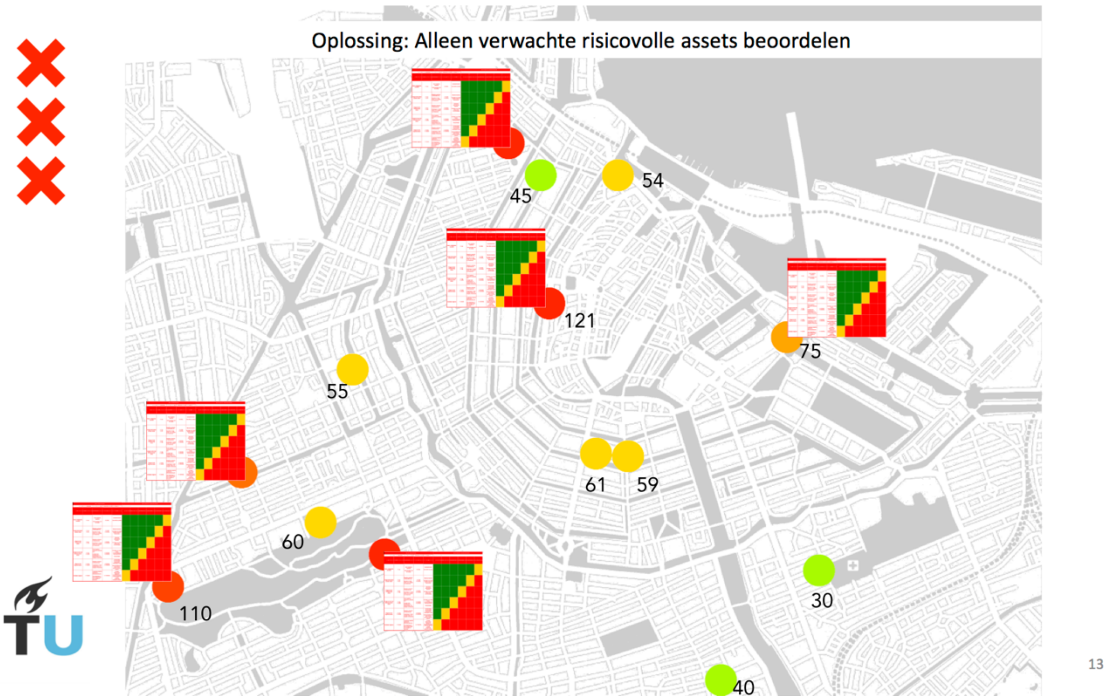
Toepassen:

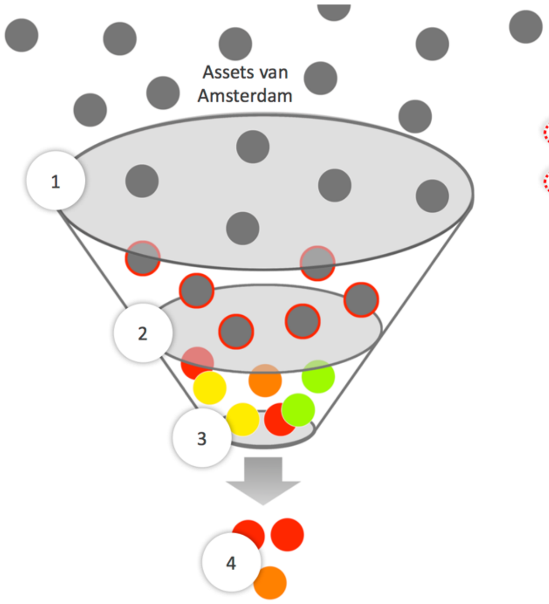
- Zonder maatregelen *(nulmeting)*
- Met huidige maatregelen *(huidige situatie)*
- Na nieuwe maatregelen *(testen)*

10

WORKSHOP 1

Hoe maken we het haalbaar?





Filteren:

1. ??
2. ??
3. Welke assets hebben de grootste risico's?
4. Resultaat: Verzameling geprioriteerde assets met risicowaarde

14

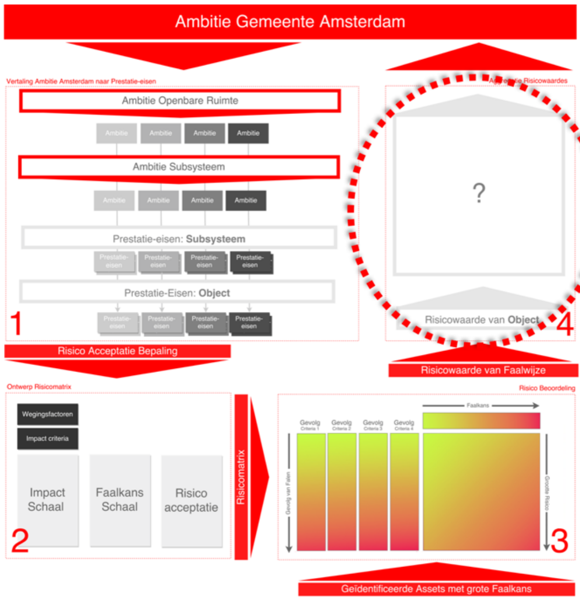
Doel Workshop 1:

Het vinden van de eisen/methodes voor het filteren van potentiele risicovolle assets:

15

WORKSHOP 2

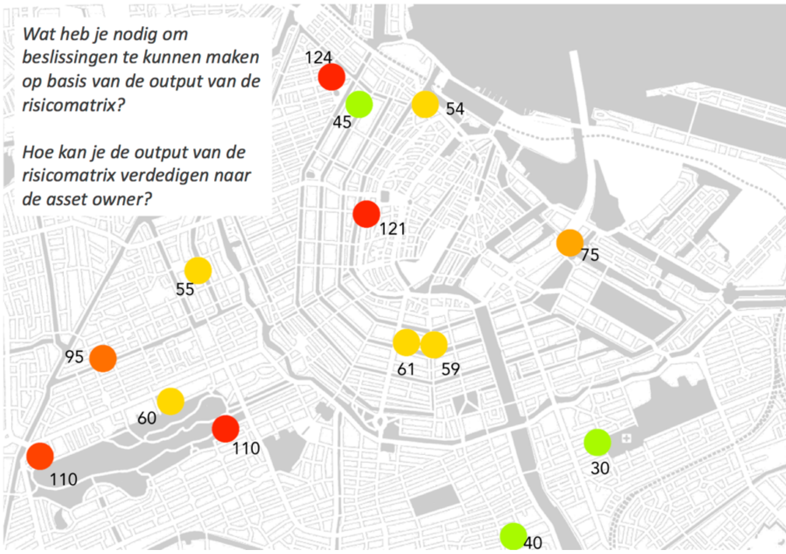
Hoe aggregeren we risicowaardes?



Wat te doen met de output van de risicomatrix?

Wat heb je nodig om beslissingen te kunnen maken op basis van de output van de risicomatrix?

Hoe kan je de output van de risicomatrix verdedigen naar de asset owner?



Doel Workshop 2:

Het vinden van de eisen van het toepassen van stap 4 zodat het haalbaar wordt in de praktijk:

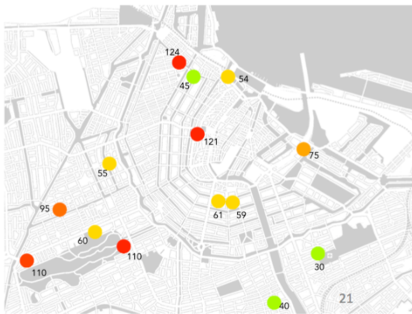
Wat is het **DOEL** van processtap 4?
Wat zijn verwachte **VALKUILEN**?
Wat zijn jullie **EISEN**?

20

Het **DOEL**

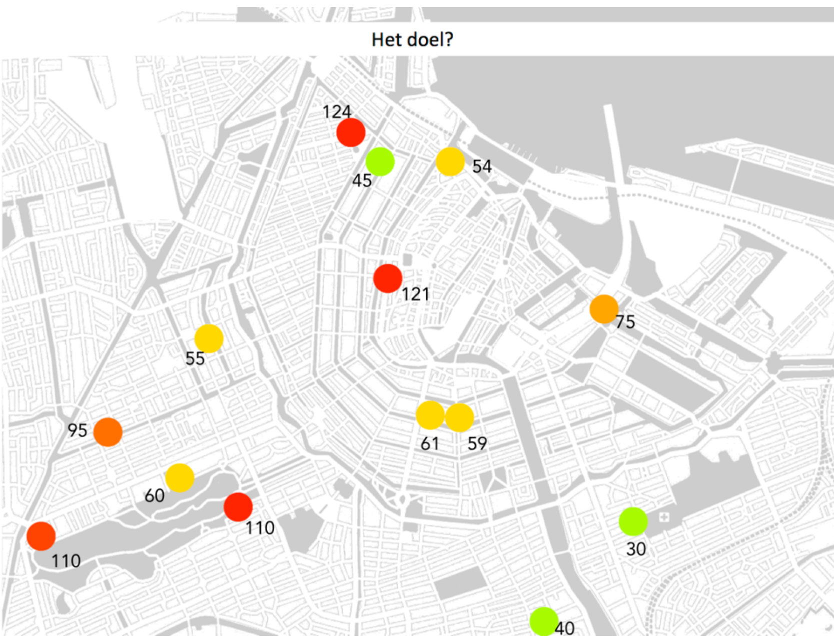
Wat wil je allemaal met de output van de risicomatrix doen?

- Output van de risicomatrix is voor het verantwoorden van investeringsbeslissingen buiten het dagelijks onderhoud aan de raad
- Output is de input voor de MIP
- Alle rode punten moeten geel/groen worden – grote risico's vermijden
- **Doel: Investeringsbeslissingen buiten het dagelijks onderhoud aan de raad verantwoorden om grote risico's te vermijden**



21

Het doel?



22

Verwachte VALKUILEN

- Matrix klopt niet
- De eerste filter klopt niet/is niet te vertrouwen
- Subjectiviteit met de beoordeling
- Faalkansen niet altijd kunnen inzien/informatie wordt niet goed bijgehouden of is actueel
- De raad denkt er toch anders over
- Niemand begrijpt die bedrijfswaarden
- Hoe kom je aan de getallen?
- Geen uniformiteit – risico's niet kunnen vergelijken

Als dit wordt toegepast in de praktijk, wat kan er mis gaan?

Jullie EISEN

- Iedereen moet de matrix begrijpen om het te kunnen toepassen
- Bij elk objecttype van tevoren een beeld hebben van faalmechanismen en risico's – meest voorkomende risico's
- Netwerken/wijken moeten in kaart worden gebracht met de gerelateerde assets om beter te kunnen verantwoorden
- AM levert risicovlle assets in auto/vaarwegnetwerk
- Portfolio AM stopt samen in gevieden
- Openbare ruimte stuurt op netwerken enr eg

Wat is er dan nodig om deze valkuilen te vermijden?

Zijn er andere belangrijke eisen aan het proces?

23

WINST

- Je kan je keuzes onderbouwen/ laten zien wat het risico is als we geen geld krijgen
- Verantwoordelijkheid wordt op de juiste plek gelegd
- Vroeger ging het meer over het overtuigen, nu beoordeel je systematisch de risico's
- Als er ergens een probleem optreed wat je niet hebt gezien, kan je jezelf wel verdedigen door te laten zien dat je systematisch hebt gehandeld
- Je handelt preventief ipv reactief
- Je kan steeds meer oorzaken van falen vermijden/controleren
- Wegingsfactoren zijn dynamisch, dus je kan inspelen op verandering van bedrijfwaarden

25