# COLOPHON

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<td>Title</td>
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ABSTRACT

The introduction of integrated contracts in the construction sector results in shifting risks and responsibilities from the client to the contractor. In contrast to traditional forms of contracting, contractors become often also responsible for an operational period. The obligation to ensure availability and reliability of infrastructural assets to the client demands Dutch contractors to create smart and innovative solutions for Asset Management (AM). Meanwhile, recent developments such as Smart Cities and Internet of Things (IoT) result in an increase in the application of sensor devices from 16 billion in 2014 to 40.9 billion forecasted in 2020. The use of smart sensor technology to detect and predict asset performance during the maintenance phase of road infrastructure projects is still in its development phase. The application of sensors to establish an asset network offers a great potential to the construction sector.

This Double Degree graduation work is a combination of two master studies from the Technical University of Delft: Construction Management and Engineering (CME) and Geomatics for the Built Environment. Although the entire research consists of two separate theses, each thesis includes an integrated approach from both studies. The partition of the research in two theses allows a holistic research into the potential of sensor technology for the construction sector and an in-depth analysis of the application of sensors. This holistic research answers the following research question: How can the construction sector incorporate sensor technology during the maintenance phase of road infrastructure projects to optimise Asset Management?

The developed theoretical framework presents three subjects: the individual asset, the asset network and AM. The research explains the potential of sensor technology by elaborating on the overlap between these three subjects. This resulted in the author’s definition of Smart Asset Management (SAM). SAM is the collection, analysis, sharing and exploitation of sensor data to balance performance, costs and risks by performing the right maintenance at the right time and at the right location.

SAM is a combination of an individual Smart Asset (SA) and a collection of SA in a Smart Asset Network (SAN). An individual SA allows to collect and analyse data of attached sensors. A SAN shares and exploits relevant sensor data between assets mutually. This network allows indicating the performance of each asset, regardless of the number of attached sensors.

The analysis of the current situation indicates the connection between Smart Cities and sensors through performance, information and data requirements. In addition, three case studies have been analyzed: (1) Project structures and embankments monitoring Haarlem, (2) Project real-time railway monitoring Zeeland, and (3) Project van Brieneoord-bridge Rotterdam. The multiple case study analysis reveals that the content of the set requirements influences the applied management style for AM, which in turn determines the incorporation of sensor technology. The research at hand therefore distinguishes 15 requirements for realising SAM, of which providing insight into the aspects availability and reliability of assets are the most important. The requirements contribute to four set objectives: 1) to store and retrieve performance data in order to improve insight in the actual and real-time condition of assets, 2) to
predict future conditions and service levels, 3) to support efficient planning of maintenance activities, and 4) to integrate new technologies and to innovate. The developed theoretical implementation describes how the SA and SAN contribute to the scenario of ‘Asset Manager of the future’.

The theory of SAM has been tested in the research of Braaksma (2016). The results of the testing were evaluated and 12 out of 15 requirements were satisfied. The combination of SA and SAN seems to be a suitable combination for realising a SAM application in the construction sector. It allows sharing sensor data when needed, and thereby utilizing the data for multiple applications. However, three requirements were not fully satisfied due to limitations in and their relevance for this test set-up: (1) defining the exact performance pattern, (2) providing the reliability factors of detected performances, and (3) data security and privacy. The requirements remain important in realising SAM, though were not of crucial importance in this research. The extension of the test set-up in a prototype is likely to resolve these requirements.

In conclusion, implementing the ‘Asset Manager of the future’ scenario answers the research question by posing SAM as a way to optimise AM: it improves insight into asset performance and supports improved decision-making by Asset Managers. It aims to support the construction sector in the obtained responsibility to ensure availability and reliability of assets. This research attempted to show the theoretical potential of sensor technology in the maintenance phase and evaluated requirements for implementing SAM theoretically. To create a completely automated process for collecting, analysing, sharing and exploitation of sensor data in the construction sector, it is recommended to translate this theoretical implementation into an operational practice. Explicitly focusing on innovation, acknowledging the importance of users in the process and realising a pilot project are focal points for research in the near future. This research shows that SAM provides the construction sector with a smart and innovative solution for AM, utilizing the potential of sensor technology to perform the right maintenance at the right time and at the right location.
PREFA CE

My name is Hiske Braaksma, master student Construction Management and Engineering (Civil Engineering) and Geomatics for the Built Environment (Architecture) at Delft University of Technology. This thesis is part of a collection of two theses as are part of a Double Degree graduation program. The research took place from November 2015 until December 2016.

I have always been interested in the innovation potential of the construction sector, resulting in an interest in BIM and the choice to start the master Construction Management and Engineering. During the master, my interest grew into the link between BIM with sensor technology. Although I was about to start my graduation research for this master, I decided to follow a few courses about sensor technology from the master Geomatics. As the quarter - highlighting database management systems and spatial decision support systems - ended, the subsequent quarter of Geomatics made me decide to take additional courses...

Resulting in my application for a Double Degree graduation program and conducting an extensive research of thirteen months, submitted in two separate theses.

This graduation research has been quite an experience: How to include knowledge from two masters, how to deal with directions from two exam committees, how to fulfil two different examination regulations and how to write an integral research, partitioned in two separate theses. Many challenges in this (political) process have been overcome.

My committee made it possible for me to complete this research and I would like to thank Marcel Hertogh (professor), Wilko Quak, Sander van Nederveen and Martinus van de Ruitenbeek for their full cooperative support throughout the process. Also, I would like to thank Gerdy Verschuure-Stuip, as the delegate of the board of Examiners and specifically her effort and support for the P5, and the company Volker InfraDesign for offering me a graduation internship.

Special thanks goes out to Birgit Ligtvoet and Philine Goldbohm, for their valuable reviews, substantive discussions, assistance and unconditional confidence.

Last but not least, I would like to thank my friends, my parents, family and others who were willing to share their time and knowledge for supporting me during this major challenge.

Hiske Braaksma
Delft, December 2016
# TABLE OF CONTENTS

COLOPHON v  
ABSTRACT vii  
PREFACE ix  
TABLE OF CONTENTS x  
ACRONYMS xii  
GLOSSARY xiii  

1 INTRODUCTION 1  
1.1 HISTORY AND CURRENT SITUATION OF THE CONSTRUCTION SECTOR 1  
1.1.1 DEVELOPMENTS IN THE CONSTRUCTION SECTOR 1  
1.1.2 DEVELOPMENTS OF PARTICULAR RELEVANCE FOR THE CONSTRUCTION SECTOR 3  
1.1.3 CURRENT SITUATION OF THE CONSTRUCTION SECTOR 4  
1.2 FORECAST IN ASSET MANAGEMENT 5  
1.2.1 LONG-TERM MAINTENANCE CONTRACTS 5  
1.2.2 DESIGN-BUILD-FINANCE-Maintain (DBFM) CONTRACTS 5  
1.2.3 THE POTENTIAL OF SENSOR TECHNOLOGY 6  
1.3 RESEARCH QUESTION AND HYPOTHESES 10  
1.4 RESEARCH OBJECTIVES AND DELINEATION 11  
1.4.1 OBJECTIVES 11  
1.4.2 FOCUS 11  
1.5 RESEARCH RELEVANCE 13  
1.6 RESEARCH METHODOLOGY 13  
1.6.1 RESEARCH DEPTH AND BREADTH OF UNDERSTANDING 14  
1.6.2 RESEARCH OUTLINE 15  

2 THEORETICAL FRAMEWORK 17  
2.1 RELATION OF THE INDIVIDUAL ASSET WITH ASSET MANAGEMENT 17  
2.2 RELATION OF THE INDIVIDUAL ASSET WITH ASSET NETWORK 20  
2.3 RELATION OF THE ASSET NETWORK WITH ASSET MANAGEMENT 21  
2.4 OVERLAP BETWEEN INDIVIDUAL ASSET, ASSET NETWORK AND ASSET MANAGEMENT 23  

3 ANALYSIS 25  
3.1 SMART ASSET MANAGEMENT AND SENSOR TECHNOLOGY 25  
3.1.1 SMART CITIES AND INFRASTRUCTURE 26  
3.1.2 SMART ASSET MANAGEMENT 26  
3.1.3 ANALYSIS AND INTERPRETATION 26  
3.1.4 SENSOR AND DATA COLLECTION 27  
3.1.5 PERFORMANCE, INFORMATION AND DATA 27  
3.2 CASE STUDIES: SENSOR TECHNOLOGY IN THE CONSTRUCTION SECTOR 28  
3.2.1 PROJECT STRUCTURES AND EMBANKMENTS MONITORING (HAARLEM) 28
3.2.2 PROJECT REAL-TIME RAILWAY MONITORING (ZEELAND) 31
3.2.3 PROJECT VAN BRIENENOORD-BRIDGE (ROTTERDAM) 34
3.2.4 CONCLUSION ON THE CASE STUDIES 38
3.3 CONCLUSION 40

4 THEORETICAL IMPLEMENTATION 41
4.1 THEORY DEVELOPMENT 41
   4.1.1 ASSET MANAGER OF THE FUTURE (SCENARIO) 41
   4.1.2 REQUIREMENTS FOR SMART ASSET MANAGEMENT 44
4.2 THEORY TESTING 48
4.3 THEORY EVALUATION 49
   4.3.1 REQUIREMENTS EVALUATION 49
   4.3.2 HYPOTHESIS EVALUATION 50

5 SPOT ON THE HORIZON 51
5.1 APPLICATION SCENARIO 51
5.2 TECHNOLOGY READINESS LEVEL 54

6 DISCUSSION AND CONCLUSIONS 57
6.1 DISCUSSION 57
   6.1.1 RESEARCH LIMITATIONS 57
   6.1.2 CONTRIBUTION TO OTHER RESEARCH 59
6.2 CONCLUSIONS 61

7 RECOMMENDATIONS 65
7.1 RECOMMENDATIONS FOR PRACTICAL IMPLEMENTATION 65
7.2 RECOMMENDATIONS FOR FURTHER RESEARCH 66

8 REFERENCES 68
## ACRONYMS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE</td>
<td>Acoustic Emission</td>
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<td>AM</td>
<td>Asset Management</td>
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<td>BC industry</td>
<td>Building and Construction industry</td>
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<td>BIM</td>
<td>Building Information Model</td>
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<td>BLSD</td>
<td>Bridge Life Span Detector</td>
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<td>CME</td>
<td>Construction Management and Engineering</td>
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<td>CSIC</td>
<td>Cambridge centre for Smart Infrastructures and Construction</td>
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<td>DAQ</td>
<td>Data Acquisition Device</td>
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<td>DBFM</td>
<td>Design Build Finance Maintain</td>
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<td>ESA</td>
<td>Event Server Application</td>
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<td>FEM</td>
<td>Finite Element Method</td>
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<td>FMEA</td>
<td>Failure Mode and Effects Analysis</td>
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<td>GIS</td>
<td>Geographic Information Systems</td>
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<td>ICT</td>
<td>Information and Communications Technology</td>
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<td>IoT</td>
<td>Internet of Things</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
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<td>NEN</td>
<td>Dutch National Standards (Dutch: Nederlandse Norm)</td>
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<td>OWL</td>
<td>Web Ontology Language</td>
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<td>RDF</td>
<td>Resource Description Framework</td>
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<td>RWS</td>
<td>Rijkswaterstaat</td>
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<td>SA</td>
<td>Smart Asset</td>
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<td>SAM</td>
<td>Smart Asset Management</td>
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<td>SAN</td>
<td>Smart Asset Network</td>
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<td>SDSS</td>
<td>Spatial Decision Support System</td>
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<td>SWE</td>
<td>Sensor Web Enablement</td>
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<td>TRL</td>
<td>Technology Readiness Level</td>
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<tr>
<td>Term</td>
<td>Definition</td>
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<td>Asset Management</td>
<td>The set of coordinated life-cycle activities of the construction sector to realise value from its assets (ISO, 2014).</td>
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<td>Sensor</td>
<td>A sensor is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument (Mukhopadhyay, 2013).</td>
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<td>Smart Asset Management</td>
<td>The collection, analysis, sharing and exploitation of sensor data to balance performance, costs and risks in managing assets in order to maintain at the right moment and the location needed.</td>
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<td>Smart Asset</td>
<td>An individual asset, which is able to detect and predict its own performance in context by collecting and analysing sensor data of attached sensors.</td>
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<tr>
<td>Smart Asset Network</td>
<td>The collection of individual assets in a network, which is able to detect and predict the performance in context of (other) individual Smart Assets by sharing and exploiting relevant sensor data.</td>
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1 INTRODUCTION

Due to the introduction of new contract types shifts risks and responsibilities to the contractor, Dutch contractors are pressured to create smart and innovative solutions for Asset Management. But how can Dutch contractors establish innovative solutions? Only recently, the future of the construction sector has been specified as a Smart Industry that uses sensor technologies, where references to the concepts Smart Cities and Internet of Things are made (Atzema et al., 2015; Elsevier, 2015). It is expected that the new approach of the construction sector in managing assets represent a major task in the coming years (Rutten, 2016).

This research provides an Asset Management approach that uses sensor technology to create Smart Assets in a Smart Asset Network. This chapter serves: an introduction and discusses respectively the history and current situation (§1.1); the forecast in Asset Management (§1.2); the research question and hypothesis (§1.3); the research objective (§1.4); the research relevance (§1.5); the research methodology (§1.6) and the research outline (§1.7).

1.1 HISTORY AND CURRENT SITUATION OF THE CONSTRUCTION SECTOR

The building and construction (BC) industry is one of the oldest industries, it is often criticised for its slowness in adapting to developments. The digital revolution happening today requires the industry to adapt rapidly (Kafai & Resnick, 1996). In addition, the behaviour of humans is changing from being product owners to demanding services, resulting in purchasing light instead of light bulbs (Philips, 2016).

As for the construction sector, the introduction of new contract types for large infrastructural projects is one of the major steps in the evolution towards more efficient Asset Management (Algemene Rekenkamer, 2013). The construction sector is obliged to manage the need for both collaboration and cooperation, because the complexity is increasing (Shen et al., 2010).

1.1.1 DEVELOPMENTS IN THE CONSTRUCTION SECTOR

The concept of BIM arose to overcome the increased complexity. The Building Information Model (BIM) (Eastman et al., 2008; van Nederveen & Tolman, 1992) approaches the complexity by introducing aspect models to store specific information. A BIM is a powerful concept for an object-based approach with loose coupling between elements and sub-elements in a 3D model (Torma, 2013). With this, a BIM is capable of combining geometric information with other properties – costs, materials, planning – and enables a range of new functionalities (Mubarak, 2010).

Although the BIM implementation offers benefits to the construction sector, the effective use of a BIM during maintenance and operation requires updated as-built

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1 Asset Management: The set of coordinated life-cycle activities of the construction sector to realise value from its assets (ISO, 2014).
models. Though the information exists during the construction phase, a lack of quick access to the information during the maintenance and operational phase results in unnecessary expenses and decision-making based on incomplete information (Meadati, 2009). In response, the construction sector is currently reaching out to concepts as “big data” and “big data analytics” in order to gain insight in maintenance processes (Wong et al., 2014). The data-driven innovation is appointed as future outlook (Benghi & Williamson, 2014) and the construction sector needs to address the future use of BIM to ensure project quality and maintain assets efficiently.

The innovation potential of Asset Management (AM) is also recognized by Rijkswaterstaat (RWS) (2014b), who is responsible for the practical execution of construction and maintenance of public works and water management in the Netherlands and thereby the main client for the construction sector. Next to allocating maintenance activities in the contract, RWS shifted the responsibilities and risks to the contractor. Underlying reasoning is the contractor being able to create a life-cycle approach for the project and being able to influence associated risks, during for example the maintenance phase, for responsibilities that initially have been the client’s responsibility (Moll, 2015).

It is the introduction of performance-based contracting as the ultimate stimulus for the BC industry to innovate (Hulshoff, 2013; Pries, 1997). In contrary to traditional ways of contracting, the construction sector must not only carry out maintenance tasks, but is directed at ensuring availability and reliability of the assets to the client.

Recently, research in AM includes the link towards sensor technology2 and Smart Assets3 (Jadoul, 2014; Marr, 2015). Cognizant (2015) appoints Smart Asset Management4 as the incorporation of both and emphasizes that the monitoring of assets will become essential. The research paper of SBRCURnet (2015) presents an overview of thirteen project cases where Dutch clients and contractors attempt to monitor the use and behaviour of infrastructural assets. The paper addresses ICT applications, such as sensors, and discusses the implementation of pilots by means of the developed monitoring framework. The monitoring framework is recommended to be used in further research as it is can be used in both an early stage as well as in a later stage of development. This will be further elaborated in section 3.2. SBRCURnet (2015) underlines that the acceptance of a certain technical innovation demands a proper integration on the strategic, tactical and operational level of the BC industry in order to be successful.

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2 Sensor technology: A sensor is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument (Mukhopadhyay, 2013).
3 Smart Asset: An individual asset, which is able to detect and predict its own performance in context by collecting and analysing sensor data of attached sensors.
4 Smart Asset Management: The collection, analysis, sharing and exploitation of sensor data to balance performance, costs and risks in managing assets in order to maintain at the right moment and the location needed.
Figure 1: The Internet of Things is a technology that uses (sensor) devices in a network in an online environment. With this, objects are linked to each other share relevant data. It entails a large potential in developing smart solutions – such as optimization of traffic control systems (Daniotti & Spagnolo, 2016).

1.1.2 DEVELOPMENTS OF PARTICULAR RELEVANCE FOR THE CONSTRUCTION SECTOR

Beside the specific efforts mentioned above, there are two other developments of particular relevance for the construction sector: The Internet of Things (Figure 1) and Smart Cities (Figure 2).

The Internet of Things (IoT) is described by Atzori et al. (2010) as “the pervasive presence around us of a variety of things or objects – such as sensors, actuators – which, through unique addressing schemes, are able to interact with each other”. Lydon (2014) encourages IoT in the construction sector by sensors and actuators to automate processes. With the potential of the IoT to capture in-use performance data, future prospects for maintenance projects in the construction sector are being directed to performance-based maintenance (HM Government, 2015).

Smart Cities is “the product of the accelerated development of new information technologies and sensor networks with the IoT technology at its core” (Elsevier, 2015). Mitchell et al. (2013) state that assets connected and interoperable via the concept of IoT can contribute to the development of Smart Cities. Smart infrastructure is one of the eight key parameters within a Smart City (Figure 2). The term refers to intelligent and automated systems used to manage, communicate, and integrate different types of intelligent infrastructure (Jeremiah et al., 2014). Since this research into Smart Assets focuses on infrastructural assets, sensor technology and (digital) management of infrastructures, it is linked to Smart Infrastructures within the Smart Cities concept.

Figure 2: Smart Cities as defined by Jeremiah et al. (2014) consists of eight components: Smart governance, smart healthcare, smart building, smart mobility, smart infrastructure, smart technology, smart energy and smart citizen. This research focuses on the smart infrastructure component within Smart Cities.
Figure 3: Smart Cities can use the Internet of Things (IoT) applications as a tool to gather information. The IoT allows connecting and managing complex sets of sensors and devices. An example of a smart city application are real time traffic maps obtained for smooth flow of traffic systems (Pawar, 2013).

Important for developing Smart Assets are the implementation of sensor networks, which is why Smart Cities is often referred together with IoT (Figure 3). Because sensors can provide the desired data to optimise AM, the interest on incorporating sensor technology in the construction sector has grown (Atzema et al., 2015). Expected is that the number of sensor devices will more than double from the current level, with 40.9 billion forecasted for 2020 (Press, 2014).

1.1.3 CURRENT SITUATION OF THE CONSTRUCTION SECTOR

According to literature, it is only a matter of time before the construction sector will fully embed sensor technology in AM (Marr, 2015; Mitchell et al., 2013). In practice, the construction sector has been mentioning the integration of sensor technology for the last fifteen years (Cobouw, 2002; Peelen et al., 2008).

The slow speed of the construction sector to incorporate sensor technology in the current situation is due to a low sense of necessity (Peelen, 2016). Although successful implementations are found in railway maintenance (Steenitjes, 2016; Van den Bos et al., 2013), asset performance is measured mostly by visual inspections. Since measurements by human eye result in accuracy issues, many maintenance activities are performed premature. Although premature maintenance is an ineffective way to perform AM, the assets performance is ensured to the client and financial resources are available (Peelen, 2016). The implementation of sensor technology to avoid unnecessary expenses and unavailability of assets in maintenance projects is often seen a ‘nice to have’ (Beijer, 2016; Peelen, 2016).

However, the performance-based contracts of RWS and other large clients pressures to think of new solutions for AM. An example is Project SAAone, which comprises the construction of a highway between Schiphol-Amsterdam-Almere. The building consortium will be responsible for 30 years of maintenance after completing the project (Rijkswaterstaat, 2012). Due to the change in responsibilities, the added value of sensor technology is gradually being recognized by the construction sector, resulting in multiple workgroups and events. Obtaining sensor data seems easy and the associated costs are low; the challenge however is to enable the required information (STUMICO, 2015). Since more large infrastructural projects with performance-based contracts are heading towards the start of long-term maintenance periods, the construction sectors opinion towards sensor technology seems to be changing into a ‘need to have’ (Van den Thoorn et al., 2011).
1.2 FORECAST IN ASSET MANAGEMENT

Current Asset Management is being directed to ensuring the performance of assets, which is stipulated in the contract between client and contractor (Rijkswaterstaat, 2013, 2014a). Performance requirements are intended to stimulate the construction sector to find solutions for gaining insight in the status of assets and perform maintenance tasks at the most opportune time when taking into account time, costs, risks and performance (Rijkswaterstaat, 2016). The focus is on effective maintenance and providing reliable performance predictions. There are two main cases for the construction sector in which sensor technology can play a major role; long-term maintenance contracts and Design-Build-Finance-Maintenance (DBFM) contracts (Peelen, 2016).

1.2.1 LONG-TERM MAINTENANCE CONTRACTS

Long-term maintenance contracts are used more often for two reasons. The contract enables the client to outsource maintenance - thereby shift responsibilities and risks of a project to the market (Rijkswaterstaat, 2014a) - and the contract allows the construction sector to determine long-term maintenance strategies as well as stimulating performance based maintenance (Van der Rhee, 2013).

However, acquiring such a maintenance contract can act as a bottleneck. Since the contracted construction company is not necessarily also the constructor of the project, the current status of the project is often unclear to the construction company (Beijer, 2016). Conclusive information about the assets lacks in many projects, which is why visual inspections are performed. Defining the accurate performance via visual inspections is a problem the construction sector faces (Peelen, 2016). It causes an undesirable low efficiency in managing assets.

1.2.2 DESIGN-BUILD-FINANCE-MAINTAIN (DBFM) CONTRACTS

The integration of sensor technology seems suitable in DBFM projects, because the contract integrates design, build, finance and maintenance activities for a set period. The contractor has the opportunity to develop an optimal life cycle solution in order to guarantee the performance of assets towards the client (Rijkswaterstaat, 2013). Although lessons learned from former projects enable the construction sector to improve estimations for the lifetime of assets, an increased reliability in estimations is desired (Peelen, 2016).

Although the construction sector continues to develop approaches for performance-based maintenance, advances from current sensor technologies are promising to close the gap between the promise and actual reality of Asset Management based on performance.
1.2.3  THE POTENTIAL OF SENSOR TECHNOLOGY

The previous section mentions sensor technology as promising solution for performance-based maintenance. It is an emerging area of information technology that has recently generated significant attention (Atzema et al., 2015; Chansin, 2015). The following discusses the current status, defines the unexplored potential and defines the focus area in this research regarding sensor technology.

What is known about sensor technology?

Currently, sensor technology is closely related to the concept of Smart Cities, as the city’s status can be continuously monitored through sensors in the real-world infrastructure (Puliafito, 2015). Creating smart solutions with sensor technology is placed on the agenda by the European Commission (2015). INSPIRE (2012) specifically refers to “sensor networks as a trend to fuel Smart Cities”.

The technological advances are needed to initiate immediate and effective information services that allow for the collection, exchange and processing of large amounts of data and information. Location is an important element that provides context to this data-rich digital world, because geospatial technologies provide a better understanding of the complex reality in a virtual context (Heller & Orthmann, 2014; INSPIRE, 2012).

An example of the implementation of sensor technology is found in a project in Nice (France) where sensors are embedded in public roads, providing car drivers information about available parking spaces in the city and routes to reach them (Daniel & Doran, 2010). Another implementation of sensors is seen in the Maastunnel in Rotterdam (the Netherlands), where the illumination in the tunnel is continuously measured to optimise maintenance activities (SBRCURnet, 2015).

The construction sector can develop a valuable tool to better understand the complex reality. Figure 4 illustrates the combination of scientific research and practical research that contributes to understand and develop the implementation for sensor technology.

![Figure 4: The application of the cycle of research, development and implementation as in the appointed research agenda of Van den Thoorn et al. (2011). Experience shows that innovation is a cyclic process, and Van den Thoorn et al. (2011) state that innovation should be placed project wide in order to realize significant results.](image-url)
What is not yet known about sensor technology resulting in an unexplored potential? Experts in the construction field (Beurze, 2016; Keesom & Taja, 2016) acknowledge that the influence of sensor technology for the construction sector is significant, due to its ability to provide reliable information and efficient decision-making during the maintenance period. In addition, since infrastructure is a key element for cities, Smart - infrastructural - Assets will be key for Smart Cities (Jadoul, 2014). This is properly understood by organizations as INSPIRE (2012), the Geospatial World Forum (2016) and Geonovum (2013).

Despite the recently launched research agenda and the monitoring framework of SBRCURnet (2015), there still is a need to explore the use of Smart Asset Networks5 (SAN) for AM and Smart Cities. This research defines the SAN to be able to predict and adapt to network changes, through gathering data of the individual Smart Asset (SA). An exploratory study is missing to understand how such a SAN collects, analyses, shares and exploits sensor data.

What is the focus area of this research concerning incorporating sensor technology in the construction sector? The geo-information production process of Lemmens (1991) describes five steps in managing data (Figure 5): Collect, store, analyse, share and exploit.

![Figure 5: The geo-information production process embedded as data stages in an asset network, based on Lemmens (1991).](image)

To create a clear understanding of the meaning of these items in context of this research, the following definitions are provided:

- The **collection of data** refers to the measurements by sensors that are attached to the asset. The data that is covered by sensors are quantitative, such as the load on a construction.

- The **storage of data** enables the user to look into the collected data at the time needed. Examples of data storages are GIS Technologies or databases. The remainder of this research considers the storage of data within the collect data stage and the share data stage. Specific current challenges regarding data storage, such as the energy consumption of data centres, are therefore not addressed.

- The **analysis of data** refers to the processing of data and identification of trends and relationships among the measured variables. An important aspect in the analysis is the proper identification of trends, since this is subject to the correct filtering of data and interpretation of findings (Lemmens, 1991).

5 Smart Asset Network: The collection of individual assets in a network, which is able to detect and predict the performance in context of (other) individual Smart Assets by sharing and exploiting relevant sensor data.
• The sharing of data over the sensor network concerns information obtained by measurements from one asset, such as an identified trend regarding a variable, which can be used by the other asset at a different location. An example of data sharing over a sensor network is the recently developed traffic signal systems in Hong Kong. The maintenance of traffic light systems is optimised by sharing data of traffic intersections to detect irregularities as junction blackouts and traffic accidents (C. Lee et al., 2014).

• The exploitation of data refers to the transforming and aggregating of data in the asset network. The individual asset provides the input from its own analysed measurements. The gathered real-time information from multiple sources can then be used to manage assets (Manzoor et al., 2014). Examples to present the gathered information are visualizations in an interactive way.

The knowledge gap includes the use of sensor data to realise an individual SA and a SAN that can be used for Smart Asset Management (SAM) applications. This research therefore continues on the geo-information production process described in Figure 5 and defines how the data stages contribute in realising SAM (see Figure 6). SAM refers to the collection, analysis, sharing and exploitation of sensor data to balance performance, costs and risks in managing assets in order to maintain at the right moment and the location needed. This research focuses on the first part of this definition – the collection, analysis, sharing and exploitation of sensor data – by researching the implementation of a SA and SAN as main contributors to both Smart Cities as for future SAM in the construction sector.
Figure 6: This research focuses on the collection, analysis, sharing and exploitation of sensor data for SAM, which is investigated through focusing on the SA and the SAN.
1.3 RESEARCH QUESTION AND HYPOTHESES

The aim of this thesis is to investigate the application of sensor technology to optimise Asset Management\(^6\). When sensor technology is properly implemented, an individual asset is considered a SA and is able to both detect and predict its performance in context. The SAN has the ability to share and exploit relevant sensor data in order to detect and predict the performance of other assets.

The research explores the potential of sensor technology for SAM. To explore these effects, the research focuses on the SA and a SAN as main contributors to SAM. The research will be supported by creating a proof-of-concept and illustrate a theoretical implementation.

The research question (RQ) is defined as follows:

RQ: How can the construction sector incorporate sensor technology during the maintenance phase of road infrastructure projects to optimise Asset Management?

To answer the research question, this research tests the following hypothesis:

H1: Asset Management can be optimised with Smart Asset Networks, which are realised by individual Smart Assets that are able to collect, analyse, share and exploit sensor data.

And the following null hypothesis:

H0: Asset Management cannot be optimised with Smart Asset Networks, which are realised by individual Smart Assets that are able to collect, analyse, share and exploit sensor data.

The hypothesis will systematically be answered through exploring five sub-questions. The sub-questions are used to structure the research and contribute to test the hypothesis. The sub-questions are as follows:

SQ1: What are the relations between the individual asset, asset network and Asset Management when focusing on sensor technology?

SQ2: What is the potential of collecting, analysing, sharing and exploitation of sensor data for realising the Smart Asset and Smart Asset Network?

SQ3: What is the potential of sensor technology for optimising Asset Management?

SQ4: Which requirements should be taken into account when incorporating sensor technology in managing assets during the maintenance phase of road infrastructure projects?

SQ5: What steps are needed to refine a future application of the theoretical implementation?

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\(^6\) Asset Management is considered to be optimised when the construction sector can make more conscious and convincing decisions in managing their assets with the objective of balancing performance, time, costs and risks (Varadan, 2013).
1.4 RESEARCH OBJECTIVES AND DELINEATION

1.4.1 OBJECTIVES
The research objective is two-fold:

- Investigating the theory of Smart Asset Management (SAM)
- Providing recommendations to the construction sector for practical implementation.

This research aims to contribute towards the theoretical discussion on the incorporation of sensor technology in current AM applications in the construction sector. To contribute, this research elaborates on the definition of SAM through identifying aspects to be considered when realising SAM as well as determining requirements that are to be taken into account.

In addition, this research provides recommendations to the construction sector that structure and emphasizes the application of sensor technology on two levels of detail:

- The large-scale level of attaching sensor(s) at the individual asset
- The small-scale level of collecting, analysing, sharing and exploiting sensor data in an asset network.

The contribution of Smart Assets within Smart Cities and the construction sector will be explored by means of investigating the two levels of detail. The construction sector will be able to make more conscious and convincing decisions for AM when the SAN provides improved insight into the asset performances. The integration of sensor technology in AM systems can result in the production of relevant information for building smart geo-applications (Garcia, 2016).

The overall result serves as an extension to the existing research on Smart Cities (Garcia, 2016; Rathore et al., 2016) and the application of sensors in AM (SBRCURnet, 2015; Ter Maaten, 2015). The final result is realised in form of a proof-of-concept and theoretical design to verify the potential for real-world application.

1.4.2 FOCUS
The research investigates the application of sensor technology at the large-scale level and small-scale level and defines their contribution towards SAM. Furthermore, this thesis is:

- Focusing on current AM in road infrastructure projects.
- Investigating the contribution of sensor technology for AM during the maintenance phase, since sensor data is considered relevant to provide insight for decision-making regarding maintenance activities and operation tasks. The research does not focus on the other lifecycle phases, although the results might still appear to be useful.
- Focusing on the technical part of the SAM definition: To collect, analyse, share and exploit sensor data. The practical application of SAM, referring to determining maintenance activities through balancing performance, costs and
risks is not in the scope of this research. To collect and analyse sensor data refers to the Smart Asset (SA) and to share and exploit refers to the Smart Asset Network (SAN).

- Defining a theory on SA and SAN, which is contributing to SAM. The thesis is explicitly focused on the area of overlap of the three subjects (Figure 6), where the research - through researching sub question 1 - investigates the added value of and relations between:
  - An individual asset and Asset Management: The research elaborates on linking sensors to components of BIM.
  - An individual asset and an asset network: The research elaborates on the data required in the process. Also, the value of an asset network, the system architecture and a use case diagram is researched.
  - An asset network and Asset Management: The research describes the theory of utilising a network for Asset Management purposes.

- Using the monitoring framework of SBRCURnet (2014) in order to structure the process.

- Limited to road infrastructure assets, which relates to Smart Infrastructures within Smart Cities and is focused within the IoT on defining the network of physical assets with sensors attached.

- Part of a collection of two theses as are part of a Double Degree graduation. The thesis “Smart Asset Management: An in-depth analysis of the application of Smart Asset and Smart Asset Network” (Braaksma, 2016) focuses on the testing of the SA and SAN. This holistic research investigates the overarching effects of applying sensor technology to realise SAM in the construction sector.

Setting this scope emphasizes that this research tries to find an integral solution for Asset Management, by focusing on establishing individual assets in an asset network (Figure 7) to empower the construction sector to maintain assets at the appropriate moment and the location needed through SAM.

Figure 7: The research scope is limited to the area where individual assets share data in an asset network and are used for Asset Management by the construction sector.
1.5 RESEARCH RELEVANCE

The potential of sensor technology is recognized both scientifically (Geodan, 2013; Sohraby et al., 2007) as in current practice (Cobouw, 2002; SBRCURnet, 2015). In the scientific field, the application of sensor technology to individual assets is currently researched (Arthur et al., 2015; Galar et al., 2015).

Conferences and events are organized regarding the implementation and added value of SA in relation to Internet of Things and Smart Cities (ISNC, 2016; STUMICO, 2015). Focusing on Asset Management, current maintenance strategies remain inefficient because the possibilities of SA in asset networks still need to be researched.

1.6 RESEARCH METHODOLOGY

As is described by Verschuren et al. (2010), the methodology of theory-oriented research aims to contribute towards the theoretical discussion on the subject and, as a consequence, towards the further development of science. This research proposes the scenario of “Asset manager of the future”, which will be tested with the creation of a proof-of-concept. The research method of Nielsen (1993) uses a basic iterative project model, but encourages independent iterative designs where new researchers are involved for each new version instead of one parallel design. This is why this holistic research uses the method described by Nielsen (1993), of which its five main phases are shown in Figure 8.

The first phase starts with the problem analysis and defines the theoretical framework where the research subjects are highlighted (Chapter 2). The first and second sub question will be answered in Chapter 2. Three small case studies will be performed, of which the selection is based on the project-type and on preliminary gathered information from literature and experts on the incorporation of sensors (Chapter 3).

Figure 8: The five phases of this research, based on the Iterative Design methodology of Nielsen (1993).
The three cases will be examined using the monitoring framework of SBRCURnet (2014) in order to obtain a quick overview of the current use of sensor technology in maintenance projects. The gathered knowledge from the analysis phase will be used to answer the third sub question and to develop a scenario for future AM. To test the scenario in a later stage, requirements\(^7\) for SAM and its context of use will be specified in Chapter 4, which answers the fourth sub question.

The theory testing will be described and performed in the report “Smart Asset Management: An in-depth analysis of the application of Smart Asset and Smart Asset Network” (Braaksma, 2016) by means of a proof-of-concept and a theoretical implementation. The fifth sub question is answered in Chapter 5, which indicates the spot on the horizon. The results from Chapter 4 and 5 will be used in the fourth and fifth phase to decide whether the developed theory and proposed scenario can be considered as a proper basis for further development.

1.6.1 RESEARCH DEPTH AND BREADTH OF UNDERSTANDING

As briefly introduced in section 1.4.2, this Double Degree graduation research is captured in two separate sub-reports:

- **Holistic research.** This, currently read, part of the research elaborates on the integration of sensor technology in Asset Management;
- **In-depth research.** The part of the research investigates the specific implementation of generating sensor data at the individual asset and enabling a network of assets via a sensor network.

The report that is currently being read is linked to the in-depth research by the theory testing as shown in Figure 9.

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\[^{7}\text{Requirement: A characteristic or feature in the form of a condition that is necessary and imposed as obligation in order to be able to realise a SAM.}\]
1.6.2 RESEARCH OUTLINE

This holistic research (see Figure 9) distinguishes multiple phases. The outline of this research is shown in Figure 10.

The introduction is covered in Chapter 1. This forms the input for defining the theoretical framework (Chapter 2) and performing the analysis (Chapter 3). The two chapters provide the results of a literature study and desk research to create context regarding the link between sensor technology and Asset Management. After establishing the context, Chapter 4 develops the theory to be tested in Chapter 5. It proposes the scenario of ‘Asset Manager of the future’ and delivers a structured list of requirements for collecting, processing and transforming sensor data in order to be used for decision-making in maintenance projects, thereby realising SAM.

The theory testing is captured in the report of Braaksma (2016). Chapter 6 evaluates the developed theory based on the results. The chapter discusses the requirements of the proposed theory and answers the hypothesis. Chapter 7 takes a look in the – near - future and describes how sensors and its technology readiness level bring opportunities and threats to future Asset Management. Chapter 8 presents the conclusion and discussion of the research, where the research question will be addressed. The discussion provides comments regarding the limitations of the research and elaborates on the contribution to other research. Thereafter, Chapter 9 provides recommendations for a practical implementation of sensor technology for the construction sector and concludes with recommendations for further research.
2 THEORETICAL FRAMEWORK

In order to develop an Asset Management approach that incorporates asset networks, more information is required about the interrelations of the three subjects of interest (Figure 7). The connection between Asset Management and individual assets (§2.1), the relation between individual assets and the asset network (§2.2) and the link between asset network and Asset Management (§2.3) are explained. The joint area of the three aspects is also discussed (§2.4).

SQ1: What are the relations between the individual asset, asset network and Asset Management when focusing on sensor technology?

SQ2: What is the potential of collecting, analysing, sharing and exploitation of sensor data for realising the Smart Asset and Smart Asset Network?

Figure 11: Adapted from Figure 7, a visualisation showing the section that discusses the overlap between the research subjects in the upcoming chapter.

2.1 RELATION OF THE INDIVIDUAL ASSET WITH ASSET MANAGEMENT

According to the ISO 55000 (2014), Asset Management (AM) is “the set of coordinated life-cycle activities of the construction sector to realise value from its assets”. Important to note is that the definition of an asset is not covered in this description. An individual asset can for example refer to a bridge itself or to all assets that function as subsystems of a bridge.

This research defines an individual asset as the physical asset, which consists of asset components and attached sensors, together with the digital asset, which consists of the BIM data and sensor data (Figure 12). Over the past years, the management of these individual assets has developed from a corrective nature towards a predictive and performance-based nature. Emerson (2013) distinguishes four maintenance strategies in AM (Figure 13): corrective maintenance, preventive maintenance, predictive maintenance and performance optimisation.
According to Welding (2015), corrective maintenance is the most commonly used approach in current AM. Corrective maintenance is carried out after the functional failure of an asset and intends to put the asset into a state in which it can perform again. This maintenance strategy is mostly used for assets that are not maintainable or when it is less expensive to replace than to perform preventive maintenance. A student bike is an example of corrective maintenance. Limitation in this approach is that failing parts could lead to damage to other parts of the bike and unplanned hinder for others, resulting in increased costs. An identical case occurs in the construction sector.

Preventive maintenance includes systematic inspections, detection and correction of incipient failures before they develop into major effects (Emerson, 2007). By performing maintenance tasks for assets at regular intervals, the functional failure of assets is minimised. Preventive maintenance tasks are usually performed frequently and require a relatively constant amount of labour and materials, such as the 20,000 km maintenance inspection of one’s car (Tzanakakis, 2013).

Predictive maintenance differs from preventive maintenance by determining maintenance needs on the actual condition of the asset. Since use of monitoring can detect degrading conditions of an asset, the maintenance activities and related costs can be optimised (Emerson, 2007). In addition, detecting the degradation curve enables to schedule maintenance activities in advance.
Challenges relate to reliability of the predictions and thus the decision-making to make the initial calls for repairs, which is the case for repairing the tires of one's car.

Performance optimization covers the systematic method to balance between preventive and corrective maintenance and to choose the right maintenance action for the right component at the right time to reach the most cost efficient solution (Nilsson, 2006). It can be seen as the optimisation initiative that introduces performance based maintenance based on the gathered knowledge in the previous stages (Emerson, 2013). The P-F interval of Nowlan and Heap (1978) is used as available time for AM decision-making (Figure 14).

Currently, the construction sector mainly performs periodic inspections as basis for maintenance activities (Beijer, 2016; Beurze, 2016). According to experts, the construction sector is balancing between the preventive and the predictive stage (Mubarak, 2010; Nilsson, 2006). This emphasizes the increasing interest in determining the P-F interval (Figure 14). Current research shows that the management of individual assets is seeking to change towards predictive and performance optimised AM (Daniotti & Spagnolo, 2016; Lam & Oshodi, 2016). To realise these maintenance strategies the balance between performance (value), risks costs and time remains important in the decision-making process (Goldbohm, 2016; Woodhouse, 2007). The relation between the individual asset and AM is the potential of connecting sensors to the individual asset to contribute to performance optimisation by enabling to monitor asset condition on continuous basis and enabling prediction of the available time for AM - as described by the P-F interval of Nowlan and Heap (1978) - in order to contribute to SAM (Daniotti & Spagnolo, 2016; Lam & Oshodi, 2016).

The more the construction sector shifts towards predictive and performance-based maintenance strategies, the more the exchange of data between the individual asset and AM is required. When the use of sensors increases, the interaction between the individual asset and AM is also likely to increase (Kim et al., 2012, p. 206).

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8 Potential failure: The identifiable condition that indicates that a functional failure is imminent.
9 Functional failure: The estimated moment in time where the asset is unable to meet the specified performance standard.
2.2 RELATION OF THE INDIVIDUAL ASSET WITH ASSET NETWORK

The individual asset is equipped with sensors to collect and analyse sensor data in order to detect and predict the asset performance. This research considers an asset network to consist of multiple individual assets that all contain one or more sensor nodes as illustrated in Figure 15.

Through sharing and exploiting relevant sensor data of other individual assets, a better insight of the detected and predicted asset performance can be acquainted. Additional information that can be gathered through sharing relevant sensor data is called “in context”. Detecting and predicting asset performance in context refers to the individual asset that uses its own sensor data and other relevant sensor data to optimise its interpretation of performance.

![Asset Network Diagram](image1.png)

Figure 15: Multiple individual assets are in an asset network (red), where the individual asset is provided with sensors (grey).

As an asset network consists of multiple individual assets that have sensors, a lot of data is generated. This has the potential of overloading the network even before the data is analysed. The process of reducing the size of data by summarizing it into meaningful information that can be propagated through the wireless sensor network is called data aggregation. To prevent network congestions, data is often pre-processed at the individual sensor prior to transmitting it (Williams, 2014). An example of how to store sensor data at the individual asset is shown in Figure 16.

Wilamowski and Irwin (2011, p. 26) distinguish three main roles within asset networks: Data sources (sensors), data processors (controllers) and data sinks (actuators). The data source refers to the individual sensor, which measures a certain data value. The data sinks are receivers of the data from the network.

![Sensor Data Storage Diagram](image2.png)

Figure 16: Storing sensor data of an individual asset: Measured data at the sensor node is pre-processed and transmitted via the sensor node coordinator to the server and database (based on Chainani (2014)).
Figure 17: The relation between the individual asset and the asset network.

Noted should be that multiple data sinks can be used and at different detail levels (Chen et al., 2009). The data processor refers to the control of some device based on the measured data, for instance an alarm. They all act as nodes in the network. The relation between the asset network and the individual asset indicates the additional functionality, which is visualised in Figure 17.

The relation between the individual asset and the asset network, which is seen in the left of Figure 17, is also disclosed in the Internet of Things (IoT) architecture. Al-Fuqaha et al. (2015) researched the 5-layer model of the IoT architecture, which includes the objects layer, the object abstraction layer, the service management layer, application layer and the business layer (Figure 18). The objects layer represents the physical sensors of the IoT that aim to collect and process sensor data (Al-Fuqaha et al., 2015). The object abstraction layer and service management layer relate to the sharing and exploitation of sensor data, where the layers transfers data and processes received data of the network. The interface between the individual asset and asset network is related to the hierarchal layers of the IoT architecture.

Figure 18: The 5-layer model of the IoT architecture (Al-Fuqaha et al., 2015) enables to relate the individual asset and the asset network.

2.3 RELATION OF THE ASSET NETWORK WITH ASSET MANAGEMENT

The 5-layer model of the IoT architecture can also be used to describe the relations between the asset network and Asset Management (Figure 18). The object abstraction layer and service management layer relate to the asset network through sharing and processing data received by the network. The application layer and business layer relate to Asset Management by providing the services to the customers (Al-Fuqaha et al., 2015).
The control mechanisms of accessing data in the application layer are also handled at the business layer. The responsibilities in the business layer are to build graphs, and flowcharts based on the received data from the application layer. It provides the interface for high-level analysis and reports. The layers of the IoT architecture enable to provide high-quality smart services (Figure 19).

Gubbi et al. (2013) state that assets will not only use data from their own environment (sensing) and interact with the physical world (actuation/control), but also use data from other assets to provide services for information, transfer, analytics, applications and communication. The asset network enables the data transfer and exploitation in order to be used for decision-making processes in SAM. The theory of SAM poses to use data from the asset network and to make this data available to AM applications in a seamless manner.

Smart grid\textsuperscript{10} efforts focus on the deployment of sensors and on using the obtained data to meaningfully combine with data from other sources to gain additional insights (Varadan, 2013). Although smart grids primarily focus on managing electricity networks, the principles allow for monitoring, analysis, control and communication within AM. Smart grids could support the construction sector in improving back-end integration and data analytics (Varadan, 2013).

The back-end integration should be built with command and control capable of meeting functional and operational requirements of an evolving asset network system in order to be suited for AM (Farhangi, 2014). An option is to analyse the required capabilities of the asset network for to allow decision-making processes. The analysis has to identify to which domain such capabilities belong, to which layer of the IoT architecture (Figure 20), and what their data processing, command and control, interface protocol and communication requirements will be (Farhangi, 2014). This will be further elaborated in the report of Braaksma (2016).

\textsuperscript{10}Smart grid: A smart grid is an evolved grid system that manages electricity demand in a sustainable, reliable and economic manner, built on advanced infrastructure and tuned to facilitate the integration of all involved (Shabanazdeh & Parsa-Moghadam, 2014).
Figure 20: The hierarchical integration of an asset network for Asset Management (based on Farhangi (2014)).

The interconnection of the assets enables on-demand or event-based reporting of the status of assets for SAM and is placed in the hierarchical smart grid system integration map in Figure 20.

The asset networks and AM are linked through the information technology infrastructure and the enterprise bus. On the asset network side, this relates to the required communication system to support the exchange and exploitation of data for the purpose of AM (Farhangi, 2014). The enterprise bus is an architecture which contains a set of rules and principles for integrating multiple applications (Zaigham, 2014). The core concept is to integrate different applications that enable applications to talk to the bus. This enables autonomous systems, allowed to communicate without dependency on or knowledge of other systems on the bus. AM applications can be realised and the link between asset, asset network towards AM is made.

2.4 OVERLAP BETWEEN INDIVIDUAL ASSET, ASSET NETWORK AND ASSET MANAGEMENT

According to Gupta (2015), the overlapping area of the individual asset, asset network and AM approaches the core of IoT. These relations between the individual asset, asset network and AM are visualized in the 5-layer model of Farhangi (2014) (Figure 18). The identification of the relations and linking them to the IoT architecture is a first step to describe future AM. Bringing the three concepts together enable to:

- Identify the potential failure (with sensor technology on the individual asset);
- Predict the functional failure (with sensor technology on the individual asset);
- Correct these predictions by using measurements from both the individual assets as from other assets shared by the network;
- Predict more accurately the functional failure of the asset (to be used for SAM), including information about the reliability of predicted performances.
Figure 21: The asset performance over time (moment of functional failure) is better predicted through using sensor data of the individual asset and relevant sensor data of assets from the network. The main advantage of using of sensor technology is that it enables to perform specific measurements on the asset and on a higher frequency than with conservative methods.

As introduced in section 2.1, the P-F interval illustrates the decreasing asset performance and indicates decision-making interval. In the current situation, the asset manager sets the minimum performance level that equals the functional failure and the potential failure curve is estimated by current inspection methods.

Figure 21, adapted from Figure 14, shows multiple curves of performance degradation. The inspection intervals most often equal half the P-F interval, which is used to correct the prediction (Sethiya, 2005). Current methods, such as visual inspections and computer models, can reveal the initial curve (T1) of performance degradation over time.

However, since the P-F interval can be long, the actual degradation curve can deviate. Resulting in a different moment of functional failure, which is shown by T2 and T3 (Figure 21). Sensor measurements can correct the predicted asset performance. It contributes to indicate whether an asset can last longer (T3) or that functional failure will occur earlier (T2) (Misra, 2008; Peelen et al., 2008). Since the time differences for functional failure can months, perhaps even years, sensor technology is promising for predicting the functional failure with a higher accuracy and for being a ‘need to have’ in the construction sector (Misra, 2008).

Executing maintenance too early lead to unnecessary costs, executing maintenance too late results in unavailability and could affect adjacent infrastructural assets. It is relevant for asset managers to optimise this prediction in order to make the right management decisions.

To conclude, the collecting, analysing, sharing and exploitation of sensor data has the potential to detect and predict the performance of individual assets, without having to attach each individual asset with all required sensors. The overlap of the three concepts describe the potential of sensors that are placed on the individual asset, which are brought into an asset network and applied for AM purposes. The identified relations between the individual asset, asset network and AM will contribute to develop a theory for realising SAM.
3 ANALYSIS

The relations between individual asset, asset network and Asset Management (AM) of the previous chapter are used to analyse the current and define the future situation regarding sensor technology in the construction sector. To optimise performance predictions for Smart Asset Management (SAM), sensor data will be collected, analysed, shared and exploited. This chapter provides an analysis of the dependencies in SAM (§3.1) and contains an analysis of three case studies (§3.2), which is used as basis for the theory development of SAM.

SQ3: What is the potential of sensor technology for optimising Asset Management?

3.1 SMART ASSET MANAGEMENT AND SENSOR TECHNOLOGY

The relations between the individual asset, the asset network and Asset Management are introduced in the previous chapter. The overlap of the three can be used to realise Smart Asset Management (SAM). SAM includes the collection, analysis, sharing and exploitation of sensor data to balance performance, costs and risks in managing assets in order to perform the right maintenance at the right time and the right location. The Cambridge Centre for Smart Infrastructure and Construction (CSIC) is a research group from the University of Cambridge established in 2011, which aims are to transform the future of infrastructure through smarter information (CSIC, 2015). The research group is active and has provided over a hundred academic applications of technology for the infrastructure sector since its inception. Their research is centred on four scales: Smart Cities and infrastructure; Smart Asset Management; analysis and interpretation; sensors and data collection. The spatial scales are connected through set requirements, shown in Figure 22, and this continues with these requirements to further define SAM in relation to sensor technology.

The value of an integrated SAM is that strategies can be realised through combining BIM with analysed and interpret sensor data. Coordinated data management is therefore needed in order to contribute to Smart Cities. The interoperability of data sources is essential and will be realised by the adoption of open specification and standards. This is further elaborated in the report of Braaksma (2016). It is an emerging research area for the coming years. Current standards that exist are the Smart City standards (PAS18211), Asset Management standard (ISO5500012), BIM data management standard (IFC13 and COINS14) and sensor web enablement (SWE15).

11 PAS 182:2014: The two UK standards aim at providing the basis of interoperability at the upper ontology level and outlines details of the Smart City Concept Model (SCCM). The PAS is intended to facilitate discussion between Asset Manager and specialists who build and design the systems and services that enable the city to function (BSI, 2014).
12 ISO 55000: The standard is an international norm that specifies requirements for the development, implementation, maintenance and improvements of Asset Management systems (ISO, 2014).
13 IFC: The Industry Foundation Classes (IFC) is an open standard for the exchange of BIM data between different software applications of contractors (BIMlcket, 2014b).
3.1.1 SMART CITIES AND INFRASTRUCTURE

Smart Cities seek to constantly collect, analyse and distribute data about the city to optimise efficiency and effectiveness through a better use of technology and represents the highest concentration of infrastructure and assets (May, 2015). The ongoing challenge is that time required to deliver proper policy and standards is longer than the cyclic development of sensor technology (Kemp, 2015). The application for AM is therefore complex. Nevertheless, spatial information gains a critical role: The economic and functional value of infrastructural assets can be provided with information from sensors. In the construction sector, this stage is currently the client’s domain and based on set performance requirements in the contract (CSIC, 2015).

3.1.2 SMART ASSET MANAGEMENT

The Smart Asset Management scale is the domain of the construction sector’s perspective. The focus is on operating, managing and maintaining assets to deliver the best whole life value and its related decision-making (CSIC, 2015). The construction sector is contractually bound to a performance guarantee, where the maintenance activities have to be based on information. Information requirements are often captured through BIM. In order to maintain at the right time and location needed, there are set information requirements in the management system.

3.1.3 ANALYSIS AND INTERPRETATION

In order to provide the information used to realise SAM, the analysis and interpretation of data is a current challenge (Gleeson & Penney, 2015). The output data collected by sensors is analysed to provide reliable and meaningful results value to asset managers (CSIC, 2015). The design, construction and monitoring of assets needs to provide useful information to ensure the performance. To provide the information needed for AM, Gleeson and Penney (2015) identify five important focus areas: Accuracy, interoperability, metadata, level of detail and generalisation. Determining what data is needed and how to extract the information is of importance. Data requirements are set to obtain the measurements required.

14 COINS: COINS (Dutch: Constructieve Objecten en de Integratie van Processen en Systemen) supports to capture information of different data sources and types, such as GIS data, IFC models and BIM, in one database (Bimloket, 2014a).
15 SWE: The Sensor Web Enablement (SWE) standard enables developers to make all types of sensors, transducers and sensor data repositories discoverable, accessible and useable via the Web (OGC, 2007).
3.1.4 SENSOR AND DATA COLLECTION

Current asset performance measurements include visual inspections, document inspections and reference models (Peelen, 2016). When applying sensor technology, the use of sensors and way of collecting data has to be defined in set data requirements.

One has to determine what variable is to be measured and how many sensor readings have to be retained before taking measurements (Hailes et al., 2009). In the case of sensor nodes, a pre-processor of sensor data, there has to be known which sensors are actually used and what information needs to be stored. Sensor systems need to be robust and reliable for data collection, which is why there are standards required to enable interoperability (Gleeson & Penney, 2015).

In order to improve the understanding of sensors, the components of a single sensor node is shown in Figure 23. A sensor consists of four components: A sensing unit, processing unit, transceiver unit and power unit. The sensing unit is most commonly composed of two subunits: sensor and converters for analogue to digital measurements (Akyildiz et al., 2002). The signals are fed into the processing unit, which has a small storage unit and manages the procedures that make sensor nodes collaborate with other sensor nodes (Matin & Islam, 2012). The processing unit is main contributor to the Position Finding System and Mobiliser, which can be used to link with other sensors and assets. The transceiver unit connects the node to the network and the power unit enables the activities of the sensor.

3.1.5 PERFORMANCE, INFORMATION AND DATA

The performance, information and data requirements have an important role to link the four scales of activity (CSIC, 2015). This research proposes a scenario that directs at the realisation of SAM in the construction sector. The three requirement categories are used to structure the definition of SAM later on in the process (see Chapter 4). It enables to distinguish three scales:

- To demonstrate performance to the client (performance requirements)
- To provide useful information to the asset manager (information requirements)
- To determine a data structure that supports the gathering of information (data requirements).
3.2 CASE STUDIES: SENSOR TECHNOLOGY IN THE CONSTRUCTION SECTOR

Three case studies are performed to gain an understanding of how the dependencies in Asset Management (§3.1) relate to the current situation in the construction sector. The goal is to get acquainted with the applied Asset Management styles and to get a quick overview of the potential sensor technology has in maintenance projects. The case studies are selected based on the different relations towards the incorporation of sensor technology and examined on the basis of the monitoring framework of SBRCURnet (2014).

The monitoring framework provides a systematic approach towards monitoring asset performance and distinguishes seven aspects; Defining goal, assessment model, variables to be measured, monitoring system, collecting data, analysing data and control measure (Figure 24). The arrow between goal and control measure is bilateral, which refers to the alignment of the control measure to the set requirements.

![Figure 24: Three case studies will be evaluated through examining the seven steps distinguished by the monitoring framework of SBRCURnet (2014).](image)

3.2.1 PROJECT STRUCTURES AND EMBANKMENTS MONITORING (HAARLEM)

The maintenance activities regarding the structures and embankments in the city of Haarlem is included in the long-term maintenance contract of the contractor VolkerInfra Haarlem. The long-term maintenance project started in 2014 and lasts for four years. The project includes the monitoring of selected structures and embankments to identify maintenance needed.

GOAL

The goal of VolkerInfra Haarlem is to monitor the performance of assets and to inform the municipality of Haarlem concerning the condition. Specifications regarding the interpretation of the term performance and quality are captured in the contract. The quality specifications are based on CROW (2013) and define several levels: A+ (very good), A (good), B (moderate), C (bad) and D (very bad). Based on visual inspections
and analysis VolkerInfra Haarlem provides information about the technical degradation and upcoming maintenance activities to ensure that the required quality is maintained on the short and long term (Beijer, 2016).

ASSESSMENT MODEL
Since the contract includes a variety of asset types - quay and banks, scaffolding, tunnels, viaducts and amongst them more than 200 fixed bridges - VolkerInfra Haarlem is contractually bound to inspect each individual asset once during the contract period. The assessment can be performed in two ways: reviewing and inspecting. Reviewing is a short drive-by assessment. Inspecting refers to the contractual obligation and involves the extensive inspection of the condition of assets by means of specifying the quality level by experts.

VARIABLES TO BE MEASURED
The contract distinguishes eleven types of assets (van Huet, 2015): Fixed bridges, scaffolds and mooring arrangements, quay walls, cycle tunnels and viaducts, shipping services and bank protection. The variables to be measured are predetermined in the inspection plans and are for fixed bridges related to the image quality - coating, dents and holes - and safety requirements such as pavement, railing and bearing structures.

MONITORING SYSTEM
There is no active monitoring system used in the current situation. Since the project comprises a large area and the contractual obligation is to inspect each asset once during the project, there is chosen to work solely with visual inspections (Beijer, 2016). The online dashboard, named iAsset, provides an overview of the involved assets and is used as a means for information storage and communication with the client (Figure 25). After the observations and inspections, the Asset Manager uploads the inspection data to iAsset. This is performed manually after each observation or inspection, which is time consuming and a duplication of effort.

Figure 25: Overview of the dashboard iAsset used in the structures and embankments monitoring project, which provides an online overview of the applicable assets and their status.
COLLECT DATA
The data is collected through visual inspections. There are two experts available on the project that have to follow a predetermined inspection plan. The inspection plan is designed on the basis of the NEN 2767-4\(^\text{16}\) and is added to the passport of individual assets in the iAsset dashboard (Figure 26).

ANALYSE DATA
The collected data in the inspection plans is analysed through examining quality specifications and prioritizing maintenance activities. The prioritization is performed in a prioritization matrix\(^\text{17}\), which includes a weighting system on aspects such as safety and availability (Beijer, 2016).

CONTROL MEASURE
VolkerInfra Haarlem prioritizes the maintenance activities and as the contractor is only responsible for quality measurements and minor maintenance activities, the control step mostly results in advice to the client. Maintenance activities are considered minor maintenance activities when the costs are below 1500 euro. Prioritized maintenance activities above this threshold are advised to the client for future maintenance. In some cases, the municipality of Haarlem requested to execute the additional work.

Evaluation
The project consists of a large variety and quantity of assets and the project area is spread throughout Haarlem. The contract binds VolkerInfra Haarlem to inspect each individual asset at least once during the contract period. The contractual budget is limited to inspections and minor maintenance activities. This is main reason why incorporation of sensor technology was considered out of scope (Beijer, 2016).

The focus of the project is to provide insight into the current status of assets through advising control measures to the client. The variables to be measured are explicitly addressed in the contract and are based on the NEN2767-4. This results in little space for innovative solutions. The contract directs to indicating asset performance in a fixed scheme and conducting minor maintenance activities. The incorporation of sensor technology is of interest once the project has a broader scope in finances, asset complexity and duration (Blommaert et al., 2016).

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\(^{16}\) NEN 2767-4: The norm is a standard to define the condition of infrastructural assets on an objective and unambiguous manner (NEN, 2011).

\(^{17}\) Prioritization matrix: A tool that provides a way to sort a diverse set of time into an order of importance. It is used as means for ranking maintenance activities to be performed, based on criteria that are determined to be important.
3.2.2 PROJECT REAL-TIME RAILWAY MONITORING (ZEELAND)

The maintenance activities regarding the monitoring of railways in Zeeland is included in the long-term maintenance contract of the contractor VolkerRail and subsidiary company Inspectation. The long-term maintenance project commenced in 2012 and lasts until 2017. The project includes the monitoring of selected turnouts, track circuits, signalling and level crossings to identify maintenance requirements.

GOAL

Availability and the reliability of infrastructure are of major concern for the railway industry. Apart from inspecting assets periodically by taking measurements, the company Inspectation acknowledges the trend of monitoring assets over longer periods to identify failures early (National Instruments, 2013). As a result, the company developed an online condition monitoring system for use in the rail infrastructure. The primary goal was to reduce avoidable faults, thereby improving reliability and availability of the network. The maintenance strategy would then change from corrective and preventive maintenance, to preventive condition based (Van den Bos et al., 2013).

ASSESSMENT MODEL

The company Inspectation identified objects that are prone to failure, such as the turnouts\textsuperscript{18}, signalling, track circuits\textsuperscript{19} and level crossings (Van den Bos et al., 2013). Since the assets serve different goals, a further analysis is performed to determine the assessment model for each asset type. The model includes measurement of the distinguished causes for specific failures. Figure 27 shows the results of the failure mode and effect analysis (FMEA) that is applied to identify indicators for a turnout.

<table>
<thead>
<tr>
<th>Cause</th>
<th>Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>No power available to drive the electric motor</td>
<td>Voltage of the power supply</td>
</tr>
<tr>
<td>Failure of steering relay</td>
<td>Status of the steering relay (up/down)</td>
</tr>
<tr>
<td>Failure of circuit between steering relay and electric motor</td>
<td>Motor current (no current)</td>
</tr>
<tr>
<td>Blockage of electric motor or point blades</td>
<td>Motor current (force to high, current is maximum)</td>
</tr>
<tr>
<td>Frozen point blades</td>
<td>Track temperature</td>
</tr>
</tbody>
</table>

Figure 27: Identified causes and indicators for turnouts, continuing on the failure mode of “no movement of the point blades after steering”, based on Van den Bos et al. (2013).

VARIABLES TO BE MEASURED

The causes for failures and indicators are investigated by Inspectation and contributed to defining the parameters to be measured for the monitoring. Since most commonly used railway signalling in the Netherlands originates from the 50s and consists of relay interlocking\textsuperscript{20}, the required condition data is measured by voltage transducers, current transducers, force sensors, temperature sensors and potential free (“dry”) contact on relays (Van den Bos et al., 2013).

\textsuperscript{18} Turnout: A turnout (Dutch: wissel) is also known as points and switches that contain several relays and electric motor to move switching tracks left or right (Van den Bos et al., 2013).

\textsuperscript{19} Track circuit: a common method of block signalling divides the track into zones where guarded automatic control devices allow only one train in a block at any time (Van den Bos et al., 2013).

\textsuperscript{20} Interlocking: The arrangement of signals and appliances that display a signal to proceed when the route is proven safe; turnouts are locked and in correct position, level crossings are activated and the railway is clear.
MONITORING SYSTEM
The set-up consists of more than two hundred monitoring units; therefore, requirements for the monitoring system are distinguished. The monitoring system was deployed and operational within a year, and the online buffering and pre-processing of sensor data had to be enabled. Additionally, as sensors are placed inside assets and connected to logging units, the system synchronization through GPS was of importance. The sensors might be related to each other. Therefore, a 3G connectivity to transfer the data to a central database was needed. An overview of the applied monitoring system is shown in Figure 28.

![Figure 28: Applied system architecture in the monitoring project (Van den Bos et al., 2013).](image)

COLLECT DATA
The sensor data is collected by the data acquisition (DAQ) device, which contains CompactRIO data loggers enabling the collection of measurements with a sample rate between 5kS/s and 30 kS/s. The DAQ Device is small and synchronizes with GPS. An example is shown in Figure 29.

The collection of data is performed continuously. The DAQ device has multiple channels where sensors are plugged in. For each channel, a measurement scenario is defined, depending on the characteristics of the used sensors and hardware. In cases where the user demands a better understanding of the event, the collected data is down sampled and transmitted (Steentjes, 2016).

![Figure 29: Example of the (CompactRIO) monitoring unit during installation in a relay cabinet (National Instruments, 2013).](image)
The collected sensor data is gathered at the DAQ device, which is connected with a LabVIEW application that stores the data in a SQL database (Van den Bos et al., 2013). As shown in Figure 28, the raw data is send to a web viewer for detailed analysis.

**ANALYSE DATA**

The data analysis is performed at the Event Server Application (ESA). The ESA combines the collected pre-processed sensor data into events and stores the data in an object and event data database. The relation between the sensor data measured and the assets these signals belong to, are known by the ESA in order to start further processing of data (Van den Bos et al., 2013). Several algorithms are used to interpret the data. When an event, programmed as a combination of certain sensor measurements, is detected in the dataset, the log is stored as event in the ESA server. Once calculations are completed the values are compared to upper and lower thresholds for alarm and warning conditions (Blenkers, 2016).

**CONTROL MEASURE**

The object and event data database stores the processed data and is linked to a web service that displays the data to the user (see Figure 28). The server runs queries constantly to provide a real-time display of the situation. Warning or alarm conditions are set and are linked to output messages to the maintenance crew.

VolkerRail is able to detect degradation of asset and perform condition based preventive maintenance based on the data visualised in the web application. An overall fault reduction of 30% (Steentjes, 2016) and a fault reduction for turnouts of 65% (Van den Bos et al., 2013) is achieved.

**EVALUATION**

VolkerRail pays special attention to the definition of variables to be measured. Key in carrying out monitoring projects successfully is determining what information is required and how this is translated into variables to be measured (Steentjes, 2016). The monitoring system and collecting of data are realised by conducting small pilots and up scaling when it was successful.

The use of algorithms to distinguish event data from the raw data enables the to detect the asset performance per event. The focus for AM is primary on the operational performance of the entire system, secondary on the individual performance of assets. The approach does not include an asset network yet. Current research is being conducted into the use of the collected data of individual assets for a broader use, such as asset network purposes (Steentjes, 2016). An asset network is currently not included, because the raw data of sensors is processed as separate single data sources and used for event detection in a later process. The project manages a predictive maintenance approach through setting alarms when irregularities are detected in the events.
3.2.3 PROJECT VAN BRIENENOORD-BRIDGE (ROTTERDAM)

The identification of asset performance at the Van Brienenoord-bridge (Figure 30) was included in the pilot monitoring project of RWS, which is executed by TNO. The pilot project started in 2010 and lasted for four years. The project included the monitoring of a selected area to predict fatigue cracks in the deck plate.

TNO, a research institute for applied scientific research, cooperated with RWS to work on the Van Brienenoord-bridge, the largest steel bridge in the Netherlands. TNO used the project as a validation for the BLSD project\textsuperscript{21}, which is focused on condition monitoring of bridges. The project uses distinguished measurement and modelling techniques by means of sensor technology.

GOAL

The goal was to conduct a test case to monitor the lifetime of the steel bridge decks, to shorten the inspection interval and to execute maintenance activities just-in-time (Peelen, 2016). The two main research goals of the project are to:

- Demonstrate added value of measuring, modelling and prediction in practice.
- Incorporate and test sensors in combination with prediction models.

ASSESSMENT MODEL

First, required steps are distinguished for calculating the lifetime prediction of the expected concrete crack growth. The variables to be measured were based on factors encountered during this first stage. Additional information about the bridge is used separately from the sensor data measurements. This information is related to BIM; Examples are the deck plate thickness, the distances between troughs, the construction of crossbars and the traffic loads (SBRCURnet, 2015).

\textsuperscript{21} BLSD project: The Bridge Life Span Demonstrator project aimed to demonstrate the added value of combining advanced measurement systems with advance predictive models (Meijer, 2015).
During the project the focus was on the right traffic lane, which bears the largest traffic loads due to freight traffic. A relative small part of the bridge is provided with sensors (Figure 31). Results for the entire bridge deck is gathered through extrapolation (Peelen, 2016).

**VARIABLES TO BE MEASURED**

Input for the predictive modelling of remaining lifetime are the strains, deck fractures and their location on relevant positions on the traffic lane. The sensor network included sixteen sensors (Timar, 2013): “thermocouples for measuring the temperature at the bridge deck, strain gauges for measuring the strains in the steel, acceleration sensors for measuring vibration and acoustic emission sensors for measuring sound waves into the steel.”

**MONITORING SYSTEM**

The monitoring system was deployed on the bridge deck as shown in Figure 32. The strain gauges, as mentioned, are used to measure the strains in the steel. The strains occur at the welds of the troughs with the deck plate (Figure 33). Since the traffic load fluctuations cause fatigue cracks in the deck plate, the strain measurements are used to estimate these fluctuations on the critical locations (Bleijenberg et al., 2014).
The acoustic emission (AE) sensors can detect the fatigue crack growth. With these measurements, the predictions can be improved, because the actual fatigue crack growths are indicated (SBRCURnet, 2015). TNO created a scalable sensor network through using their developed DynAA\textsuperscript{22} tooling program. The sensor measurements are combined with the probabilistic models developed by research institute and allow condition based maintenance of assets by enabling accurate monitoring of fracture growth in the bridge deck and location of the crack (Pasman et al., 2014).

**COLLECT DATA**

In order to filter out errors in advance, the maximum strains are collected from the measured strains. Next to this, the AE output and the air temperature are collected. The sensor data is stored on a local server, which transfers the data to the TNO data server. The measuring instruments are linked to a data-acquisition system, which realizes the data connection to the TNO server (Figure 34). The data transfer to the TNO server is not performed real-time, but through uploads on a periodical basis. The raw sensor data is then converted to the correct input for the prediction models (Peelen, 2016).

\textsuperscript{22} DynAA: DynAA is a developed computer program by TNO which can analyse and simulate sensor networks, thereby identifying risk events
Figure 35: Stress distribution on a solid model bridge using the FEM technique (InfoGraph, 2016).

ANALYSE DATA
Several models are used to validate, analyse and evaluate the data. The conversion of the measured strains is based on the basis of a Finite Element Method (FEM) with additional calculation steps (SBRCURnet, 2015). The FEM is a numerical technique to solve partial differential equations that are used for strength visualizations. An example is shown in Figure 35.

The AE sensors are analysed through using empirical knowledge of TNO experts and with additional measurements the crack size of the largest cracks is determined. The data is input for the crack growth model that provides a prognosis of the crack development. An extrapolation model predicts the future cracks for the entire bridge. The results show that the predicted remaining lifetime increases when compared to conventional measuring techniques, e.g. visual inspections (Peelen, 2016).

Additional tooling is developed to evaluate the efficiency of the system architecture (Figure 34). Data-analysis technologies are used - sensor clustering and anomaly detection – for data processing and information extraction. The technologies were developed for the pilot project and are currently analysed for their applicability in real time situations (Pasman et al., 2014). The sensor network is referred to as the collection of sensors contributing to determine the performance of an asset. Referring to the sharing sensor data to other infrastructural assets at other locations, the pilot project has not deployed sensors for the extrapolation in an asset network.

CONTROL MEASURE
The results of the pilot project show that it is possible to increase the understanding of the condition of the bridge compared with the usual inspection techniques. Next steps are to develop generic measurement systems for steel bridges (Timar, 2013). The gathered information is intended for optimising the interval of inspections, repairs and replacements. In order to realise this, the project indicated that crack growth detection requires further research. Since TNO is not involved for maintenance activities, the control measure regarding decision-making for AM is not included. The predictions of the cracks and crack development over time is handed of to RWS as asset information (Peelen, 2016).

EVALUATION
The Van Brienenoord-bridge is a proper example of applying sensor technology for predictive asset performance. In advance of conducting the monitoring of the bridge itself, TNO defined the variables and the correlations. The monitoring system focused on a small area of the bridge deck and detected correlations are used to extrapolate
to the other parts of the bridge deck. Since the project was focused on enabling new technologies to be used by the construction sector and TNO is a research institute, the link towards AM has not been made. Nevertheless, the combination sensor technology and human inspection is considered a required combination, where the use of sensor techniques could aid humans in better understanding the complex reality (Peelen, 2016).

Sensor data is processed periodically each time a data dump is received. Experts from TNO perform the data analysis and utilize a sensor network for extrapolation purposes across the bridge deck. The sharing and exploitation of sensor data in a two-way between assets is to be further researched. According to Peelen (2016), “a successful sensor network depends on the correlation between the different assets”. Correlation is necessary to be detected in monitoring projects. Preferably, this correlation is strong. Though, simple measurements on assets could still provide information and feed a weak correlation (Peelen, 2016).

3.2.4 CONCLUSION ON THE CASE STUDIES

This chapter analysed three case studies on the basis of their management styles for Asset Management and the incorporation of sensor technology. All three case studies addressed the variables to be measured as important factor. When a correlation is drawn between assets, the variables could be used to establish an asset network. The railway-monitoring project made a first attempt through identifying events from (big) sensor data. The identified event can be linked to an individual asset and be used as input for the asset network. This is indicated to be of interest for further research (Peelen, 2016; Steentjes, 2016).

Determining ways to collect the data is straightforward, as many types of sensors are available on the market. The suitability of the monitoring system to transfer the sensor data efficiently seems challenging. The system architecture is considered an essential part for realising an asset network in a later phase.

The three case studies have different goals; therefore the control measures differ. The Project Van Brieneoord-bridge for example was not intended for AM applications directly; the control measure included a prediction model. The link between the goal for the monitoring project and the actual output at the control measure is considered to be examined both in the end as evaluation as in the beginning of the monitoring project to set the demanded output and expectations. An overview of the three case studies is shown in Table 1.
<table>
<thead>
<tr>
<th>Case study</th>
<th>Structures and embankments monitoring</th>
<th>Real-time railway monitoring</th>
<th>Van Brienenoord bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal</td>
<td>Monitor performance and inform client</td>
<td>Monitor performance and perform maintenance if needed</td>
<td>Monitor performance and inform client Create scalable sensor network</td>
</tr>
<tr>
<td>Assessment model</td>
<td>Predetermine by contract: Visual inspections of all individual assets</td>
<td>FMEA identified suitable objects for monitoring</td>
<td>Previously conducted research identified variables to be measured, and focus shift to small part of the area</td>
</tr>
<tr>
<td>Variables to be measured</td>
<td>Predetermined by contract: image quality and safety requirements</td>
<td>Voltage transducers Current transducers or clamps Force sensors Temperature sensors Potential free contact relays</td>
<td>Strains in steel Acceleration to measure vibration Acoustic emission for sound waves in steel Temperature bridge deck</td>
</tr>
<tr>
<td>Monitoring system</td>
<td>Online dashboard, manual input of data</td>
<td>Online dashboard, partly automatic input of data System architecture for data support</td>
<td>DynAA tooling program which enables a scalable sensor network and probabilistic models</td>
</tr>
<tr>
<td>Collect data</td>
<td>Visual inspections</td>
<td>Sensor-based inspection of individual assets (with CompactRIO data loggers)</td>
<td>Sensor-based inspection of assets (with sixteen sensors). Data is collected real-time, stored manually.</td>
</tr>
<tr>
<td>Analyse data</td>
<td>Prioritization matrix (manually)</td>
<td>Performed at the ESA server, which combines pre-processed sensor data into events. Algorithms are used for this. Alarm conditions set based on calculations.</td>
<td>Performed with FEM and additional calculations. Extrapolation model for cracks over time entire bridge.</td>
</tr>
<tr>
<td>Control measure</td>
<td>Link data to Excel for visualisation and human interpretation. Perform minor maintenance activities Advice client for larger maintenance activities</td>
<td>Link data to a web service for visualisation and human interpretation. Able to detect degradation of individual asset and perform condition based maintenance.</td>
<td>Link data to local server for visualisation and human interpretation. Advice client by providing prediction models for cracks and crack development over time.</td>
</tr>
</tbody>
</table>

Table 1: The applied management styles of the three case studies that are analysed through examining the steps as defined in the monitoring framework of SBRCURnet (2014).
3.3 CONCLUSION

Smart Asset Management (SAM) is positioned as one of the four scales of activity (CSIC, 2015). The four scales - Smart Cities and infrastructure, Smart Asset Management, analysis and interpretation and sensor and data collection - are linked through performance requirements, information requirements and data requirements.

The performance requirements relate to the domain of the clients’ perspective and include the use of sensor data for a broader purpose than SAM in the construction sector. The realisation of SAM is seen as the response to the need for linked and interconnected systems and sub-systems of asset information to be realised within Smart Cities. The information requirements relate to the current domain of the construction sectors’ perspective and include the requirements set in the management systems in order to maintain at the right time and location needed. The analysis and interpretation of collected data is an important aspect, because it has to provide reliable and meaningful results to asset managers. The data requirements relate to sensors and include aspects such as accuracy, interoperability, metadata, level of detail and generalisation. The developed sensor systems need to be robust and reliable for data collection.

The case studies Structures and embankments monitoring Haarlem, Real-time railway monitoring Zeeland and Van Brienenoord bridge were examined using the monitoring framework of SBRCURnet (2014) in order to gain insight in current AM strategies. The analysis of the Haarlem project shows an applied AM strategy based on visual inspections. Due to limited budget and contract duration, the use of sensors was out of the project scope and considered a ‘nice to have’. The railway-monitoring project of VolkerRail on the other hand, applies an active sensor system to indicate asset performance real-time. The project shows that it is possible to predict operational performance of assets through identifying events from sensor data. The pilot project of the Van Brienenoord-bridge shows the potential of sensor networks. Through identifying correlations between assets, a sensor network is created and used for extrapolation purposes. The case studies emphasize the importance of defining variables to be measured, defining correlations to link assets and composing a monitoring system capable of sharing data through wireless connections.

The gathered knowledge from the three case studies (see Table 1) is the insight that the different contractual goals result in different applied AM strategies and influences the application of sensors. Furthermore, the case studies indicate that the analysis and interpretation of sensor data is to be handled carefully. Only then, sensor technology has the potential to provide sensor data that through sharing and exploiting in asset networks can balance performance, risks and costs in managing assets in a smart way.

Concerning realising SAM in the construction sector, the identified requirements for performance, information and data should be taken into account. The findings of this chapter are included as requirements in the Theory Development (Chapter 4).
With the current situation analysed and the potential of sensor technology identified, this chapter provides the theoretical implementation of SAM. The theoretical implementation is split into three parts: the theory development (§4.1), the theory testing (§4.2) and the theory evaluation (§4.3). The chapter continues on the previous findings of the theoretical framework, case studies, interviews with experts and a literature study in order to define the requirements for SAM. In the subsequent sections, the requirements will be tested and evaluated. This chapter contributes to answering the third sub-question:

SQ4: Which requirements should to be taken into account when incorporating sensor technology in managing assets during the maintenance phase of road infrastructure projects?

4.1 THEORY DEVELOPMENT

With the current situation analysed and the potential of sensor technology identified, this section defines a theory for incorporating sensor technology to optimise Asset Management. The theory development provides the scenario of the asset manager of the future (§4.1.1), indicating the need for information and what is needed to move from data to this needed information. Subsequently, this chapter offers a complete overview of the performance, information and data requirements (§4.1.2), which will be tested and evaluated in the subsequent sections.

4.1.1 ASSET MANAGER OF THE FUTURE (SCENARIO)

Imagine the near future where Asset Managers access the real-time performance of assets on their computers. Imagine that sensor technology is implemented in current AM systems. To define the requirements to realise Smart Asset Management (SAM), the scenario of “Asset Manager of the future” proposes an implementation to the construction sector for incorporating sensor technology:
John is a asset manager at a construction company. Being an asset manager, John has the responsibility to look after the performance of two hundred expansion joints.

The Smart Asset Management (SAM) system facilitates to plan proper maintenance activities, because the current status of all expansion joints and relevant asset-information are easily found.

Individual assets are equipped with sensors that monitor the real-time performance of the asset accurately. Relevant sensor data of other assets is shared over the network to improve the prediction of the individual asset performance; hence a Smart Asset (SA) and Smart Asset Network (SAN) are created. This enables John to view the individual performance of assets along with their corresponding performance graphs as well as to gain an overview of multiple assets in the project area.

The sensor data is also used to conduct predictive maintenance analysis. Through using sensor data of attached sensors and relevant sensor data of other assets in a Smart Asset Network (SAN), predictions regarding future performance are generated. The visualisation of the filtered data links geodata with BIM data and is accessible for John in an interactive web viewer.

NEED FOR DATA

The scenario entails multiple subjects that require data requirements in order to present useful information. As described in section 3.1, sensor technology and SAM are linked through defining information and data requirements.

The need for data depends on the required information (see §3.1). In this, the reliability of the sensor data is important to be taken into account. The effects of resampling, filtering, structuring and combining data sources could result in semantic problems (Horst & Sinitsyn, 2012). The semantic web languages RDF\textsuperscript{23} and OWL\textsuperscript{24} can be useful. Asset managers are mainly interested in the performance degradation of the assets and request an alarm when the performance is below a certain threshold. Semantics are important here as the system has to decide which sensor data and operations are required to answer this request (Whitehouse et al., 2006).

NEED FOR INFORMATION

The adoption of sensor technology in Asset Management (AM) also introduces information requirements to support AM decision-making and to ensure the performance of assets to be managed.

From a Geomatics perspective, the analysis of the required geospatial information - by performing required processing and analysis of available sensor data - allows turning sensor measurements into useful information and knowledge. From a

\textsuperscript{23} RDF: Resource Description Framework (RDF) is a standard (metadata) model for data interchange on the Web. It defines statements comprising of a predicate (property) and an object. The subject, predicate, object relationship is called a triple (W3C, 2014).

\textsuperscript{24} OWL: Web Ontology Language (OWL) is a semantic web language designed to represent rich and complex knowledge about things, groups of things and relations between things (W3C, 2012).
Construction Management perspective, the analysis of the required asset information – by performing required processing and analysis of available BIM data - allows the asset manager to assess the reliability, availability, maintainability and safety of assets. An example of information required by the asset manager is the correlation factor and reliability factor of the presented individual asset performance. The asset manager uses this information for the decision-making process.

SUBJECTS TO BE CONSIDERED IN DETERMINING REQUIREMENTS

The proposed scenario is split up into building blocks. The development starts with the smallest block – SA – which lies within larger blocks – SAN and SAM – when further developing (Figure 36). The subjects to be considered relate to the different goals within each block: To collect and analyse sensor data, to share and exploit sensor data and to determine proper maintenance strategies. As the goal deviates for each level, different requirements occur at these blocks. Smart Asset Management – the largest block – is built upon the requirements from the inner blocks. This research includes the requirements for SAM and addresses them in the upcoming sections. The research of Braaksma (2016) analyses to what extent the SA and SAN can fulfil the requirements and contribute to realising SAM. Important to note is that Braaksma (2016) also researches and determines requirements specifically for the SA and SAN, these are excluded from this research.

Figure 36: The subjects to be considered include the ability to collect and analyse sensor data to detect and predict the individual performance (hence a SA), to share and exploit sensor data to be shared over the network (hence a SAN) and to enable efficient decision-making based through maintaining at the right moment and location needed (hence SAM).
4.1.2 REQUIREMENTS FOR SMART ASSET MANAGEMENT

On the basis of the conducted literature research, case studies and insights from experts, this section discusses the distinguished requirements for Smart Asset Management (SAM). The maintenance of assets is dedicated to the reliability and availability towards the client (Rijkswaterstaat, 2014a). The client of large infrastructural maintenance projects is often RWS, who has the responsibility towards the users of road infrastructure projects. The construction sector could use the potential of sensor technology to improve these performance guarantees to RWS with the following objectives:

- Storing and retrieving performance data improves insight in the actual and real-time condition of assets
- Predicting future conditions and service levels based on set performance requirements
- Supporting efficient planning of maintenance activities by better informed decision-making
- Integrating new technologies and innovating, through establishing goals, identifying the need for performance measures and developing a SAM system

To exploit the potential of sensor technology for these objectives in a structured way, the monitoring framework of SBRCURnet (2014) is used to test the proposed scenario. The monitoring framework is used in the case studies (§3.2) and provides a systematic approach for evaluating monitoring projects. The use of the monitoring framework to evaluate a SA and a SAN is discussed in the report “Smart Asset Management: An in-depth analysis of the application of Smart Asset and Smart Asset Network” of Braaksma (2016).

Continuing on the analysis of the dependencies in SAM in section 3.1, the subsequent sections discusses the performance requirements, referring to the guarantee of performance to the client, the information requirements, referring to providing useful information to the asset manager, and data requirements, referring to determining a data structure that supports the gathering of information.

PERFORMANCE REQUIREMENTS

The aim of contractors is to ensure the performance of assets by enabling insight into the current and future performance status to the client. The performance requirements refer to the contractually defined performance guarantee to the client (see §3.1). In order to improve insight in the actual and real-time behaviour of assets, two main performance requirements are addressed (Table 2).

<table>
<thead>
<tr>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide insight into the reliability of assets</td>
</tr>
<tr>
<td>Provide insight into the availability of assets</td>
</tr>
</tbody>
</table>

*Table 2: The identified performance requirements.*
Based on the theoretical framework, conducted interviews with experts and the literature study, the performance requirements direct to:

- **Provide insight into the reliability of assets.** There are four sub-aspects distinguished by Rijkswaterstaat (2013) that are considered relevant: Asset lifetime, implementation sensitivity, wear resistance and corrosion sensitivity. The reliability of assets is a challenging measurement, where the reliability strongly depends on the performance indicators and the reliability of the information they provide.

- **Provide insight into the availability of assets.** The term refers to the extent to which assets are unavailable for users. The case study of VolkerRail (§3.2.2) emphasizes the need for the availability of assets. Maintenance contracts often address a reward and penalties system for the availability of assets (Blenkers, 2016). An unreliable asset has a bigger chance of failure and a lower availability (Van den Boomen, 2015). This is why the inseparable subjects are the two important performance guarantees to the client (Huitema, 2016).

**INFORMATION REQUIREMENTS**

Informed decision-making can only be realised when collected data is correctly analysed and interpreted to become information. Current Asset Management is policy driven, option and trade-off analyses based and related to decision-making of quality information and personal feedback (Goldbohm, 2016). By taking sensor technology into account this approach is improved by enabling performance optimisation (§3.1).

The addressed need for information (§4.1.1) indicates that informed decision-making is key in realising SAM. Seven main information requirements are identified (Table 3).

<table>
<thead>
<tr>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Select applicable assets for monitoring purposes</td>
</tr>
<tr>
<td>Determine the need for information and therefore the needed data to be collected</td>
</tr>
<tr>
<td>Store the data and information in an online server or database in order to be accessible at all times</td>
</tr>
<tr>
<td>Define the performance pattern of an asset type</td>
</tr>
<tr>
<td>Detect individual asset performance</td>
</tr>
<tr>
<td>Predict individual asset performance</td>
</tr>
<tr>
<td>Provide the reliability factor for the detected asset performance</td>
</tr>
</tbody>
</table>

*Table 3: The identified information requirements.*

Based on the theoretical framework, conducted interviews with experts and the literature study, the identified information requirements direct to:

- **Select applicable assets for monitoring purposes.** The collected data and information must be detailed enough to support the understanding of the involved assets. At the same time, the assets must be aggregate enough to allow assets of different nature and scope within the network to be addressed.

- **Determine the need for information and therefore the required data to be collected** (see §4.1.1 and §4.1.2). The collected and stored information should support an explicitly defined decision need (WERD, 2003). The case study of
VolkerRail is an example where the gathered information is stored as events in order to be used by asset managers. The information should be relevant for decision-making as presenting redundant information to asset managers may result in misinterpretations and thereby poor decision-making.

- Store the data and information in an online server or database in order to be accessible at all times. By storing the data and information in an online server, the data and information can be re-used for other application purposes, for example Smart Cities applications. Indirectly, the requirement addresses the need to balance the amount of sensor data values needed to identify the required information (Steentjes, 2016).

- Define the performance pattern of an asset type. This requirement relates to the identification of the potential failure and functional failure. The detection of the potential failure is the first evidence of deterioration of an asset and can be used as starting point for managing asset performance (see §2.1 and §3.2.2). The functional failure is the moment when the asset is performing below its set functional requirement. The sooner a potential failure is discovered, the longer the associated P-F interval (see §2.1). Longer P-F intervals mean that there is more time to avoid the consequences of the asset failure (Moubray, 1997).

- Detect individual asset performance. The performance of an asset can only be controlled when the performance is detected. The implementation of an individual SA and additional information from the SAN could be used for this, which is researched by Braaksma (2016).

- Predict individual asset performance. The performance of the asset is not only detected, but the sensor data can also be used to predict asset performance. Sensor data can be used from attached sensors or be collected by the network through extrapolation methods. The implementation of a SAN addresses the correlation and extrapolation and is researched by Braaksma (2016).

- Provide the reliability factor for the detected asset performances. In order to realise a SAN that can share and exploit sensor data, the correlation between different assets is to be detected (Peelen, 2016). This is also subject to correct filtering and interpretation of findings (Lemmens, 2015). This correlation is preferably strong, but will deviate between assets (see §3.2.3). The reliability factor serves as indicator for the quality of the detected correlation and therefore the detected performance. The reliability factor for detected performances can differ due to differences between assets’ location, construction type and usage (Guo, 2014).

DATA REQUIREMENTS

Data collection, data management and data integration are three essential parts for the success of AM. Related and accurate data lead to information and can form the basis for decision-making (Flintsch & Bryant, 2009). The data collection has to be dependent on the intended use of the data. Data requirements are needed to specify how the collected data is going to be used at the management decision levels.
Having sufficient, detailed data in a usable format is critical to successful AM implementation (NHCRP, 2009). There are six data requirements identified (Table 4).

<table>
<thead>
<tr>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide metadata and semantics</td>
</tr>
<tr>
<td>Serve interoperability between different sensor data types</td>
</tr>
<tr>
<td>Determine the connection between BIM data and sensor data</td>
</tr>
<tr>
<td>Ensure proper data collection</td>
</tr>
<tr>
<td>Ensure data security and privacy</td>
</tr>
<tr>
<td>Specify the method of sharing sensor data</td>
</tr>
</tbody>
</table>

Table 4: The identified data requirements.

Based on the theoretical framework, conducted interviews with experts and the literature study, the following data requirements are distinguished:

- Provide metadata and semantics of sensor data. The Open Geospatial Consortium (OGC) introduced a new set of standards called Sensor Web Enablement (SWE) in 2008. The standards enable to link sensors and retrieve data in a uniform way. Descriptions of sensor metadata, encoding specification for sensor data and data retrieval are addressed (de Liefde, 2016). The metadata and semantics are to be addressed when realising a SA and especially when realising the SAN.

- Serve interoperability between different data types. The interoperability of data sources is a current challenge (see §3.1). The connection between different sensor types and different units of measurement has to be addressed in order to provide meaningful results to the asset manager (CSIC, 2015).

- Determine the connection between BIM data and sensor data. The interoperability between geodata and BIM data addresses two fundamental issues of handling spatial referencing and interchanging of formats (Gleeson & Penney, 2015). The link between BIM data and sensor data challenges the traditional approaches to data management, due to the volume of data, and has to be carefully handled by the monitoring system (Riaz et al., 2015).

- Ensure proper data collection. In this, the data accuracy reflects on two aspects: Data values should represent as closely as possible the considered piece of information, and should be collected at a proper sampling rate. King (2015) states the sampling rate is to be considered in order to avoid “data obesity”. Quite possibly, the collected measurements contain redundancy. This necessitates the need for validating the veracity and requisite of data (WERD, 2003).

- Determine a proper solution to ensure data security and data privacy. Current data security mechanisms in wireless sensor networks are insufficient due to their novelty and their increasing dissemination (Ramos & Filho, 2015). Adversaries can gain access to individual sensor nodes due to the open nature of wireless communication channels and lack of physical protection of the sensor nodes, which is why this is a current trending topic (IARIA, 2016; Ramos & Filho, 2015). The data privacy reflects on the way of handling with privacy.
sensitive data along the sensor network (van den Beld, 2008). Although the intention may not be to collect personal data, many sensor network applications involve collecting personally identifiable information, which is the case when monitoring traffic (Anand et al., 2006).

- Specify the method of sharing sensor data. The technical challenge of transferring pre-processed sensor data are clearly seen in the case studies (§3.2) and needs to be handled by the monitoring system.

4.2 THEORY TESTING

With the scenario of ‘Asset Manager of the future’ proposed and the requirements for SAM identified, this section includes the theory testing for incorporating sensor technology to optimise Asset Management. The theory testing is performed in “Smart Asset Management in the construction sector: An in-depth analysis of the application of Smart Asset and Smart Asset Network” of Braaksma (2016) as a separate research report. This section provides an overview of the results.

The objective of the research report of Braaksma (2016) is to identify influential aspects when realising the SA and SAN in the construction sector. The research focuses on the expansion joint as a characteristic asset and examines the set requirements of the theory development (§4.1). Braaksma (2016) indicates the following influential aspects when realising SA and SAN in the construction sector:

- Smart Asset
  - Manage expectations and added value of incorporating sensor technology in AM
  - Collect relevant sensor data for asset monitoring through explicitly defining the performance indicators and the variables to be measured
  - Define proper methods to handle the transfer of sensor data within the monitoring system
  - Adapt SAM systems through extrapolation of sensor results in order to be suited for decision-making

- Smart Asset Network
  - The willingness of asset managers to work with and rely on a SAN
  - The application and interpretation of sensor and BIM data sources in order to provide information on the performance of assets
  - The successful detection of inter-correlation and further research into calculation techniques to achieve this correlation
  - The representativeness of sensor data for extrapolation purposes

After evaluating the potential of using sensor technology in realising the SA and SAN for expansion joints, the report concluded with evaluating the set requirements of Chapter 4. An overview of the results is shown in Table 5.
<table>
<thead>
<tr>
<th>Type</th>
<th>Requirement</th>
<th>✓/✗</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>Provide insight into the reliability of assets</td>
<td>✓</td>
</tr>
<tr>
<td>Information</td>
<td>Provide insight into the availability of assets</td>
<td>✓</td>
</tr>
<tr>
<td>Information</td>
<td>Select applicable assets for monitoring purposes</td>
<td>✓</td>
</tr>
<tr>
<td>Information</td>
<td>Determine the need for information and therefore the needed data to be collected</td>
<td>✓</td>
</tr>
<tr>
<td>Information</td>
<td>Store the data and information in an online server or database in order to be accessible at all times</td>
<td>✓</td>
</tr>
<tr>
<td>Information</td>
<td>Define the performance pattern of an asset type</td>
<td>✗</td>
</tr>
<tr>
<td>Information</td>
<td>Detect individual asset performance</td>
<td>✓</td>
</tr>
<tr>
<td>Information</td>
<td>Predict individual asset performance</td>
<td>✓</td>
</tr>
<tr>
<td>Information</td>
<td>Provide the reliability factor for the detected correlations</td>
<td>✗</td>
</tr>
<tr>
<td>Data</td>
<td>Provide metadata and semantics</td>
<td>✓</td>
</tr>
<tr>
<td>Data</td>
<td>Serve interoperability between different data types</td>
<td>✓</td>
</tr>
<tr>
<td>Data</td>
<td>Determine the connection between BIM data and sensor data</td>
<td>✓</td>
</tr>
<tr>
<td>Data</td>
<td>Ensure proper data collection</td>
<td>✓</td>
</tr>
<tr>
<td>Data</td>
<td>Ensure data security and privacy</td>
<td>✗</td>
</tr>
<tr>
<td>Data</td>
<td>Specify the method of sharing data order to be accessible at all times</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 5: Requirements evaluation as conducted in the report of Braaksma (2016).

4.3 THEORY EVALUATION

The proposed scenario is tested by means of identifying aspects to be considered when realising SA and SAN and examining the set requirements for SAM. The proof-of-concept and theoretical implementation provides input for adjustments and improvements of the scenario. This section evaluates the results of the tested requirements (§4.3.1) and evaluates the hypothesis of the research (§4.3.2).

4.3.1 REQUIREMENTS EVALUATION

The previous chapter provides the results of the conducted research of Braaksma (2016) regarding the identification of influential aspects and testing of the set requirements. The elaboration per requirement is found in the report of Braaksma (2016). The requirements related to three scales for defining SAM:

- Performance requirements: To ensure the performance to the client
- Information requirements: To provide useful information to the asset manager
- Data requirements: To determine a data structure that supports the gathering and processing of information

The set (technical) requirements contribute to these three requirement categories. The results of the in-depth research of Braaksma (2016) shown in section 4.2 indicate a large number of requirements that are fulfilled. This means that the conducted research into SA and SAN has given a proper interpretation of dealing with the requirements set for SAM. As explained in section 4.1, the SA and SAN are contributing to realising SAM due to the ability to collect and analyse (SA) and share and exploit (SAN) sensor data used to indicate asset performances.
The results show that twelve out of fifteen requirements for SAM are properly addressed. These are fulfilled theoretically, therefore now eligible for further investigation into operational implementations. This will be elaborated in the recommendations (Chapter 7).

On the other hand, three requirements remain to be resolved, of which two are related to the information requirements and one to the data requirements. The information requirements relate to the definition of the performance pattern and to providing the reliability factor for the detected asset performance. These are yet very important and influence further application. Braaksma (2016) evaluates the two requirements negatively due to the results of the proof-of-concept. Improvements of the proof-of-concept are addressed and are likely to resolve these requirements.

The data requirement that is not satisfied relates to the security and privacy of sensor data. Braaksma (2016) appoints that security and privacy are covered through restricted access to the sensor databases and the indication by the use case that users only receive a visualisation and generic value from the processed sensor data. This way, the research provides the incentive of dealing with privacy and security. Nevertheless, additional research is required in order to demonstrate this.

Ultimately the requirements for SAM are to be traced back to the four main objectives for the construction sector for utilizing the potential of sensor technology, of which the outcomes will be examined in the discussion (§6.1).

4.3.2 HYPOTHESIS EVALUATION

The null hypothesis from section 1.3 is:

\[ H_0: \text{Asset Management cannot be optimised with Smart Asset Networks, which are realised by individual Smart Assets that are able to collect, analyse, share and exploit sensor data.} \]

This research, supported by the findings of Braaksma (2016), has demonstrated that \( H_0 \) is rejected and therefore \( H_1 \) is supported, despite of the fact that not all requirements are satisfied. However, this research identified the added value of sensor technology, developed a theory for SAM that is supported by the SA and SAN and appointed the added value of collecting, analysing, sharing and exploiting sensor data for optimising Asset Management. It is considered a good solution if the construction sector would change her view and adapt current AM decision-support systems. This is further elaborated in the discussion and conclusion (Chapter 6). Another reason why it is considered a valid solution are the developments in the BIM and geo-domain. This is discussed in the recommendations (Chapter 7).
5 SPOT ON THE HORIZON

The forecast in Asset Management (§1.2) introduced the concepts of SA and SAN used for realising SAM in the construction sector. This chapter illustrates the so-called ‘spot on the horizon’ of applying SAM as AM decision support system (§5.1). In order to further define the forecast, this chapter also addresses the Technology Readiness Level (TRL) of the solution to be used in the construction sector (§5.2).

SQ5: What steps are needed to refine a future application of the theoretical implementation?

5.1 APPLICATION SCENARIO

Imagine that the proposed solution from this research is fully functional in a live environment. The databases store the BIM and sensor data accordingly, with lots of data that is linked to other data.

An example of the application scenario of the SAM system is shown in Figure 37 and Figure 38. The two figures show a user interface for SAM decision-making. An overview can be seen of all assets, this particular case filters expansion joints. The user receives a quick and clear overview of the individual asset performances and the user interface changes the information presented on the map through user interaction. By selecting an individual asset, the user can gain more information about the specific asset.

Figure 38 shows a user interface for all information of one specific asset. Photos, object information and its location are retrieved. Also, the performance degradation curve is presented to the user. Through attached sensors – and possibly using the sensor extrapolation service - the performance of the individual asset is detected and predicted. The detected performance was already visible in the overview and the predicted performance is hereby also presented. Additional links for more detailed information about the asset, its sensors and other available resources linked to the SAM system can be seen by the user through clicking on the subjects.

This application scenario provides a quick overview into the practical application opportunities that can be achieved by the construction sector when the research into SAM is continued. Figure 37 and Figure 38 are created to provide an understanding of the possibilities for the construction sector when combining the BIM and GIS. When looking at previously conducted research, Wiggers (2015) researched how a vendor and technology independent indexer can be used for retrieval and linking of BIM data. The results are promising and, when combined with this research, contribute in determining ways to store, link and retrieve BIM and sensor data in a SAM environment. When looking at current practice, the described developments of a GIS-loket in Braaksma (2016) can be enriched with the collected sensor data. This way, the currently human-driven information provision of GIS-loket can be adapted to be both human-driven and data-driven.
Figure 37: An impression of the overview of a potential Smart Asset Management application.

Figure 38: An impression of the asset specific overview of a potential Smart Asset Management application.
The impressions of the SAM application serve as a potential response to the four objectives for SAM (§4.1.2). The future application integrates these objectives, which are to: 1) store and retrieve performance data to improve insight in the actual and real-time condition of assets, 2) predict future conditions, 3) support efficient planning of maintenance activities and, 4) integrate new technologies in a SAM system.

To elaborate on the two impressions of the SAM application, the use case in Figure 39 visualises the distinguished functions in the system. The asset manager and maintenance engineer are positioned outside the system. Four functions are distinguished (Figure 39): view an overview of asset performances, view individual asset status, view asset maintenance records and view alerts.

The “view overview of asset performances” uses a base map geometry and the performance index, which derives it input from the “provide performance graph”. Provided metadata and the graph of asset performance is used to “view individual asset status”. The “provide performance graph” and “calculation of intra-correlation and inter-correlation” has an include relationship. Meanwhile, the latter is in some situations dependent on the extrapolation of sensor data, therefore having an extend relationship. The third option is to “view asset maintenance records”, being able to add, delete or update maintenance records. Lastly, the asset manager and

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25 Include relationship: An include relationship is needed when the base use case is incomplete without the included use case and has to include the functionality of the target element (Silva, 2015).
26 Extend relationship: An extend connection is used to indicate that an element adds more functionality to the system and is usually optional (Silva, 2015).
maintenance engineer have an association with the option “view alerts”. Both have access to the alert system, where the asset manager is mainly interested into the asset alerts, and whether they are below a set threshold, and the maintenance engineer is likely to be interested in the sensor maintenance.

5.2 TECHNOLOGY READINESS LEVEL

When the construction sector starts to realise the application scenario, the maturity of the technology to be used for certain purposes is to be assessed. The Technology Readiness Levels (TRLs) are a systematic measurement system to assess maturity of a particular technology (Mankins, 1995). The use of TRLs is known from the aircraft industry, commonly used by NASA, and currently adapted by other industries (Sauser et al., 2010; Siebelink, 2013; Smith, 2005; Tetlay & John, 2009). Mankins (1995) distinguished nine levels, which relate increasingly to the maturity of the technology. The nine levels are adjusted to address the subjects in this research and are shown in Figure 40. By indicating the TRL of the theoretical implementation in this thesis, the current position of SAM is placed in literature and future research is identified.

When looking at the distinguished TRLs in Figure 40, there is concluded that this research includes up to TRL-3. According to Mankins (1995), the TRL-1 and TRL-2 relate respectively to the scientific research beginning to be translated into applied research and development, and the operational applications are speculatively to be defined. Active research and development is initiated in the research. Although laboratory-based studies to physically validate the analytical predictions are not entirely encapsulated in this research, the TRL-3 also relates to components that are not yet integrated or representative for the real-world situation through a characteristic proof-of-concept. The theory for SAM, tested through examining the SA and SAN as is reported in Braaksma (2016), is in TRL-3.

![Figure 40: This research provided a solution for the proposed theory of SAM up to TRL-3 (the indicated TRLs are based on Mankins (1995)).](image)
The distinguished concepts used within the SAM theory are influential in defining the maturity of the proposed theory. Regarding technology readiness, the research of Braaksma (2016) introduces the following concepts concerning sensor technology for realising SAM: intra-correlation\textsuperscript{27}, inter-correlation\textsuperscript{28} and sensor extrapolation service\textsuperscript{29}.

The use of intra-correlation is not a new concept. The case study of VolkerRail shows that it is able to determine the asset performance based on indicators. The company Mageba (2014) and Jang et al. (2013) researched monitoring purposes of bridges and identified indicators to be used for expansion joints specifically. As well, Cuzzocrea (2010) discovers time correlation, referring to pattern evolution to be determined with sensors in his research. Likewise, the use of inter-correlation is not entirely a new concept. The Van Briencnoord-bridge case study defines inter-correlation as segments within one single asset, and Aggarwal and Reddy (2013) researched sensor cluster analysis to address the correlation between assets. On the other hand, the sensor extrapolation service is a new concept. The case study of the Van Briencnoord-bridge uses extrapolation, however on a limited scale of one single asset. The application of a sensor extrapolation service as described in Braaksma (2016) is yet to be further researched. The added value of extrapolation services however is acknowledged, indicating that the concept aligns with near future research (Meijer, 2015; NedTrain, 2015; Timar, 2013; Van Heusden, 2011). Chu et al. (2006) conclude that experience with adopting sensor query engines is in an early-phase of research. Database query processing ideas, used for inter-correlation calculations, can play an important role in sensor networks (Chu et al., 2006; Matin & Islam, 2012).

To conclude, the concepts intra-correlation and inter-correlation are known in current research and are yet to be further researched for the application in the construction sector. The sensor application service is a new concept, though continues on sensor networks and sensor clustering. Next steps to be taken for the incorporation of SAM are shown in Figure 40. In order to achieve TRL-4 and higher, the validation of the SA and SAN is to be researched in both a laboratory set-up as real-world situation. Continuing with a prototype, pilot project and a complete and qualified SAM system. Only then, the SAM system can reach the TRL-9: A successful operation. And this is when other factors besides technology have to be addressed, as the attitude towards adopting new technologies are influenced by organizational factors, individual factors and social factors (Kimberly & Evanisko, 1981).

\textsuperscript{27} Intra-correlation: The correlation of the individual sensors attached to the individual Smart Asset in order to determine the performance.

\textsuperscript{28} Inter-correlation: The correlation of Smart Assets that is detected through examining BIM-data and additional data sources, such as location, weather and traffic loads.

\textsuperscript{29} Sensor extrapolation service: The service enables the extrapolation of sensor data from assets that have the needed sensors attached to assets that lack the sensor measurements, through calculating the inter-correlation between assets.
6 DISCUSSION AND CONCLUSIONS

Since sensor technology is a rapidly evolving technology, and is successfully implemented in other industries, it is a promising ‘need to have’ for the construction sector. The objective of this research is to define how to incorporate sensor technology during the maintenance phase of road infrastructure projects to realise SAM. To establish this, the framework of SBRCURnet (2014) is used to identify aspects that are to be taken into account when realising SA and SAN.

This chapter reflects on the previous chapters and the overall research in order to provide an answer to the research question. Therefore, the findings of this research in the context of the research into the theory of SAM will be discussed (§6.1.1), as well as the contribution to other research (§6.1.2). The four sub-questions posed in the introduction will be answered and the chapter concludes with answering the main research question (§6.2).

6.1 DISCUSSION

6.1.1 RESEARCH LIMITATIONS

The objective of investigating the theory of SAM and identifying recommendations to the construction sector is achieved. One is encouraged to further develop this theory and through observing the identified recommendations adapt the proposed theoretical solution into an operational implementation. The research into SAM encapsulates the research subjects SA and SAN, which is discussed in the report of Braaksma (2016), which is why the research limitations are aimed to move the focus onto the SAM specifically. There are five research limitations identified:

- The research scope indicates that the research is limited to focus on the technical part to collect, analyse, share and exploit sensor data for AM purposes. Lemmens (1991) however also includes the data stage “store” (see §1.2.3). This data stage is excluded in this research, because it introduces a wide additional research scope. Previously conducted research of Mathur et al. (2009), Wang et al. (2011) and Van der Veen et al. (2012) conclude that the use of sensors increases, leading to an increasing demand for sensor data storage platforms. Key issue becomes the performance of databases. Data storage schemes are proposed and further research is directed to ensure data integrity, execution protocols and data pollution attacks. Quickly, the store data stage becomes an operational problem and deviates from the initial focus on the ability of sensor data used for SAM purposes.
The monitoring framework of SBRCURnet (2014) provided an easy 7-step framework for conducting the case studies. It enabled a quick understanding of the current situation of sensor technology in the construction sector. For investigating the SA and SAN, the research of Braaksma (2016) continued with the framework and identified aspects to be considered when realising SAM in the construction sector. Although the monitoring framework is considered useful, it is unclear whether more aspects will be identified when a different framework is used. The monitoring framework itself distinguishes 7 steps, leaving room for interpretation per step. It did however provide an easy accessible and usable structure.

- This research identified fifteen requirements, distinguished as performance, information and data requirements. The requirements for SAM might not comprehend all necessary requirements, which is inherent to conducting research. A research with the focus on a different project phase, different framework or different asset can result in additional requirements for SAM.

- The pitfall of developing and evaluating a new theory for Asset Management is that a lot is possible from a theoretical point of view. This is why the contributing research of Braaksma (2016) provides a more in-depth analysis of the proposed theory. In addition, the addressed technology readiness (§5.2) indicates the extent to which SAM actually encompasses new or existing research fields. The theory for SAM continues building on existing concepts - though which are not yet applied in this combination and in the construction sector - resulting in a way to optimize Asset Management.

- The forecast in AM introduces the definition of SAM as “the collection, analysis, sharing and exploitation of sensor data to balance performance costs and risks in managing assets in order to maintain at the right moment and the location needed”. The research scope limits to the first part that includes how to collect, analyse, share and exploit sensor data. It enables to focus on the technical boundary conditions. However, the adoption of SAM is also influenced by organizational, individual and social factors (§5.2). Although technically the use of SAM could be beneficial for gaining insight in asset performances and improved decision-making, the non-technical influential factors can play a role in this matter.

- The research aims to contribute to the theoretical discussion and further development of science. This research is limited to contributing a theoretical concept, which is tested in a proof-of-concept and theoretical implementation by Braaksma (2016). The research focused on the technical aspects and direct effects and opportunities for the end-user. According to Whetten (1989), there are four essential elements that a complete theory must contain: What, How, Why and Who-Where-When. This research included all four, though focused mostly on the first and second element.
6.1.2 CONTRIBUTION TO OTHER RESEARCH

According to Whetten (1989), the theoretical contribution to other research is to be split into four elements: What, How, Why and Who-Where-When. These four together enable a legitimate, value-added contribution to research.

What. This research started with defining the area of research, through analysing three subjects in a theoretical framework. The three subjects related to the individual asset, the asset network and Asset Management and were represented by three circles (see Figure 7 on p. 12). The overlap of the circles resulted in the identification of the concept SAM. Contributing to SAM, the individual SA and SAN are investigated. The SA is not a new concept, where the case studies of VolkerRail (§3.2.2) and TNO (§3.2.3) provide implementations of using sensors to collect and analyse data to be used to indicate the performance of assets. The SAN however is a new concept that relates to a hybrid way of a communicating network of assets (Braaksma, 2016). The definition of an asset that collects and analyses sensor data in order to detect its performance – and gathers data from the asset network that shares and exploits sensor data amongst other assets – is complementary to existing research. The theory on SAM addresses a way to combine assets and sensors in such a way so that the construction sector can utilise the potential of sensors for AM decision-making.

How. In order to specify the theory on SAM further, the distinction is made between performance requirements, information requirements and data requirements (CSIC, 2015). The requirements are tested and aspects specifically relevant for realising SA and SAN are identified. This research contributes to the currently researched ways to integrate sensor data in the construction sector (Deshpande et al., 2014; Heller & Orthmann, 2014; Hoover, 2015). Also, the link between Smart Infrastructures and Smart Cities was made, where the collected sensor data might also be applicable for broader application (§3.3). This research serves as an extension to the previously conducted research of J. Lee et al. (2013) and Al-Hader and Rodzi (2009), who researched ways to connect smart infrastructure solutions to smart city frameworks. J. Lee et al. (2013) also addresses the use of TRLs for technology road mapping, which is why this research provided the TRL of the proposed theory for SAM.

Why. The explanation for defining the theory for SAM finds its basis in the identified potential of sensor technology (§1.2.3). The theory continues on the findings of Cognizant (2015) who appointed the relevance of sensor technology for monitoring purposes in the construction sector. The SAM theory addresses the need for improved decision-making and innovation in the construction sector (Loosemore & Richard, 2015) and the need for linking BIM and GIS applications in the construction sector (de Laat & van Berlo, 2011; Irizarry et al., 2013).

Who-where-when. This research is intended for use by the construction sector in situations where the desire is to monitor performance of road infrastructure assets in order to maintain at the right moment and location needed. The boundary condition
in these situations is the presence of an asset, applicable of its performance to be measured with sensors. The seven steps of the monitoring framework of SBRCURnet (2015) are used in this research to systematically elaborate on the SA, SAN and SAM. This research focuses on the goal of the statement of this theory, rather than specific limitations for current practice, and its influence on the How and What of the situation. The spot on the horizon (Chapter 7) serves as an incentive for the road mapping for implementations.

Since the research of Braaksma (2016) together with this research are submitted as theses for the double degree of Master of Science in Geomatics and Construction, Management and Engineering (CME), the specific contribution to both Master studies is addressed.

Geomatics. This research, together with the conducted research of Braaksma (2016), contributes to the Master Geomatics in multiple ways. Previously conducted research indicates that the link of BIM and sensor from the world of GIS still has to be addressed before applications in the construction sector are properly established (Corcoran et al., 2015; Kuehne & Andrews, 2016; Van den Thoorn et al., 2011). The main contribution is that the conducted research elaborates on combining BIM and sensors through researching the theory of SAM that distinguishes the separate roles of assets and sensors. Also, the research elaborates on the alignment between BIM and sensor standards. Continuing on the research of Hoult et al. (2009) and (2015), who researched the use of sensor networks for condition monitoring, this research provided a theoretical solution for enabling asset networks in the construction sector. This way, the asset (meta)data, often captured in BIM, and sensors (meta)data is linked in a new way. The research continues to build on the recently launched SensorThings API from the OGC and provides an incentive for realizing a spatial decision support system (SDSS) for managing infrastructural assets. The general knowledge about these smart infrastructures is improved through focusing on the expansion joint and its ability to become smart. This improvement also includes the introduction of a theoretical basis considering sensor extrapolation services, which is a new concept and proposed as an incentive for further research.

CME. This research, together with the conducted research of Braaksma (2016) also contributes to the Master CME in multiple ways. Previously conducted research concludes that the sensor technology is perceived a ‘nice to have’ and the innovation potential is not fully understood by the construction sector (Andriamamonjy et al., 2015; Hancke, 2013; Ong, 2013; Peelen et al., 2008). The main contribution of the research is that it identifies the potential of sensor technology for performance monitoring of road infrastructure assets. The forecast in AM due to new contract types and the innovation potential of sensor technology is included in the proposed theory for SAM. In addition, the research defines and elaborates on the SA and SAN and the research contributes, by identifying aspects to be considered for realisation, to an improved understanding of what is needed to innovate in the construction sector.
6.2 CONCLUSIONS

This research answers the following research question:

*How can the construction sector incorporate sensor technology during the maintenance phase of road infrastructure projects to optimise Asset Management?*

The forecast in Asset Management (AM) by collecting, analysing, sharing and exploitation of sensor data for Smart Asset Management (SAM) purposes is proposed as a way to optimise AM. Until now, there has been no research into the potential of sensor technology for SAM during the maintenance phase of road infrastructure projects in the construction sector. The objective of this research was to investigate the theory of SAM, its suitability for future AM and to provide recommendations for operational implementation. To establish this, a theoretical framework, case studies and the research of Braaksma (2016) support to define, test and evaluate SAM requirements.

The theoretical framework makes is a distinction between the individual asset, the asset network and AM. The ultimate objective of the research into the interrelations was to define the research area, which covers the overlap of all three subjects:

- The individual asset: A physical asset, consisting of asset components and attached sensors, together with the digital asset, consisting of BIM data and sensor data.
- The asset network: The collection of multiple individual assets that can contain sensor nodes.
- AM: The set of coordinated life-cycle activities of the construction sector to realise value from its assets.

The analysis of the relation between individual asset and AM leads to the interest in determining the P-F interval, indicating the available time for deciding maintenance activities before functional failure of the asset. The relation shows the potential of connecting sensors to the individual asset to support reaching the performance optimisation as AM maintenance strategy.

The individual asset and asset network analysis is used to further elaborate on the 5-layer model of the IoT architecture. The objects layer represents the physical sensors of the asset and the object abstract and service management layer represents the sharing and exploitation of sensor data by the asset network. The relation shows the potential to use collected and analysed sensor data of the individual asset for sharing and exploitation of sensor data by the asset network.

The relation between asset network and AM is a continuation on the 5-layer model of the IoT architecture. The business and application layer relate to AM, where this provides the services to the Asset Manager. Assets will not only use data from their own environment, but also interact with the physical world and use data from other assets. Connecting assets in an asset network allows on-demand measuring of assets status, which contributes to AM decision-making.
Together, the analysis resulted in identifying the potential of collecting, analysing, sharing and exploitation of sensor data. The performance of the individual asset is detected and predicted directly by the Smart Asset (SA) when all the necessary sensors are available, and if not, additional sensor data is provided by the Smart Asset Network (SAN). This way, the potential is to measure performances of individual assets regardless of the amount of sensors attached.

The current situation of adopting sensor technology in the construction sector is examined through three case studies: 1) Project structures and embankments monitoring Haarlem, 2) Project real-time railway monitoring Zeeland, and 3) the Project van Brienenooord-bridge. The case studies are analysed by systematically elaborating on the seven steps of the SBRCURnet (2014) monitoring framework. The case studies show examples of the application of sensor technology, but no formal asset network is defined. The case studies, together with knowledge from experts and literature, contributed to define requirements for realizing SAM.

The requirements are split in three categories: 1) performance requirements, 2) information requirements, and 3) data requirements. The performance requirements refer to the performance guarantee to the client and are the link between Smart Cities (client) and SAM (contractor). The information requirements refer to providing useful information to asset managers and serves as link between SAM and the interpretation and analysis. The data requirements refer to determining a data structure that supports the gathering of information and relates to the scale of sensors and data collection, analysis and interpretation. The research identified 15 requirements:

- **Performance**
  - Provide insight in the reliability of assets
  - Provide insight into the availability of assets

- **Information**
  - Select applicable assets for monitoring purposes
  - Determine the need for information and therefore the needed data to be collected
  - Store the data and information in an online server or database in order to be accessible at all times
  - Define the performance pattern of an asset type
  - Detect individual asset performance
  - Predict individual asset performance
  - Provide the reliability factor for the detected asset performance

- **Data**
  - Provide metadata and semantics
  - Serve interoperability between different sensor data types
  - Determine the connection between BIM data and sensor data
  - Ensure proper data collection
  - Ensure data security and privacy
  - Specify the method of sharing sensor data
The requirements are tested in the report of Braaksma (2016) through researching the SA and SAN. The results show that in the context of the set scenario 12 out of 15 requirements are satisfied. These are fulfilled theoretically and therefore now eligible for further investigation into operational implementations. Three requirements remain to be resolved: 1) The definition of the performance pattern, 2) the reliability factor for the detected asset performance, and 3) the security and privacy of sensor data. Improvements of the proof-of-concept are likely to resolve these requirements.

The spot on the horizon for SAM illustrates the application scenario and technology readiness level (TRL). The application scenario describes the future implementation and presents two impressions of a potential SAM system. In addition, a use case explains the capabilities of a future application. It provides a quick overview of the practical application opportunities that can be achieved by the construction sector. To identify the steps to be taken for this future application, the consideration of the maturity of the proposed technology is taken into account. The TRL assessment determines the current position of SAM and supports identifying future research. There are nine levels, which relate increasingly to the maturity of the technology. This research includes up to TRL-3. It means that the new concept of SAM is proposed (TRL-1), a technology concept is formulated (TRL-2) and a proof-of-concept and theoretical implementation is completed (TRL-3). Required steps to be taken in order to realize an entire successful operating system are therefore to continue on TRL-3 up to TRL-9. The first following steps include validating SA and SAN in a laboratory set-up and in the real-world situation. A combination of theoretical and practical testing and evaluating is valued when developing this application. Theoretical research can be supported by practical validation and vice versa, contributing to a well-founded solution for future application.

Additional research is encouraged to further define this way and to develop operational implementations according to the identified TRL for further research. In the context of the construction sector, recommendations are provided as an incentive for developing a step-by-step integration. In the context of scientific research, the first steps are made in defining the theory of SAM and the associated points for discussion that are to be further researched.

In conclusion, this research has identified SAM as a way to optimise AM. The theory of SAM is developed as a response to the identified potential of sensor technology for the construction sector. SAM comprises two important parts: The SA and the SAN. Through identifying and evaluating the requirements for implementing SAM and determining aspects to be considered for realisation, the current situation and future steps are determined. The research builds the theoretical basis for the construction sector for implementing SAM and recommendations to further develop this theory and to perform practical implementations.
The recommendations serve as basis to the construction sector for determining and realising the future prospect of managing assets. This research has defined and evaluated requirements for realising SAM and has identified influential aspects to be considered when realising SA and SAN within the theory of SAM. This chapter provides a helping hand in continuing on the research subjects and provides directions for practical implementation (§7.1) and for further research (§7.2). Main input for defining these recommendations are the case studies, the identified aspects to be considered and the gained insight in the theory of SAM.

7.1 RECOMMENDATIONS FOR PRACTICAL IMPLEMENTATION

The research into the theory of SAM introduces a theoretical, and therefore more scientific, approach for AM in the construction sector. Recommendations for practical implementation are addressed to translate the conclusions of this research into actionable steps. The following recommendations are made to improve management of assets in the construction sector:

- To contractors: Innovation is a cyclic process (see §1.2), addressing research, development and implementation of innovative ideas. It is discussed that innovation should be placed project wide in order to realise significant results. The construction sector is known to ‘innovate on projects’, often directing on a payback time within the project period (Van den Thoorn et al., 2011). These innovations are not always applied company wide, resulting in missed opportunities. It is recommended to address innovation on a higher level in order to contribute to significant changes in the construction sector. This way, this research provides a theoretical contribution and encourages new developments, followed by practical implementations. Practical experiences then again will be directing to new research and this way innovation enables both scientific as practical research.

- To contractors and innovators within the construction sector: In order to continue on the conducted research into SA and SAN contributing to SAM, it is recommended to continue increasing the TRL. The next step involves measuring asset performances using sensor technology in a laboratory set-up (TRL-4) and real-world prototype (TRL-5). Preferably, the focus is on expansion joints where Braaksma (2016) provided a solid reasoning for monitoring applications. Other assets can appear to be used, such as other bridge parts or road traffic signalling nearby bridges or tunnels.

- To contractors: The monitoring framework of SBCURnet (2014) provided a structured approach. The seven steps - goal, assessment model, variables to
be measured, monitoring system, collect data, analyse data and control measure - enabled to systematically address the suitability of expansion joints for SAM purposes. However, the framework provides only basic steps that are eligible for one’s interpretation. Additional explanation and conditions for use of the framework will resolve ambiguities. Because the framework does not address the sharing and exploitation of sensor data, the research into SA and SAN is conducted as two separate framework cycles. The steps collect data and analyse data were then considered representative for SAN interpretation of sharing data and exploitation of data. In conclusion, the framework offered a guideline for determining the eligibility of the expansion joint. It is therefore recommended to use the framework for identifying the eligibility of other assets to be monitored. In advance for using the framework, indicators such as standardization in application types, importance (due to costs and associated risks) of the asset in civil infrastructures and degradation types are recommended to explore.

- To contractors and researchers: The importance of Asset Managers as the decision-makers has to be acknowledged, because the subjectivity in the Asset Managers performing Asset Management is not likely to disappear (Wijnia & de Croon, 2013). One should not forget that, although the information provision becomes more data-driven, the human factor remains in the process. The Asset Managers are key in the success rate of SAM, which is why it is recommended to involve them in the process. When adopting this theory in realising practical implementations, it will actually no longer be about the technology readiness, but about the willingness of the future users to work with and rely on the provided data. Since the current theory is based on a set scenario, the operational implementation is recommended to adjust this basis with valid explanations from the real-world situation.

7.2 RECOMMENDATIONS FOR FURTHER RESEARCH

Due to the limited scope of the thesis, there are four remaining topics for further research. The following recommendations are made to explore the future implementation of SAM for optimising AM in the construction sector:

- The storage of sensor measurements – either local storage or database storage – is considered out of scope in this research (§1.2.3). Further research has to determine the need for data sinks at the node level or at database level. Diao et al. (2007) state that networks that collect and store data in a traditional database are referred to as “dumb sensor networks” with limited intelligence embedded in the network. A proposed model views the sensor network as database, supporting querying data from sensors locally. Mathur et al. (2009) and Weimin and Lingzhi (2015) conclude that problems of congestion and energy consumption could be solved when the data is stored in sensor nodes. It is recommended to continue on these research findings,
together with this research, to address data storage in asset networks. Ultimately, further research can enable the fulfilment of the data requirement (see Chapter 5) by elaborating on security and privacy of data storage as well.

• The proposed theory for SAM is directed at the operation and maintenance phase. In addition, the construction sector is recommended to integrate the theory in other phases, such as the contracting phase and design phase. The relevance for the contracting phase is that contractors could utilize the added value of sensor technology in tenders. The relevance for the design phase is to integrate sensors in the technical designs in order to facilitate maintenance actions in an accessible way. Vice versa, knowledge from monitoring in the maintenance phase can be of use in the design phase. Further research can indicate the influence of SAM in these phases.

• The proposed theory for SAM provides a way to go, in which adjustments can be made. For example, the use of additional technologies such as User Generated Data or drones can contribute to an improved understanding of the current situation and future performance of assets (Irizarry et al., 2012; Sorensen et al., 2016). As mentioned in section 1.4, the proposed SAM theory aims to encourage the theoretical discussion on the subject, and innovative side, of this way to utilize new technologies in the construction sector.

• Since this research purpose was to research ways to collect, analyse, share and exploit sensor data, no test cases with real Asset Managers and sensor information are conducted. Before developing this solution in a SAM system, it is recommended to conduct user analyses and evaluate the results. Further research should also investigate what is needed to give users confidence to rely on sensor data and investigate when information is sufficiently reliable. The research has not investigated user acceptance, although literature shows that the perceived need for the technology is an important acceptance factor (Peek et al., 2014). Recommended is to continue on the findings of this research and conducted research of Duzgun (2016), who addresses the effects of different data sources on the decision-making process for Asset Managers.
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