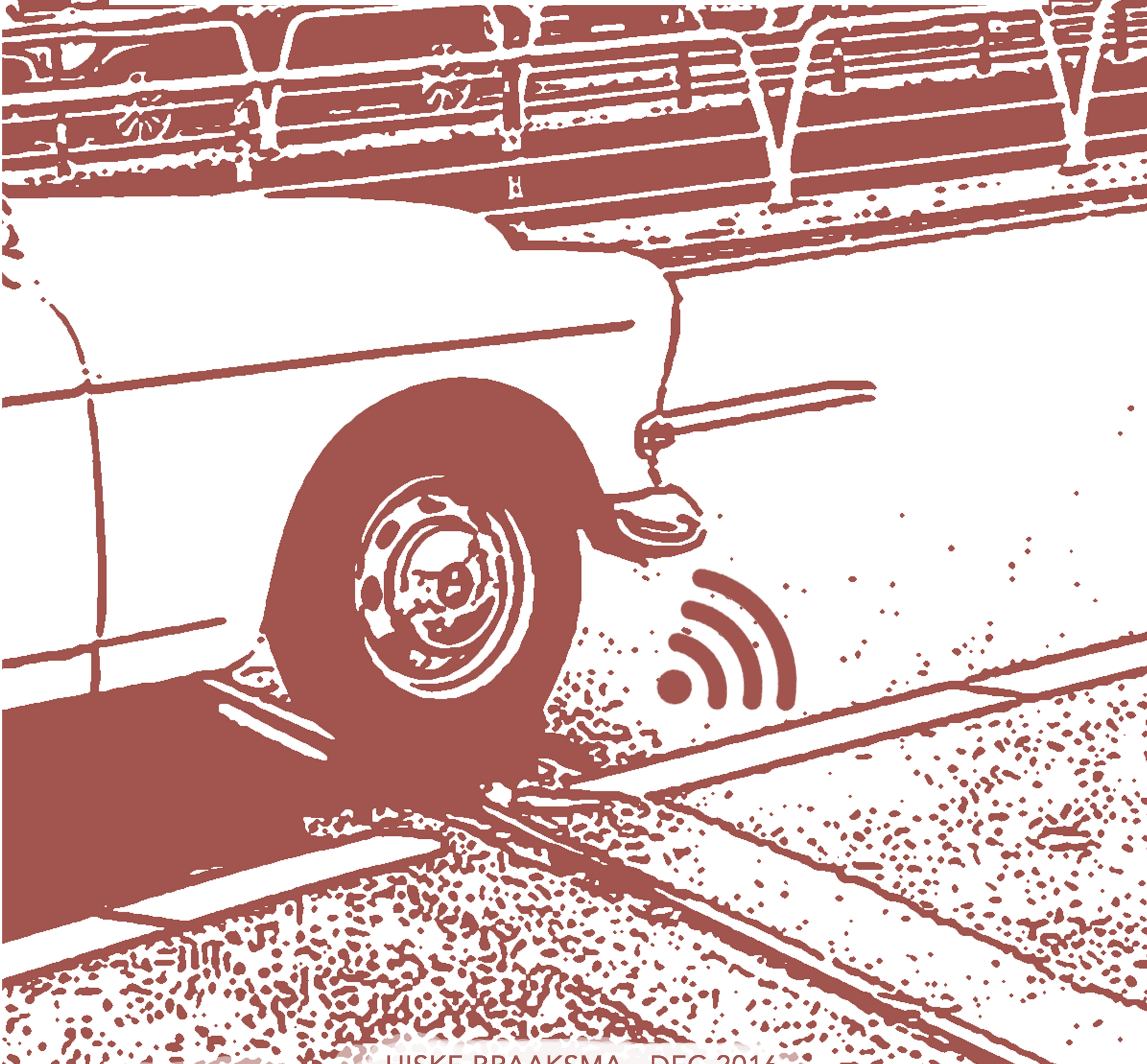
SMART ASSET MANAGEMENT IN THE CONSTRUCTION SECTOR

AN IN-DEPTH ANALYSIS OF THE APPLICATION OF SMART ASSET AND SMART ASSET NETWORK



HISKE BRAAKSMA - DEC 2016
MSC CONSTRUCTION MANAGEMENT & ENGINEERING - MSC GEOMATICS

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COLOPHON

Document	
Title	Smart Asset Management in the construction sector
Subtitle	An in-depth analysis of the application of Smart Asset and Smart Asset Network
Location & date	Delft I December 2016
Author	
Name	Hiske (H.H.) Braaksma
Student number	4037022
Education	MSc Construction Management and Engineering MSc Geomatics for the Built Environment
University	Delft University of Technology
Graduation committee	
First supervisor	drs. C.W. Quak Geomatics for the Built Environment: OTB
Second supervisor	dr. ir. G.A. van Nederveen Civil Engineering, Infrastructure Design and Management: Engineering Asset Management
Chair	Prof. dr. ir. M.J.C.M. Hertogh Civil Engineering, Infrastructure Design and Management: Integral Design
External supervisor	dr. ir. H.K.M. van de Ruitenbeek Volker InfraDesign
Board of Examiners Delegate	ir. G.A. Verschuure-Stuip (Assistant Professor, TU Delft)
Institutions	
	Delft University of Technology Civil Engineering and Geosciences Stevinweg 1 2628 CN Delft
	Delft University of Technology Geomatics for the Built Environment Julianalaan 134 2628 BL Delft
	Volker InfraDesign Korenmolenlaan 2 3447 GG Woerden

ABSTRACT

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 role of sensor technology is increasing in importance due to the decreasing costs of acquiring sensors and due to more practical implementations that are available on the market. In the meantime, the introduction of integrated contracts demands Dutch contractors to ensure availability and reliability of infrastructural assets to the client. Dutch contractors face the need to realize smart and innovative solutions for Asset Management (AM). The use of smart sensor technology to detect and predict asset performances during the maintenance phase of road infrastructure projects is still in its development phase. Meanwhile, 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. The purpose of this study is to conduct an in-depth analysis that specifically focuses on expansion joints to test the proposed theory and to evaluate the set requirements for Smart Asset Management (SAM) of Braaksma (2016). SAM is defined as the collection, analysis, sharing, and exploitation of sensor data to balance performance, costs, and risks in managing assets in order to perform maintenance at the right moment and the right location. This research answers the following research question: *How can sensor technology be used in the construction sector to facilitate Smart Asset Management during the maintenance phase of road infrastructure projects?*

SAM is a combination of an individual Smart Asset (SA) and a collection of assets in a Smart Asset Network (SAN). An individual SA allows to collect and analyse data from 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.

A theoretical implementation of an SA, by means of a proof-of-concept, builds on the current methods of asset monitoring in the construction sector and on a developed monitoring system. The proof-of-concept is able to collect and analyse sensor data by executing multiple runs on simplified representations of expansion joints. The use of intra-correlation, which is the correlation between sensors and asset, supports to indicate the degradation of the expansion joint, despite addressed limitations of the test set-up. The research indicates four influential aspects to be considered when realising an operational use of the SA. These aspects are (1) to manage expectations of Asset Managers, (2) to collect relevant sensor data, (3) to define proper ways to handle data transfer, and (4) to adapt current SAM systems.

A use case for the expansion joint in an SAN builds on the current situation of adopting asset networks and on the analysed alignment of standards in Building Information Modeling (BIM) and sensors. The use case defines the components that are taken into account when the user requests information from the SAM system. The use case introduces inter-correlation, which is used to determine the extrapolation of

sensor data from one asset to the other. In addition, a developed class diagram describes the SAN data model and its relation to the SensorThings API model, a recently released sensor standard by the Open Geospatial Consortium (OGC). The class diagram defines the link between BIM and sensor models. The use case continues on the class diagram and describes how SAN allows measuring the performance of each asset. The research indicates four influential aspects to be considered when realising an operational use of the SAN. These aspects are (1) to manage the willingness of Asset Managers to work and rely on a SAN, (2) to integrate and interpret sensor and BIM data sources, (3) to detect inter-correlation and needed calculation techniques, and (4) to determine the representativeness of sensor data.

In addition, the requirements set for SAM have been evaluated by elaborating on the findings of the research into SA and SAN. The results serve as input for the research of Braaksma (2016).

In conclusion, implementing the SAM scenario answers the research question by identifying SA and SAN as a way to incorporate sensor technology: it is able to measure asset performances and supports the realisation of SAM decision-making. This research investigates the added value of attaching sensors to expansion joints and provides a total of eight influential aspects to be considered when realising a SA and SAN for expansion joints. Also, this research includes a view on the extent to which components of BIM relate to sensor technology. The combination of using intra-correlation, inter-correlation and extrapolation is utilised in the developed use case. These results support the construction sector in the obtained responsibility to ensure availability and reliability of assets. Properly addressing the identified aspects of influence, acknowledging the importance of users in the process and investigating how to apply intra-correlation, inter-correlation and extrapolation in a pilot project are focal points for research in the near future. This research provides an insight in maintaining assets – expansion joints in specific – in such a way that individual asset performances can be detected and predicted, utilising the potential of sensor technology in assets networks.

PREFACE

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

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ACRONYMS

Abbreviation	Explanation
AI	Artificial Intelligence
AM	Asset Management
API	Application Programming Interface
BIM	Building Information Model
CB-NL	The Dutch Concept Library (Dutch: Nederlandse Conceptenbibliotheek)
CBR	Case-based reasoning
COINS	Constructive Objects and the Integration of Systems (Dutch: Constructieve Objecten en de Integratie van Processen en Systemen)
GIS	Geographical Information Systems
GOTIK	Cost, Organisation, Time, Information and Quality (Dutch: Geld, Organisatie, Tijd, Informatie en Kwailteit)
GUID	Globally Unique Identifier
IFC	Industry Foundation Classes
IFTTT	If This Then That
IoT	Internet of Things
MCA	Multi-Criteria Analysis
O&M	Observations and Measurements standard
OGC	Open Geospatial Consortium
PVO	National platform for expansion joints and bearings in the Netherlands (Dutch: Platform Voegovergangen en Opleggingen)
RAMS	Reliability, availability, maintainability and safety
RWS	Rijkswaterstaat
SA	Smart Asset
SAM	Smart Asset Management
SAN	Smart Asset Network
SAS	Sensor Alert Service
SBS	System Breakdown Structure
SE	Systems Engineering
SensorML	Sensor Model Language
SFRC	Steel Fibre Reinforced Concrete
SOA	Server-oriented architecture
SOS	Sensor Observation Service
SPS	Sensor Planning Service
SWE	Sensor Web Enablement
UGD	User Generated Data
UML	Unified Modeling Language
WFS	Web Feature Service
WNS	Web Notification Service
WSSN	Wireless Smart Sensor Network

GLOSSARY

Term	Definition
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.
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.
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.
Expansion joint	An infrastructural asset that allows continuous traffic along road infrastructure projects while accommodating structural movements due to contraction, temperature variations and deformations.

1 INTRODUCTION

The introduction of integrated contract types shifts risks and responsibilities to the contractor. Dutch contractors in the construction sector 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 is specified as a Smart Industry that uses sensor technologies. Often is referred to the concepts Smart Cities and Internet of Things (Atzema et al., 2015; Elsevier, 2015). It is expected that this new approach of the construction sector in managing assets represent a major task in the coming years (Rutten, 2016).

This research provides an in-depth analysis that specifically focuses on expansion joints to test the proposed theory in the research of Braaksma (2016). This chapter serves as an introduction and discusses respectively: the research incentive (§1.1); the theoretical background on asset performance (§1.2); forecast in managing expansion joints (§1.3); research question and hypothesis (§1.4); research objective (§1.5); research relevance (§1.6); research methodology (§1.7) and research outline (§1.8).

1.1 RESEARCH INCENTIVE

The role of sensor technology is increasing in importance due to more practical implementations are becoming available on the market. Although the digital revolution requires the construction sector to think of new and innovative solutions, the application of sensor technology proceeds slowly (Peelen, 2016).

It has become known to the construction sector that the Building Information Model (BIM) enables to create the loose coupling between elements and sub-elements in 3D (Torma, 2013; G. van Nederveen & Tolman, 1992). Although implementations exist, the active use of geographic information systems (GIS) remains a new and unexplored path (Cobouw, 2013). To implement sensor technology successfully, the potential of combining assets from BIM with GIS solutions has to be properly understood (Corcoran et al., 2015).

The report "Smart Asset Management in the construction sector: A holistic research into utilising the potential of sensor technology" (Braaksma, 2016) describes the need for an in-depth analysis for the proposed theory: to realise an asset network where assets are connected and share relevant sensor data. Through connecting detailed BIM information with geographic data, such as sensors, informed decisions are made and Smart Asset Management[1] (SAM) is realised (Bragg, 2015). Sensors become inexpensive and expected is that the number of devices will more than double from the current level, with 40.9 billion devices forecasted in 2020 (Press, 2014). Testing an implementation is important to determine the theoretical possibility, as the practical implementation does not yet exist. This research identifies aspects to be considered to realise a Smart Asset and a Smart Asset Network.

[1] 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.

1.1.1 THE SMART ASSET AND SMART ASSET NETWORK

This research focuses on the scenario to incorporate sensors on individual assets to enable Smart Assets, utilised in a Smart Asset Network and used for Smart Asset Management purposes through asset monitoring as discussed in Braaksma (2016). The research continues upon the principles of sensor networks, referring to the communicating sensors, though focuses on asset networks that use sensors as input to allow communication between sensors. The two main subjects are defined as follows:

Smart Asset (SA) - An individual asset, which is able to detect and predict its own performance in context by collecting and analysing sensor data of attached sensors.

Smart Asset Network (SAN) - 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.

In order to enable SA, the relation of individual sensors to individual assets has to be defined. As well, the connection of individual assets to the asset network, with the associated data sharing of their sensor data, has to be discussed. Two research areas are hereby depicted (Figure 1).

In order to properly investigate these research areas, the research will focus on one asset type: The expansion joint. With this, the research, regarding the relations between sensors, asset and asset network (Figure 1) is performed more in-depth. Although the remainder of this research will focus on the expansion joint specifically, the results of this research are considered to be valid for other types of infrastructural assets as well. Since the real-world situation of other assets may vary, the extent to which the findings of this research have to be adjusted due to these differences is then to be investigated.

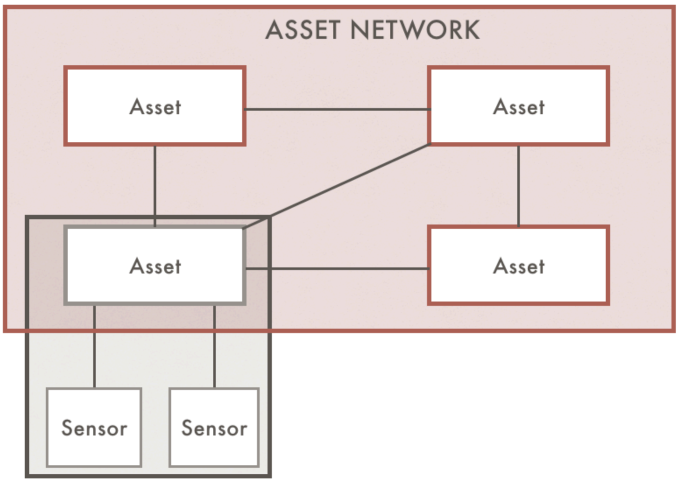

Figure 1: The scenario is visualised by two research areas. The incorporation of sensors on individual assets (grey) will be investigated first. The second step is to determine how individual assets perform in an asset network (red).

1.2 THEORETICAL BACKGROUND ON ASSET PERFORMANCE

Insight into the performance of an asset is important for contractors in order to determine the proper maintenance activities and avoid unnecessary costs and unavailability of for example roads. In scientific research, this is where the fundamentals of the bathtub curve are researched (Klutke et al., 2003). The curve describes to the fai lure rate of an asset over time and defines three stages of asset performance: Infant mortality, normal operation and wear out (Figure 2). The 'wear out' period is important for Asset Management during the maintenance phase, as the asset performance is decreasing after a stable period of performance.

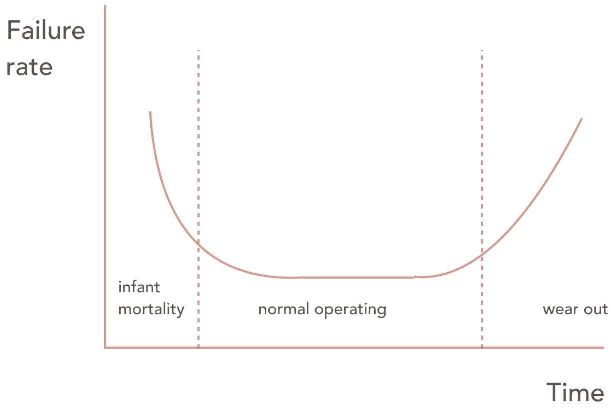

Figure 2: Overview of the bath-tub curve as based on Klutke et al. (2003).

Braaksma (2016) discusses the P-F curve to illustrate this decreasing asset performance (Figure 3). The P-F curve provides a better understanding of this 'wear out' period and identifies the potential failure[2] and functional failure[3]. By detecting the potential failure, the time of functional failure can be estimated. The interval between the potential failure and functional failure is called the P-F interval, indicated with delta T (ΔT) in Figure 3. The P-F interval is a valuable piece of information for decision-making for maintenance activities, because it supports the construction sector in determining the right maintenance to perform at the right time (Apelgren, 2008).

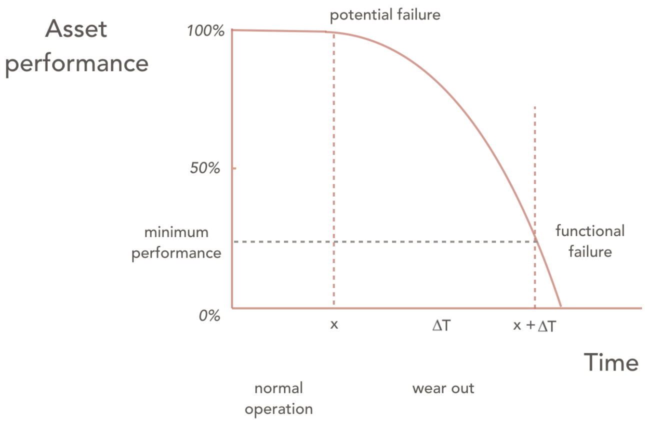

Figure 3: The P-F curve represents the gradual decrease of asset performance over time. The asset performance is expressed in percentages, 100% referring to a proper functioning and 0% to an improper functioning of the asset.

[2] Potential failure: the identifiable moment in time that indicates the degradation and that a functional failure is imminent.
[3] Functional failure: the estimated moment in time where the asset is unable to meet the specified performance standard.

1.3 FORECAST IN MANAGING EXPANSION JOINTS

With its high compressive strength and hardness, concrete is commonly used for application in road infrastructures. Since concrete moves during expansion and contraction due to temperature fluctuations, the collision of two concrete segments result in failure of the road infrastructure. The expansion joint is used as junction between the separate segments (Figure 4). It asset exists of a steel construction combined with steel fibre reinforced concrete (SFRC) and a sealant composed of a wedged rubber profile (Smits Neuchatel, 2011). The definition of an expansion joint is as follows (Freyssinet, 2012):

Expansion joint - An asset that allows continuous traffic along road infrastructure projects while accommodating structural movements due to contraction, temperature variations and deformations.

Figure 4: A picture of an expansion joint of type SN ESV-R1, located at the bridge "Zandbergen" (N238).

1.3.1 WHAT IS KNOWN ABOUT THE EXPANSION JOINT?

The expansion joint is known as a vulnerable asset in the road infrastructure (Peelen, 2016). However, since the performance of an expansion joint can be twenty years consistently when properly installed, there is currently no active monitoring system (Doorn, 2016). Nevertheless, three valid reasons to focus on expansion joints for monitoring purposes will be discussed in the following sections: The manner of degradation, the increased attention over the last years and the presence of the asset in standardised ways.

Types of degradation

Due to its specific purpose and location, the expansion joint has to be designed, positioned and constructed with high precision. Since the asset can only be installed near the end of projects, the placement is often to be executed in a limited timeframe. The incorrect execution of installing expansion joints during road infrastructure projects however can greatly affect the reliability of the asset and will result in rapidly evolving failures (Pfeifer, 2016). There are examples of critical failures

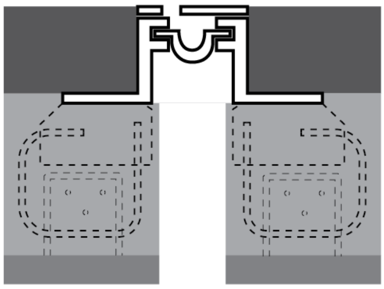

Figure 5: A simplified representation of an expansion joint, consisting of a steel construction filled with steel fibre reinforced concrete and a rubber padding (Doorn, 2016).

within months after first indication of deterioration. Two types of degradation of expansion joints are distinguished: (1) the asset displaced entirely due to crushing the concrete and (2) the detaching covering plate (Doorn, 2016). These are further explained in section 2.2. By focusing on these two types of degradations, the purpose and position of sensors is determined.

An increase in importance

Sustainability and noise reduction are currently important keywords in the construction sector and experts call for action (Mooyman, 2016). The workgroup "Platform Voegovergangen en Opleggingen" (PVO) was established in 2010 and aims to create awareness of the crucial role of the expansion joint in road infrastructure projects (Vliet & Leendertz, 2010). Mooyman (2016) states that expansion joints deserve increased attention, because "conducted research showed that 30% of all maintenance costs of a civil structure could be traced back to expansion joints". It is likely that due to the increasing importance and attention for expansion joints, the construction sector is eager to find new ways to manage them.

Standardised applications

Multiple expansion joints are located on one bridge and in the Netherlands many types of expansion joints exist. Thirteen main types of expansion joints are applied (Booij & ten Boom, 2010) and the renovation model "SN-ESV-R1" of Rijkswaterstaat is used most frequently (Pfeifer, 2016). The expansion joint is a simple structure, because it consists of a steel construction filled with steel fibre reinforced concrete and a rubber padding (Figure 5). Due to the standardised applications of the expansion joint, the potential of applying sensors, either located inside the concrete or on the outside, is recognized and researched (Jang et al., 2013; Mageba, 2014).

1.3.2 WHAT IS NOT KNOWN YET AND RESULTS IN UNEXPLORED POTENTIAL?

This research could identify what is required to realise the expansion joint as a SA. Current challenges in costs, time and quality are addressed (Jang et al., 2013; SBRCURnet, 2015; Voskuilen et al., 2016) and investigating the expansion joint is therefore considered to be relevant.

In the past years, some studies into monitoring techniques for expansion joints are performed. Mageba (2015) applies sensors on the Taizhou Bridge in China in order to detect the measure deck movements near the expansion joint. A structural health monitoring system is developed and is used to detect movement and rotations of the deck. The support for indicating performance of expansion joints and on remote inspections is considered to be further investigated (Mageba, 2015, p. 5).

The research of Jang et al. (2013) presents the potential of using a monitoring system based on wireless smart sensor networks (WSSN). With a WSSN, autonomous sensors monitor the physical conditions and pass their data through the network to a main location. By testing the WSSN in a field experiment, Jang et al. (2013) has shown the suitability of a wireless monitoring system for managing expansion joints.

SBRCURnet (2015) indicates that monitoring techniques could help improving the construction, management and maintenance of constructions, by enabling lessons learned from existing and running case studies. The final report contains thirteen case studies, of which three are focused on expansion joints: A case study proposal for optimising maintenance of expansions joints at the A73 near Venlo, the monitoring of functional performance at the 24 Oktoberplein in Utrecht and the monitoring of expansion at the Martinus Nijhoffbrug in Zaltbommel to determine whether maintenance can be postponed. The proposed monitoring framework (§1.7) is used in all case studies and suitable for further research.

Despite the conducted research into the monitoring of expansion joints, there is still a need to define the implementation of the SA in a SAN for the construction sector. The knowledge gap includes the use of sensor data of individual SA in order to realise a SAN. A theoretical implementation of the SA and SAN for the construction sector will be researched.

1.4 RESEARCH QUESTION

This report aims at investigating the incorporation of asset networks in Asset Management and serves as an extension to the research report "Smart Asset Management in the construction sector: A holistic research into utilising the potential of sensor technology" of Braaksma (2016). This report explores the effects of using a SAN for SAM, thereby creating SA, tests a proof-of-concept and illustrates a theoretical implementation.

The research question (RQ) is defined as follows:

RQ: *How can sensor technology be used in the construction sector to facilitate Smart Asset Management during the maintenance phase of road infrastructure projects?*

As is explained in Figure 1 (p.2), two research areas are depicted; the application of sensors on the individual SA and the implementation of a SAN. Two sub questions (SQ) are distinguished:

SQ1: *Which aspects influence the incorporation of sensor technology for Smart Assets in the construction sector?*

SQ2: *Which aspects may be expected to be of determining influence on the incorporation of Smart Asset Networks in the construction sector?*

1.5 RESEARCH OBJECTIVES AND FOCUS

1.5.1 OBJECTIVES

The research objective is twofold:

- Investigate whether the application of sensors enable the individual SA and determine what aspects influence the incorporation of the SA in the construction sector;
- Investigate whether these individual SA can be used in a SAN and determine what aspects influence the incorporation of a SAN in the construction sector.

The construction sector can make more conscious and convincing decisions in managing their assets by using a SAN. The integration enables steps towards SAM and results in the production of relevant information for building smart geo-applications (Garcia, 2016).

1.5.2 FOCUS

This research focus is on testing the proposed scenario in the report of Braaksma (2016). The developed scenario reflects on the incorporation of sensor technology for SAM in the construction sector. This report is:

- Continuing on the definitions of SA, SAN and SAM as described by Braaksma (2016).
- Limited to expansion joints as characteristic asset for theory testing. The research regarding the expansion joint is limited to define how the asset performs over time and in what ways the degradation is measurable with sensors.
- Limited to data that is considered relevant for Asset Management applications of expansion joints. The term data refers to either BIM data or geodata. BIM data concerns object-based data as commonly used during design and construction. Geodata refers to sensor data holding a location as attribute.
- Including a proof-of-concept to test a SA and a theoretical implementation for a SAN by means of discussing the monitoring system and use case explaining the sensor data transformations. The research also includes how BIM standards relate to sensor standards, though is limited to examining this relation instead of developing a new standard.
- Using the monitoring framework of SBRCURnet (2014) to test the defined relations that are shown in Figure 1 (p. 2). In case the framework is not sufficient, proper adjustments will be made and recommendations regarding the use of the framework to establish a SA and SAN will be provided.
- Part of a collection of two reports. The report "Smart Asset Management in the construction sector: A holistic research into utilising the potential of sensor technology" (Braaksma, 2016) focuses on the overarching effects for the construction sector and contribution to Smart Cities. This in-depth research investigates the proposed scenario by testing the twofold objectives on a theoretical level.

1.6 RESEARCH RELEVANCE

The potential of sensor technology is recognized both scientifically (Sohraby et al., 2007) as well 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). The term "asset network", implying that the sensor data is shared and exploited based on the correlation between assets, has been found a quite unknown topic in literature.

No evidence is found of research that examines the extent to which components of BIM relate to sensor technology as is known in the field of Geomatics. Focusing on relating sensor technology in Asset Management of large infrastructural projects specifically, current strategies remain inefficient because the potential of SA that share data in asset networks still need to be researched.

1.7 RESEARCH METHODOLOGY

Verschuren et al. (2010) states that the methodology of theory-oriented research is aimed to contribute towards the theoretical discussion on the subject and, as a consequence, towards the further development of science. The research method of Nielsen (1993) makes use of a basic iterative project model, but encourages independent iterative designs by researchers involved for each new version instead of one parallel design. This is why this in-depth research uses the method described by Nielsen (1993) as a general guideline, and is divided into five main phases (Figure 6).

The first and second phase will further elaborate on the developed theory by Braaksma (2016) and will specify the strategy in the third phase for testing the two research areas (see section 1.1). The fourth and fifth phase will evaluate the theory and provide the discussion and conclusion of the research.

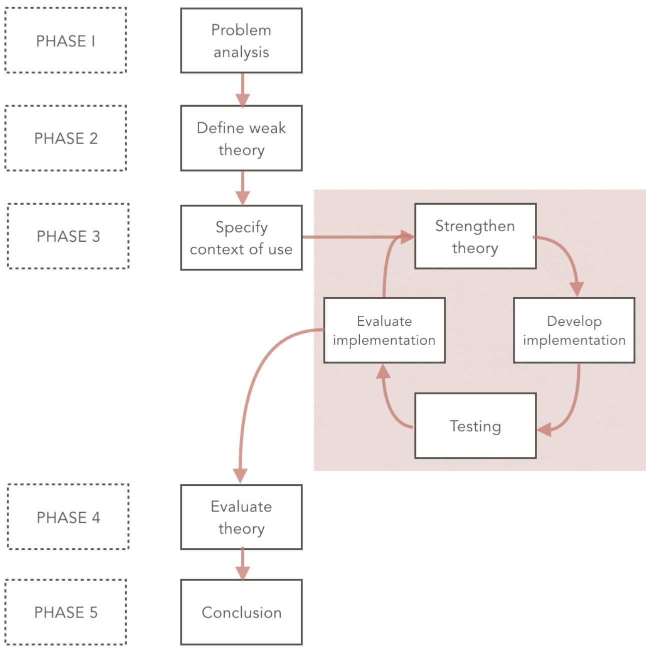

Figure 6: The five phases of this research, based on the Iterative Design methodology of Nielsen (1993).

To elaborate on the third phase: The developed theory regarding the individual SA will be tested with a proof-of-concept. The proof-of-concept will focus on the expansion joint with attached sensors in order to determine whether performance can be detected and predicted. Subsequently, the SAN will be tested by means of a theoretical implementation. An analysis will define the relation between standards in BIM and sensors, because the SAN imposes to connect components of BIM with sensors from GIS. The theoretical implementation will define the monitoring system and a use case diagram of data handling in the asset network. The monitoring framework of SBRCURnet (2015) is used as guideline for the development of both the proof-of-concept and theoretical implementation.

1.7.1 EVALUATE ASSET PERFORMANCE MONITORING

SBRCURnet (2014) developed a monitoring framework (Figure 7) in order to evaluate monitoring projects that aim to detect and predict asset performance. The monitoring framework is validated on thirteen case studies in the Dutch construction sector and distinguishes seven aspects; Defining goal, assessment model, variables to be measured, monitoring system, collecting data, analysing data and control measure. The arrow between goal and control measure is bilateral, which refers to the alignment of the control measure to the set requirements. The case studies differ in goal and assets of focus, but all aim to determine asset performance collecting data from sensor attached to assets.

This research uses the monitoring framework with its systematic approach to research the Smart Asset (Chapter 2) and Smart Asset Network (Chapter 3). The aim is to identify influential aspects when realising the SA and SAN. The results are used to evaluate the set requirements for the proposed scenario of 'Asset Manager of the future' by the report of Braaksma (2016). The research identified 15 requirements that are to be considered when realising Smart Asset Management (SAM), of which the SA and SAN are essential components (Table 1).

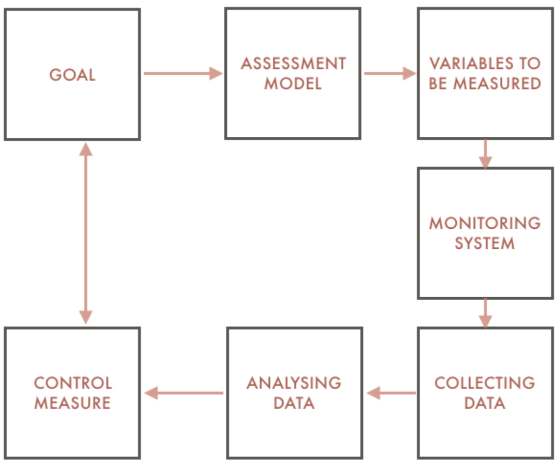

Figure 7: An overview of the monitoring framework developed by SBRCURnet (2014).

Requirement type	Requirements
Performance	Provide insight into 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 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 data order to be accessible at all times

Table 1: When all set requirements for performance, information and data requirements by Braaksma (2016) are satisfied, the Smart Asset Management can be realised.

1.7.2 RESEARCH DEPTH AND BREADTH OF UNDERSTANDING

As briefly introduced in the research scope, this Double Degree graduation research is captured in two separate sub-reports. This in-depth research is linked to the holistic research by the theory testing as is shown in Figure 8. The two sub-reports are:

- Holistic research. The research elaborates on the integration of sensor technology in Asset Management;
- In-depth research. The research investigates the specific implementation of collecting and analysing sensor data at an individual asset and enabling an asset network that shares and exploits sensor data to indicate asset performance.

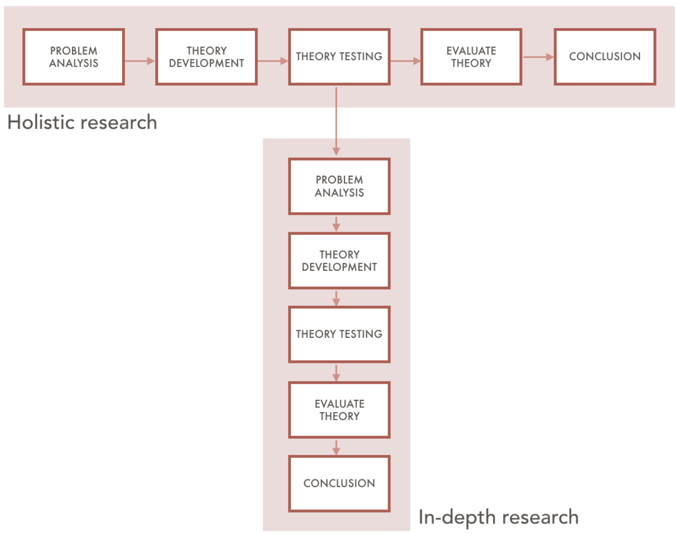

Figure 8: At the third phase of the holistic research, where the theory is to be tested, the link towards the in-depth research is made. With this, the holistic research (horizontal bar) enables to provide an overview of the research subjects and define its context with respect to other research areas. The in-depth research (vertical bar) enables to perform the specific in-depth analysis. At this point of reading, we are in the problem analysis of the in-depth research.

1.8 RESEARCH OUTLINE

As explained in the research methodology (§1.7), the research is divided into multiple phases. The outline of this thesis is shown in Figure 9.

Chapter 1 describes the motivation for this in-depth research and initiates the two subjects to research. Chapter 2 researches the potency of sensors on the individual asset. Since the expansion joint is chosen as specific asset-type to research, the asset lifecycle and current monitoring techniques are analysed. A theory is developed on the basis of the analysis and a proof-of-concept is developed and evaluated. This results in defining the conclusion on the potential of sensors on individual assets to realise the SA.

Chapter 3 covers the scaling from one individual asset to an asset network. First, a literature study and desk research is performed to create context regarding existing standards in BIM and sensors and the added value of a SAN. Afterwards, requirements for collecting, processing and transforming data to realise SAN for decision-making in maintenance projects are defined. The theoretical design presents the SAN for expansion joints by means of the monitoring system and a use case diagram. Chapter 4 provides an evaluation of the SA and SAN and evaluates the set requirements of Braaksma (2016) to realise SAM. Chapter 5 presents the discussion and conclusion of the research, where the research question will be addressed. The discussion provides comments regarding the reliability and limitations of the research and reflects on the application of SA and SAN for current practice. Chapter 6 provides recommendations for a practical implementation for the construction sector and concludes with recommendations for further research.

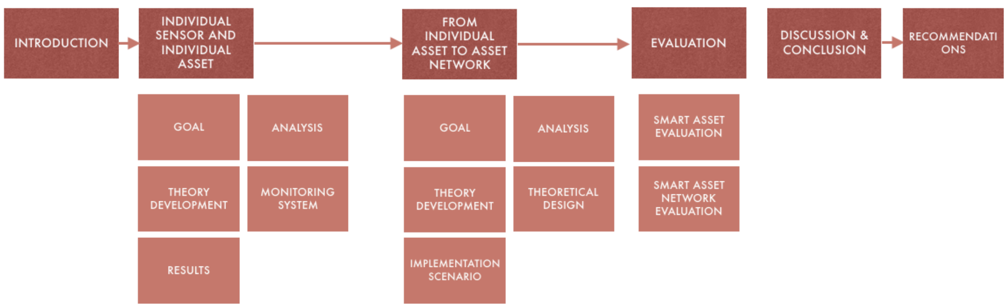

Figure 9: Outline of the in-depth research report.

2 THE INTEGRATION OF INDIVIDUAL SENSOR WITH THE INDIVIDUAL ASSET

This chapter provides an implementation of the monitoring framework of SBRCURnet (2014) to indicate how an individual SA can be realised. By systematically elaborating on each step of the monitoring framework, a use case is developed by means of a proof-of-concept. Additionally, knowledge from case studies as is captured in the report of Braaksma (2016) and knowledge from experts is used. The chapter focuses on the application of the individual sensor on the individual asset. This integration is important, because it forms the basis for determining the integration of the individual SA in a SAN (see Figure 10).

SQ1: Which aspects influence the incorporation of sensor technology for Smart Assets in the construction sector?

2.1 GOAL

The monitoring framework of SBRCURnet (2014) describes that a clear goal is to be determined by the initiator. The goal of the SA is to determine what is needed to turn the expansion joint in a Smart Asset (SA) and identify eventual bottlenecks. An expansion joint can be seen as a SA when it is able to meet the requirements to collect and analyse sensor data of attached sensors and its performance can be detected and predicted.

Through monitoring an indication of performance degradation is to be determined. The contribution to the concepts of Internet of Things[4] (IoT) and Smart Cities is also investigated. Sensor technology of the IoT is closely related to the concept of Smart Cities, because the city's status can be continuously monitored through sensors in the real-world infrastructure (Puliafito, 2015). The IoT and Smart Cities concepts enable to define the link between BIM and sensors. The combination of sensor data models with semantic BIM is currently researched (Andriamamonjy et al., 2015; Wang et al., 2013). This link will be further discussed in section 3.5.

The goal of the research into SA is summarized in Figure 10 and is as follows:

- Define how the SA collects and analyses data of attached sensors;
- Define the SA that is able to detect and predict its own performance;
- Define the relation between BIM and GIS for the individual asset through using the concepts of IoT and Smart Cities.

[4] Internet of Things: A technology that uses (sensor) devices in a network in an online environment. With this, objects can be 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).

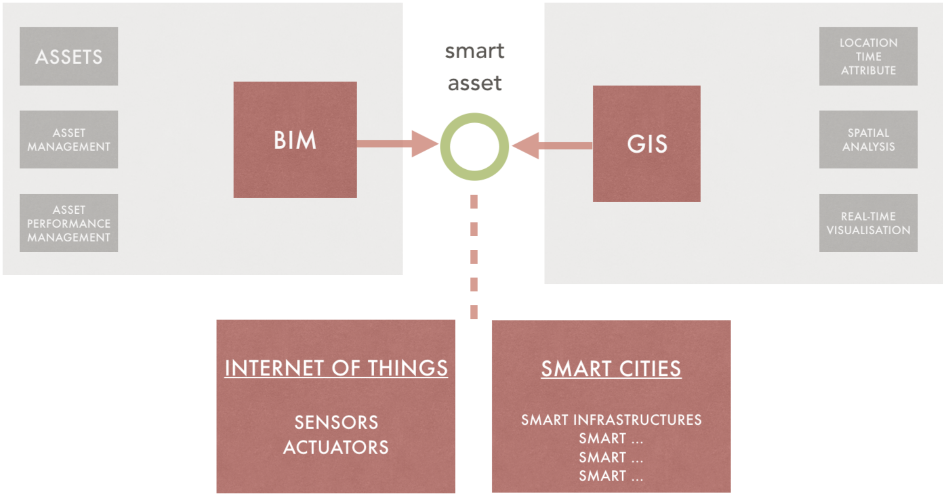

Figure 10: Research goal of the integration of the individual sensor with the individual asset.

2.2 ANALYSIS OF THE CURRENT SITUATION OF MONITORING EXPANSION JOINTS

As explained in section 1.3.1, the expansion joint has potential to be used for monitoring purposes. The section distinguishes three reasons: (1) types of degradation, (2) the increase in importance and (3) the standardized applications.
This section continues on these characteristics and describes the opportunity for monitoring the expansion joint with sensors. The degradation types of the expansion joint (§2.2.1) and the current methods for monitoring (§2.2.2) are discussed and used to illustrate the need for using sensors in the assessment model.

2.2.1 DEGRADATION TYPES

Two types of performance degradation are distinguished for expansion joints (Doorn, 2016; Hibbens & Wiseman, 2013): The expansion joint can displace entirely due to slowly crushing the concrete (Figure 11) or the covering plate can detach (Figure 12).

The improper connection between expansion joint and road surface is a frequently occurring problem. The improper connection is either due to slowly increasing height differences in the road surface, called 'rutting', or due to the incorrect construction of the road surface. The (local) height differences leads to an increased pressure on the asset when traffic is passing over. This irregular pressure is passed to the concrete, resulting in crushing concrete and damage to the construction (Figure 11).

Metal fatigue occurs in the prestressed steel compounds that are used to join the sound-damping cover plates with the expansion joint. A prestressed compound can be seen as a bolt, which is just slightly shorter than required. When the nut is tightened, the bolt is slightly stretched and thereby stressed. Because of this expansion of the bolt, the compound is very tight (Doorn, 2016). A main issue of this compound type is the sensitivity during the installation. Examples are small grains of sand on the expansion joint, unsmoothed welds or zinc droplets (Doorn, 2016). These examples have a negative affect on the connection and results in less tight prestressed steel compounds, causing the cover plate to start resonating which in turn leads to damage and sudden failure of assets.

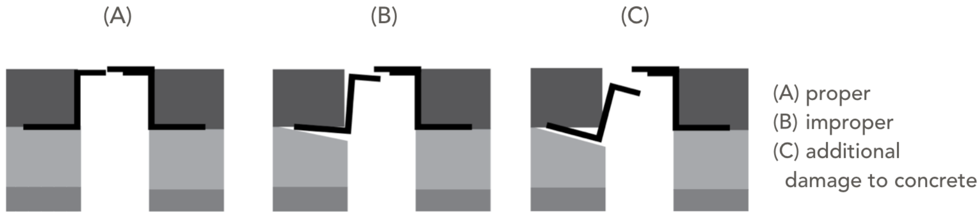

Figure 11: Since the expansion joint itself is created out of steel, the concrete underneath it can be crushed due to irregular pressure on the joint.

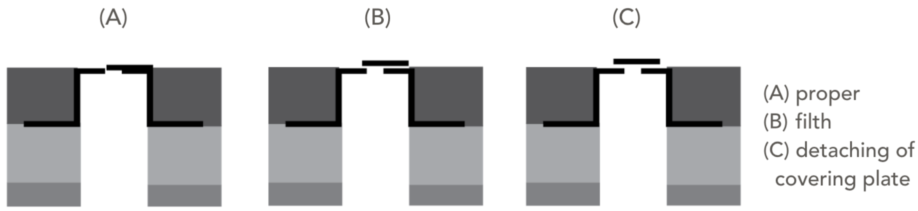

Figure 12: A second type of degradation is that the covering plate of the expansion joint can detach. This event often occurs due to the presence of filth during the deployment of the joint.

2.2.2 CURRENT METHODS OF MONITORING

Current monitoring of the performance of expansion joints is applied according to the RAMS analysis: Reliability, Availability, Maintainability and Safety. The aim of RAMS is to express the performance level on the four aspects in an explicit way (Rijkswaterstaat, 2014).

Reliability is defined as the probability that the required function of the asset is carried out under the given conditions for a given time interval (Rijkswaterstaat, 2013). In the case of expansion joints, four sub-aspects are considered relevant to be taken into account (Pfeifer, 2016; Rijkswaterstaat, 2013):

- Asset lifetime. The term refers to the time duration in which the expansion joint, given the various loading conditions, is performing reliable.
- Implementation sensitivity. The term refers to the extent to which the reliable functioning of the expansion joint is insensitive to execution errors. This results in so-called 'hidden defects' during the maintenance phase.
- Wear resistance. The term refers to extent to which the expansion joint is resistant to wear as a result of movements and traffic loads.
- Corrosion sensitivity. The term refers to the extent to which the expansion joint is resistant to chemical-physical damage.

Availability is defined by the time duration that the required performance can be carried out. The term refers to the extent to which the expansion joint will be unavailable for traffic loads due to maintenance activities. The maintenance activities can be quantified by using the Unavailability (Dutch: Niet-beschikbaarheidindex) systematics of Rijkswaterstaat (2013) (see Appendix A), which often can have large – mainly financial – consequences for the contractor.

Maintainability is defined as the probability that maintenance activities can be performed within the set time schedules in order to remain functioning at the required level (Rijkswaterstaat, 2013). A distinction is made between fixed and variable maintenance. Fixed maintenance is the regular maintenance activities in order to

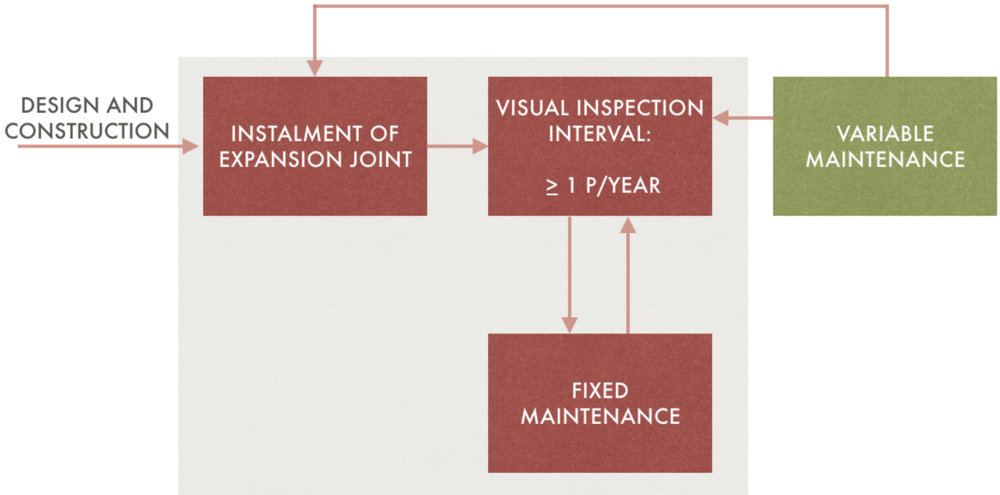

Figure 13: The conservative approach towards the maintenance of expansion joint (based on Smits Neuchatel (2011)).

remain optimal performance of the expansion joint and avoid consequential damages. Variable maintenance is the replacement of replaceable parts or the entire expansion joint when it reached its end of life (Smits Neuchatel, 2011).

<u>Safety</u> refers to the prevention of undesired events, implying unacceptable risks towards the safety of humans, employees and the built environment as due poor design, execution or maintenance of the expansion joint (Rijkswaterstaat, 2013). Risks are identified and control measures are defined to mitigate these risks.

The current approach towards maintaining expansion joints is summarised in the block scheme of Figure 13. After the instalment of expansion joint, the supplier advises to inspect at least once a year (Pfeifer, 2016). As defined in the aspect maintainability, the inspection observes fixed or variable maintenance. Examples of fixed maintenance are the cleaning of the dilation and repair of small rut formations (Smits Neuchatel, 2011). The visual damage, degree of corrosion and potential leakages on the bottom of the asset are reported. The inspector reports his opinion about the state of performance of the expansion joint as well (Smits Neuchatel, 2011). The explained degradations of the expansion joint (§2.2) are often not observed. An example: The metal fatigue does not occur on the same place each time, where it depends on the relation with the adjacent infrastructural assets. Metal fatigue cannot be observed, because it is not visible with the human eye (Doorn, 2016). It is a logical step to use additional technologies to discover variable maintenance activities.

Although the GOTIK-method is used for project management purposes, it is suitable to illustrate the current problems existing in monitoring expansion joints. GOTIK is a Dutch acronym for the words Cost, Organisation, Time, Information and Quality and the five aspects together are considered to provide a thorough foundation for basic project management (Wijnen & Kor, 2002). Relating to expansion joints, the following can be stated:

- Costs: The cost of yearly inspections and fixed maintenance are rather low. The costs for unexpected variable maintenance however are high. Placing sensors are considered relevant when the costs of the maintenance activities outweighs the installation costs for sensors (Peelen, 2016).

- Organisation: There are multiple actors involved. The contractor has the responsibility to maintain the assets for a contractual period. The inspector performs the visual inspections on behalf of the contractor. Although RWS sets the boundaries in the contract, it is up to the contractor to handle the reliability, availability, maintainability and safety of the road infrastructure. RWS and the road users are dependent on the contractor. Especially when considering the use of SAM systems by Asset Managers, adaptions are to be made in order to fulfil the suitability for decision-making.
- Time: The interval of inspections for expansion joints is set once a year as a minimum. This entails low costs and as the expansion joint could seamlessly perform for over twenty years would be sufficient (Pfeifer, 2016). The real-world situation shows us that when one of the two degradation types (§2.2) starts developing, the interval of inspection is insufficient (Doorn, 2016).
- Information: The data that is generated throughout the lifetime of an expansion joint is mainly by visual inspection reports. The inspection focuses on filth in the dilation, steel corrosion and cracks in the concrete beam (Doorn, 2016). This information is leading for the Asset Management (AM) decision-making processes. The current provision of information is not sufficient for optimal AM since no additional technologies are used to detect degradation that cannot be seen with visual inspections.
- Quality: The quality of the visual inspection and subsequent decision-making is arguable. There are currently no exact boundaries set for the performance of expansion joints. Certain indicators are set for the rutting of the concrete and steel corrosion to enable preventive maintenance, but the AM strategy for variable maintenance appears to be based on corrective maintenance. Currently, research indicates the opportunity of measuring performance of expansion joints with other techniques than human eye, where sensors seem promising to enhance the quality of decision-making (Flintsch & Bryant, 2009).

2.2.3 CONCLUSION ON THE ANALYSIS OF THE CURRENT SITUATION

This section provided the insight in the two main types of performance degradation for expansion joints; the displacement of the expansion joint and the detachment of the covering plate. As mentioned by Van den Bos et al. (2013), the assessment model has to make a distinction between fixed maintenance and variable maintenance. Since the fixed maintenance consists of routine maintenance activities, the focus for monitoring is to be on the variable maintenance. The current method of assessing the asset performance indicates that visual inspections are inadequate for effective decision-making. In order to incorporate sensor technology effectively in the construction sector, the expectations of the purpose and added value has to be addressed. Monitoring through using sensors is however a promising solution. The potential of sensors to detect metal fatigue or changes within the construction is to be investigated.

2.3 THEORY DEVELOPMENT

This section uses the previously described aspects in the development of a theory that is used defining the SA. It elaborates on the variables to be measured (§2.3.1) for monitoring expansion joints and defines the requirements for a successful SA (§2.3.2).

2.3.1 VARIABLES TO BE MEASURED

The current method of visual inspections for assessing asset performance is not able to detect metal fatigue and changes inside the expansion joint. Sensors are applied in a proof-of-concept in order to determine whether the performance of an expansion joint can be identified with sensor technology.

Previously conducted research identified the following indicators for the performance of expansion joints (Doorn, 2014; Jang et al., 2013; Mageba, 2015; SBRCURnet, 2015; Timar, 2013):

- The sound caused by wheel passages.
- The vibration caused by wheel passages.
- The movements in the horizontal direction caused by wheel passages.
- Axle loads caused by wheel passages.
- The humidity inside of the expansion joint, which can indicate leakages.
- The chloride content and pH of the concrete.
- The temperature inside the expansion joint.
- The strain of the expansion joint, as effect of traffic loads and temperature. This considers both the temporary strains as the deformation[5].
- The crack growth of the steel bridge deck plates.

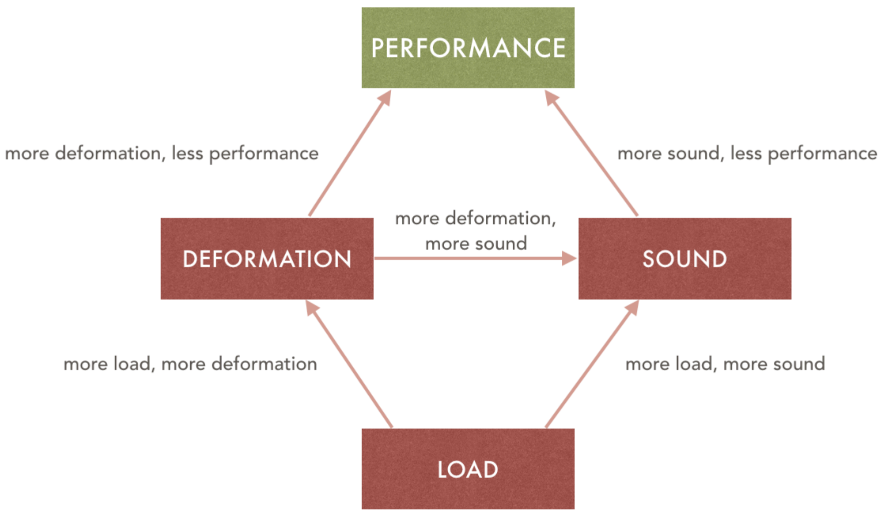

Figure 14: The presumed relations between deformation, load and sound towards the performance of the expansion joint.

[5] Deformation of the expansion joint refers to the degradation of the entire expansion joint, thereby referring to the deformation of the concrete structure.

A proof-of-concept is created as pilot to determine whether relations between sensors can be identified in determining the asset performance. It encapsulates a simplification of the real-world situation, causing that not all indicators qualify to be included. The presumption is that measuring sound, load (axle load) and deformation (Figure 14) identifies the asset performance degradation.

As stated by Doorn (2016) and shown in section 2.2.1, the deformation of the expansion joint is due to the crumbling concrete instead of a deformed steel construction. The often-mentioned variable of measuring the strains itself is therefore left out of scope, due to the impossibility to measure this in the proof-of-concept. The expansion joint deforms entirely - by distortion - but is not deformed itself (Doorn, 2016).

The effects on current working methods when measuring with sensors are that data is collected continuously and effects of traffic loads on the expansion joint can be analysed. This contributes to an improved insight in the asset performance when compared with visual inspections in current methods. Through explicitly defining the performance indicators and the variables to be measured, the relevant sensor data to be collected can be determined. To prevent the asset manager of being overwhelmed with raw sensor values - his basic interest is to gain insight into the performance - it is likely that in the future the sensor measurements are collected and analysed on the background and only performance numbers are presented to asset managers.

2.3.2 REQUIREMENTS FOR THE SMART ASSET

The performed case studies of Braaksma (2016) emphasize to specify what information is desired and how this is translated into variables to be measured. Before the monitoring system is designed for this proof-of-concept, requirements are to be set for the proper handling of sensor data. Braaksma (2016) explains five data stages in the geo-information production process of Lemmens (1991) (Figure 15).

The five stages indirectly imply requirements to be taken into account when realising the individual SA. Similar to the system thinking within Systems Engineering, where each system is part of a collection of elements to serve a larger goal (LeidraadSE, 2013). In this research, Smart Asset Management (SAM) pertains the larger goal and the individual SA and is one of the systems that contain multiple elements that have interrelationships that are focused on.

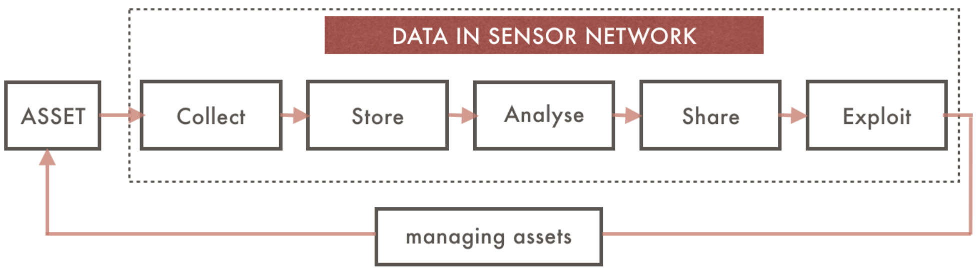

Figure 15: The geo-information production process embedded as data stages in an asset network, adapted from Braaksma (2016).

Throughout the process the data quality is to be considered. This research defines data quality as the suitability of the data set for the intended application. The following requirements are to be taken into account for the processing of sensor data of the individual asset:

- Collected sensor data should be pre-processed to resolve data quality issues such as noise, outliers and missing values (Peelen, 2016).
- The strategy for storing the data has to be pre-determined. An option is to collect 50.000 data values per day, or to retrieve 350.000 data values weekly. The strategy also relate to pre-processing sensor data in the SA, thereby retrieving 50 performance numbers per week. The balance between generating large amounts of sensor data values and the desired accuracy of the outcome has to be found (Steentjes, 2016).
- The data that is analysed should be within a 95% confidence interval, through setting two times the standard deviation as a threshold (McZoey, 1994).
- The sensor data to be shared and exploited has to be determined. This is an important requirement to be taken into account in order to prevent the asset manager to be overwhelmed with processed performance values.
- The link between data measurements by sensors and usability for AM is to be considered. Relevant information can be linked via BIM only when there is a direct link between sensor and asset. An example: An expansion joint with a length of 15 meters contains three sets of sensors, one set per each 5 meters. It is relevant to know the sensor locations and which sensor registers the bad performance. This is also relevant for detecting malfunctioning of sensors. The attachment of sensors, in terms of its location, capabilities and area of measurement, is to be linked to BIM in order to be used properly for AM.

These steps in the process lead to determine the control measure for maintenance activities. The interpretation of the provided data is leading for the decision-making process. The control measure has to align with the pre-set goal of monitoring in order to be integrated in the SAM system. The relation of the individual asset, defined via the concepts of BIM, with the individual sensors, has to be taken into account. The alignment between standards from BIM and sensors will be discussed in section 3.2.

2.4 MONITORING SYSTEM

The research of Hodge et al. (2015) shows that a monitoring system in general consists of four essential parts: sensor devices, base station, server and a database. One or more sensors are communicating with a base station using either a cable connection or a wireless transmission protocol such as with Wi-Fi, LORAN or Bluetooth. The base station collates the data and transfers it to the server. The server provides database services to other computers as is defined by the client-server model and is connected to the database. The database is a collection of information that is stored in relational format so that it is easily accessed, managed and updated. Hodge et al. (2015) emphasise the need for pre-processing sensor data, either by geometric correction or re-sampling measurements.

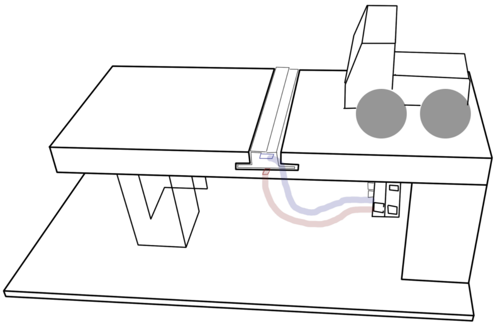

Figure 16: Overview of the test set-up, consisting of a simplification of a bridge part where the expansion joint is located. The blue and red lines indicate the connection between the sound sensor and load sensor to the micro-controller that is collecting the sensor data.

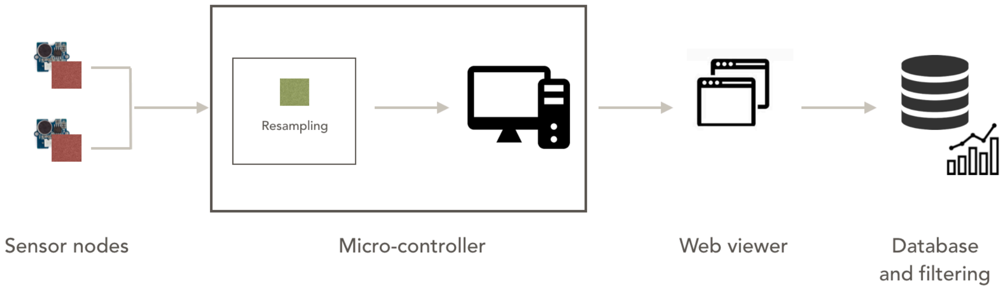

Figure 17: System architecture of the test set-up.

The design of the monitoring system is shown in Figure 16. The test set-up shows a simplification of the real-world situation. The test set-up makes use of aluminium expansion joints, instead of a combination of steel and concrete, which allows to attach sensors at the expansion joint and to ensure measurability. Also, the road and the car are made out of wood. When the car crosses the expansion joint, two sensors are collecting data. The sensors are located inside and beneath the expansion joint and measure the sound and load as a result of wheel passages.

The system architecture of the proof-of-concept is shown in Figure 17. Four main parts are distinguished: Sensor nodes, the micro-controller (Arduino TM Uno), the web viewer and the database and filtering.

- The sensor nodes are represented by the sound sensor and load sensor that are able to collect sensor data values when performing runs.
- The micro-controller retrieves and pre-processes - by re-sampling - the sensor data and sends the sensor data to an online web viewer. The used script can be found in Appendix D. In this proof-of-concept, sensor data is transferred via a connected cable. In the real-world situation, a proper solution for the wireless transfer of data is to be determined.
- The online web viewer is accessible by the user and shows the data entries as is captured by the sensors and uploaded by the micro-controller.
- The database and filtering part is situated at a local computer, where the data values are stored. The filtering is performed through using the Least Squares Adjustment (LSA) method to detect outliers.

A more detailed description of the proof-of-concept can be found in Appendix B.

2.5 RESULTS

Continuing on the previously described system architecture and test set-up, this section elaborates on the data collection and analysis during the test stage (§2.5.1). As well, the results elaborate on the relations between the measurements (§2.5.2).

2.5.1 DATA COLLECTION AND ANALYSIS

Two types of degradation of expansion joints are distinguished: The expansion joint can displace entirely or the covering plate can detach (see §2.2.1). Each degradation type is represented by a combination of three expansion joints with fixed performances (see Appendix B). This way, a distinction is made in the status "new", "halfway lifetime" and "end of lifetime". Next to this, traffic loads are taken into account by applying three different weights - 600g, 1030g and 1460g - in the car to explore the effect on the results. The proof-of-concept therefore researches six combinations, which are shown in Table 2. Each combination is measured through 150 runs[6] to provide an indication for the load and sound for the fixed performance.

Combination	Explanation
1.A	Degradation type 1; Traffic load A [600g]
1.B	Degradation type 1; Traffic load B [1030g]
1.C	Degradation type 1; Traffic load C [1460g]
2.A	Degradation type 2; Traffic load A [600g]
2.B	Degradation type 2; Traffic load B [1030g]
2.C	Degradation type 2; Traffic load C [1460g]

Table 2: Overview of the combinations of interest. Combination 1.A for example relates to the first degradation type, represented by the three expansion joints (status new, halfway lifetime, end of lifetime) with a traffic load of 600g. For each combination are 150 runs conducted.

The collected data resulted in about 10.000 data values in the raw dataset. The data filtering is performed through using Least Squares Adjustment (LSA). The LSA uses the vectors of observations to calculate the standard deviation, which is used to detect outliers. Detected outliers are removed one at a time, after which iterations are performed on the basis of a pre-set threshold for convergence (Lemmens, 2013).

The dataset is exported to Excel and multiple functions are used to filter outliers. The threshold is set to a two-sigma interval, corresponding to a 95% probability interval. When multiple outliers are detected, the highest outlier is removed and the script re-runs. This process is called data snooping (Lemmens, 2013). Once no outliers are detected, the remaining data is used to fit polynomials for each combination. The used Python script for data filtering can be found in Appendix E. The filtering function for detecting and removing outlier x is defined as follows:

$$If\ |x| > T$$

Where:

$$T = 2 \cdot \sqrt{\frac{\Sigma\,(x-\bar{x})^2}{n}}$$

Figure 18: Equation to detect outliers. When the observation |x| is larger than the threshold T, x is considered an outlier and removed from the dataset.

[6] Run: A run is defined by one car that crosses the expansion joint through manually pulling the cord that is connected to the car.

2.5.2 DATA EVALUATION AND RELATIONS

Below in Figure 19 two graphs show the sound and load that is measured during a single run. The increasing sound is clearly seen and the front axle and rear axle of the car that is detected by the load measurement. The sound curve shows a minor decrease between the axles, which can be the result of resampling.

The filtered data of each combination is shown in a scatter plot and additionally Table 3 shows the average and standard deviation of the measurements. The results of all six combinations can be found in Appendix C. Figure 20 shows the results for combination 2.A and places bounding boxes around the measurements. Regarding the detection and prediction of performance of the asset, the degrading performance is seen gradually. The overlapping area of all three boxes is considered a limitation of the proof-of-concept and is recommended for further research.

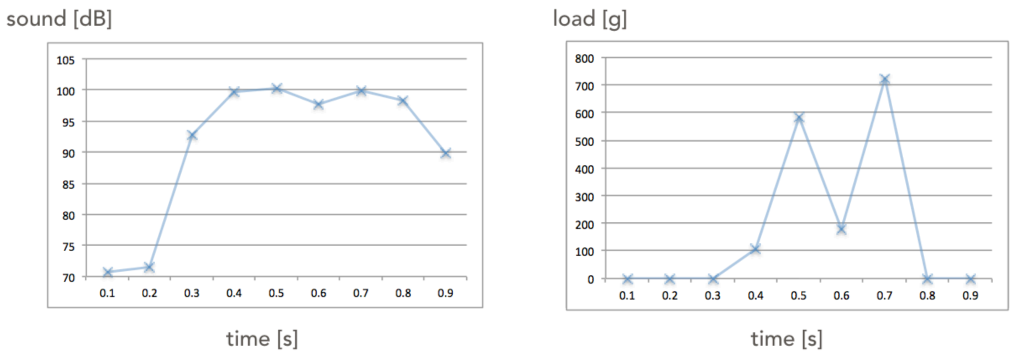

Figure 19: Overview of a single run. The peak of the sound (left) and the axle loads (right) can be seen.

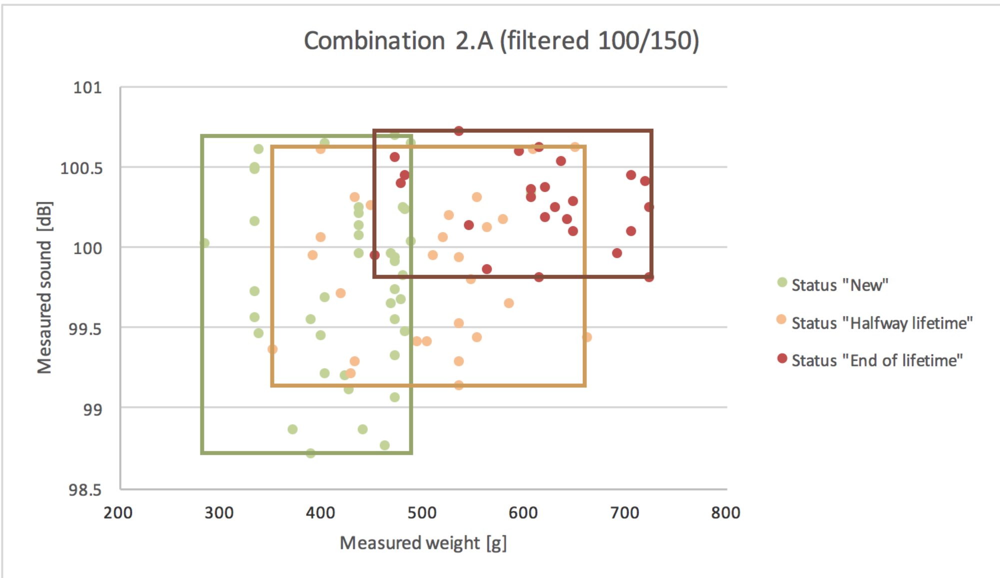

Figure 20: Overview of the results of combination 2.A.

Status	Average load [g]	Average sound [dB]	SD load [g]	SD sound [dB]
"New"	429,7	99,8	80,4	0,5
"Halfway"	507,8 (+78,1)	99,8 (0,0)	63,7	0,5
"End of lifetime"	590,3 (+82,5)	100,3 (+0,5)	100,6	0,2

Table 3: Overview of the averages and standard deviations of the measurements of combination 2.A.

Combination 2.A is the situation where traffic load A is tested on degradation type 2. A detailed description can be found in Appendix B. The scatter plot provides an overview of the filtered data and includes the measurements of three fixed performances: the status "New", "Halfway lifetime" and "End of lifetime". An increase is seen in both the measured load and sound the more the expansion joint's performance decreases. The average sound indicates no change in the first two fixed performances, but increases seen in the domains of the performance states.

The standard deviations of load indicate small deviations (resp. 80.4, 63.7 and 100.6) in comparison to the differences in average loads (resp. 429.7, 507.8 and 590.3). However, the differences in average load between the performance-states indicate are rather small as well (resp. 78.1 and 82.5). This is not ideal, since the two-sigma level, relating to two times the standard deviation, will not represent a clean division. In case of the sound measurements, a similar situation occurs. The sound measurements do show a neat division between the performance-states "Halfway lifetime" and "End of lifetime".

Cuzzocrea (2010) and Akyildiz et al. (2006) define two types of correlation: spatial correlation and time correlation. Spatial correlation relates to the similarity in the environment of the sensors. The time correlation relates to on the one hand the correlated phenomena, referring to pattern evolution, and at the other hand to correlated measurements of the same parameter, referring to variation patterns.

Combination 2.A indicates a time correlation, because the measured load and sound increases the more the expansion joint decreases in performance. Nevertheless, the standard deviations indicate that the boundaries are fuzzy which makes the distinction between the performance-states more challenging and the correlation weak. However, Peelen (2016) states that a weak correlation can still be useful. The probability theory of sensor clustering techniques of Chu et al. (2006) and Deshpande et al. (2005) support this statement. Although a weak correlation between the indicators is detected, it can still be used to realise the SA.

2.6 CONCLUSION: IDENTIFICATION OF INFLUENTIAL ASPECTS

This chapter provides an answer to the following sub-question:

SQ-1: Which aspects influence the incorporation of sensor technology for Smart Assets in the construction sector?

There are four aspects distinguished of a determining influence on the successful realisation. One is encouraged to identify aspects, through testing in a different test set-up, with a different monitoring system or with a different asset. The following aspects are identified:

- Collect relevant sensor data for asset monitoring through explicitly defining performance indicators and variables to be measured.

According to Van den Bos et al. (2013), a monitoring project is carried out successfully when precisely defining what information is desired and how to translate this into the required data and associated measurable variables. The variables in the test set-up are determined based upon a literature study and expert knowledge, and selected on the basis of applicability and measurability in the proof-of-concept. The identified aspects relates to the step "variables to be measured" of the monitoring framework of SBRCURnet (2014) (see I in Figure 21).

- Define proper ways to transfer sensor data within the monitoring system

The ability to transfer sensor data directly to a server is concluded challenging in current practice (Steentjes, 2016). The identified aspect is related to the step of "collecting data" from the monitoring framework (see II in Figure 21). The data transfer is not a relevant aspect in the current test set-up, but will be when developing operational implementations. Current research is performed into the data collection that is performed within Wireless Sensor Networks (Heller & Orthmann, 2014) and focuses on the reliability of networks and data aggregation techniques (Sohraby et al., 2007; Williams, 2014). Contenders Sigfox and LoRa are operators for wireless networks aiming at the adoption of their technologies for Internet of Things applications (Linklabs, 2016) and are developing solutions for wireless data transfer.

- Manage expectations of incorporating sensor technology in Asset Management

The link between the goal of monitoring and the actual output at the control measure is appointed by Braaksma (2016) to be examined both in the beginning and end-evaluation of the monitoring project to set the desired output and expectations. This identified aspect relates to the "goal" step within the monitoring framework (see III in Figure 21). Parsons-Baker and Kay (2016) state that managing expectations, through determining value, alignment and strategic planning of using new technologies, is key to successfully embed the principles within AM systems.

- Adapt SAM systems to be capable of handling sensor data as data input

It is recommended that the contractor, being asset owner, bases his final decision on the gained knowledge from the sensor measurements. By applying the sensor data, SAM can be performed by the contractor. According to Peter Vanderzee in Brown (2014), the estimation is that 30 to 40 percent of the bridges evaluated by company SC DOT using advanced sensor technologies are in a much better condition than presumed based on previous visual inspections. The AM system has to be designed in such a way that it is capable to use the sensor data as data input. This aspect relates to "control measure" step within the monitoring framework (see IV in Figure 21) as it defines the interaction between the goal and expectations of performance monitoring and the control measure of providing indicators and meeting these set expectations.

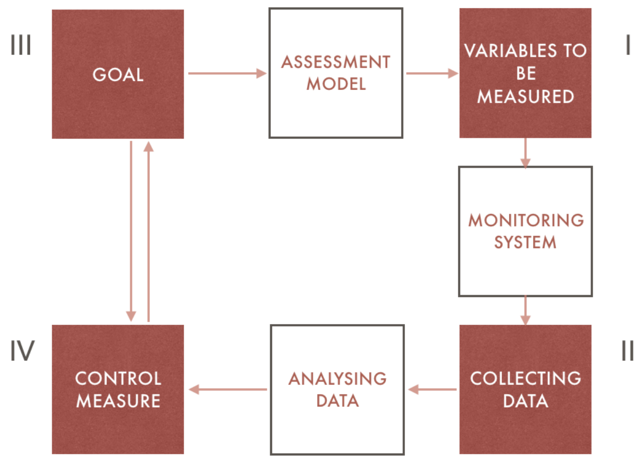

Figure 21: Overview of the identified aspects of the SA associated to the steps of the monitoring framework of SBRCURnet (2014).

The four identified aspects relate to four steps of the monitoring framework (Figure 21): Defining goal, determining variables to be measured, collecting data and defining the control measure. The described research findings create a dialogue between different actors at strategic, tactical and operational level. It enables to capture multiple perspectives, based on sensor measurements and human knowledge and experience, on the maintenance of expansion joints. It is recommended that contractors conduct pilot projects to determine the effects in relation to quality, costs and benefits over time and to properly address the aspects in further applications.

3 FROM INDIVIDUAL ASSET TO ASSET NETWORK

This chapter provides an implementation of the monitoring framework of SBRCURnet (2014) to indicate how a Smart Asset Network (SAN) can be realised. By systematically elaborating on each step of the monitoring project, a system architecture and use case diagram is developed. Also, knowledge from case studies as is captured in the report of Braaksma (2016) and knowledge from experts is used. The chapter focuses on the integration of the individual asset in an asset network. This integration is important, because it forms the basis for determining the integration of the SA and SAN for Smart Asset Management (SAM).

SQ2: Which aspects may be expected to be of determining influence on the incorporation of Smart Asset Networks in the construction sector?

3.1 GOAL

Once the SA is successfully realised in the construction sector, the next step is to connect these individual assets in a SAN. The goal of this chapter is to learn about asset networks by means of determining what is required to realise the smart expansion joint in a SAN and identify eventual bottlenecks.

Expansion joints are integrated in a SAN when they are able to meet the requirement of sharing and exploiting data of the individual SA, thereby improving the detection and prediction of individual asset performances.

The added value of sharing and exploiting sensor data among the asset network is currently researched (Peelen, 2016; Steentjes, 2016). According to the case studies in Braaksma (2016), the construction sector could benefit of implementing extrapolation techniques for correcting detected and predicted asset performances.

This approach of a SAN is defined through developing a system architecture and use case for data processing. Since the SAN is to be used for Smart Asset Management (SAM) purposes, the relation with BIM has to be defined as well.

The goal is as follows:

- Define the alignment between BIM and sensors within SAN.
- Define the added value of extrapolation and the effects when used for expansion joints in a SAN.
- Develop a system architecture and use case that gives insight in the data aggregations and transformations to be performed.

3.2 ANALYSIS OF THE CURRENT SITUATION OF ADOPTING ASSET NETWORKS

The current use and deployment of asset networks leaves much space for new applications, which is indicated by research on the subject in the past years (Geodan, 2013; Hodge et al., 2015; ISNC, 2016). However, no evidence is found showing the use and deployment of the intended application of asset networks in the construction sector.

This section discusses the current application of SAN for Asset Management (AM) purposes within the construction sector and elaborates on the 'smart' aspect of the asset network. Additionally, the relation between standards in BIM and sensors are analysed. As mentioned by Wang et al. (2013), the connection between live sensor data and the comprehensive BIM is a challenge, due to differences in semantics, level of detail, data formats and data sources. The application and added value of extrapolation will also be discussed.

3.2.1 APPLICATION OF ASSET NETWORKS

The conducted case studies of Braaksma (2016) indicate the current implementation of asset networks in the construction sector. It is seen that assets can be linked in online servers and database through using sensors. The railway monitoring project of VolkerRail manages to detect events from sensor measurements into events and link them to assets from BIM (Van den Bos et al., 2013). The case study of project Haarlem uses the online viewer iAsset, which makes asset information accessible at all times (Beijer, 2016).

Recent developments are seen in the efforts for combining BIM and GIS applications (Kuehne & Andrews, 2016; Mommers, 2015). VolkerInfra is developing the GIS-loket: An online accessible geographical information system that enables the accessibility of asset information of multiple construction and maintenance projects (ter Maaten, 2016). The GIS-loket is used for communication purposes for planning and maintenance engineers and fulfils end-user visualisations. It does not include an active asset network yet, but provides the basis to build future applications upon.

The case study of the Van Brienenoord-bridge – in the report of Braaksma (2016) - shows that the use of sensors enabled extrapolation purposes throughout the inspected asset. By using the detected correlations in the bridge deck in a simulation model, TNO was able to extrapolate measurements and predict the performance of unmeasured areas of the asset (Peelen, 2016).

The first steps towards managing multiple assets in an online environment are taken, but there is no formal defined asset network. The main reason is that the information provision in Asset Management systems remains mainly human-driven (O'Dea, 2016). Though the Van Brienenoord-bridge project was a pilot project for RWS and limited to the extrapolation of sensor data within one individual asset, it provides an example where the information provision on asset performance is data-driven. Current AM systems are provided with human interpret data, stored in the system, and information is retrieved from the system by humans again.

Asset Management becomes "clever" when it becomes data-driven. According to Manville et al. (2014), operational systems are to be implemented, to manage communication among the interconnected assets with minimal direct human involvement. ICT-enabled infrastructure is used for piloting a network of technologies that interact in a specific project area. This involves sensors and devices creating data, therefore human involvement is by-passed (Manville et al., 2014).

Asset Management however become "smart" when it is both human- and data-driven (Steentjes, 2016; Von Plate, 2015). The idea behind this is that input is to be provided by both humans as sensor technology. The system gains capabilities in managing different types of sensor data, and accompanied with input from the user, the system generates an output to be used by the user. For example: The user sets a threshold for the expansion joints' performance. The system gains processed sensor data and notifies the user when the performance is below the threshold. This way, the user make informed decisions for maintenance activities on the basis of the collected information (Von Plate, 2015).

The current trend of asset networks shows that solutions are slowly adapted. The human touch remains when applying a SAN, though the digital capabilities of sensors are essential. It is the future outlook that SAN through the use of information is smart enough to predict and detect asset performance (Meyers, 2012).

3.2.2 ALIGNMENT OF STANDARDS FOR BIM AND SENSORS

Sensor technology is key in the Internet of Things (IoT), because the networked interconnection of objects lead to a distributed network of devices that communicates with other devices (Xia et al., 2012). In order to properly define an implementation for the construction sector, the connection between components of BIM and sensors are to be addressed. The asset network relates to the sensors and associated sensor data. Asset Management on the other hand, is related to the principles of BIM from the construction sector. Both the world of BIM and sensors developed their own standards in order to exchange data sufficiently (Geonovum, 2014; Percivall, 2016).

3.2.2.1 Analysis of common ground between BIM and sensor standards

The open geospatial consortium (OGC) adopted sensor standards in a Sensor Web Enablement (SWE) framework in order to make sensors, transducers and sensor data repositories discoverable, accessible and useable via the Internet (Percivall, 2016). The SWE framework is divided into two groups (Figure 22): The SWE information model, dealing with data formats, and the SWE service model, dealing with the interfaces of (web) services.

The standards within the SWE are the following (Botts et al., 2007; Jirka et al., 2009; OGC, 2007):

- Observations and Measurements (O&M). The standard defines the data model and the encoding for observations data.
- Sensor Model Language (SensorML). The standard defines the data model and the encoding for the sensor metadata. The main objective is to enable interoperability, so that sensors and processes can be better understood by machines and be shared.

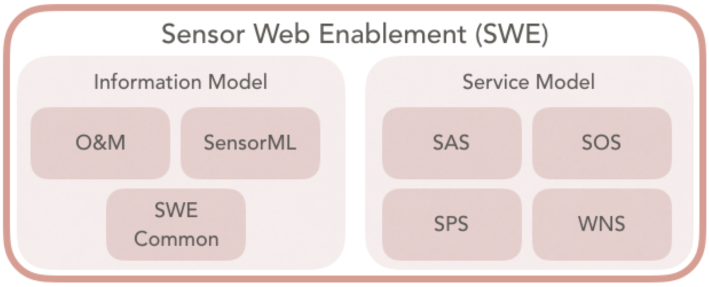

Figure 22: Overview of the sensor web enablement (SWE) architecture (based on Botts et al. (2007) and Jirka et al. (2009).

- SWE Common. This is a low-level data model for exchanging sensor related data. The model allows applications and servers to structure, encode and transmit sensor datasets in a semantically enabled way.
- Sensor Alert Service (SAS). The standard enables to receive alerts about subscribed events of users (Example: Receiving alerts when the measured sound is above threshold).
- Sensor Observation Service (SOS). The standard allows to query observations, metadata and representations.
- Sensor Planning Service (SPS). The standard is used for planning actions for sensors. Also, queries about the capabilities and the tasks of the sensor can be performed.
- Web Notification Service (WNS). The standard provides notification mechanisms, message interchanges, with one or more services.

When looking for the relation between SWE and BIM, the recently added SensorThings application Programming Interface (API) has to be mentioned. It is not a new standard - it is developed based on the existing O&M, SensorML and SOS standards (OGC, 2016a) – but the SensorThings API provides an open and unified way to interconnect IoT devices, data and applications over the Web. The use of the SensorThings API is a step in the direction for connecting assets in a network and application purposes for future AM. An overview of the SensorThings API is shown in Figure 23.

Geodan (2016), a geo-ICT organisation in the Netherlands, is currently developing an open source IoT platform that enables to share information of 'Things'. Anno July 2016, the company continues on the available SensorThings API in order to enable the exchange and exploitation of information from different sources to realise 'Real Smart Cities'.

The demand for interconnecting assets increases the complexity of projects and several BIM standards arose in the past years. The interoperability of BIM standards is defined by buildingSMART (2012). The distinction is made to focus is on processes, data formats and semantics (Figure 24): Processes relate to the arrangements made about the information provision, data formats relate to the information carrier and semantics to the terms and definitions applied in these information sources for proper interpretation.

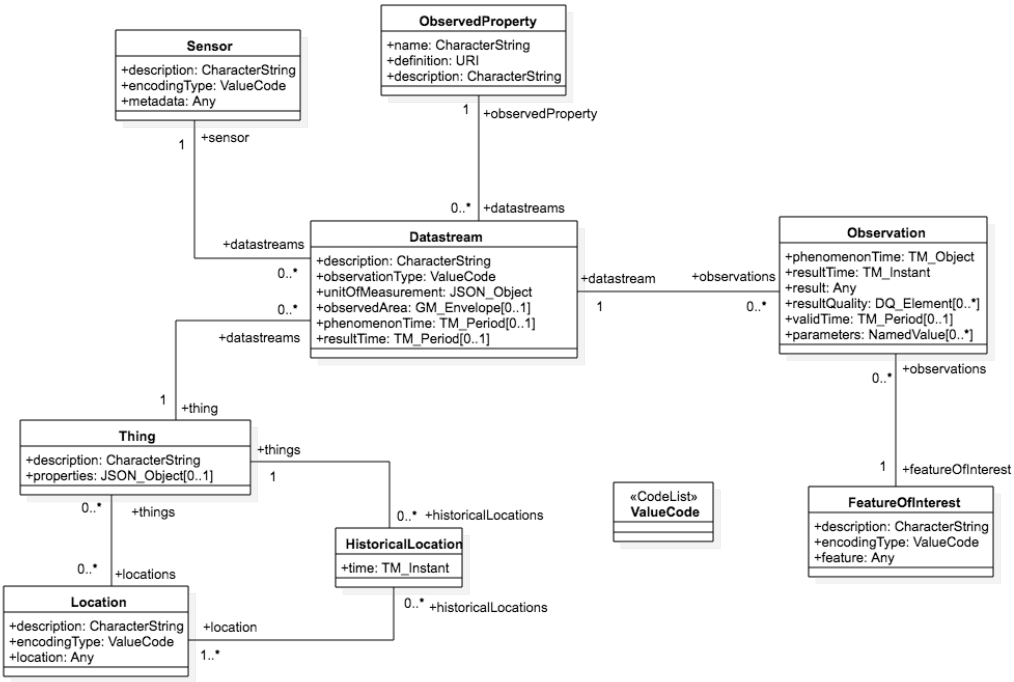

Figure 23: The UML diagram of the SensorThings API data model (OGC, 2016c). The model consists of two parts: the sensing profile and tasking profile. OGC (2016c): "The sensing profile allows the IoT devices and applications to create, read, update and delete IoT data and metadata in a SensorThings service." The tasking profile is currently researched and will provide functions similar to the Sensor Planning Service. In this research, the class "Thing" of the sensor network indicates a link to the BIM of the individual asset.

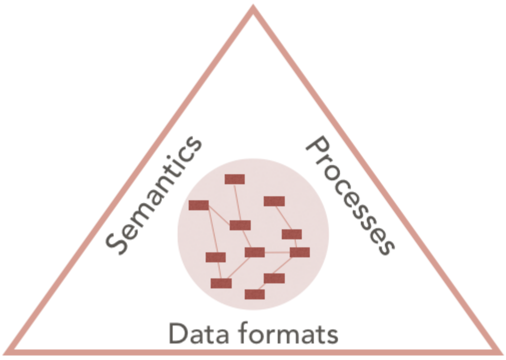

Figure 24: The interoperability triangle of buildingSMART relates to the processes, data and semantics applied within BIM (based on buildingSMART (2012)).

The overall aim is to integrate the distinguished specialisations of contractors in a single information model (Eastman et al., 2008). The extent to which the building process is integrated and the extent to which information is to be shared digitally are contributors in determining which standards are relevant (Geonovum, 2014). This research indicates that there are four BIM standards at this moment relating to the interface with sensor technology:

- The National BIM protocol. In order to collaborate effectively within projects, agreements are made between contractors about the integration of work fields to deliver an integrated process in BIM. The protocol facilitates the operational and juridical agreement in the development process (Spekkink, 2013).
- COINS[7]. The exchange of digital information between IT-platforms that are involved in projects, mostly related to Systems Engineering, is covered by this standard. COINS is an extension to IFC and facilitates BIM on process and data formats level (Schaap et al., 2010).
- Industry Foundation Classes (IFC). The IFC defines a neutral and standard file format for sharing and exploitation of BIM-information. The focus is on semantics agreements for data sharing. In theory, IFC enables communication without information loss (Beetz et al., 2010).
- The object-type library (CB-NL[8]). To enable efficient BIM processes, the CB-NL is developed. This describes a standard digital semantic library, which uses uniform definitions for objects and products. The standard aims at the development of a defining and uniform language to be spoken when collaborating with BIM (Bakker, 2013).

Virtual Construction for Roads (V-Con) is a European project that concerns the standardisation and implementation of Building Information Modelling standards in the sector of road construction and road management (Koehorst, 2012). The focus of the project is on the use of open standards, with the aim to establish efficient information management. The evolving multi-standard worlds of BIM and GIS are researched and the main technical challenges address the support for processing data

[7] COINS: An abbreviation of "Constructieve Objecten en de Integratie van Processen en Systemen" (Dutch).
[8] CB-NL: An abbreviation of "Nederlandse Conceptenbibliotheek" (Dutch).

formats, managing and storing datasets, ensure system quality and ensure a future proof system (Nilsson et al., 2016). Multiple BIM standards are evaluated and the project emphasises the need for using strengths of individual standards and the future task to make links between them. This way the top down static structure could be replaced by a cloud of flexible structures that are reused, interrelated and aligned to each other (Van Nederveen & Bektas, 2013) .

3.2.2.2 Conclusion on common ground between BIM and sensor standards

The SAN should combine the BIM standards and the SWE standards to allow data to be shared and re-used across application and domain boundaries (Wang et al., 2013). As discussed in previous sections, BIM provides a shared knowledge resource for the whole life cycle of a building. The BIM standards show that they all provide open data service although they are using different implementation methods. Similarly, the SWE enables to assess sensor information in an open and interoperable way, but has to be adopted efficiently (Wang et al., 2013).

The standards of BIM and sensors both serve different goals, resulting is no evidence found on conflicts between standards. A logic follow-up question is whether IFC, from the BIM domain, has to be extended with support for sensor standards, or vice versa. There has to be determined where the spatial analysis is to be performed and where the data management is regulated.

This is where Linked Data becomes useful. The research into Linked Data by Berners-Lee (2006) focuses on using the Web to create typed links between data from different sources. Technically the term refers to data published on the Web in such a way that it is machine-readable, its meaning is explicitly defined and linked to external datasets (Bizer et al., 2011). Resulting in a future Web of Data, or Web of Things, described by data on the web. The concept is ambitious, but there is considerable ambiguity to the exact nature and applications for near future (Campbell & MacNeill, 2010). According to Stoter (2016), the idea of creating an overall standard is not an option. Too many differences between geometries, semantics and level of detail are found in both concepts. The challenge is to create "geo-friendly BIM" or "BIM-friendly geo" specifications (Stoter, 2016). Because the sensors are seen as data input for the AM decision-making, the most likely solution is to continue on the principles of Linked Data in order to link BIM and sensor data in the system.

The link of sensor technology to a BIM-environment for AM purposes, through adopting a specified and tested relation between the worlds of BIM and sensors, is not yet made. The construction sector has still challenges to overcome to make the transition from current practice to this outlined future (Siebelink et al., 2015).

3.3 THEORY DEVELOPMENT

This section discusses the requirements for the SAN and the variables to be measured. These are based on the conducted analysis in the previous sections and the analysis as performed in the report of Braaksma (2016). The implementation of expansion joints in a SAN is specifically addressed, as continuing on the research into the expansion joint being a Smart Asset (Chapter 2).

3.3.1 REQUIREMENTS FOR THE SMART ASSET NETWORK

Based on the previously conducted analysis of Smart Assets (Chapter 2) and Smart Asset Network (§3.2), the set of requirements in this research for realising a SAN are defined.

The requirements are identified using the MoSCoW Prioritisation. The MoSCoW method distinguishes four aspects – must, should, could and won't – that enables to prioritise requirements and tasks (DSDM, 2008). The Must requirements have to be fulfilled in order for the SAN to succeed. The Should requirements are important, though not vital and therefore remain the solution to be viable. The Could requirements on the other hand are desirable, though less important than Should requirements and therefore have less impact if left out. The definition of Won't requirements encapsulate the SAN by defining subjects that may relate to the project, but is not taken into account in this research. The identified requirements for realising the SAN specifically for expansion joints are summarised in Table 4.

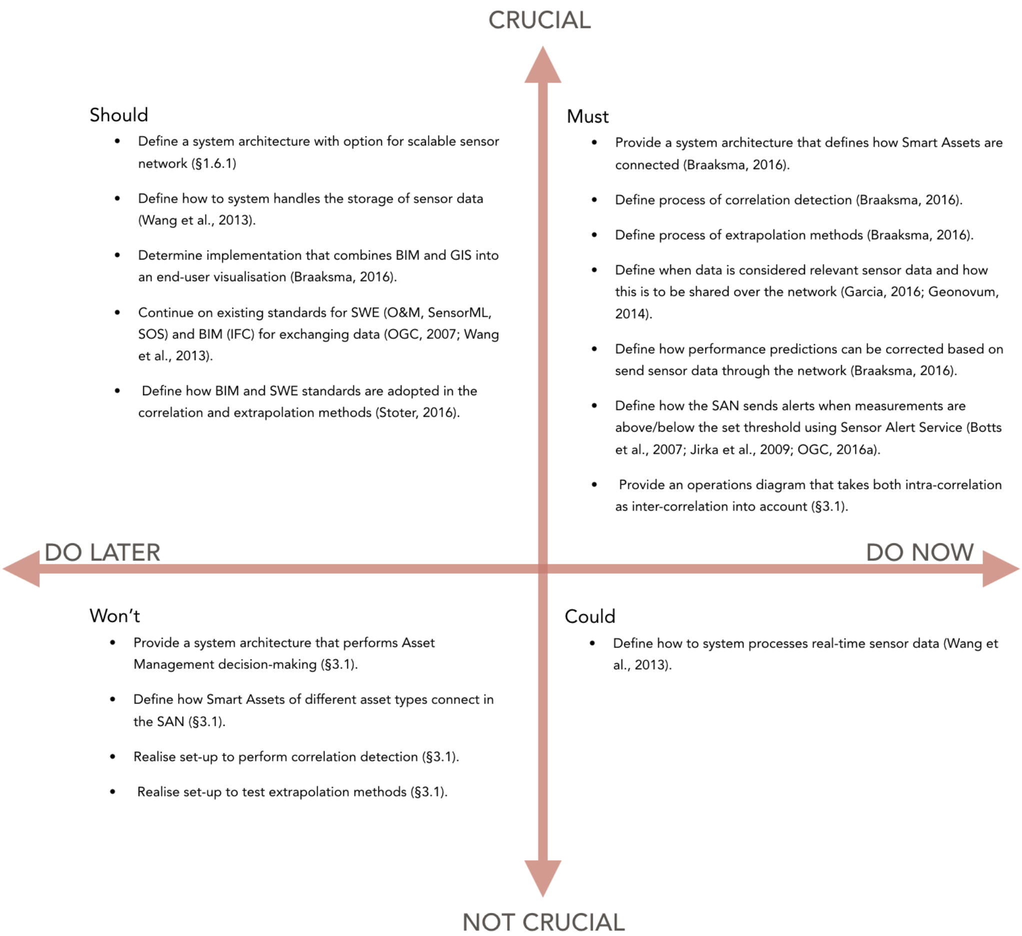

Table 4: The prioritisation of requirements to realise SAN of expansion joints.

3.3.2 CORRELATION AND EXTRAPOLATION WITHIN SMART ASSET NETWORKS

The realisation of SAN refers to the sharing and exploitation of sensor data along the asset network. The terms correlation and extrapolation are important factors in the process. This research defines the two subjects as follows:

Correlation – A statistical measure that indicates the extent to which two or more variables fluctuate together.

Extrapolation – The process of estimating and correcting values for a (virtual) sensor on the basis of its correlation with a value from a known existing sensor.

An existing sensor hereby refers to an actual sensor that is attached to an expansion joint. The virtual sensor enables to register sensor measurements, although no physical sensor is attached to the expansion joint. This will be further explained in the subsequent section. Through estimating values by using detected correlations between two expansion joints, the measured sensor data at the existing sensor can be used to estimate a value for the virtual sensor.

The analysis of the current situation of SAN provided the insight that the pilot project Van Brienenoord-bridge applied extrapolation techniques. The project used sensor measurements from a small area of the bridge deck to extrapolate this along the bridge deck. In their approach, a small area of an individual asset is monitored with sensors and via extrapolation the performance of the entire asset is estimated.
The pilot project proved that extrapolation techniques can be used to indicate the performance of a single asset. The use of correlation and extrapolation techniques in order to detect and predict the performance of multiple assets based on limited sensor measurements is addressed research in the upcoming years (Peelen, 2016).

When the correlation cannot be detected by using sensor measurements, the correlation is to be detected with additional data in order to remain a satisfied reliable extrapolation. Examples of additional data are the asset location, weather or the traffic loads. This is main reason to distinguish two types of correlations:

Intra-correlation – The correlation of the individual sensors attached to the individual Smart Asset in order to determine the asset performance.

Inter-correlation – The correlation of Smart Assets that is detected through examining BIM-data and additional data sources.

The intra-correlation is examined in realising the Smart Asset (Chapter 2). The inter-correlation focuses on the relation between assets and is used in this chapter for the implementation of SAN. The distinction in two types of correlation is of high importance, because the use of correlations allows determining extrapolation purposes (Figure 25).

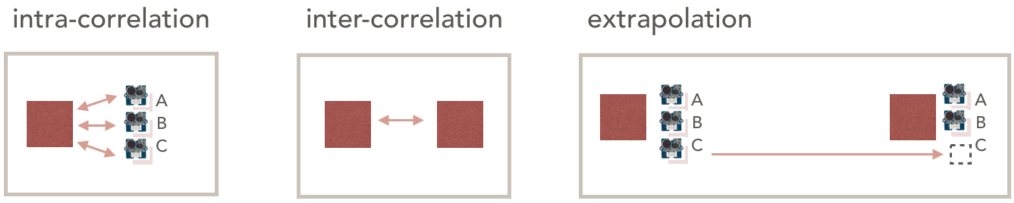

Figure 25: Illustration of intra-correlation, inter-correlation and extrapolation. The intra-correlation relates to the correlation of sensors to the individual asset performance, the inter-correlation relates to the correlation between assets. When the inter-correlation is detected, sensor values can be extrapolated to other assets.

3.3.3 VARIABLES TO BE MEASURED

The measurements to be performed in order to successfully realise the SAN, depend on situations that occur in the real-world situation. Following on section 3.3.2, sensor data can be shared through the asset network and exploited to determine unknown values for expansion joints: Hence realising a so-called virtual sensor. Figure 26 shows three situations of assets and attached sensors that occur in the real-world situation.
The three situations are described as follows:

- Situation 1: Each asset is attached to the required sensors.
  This is the ideal situation where each expansion joint is provided with all required sensors to obtain the sensor measurements and intra-correlation can be used to determine the individual performances. The SAN can be used to share and exploit the sensor data from sensors A, B and C in order to improve detection and prediction of asset performance. This situation is however rather expensive and there is hardly any need for data to be shared.
- Situation 2: One expansion joint is attached to all required sensors and others have a few sensors.
  This situation fits the description in section 3.3.2: Assets 2 and 3 are lacking sensor C, therefore the sensor measurements of Asset 1 can be extrapolated to determine the unknown data values. The identification of inter-correlation between the expansion joints is important for this.
- Situation 3: Only one expansion joint is attached with all required sensors.
  When incorporating sensor technology in the construction sector, this is likely to be the situation in the early days. Where one expansion joint has all required sensors attached, and is considered a SA, other expansion joints lack any sensors. Extrapolation still can be useful in this situation. However, the inter-correlation has to be determined via other ways. The use of additional data could help to determine this correlation and extrapolation possibilities, although the reliability of proper detection and prediction of performance over time is to be researched.

The three situations describe the use and need of correlation and extrapolation for SAN. As mentioned in section 3.3.2, there is intra-correlation and inter-correlation. In order to realise SAN in the construction sector, the definition of what data is to be shared has to be clear. Sensor data is only to be shared over the network when required and the detected correlation between two assets is sufficiently established and reliable.

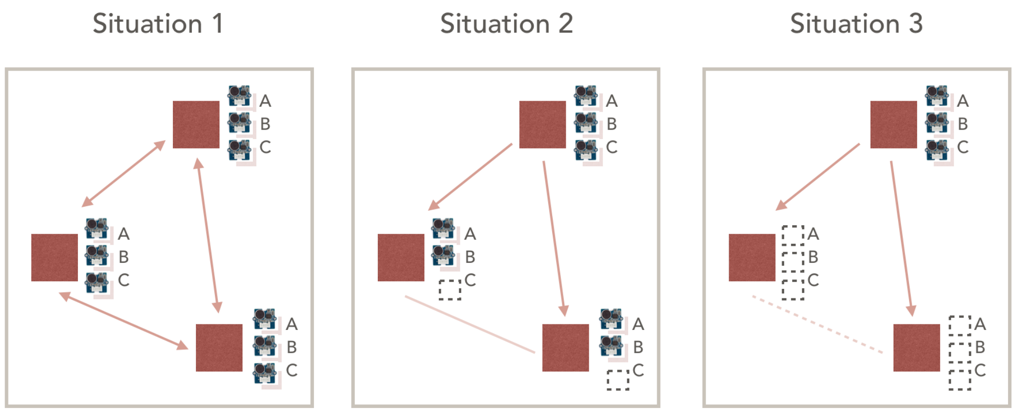

Figure 26: Three situations can occur when incorporating sensors in the construction sector. The assets (red) can have many, few or no sensors attached. By focusing on these three situations, the use and need for correlation and extrapolation can be explained.

3.4 MONITORING SYSTEM

On the basis of the set requirements of the previous section (§3.3), this section distinguishes the system architecture and the use case diagram. The system architecture defines the structure of the system and describes the components required in order to work properly. The use-case elaborates further on the components of the system architecture by using the scenario to identify data operations that are to be performed within these components.

3.4.1 CONCEPTUAL SYSTEM ARCHITECTURE

The conceptual system architecture serves as a theoretical design for the SAN in the construction sector. The theoretical design builds upon the performed research in Chapter 2 and focuses on realising the expansion joint in a SAN.

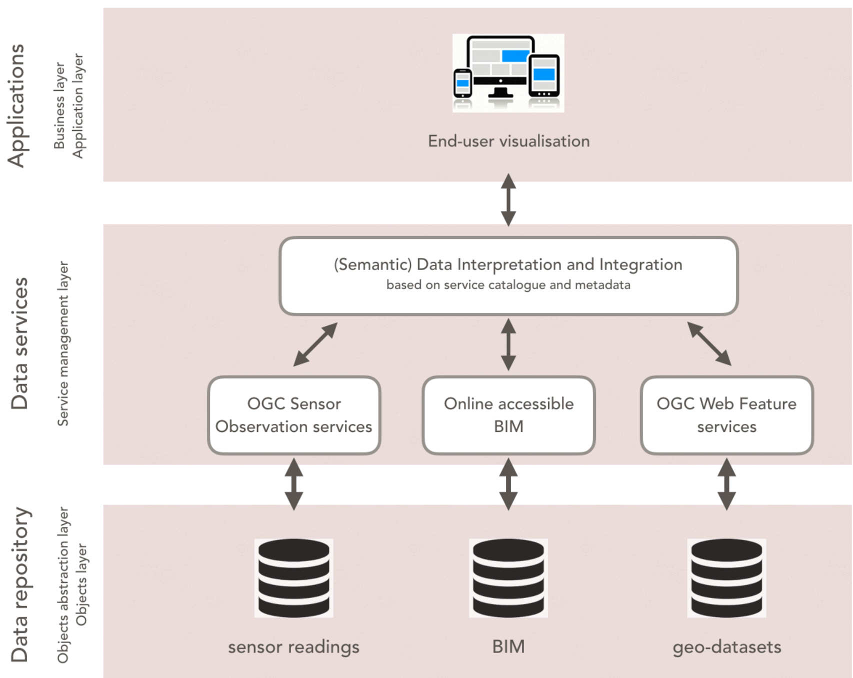

Figure 27: The proposed system architecture for Smart Asset Networks can be divided into three levels; Data repository, data services and applications (based on Andriamamonjy et al. (2015)). The levels relate to the set data, information and performance.

Continuing on the research of variables to be measured (§2.3.1), the load and sound are used indicators for the expansion joint as SA and therefore used within the SAN. The SAN system architecture includes the sharing and exploitation of sensor data: Hence correlation and extrapolation (§3.3) taken into account. The conceptual SAN system architecture is shown in Figure 27. The system architecture relates to the explained 5-layer model of the IoT architecture in Braaksma (2016) and defines three levels: data repository, data services and applications.

The data repository and data services are explained in the following sections, where the applications level is discussed in the use case in section 3.4.2.

3.4.1.1 Data repository

Within the data repository, there are three data sources: Sensor readings, BIM and geo-datasets. Each data source represents an aspect of the asset network architecture and as such has impact defining the SAN performance.

The individual sensors are linked through the connected assets in what this research defines an asset network. The asset network topology for the use case of expansion joints combines the star network topology (Figure 28) and mesh network topology (Figure 29).

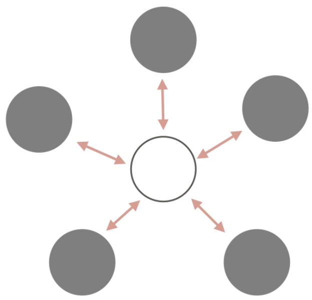

Figure 28: Star network topology.

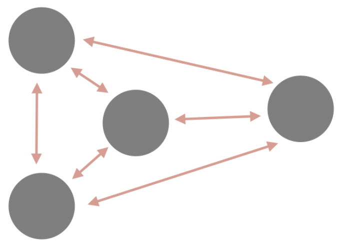

Figure 29: Mesh network topology.

A hybrid combination of the two existing topologies enables to send data from an individual sensor node to higher power nodes and to eliminate each other's weaknesses. The network topology for the SAN of expansion joint relies on the hybrid star – mesh network topology, shown in Figure 30. It defines the relation between the individual expansion joint (white) and its sensor (grey) attached. It also shows the intra-correlation (red) and inter-correlation (blue).

To further describe how the asset and sensor of the hybrid network topology is positioned to enable a SAN, Figure 31 shows the class diagram of the SAN. The data model is built on the currently researched SensorThings API data model (§3.2.2), taking the OGC standards for publishing, finding and binding data into account.
The key to the model is that an observation is modelled as an act that produces a result whose value is an estimate of a property of the observation target: the asset. Each *Datastream* observes one *ObservedProperty* with one *Sensor* and has many *Observations*. Each *Observation* read by the *Sensor* observes one particular *Asset*. The *Datastream* is central in the model, representing the collection of *Observations* from a *Sensor* and sensing one *ObservedProperty*. It allows creating, reading and updating sensor data and metadata in a service. Together, the relationships provide a flexible standard way to describe and model the system (OGC, 2016b).

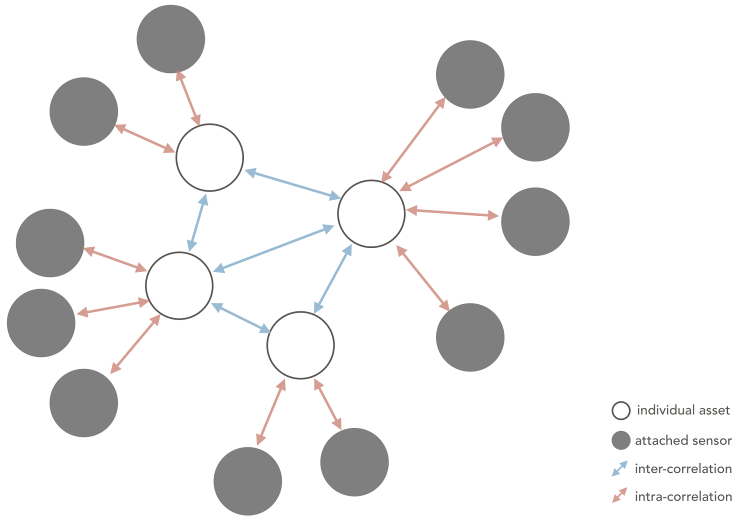

Figure 30: The hybrid star-mesh network topology enables to combine the star topology for the individual asset (white) with its attached sensors (grey) in a mesh network (based on Matin and Islam (2012)). The blue connections provide sensor data for assets to be used for inter-correlation and the red connections enable intra-correlation.

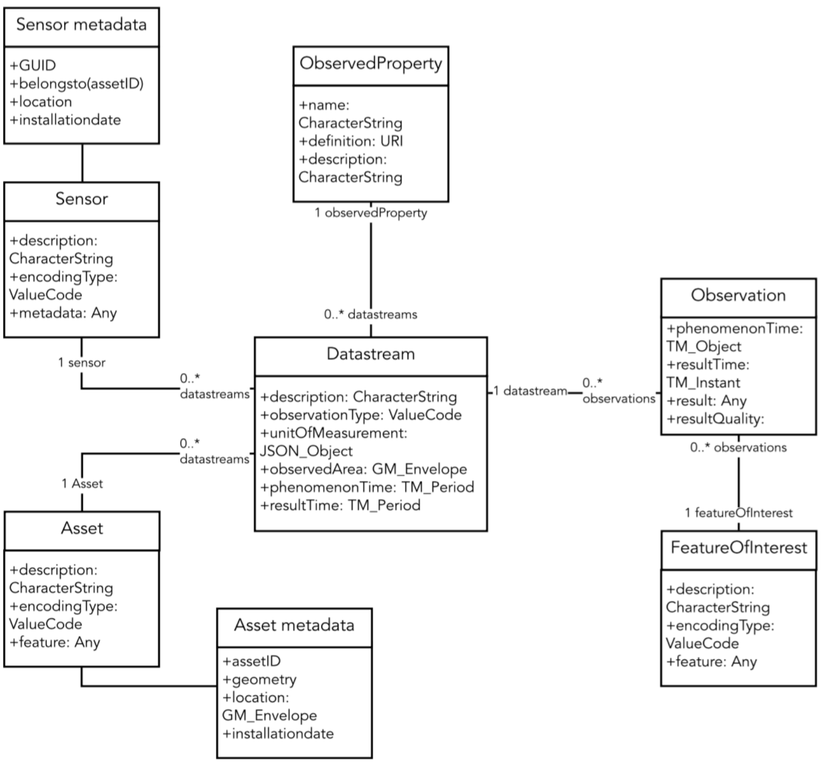

Figure 31: The class diagram shows that the SAN data model fits in the SensorThings API data model of OGC (2016c).

The link towards Systems Engineering (SE) is derived from both Figure 30 and Figure 31. The value added by the asset network is primarily created by the interrelationship; that is, how the assets are interconnected. The interconnection is seen in Figure 31: the instance *GUID* for the class *Sensor metadata* and the instance *AssetID* for the class *Asset metadata*. The *GUID*[9] and *AssetID* are reference numbers used for identifying the individual sensor or asset. Within SE, the assets are often structured via a System Breakdown Structure (SBS), which appoints the ID's and interrelationships. Where SE is a well-known concept within the construction sector, Linked Data[10] is a known concept in the geo-domain. It involves the large-scale integration of, and reasoning on, data on the Web (Clivaz et al., 2016). With help of Linked Data, semantic queries can be executed, which is of importance when requesting sensor data for extrapolation. Linked Data is used without physically linking systems, by referring to other elements through using identifiers. So what we see is when we use the Linked Data and SE concepts, it enables to link assets from BIM and sensors from the geo-domain. It is seen in Figure 31, that the class *Thing* is where the two worlds meet.

3.4.1.2 Data services

The input from the three data sources at the data repository layer is used in the data services layer. The data interpretation and integration is to be performed based on the service catalogue[11] and metadata[12]. In particular this second and third step are important, because the SAN should be able to share and exploit relevant sensor data.

The connection between the sensor reading and BIM has to be made. Using the SOS, the sensor measurements can be retrieved. The required metadata is then collected with help of the O&M and SensorML standards (§3.2.2). The metadata of sensors can be foreseen with a GUID[13] to identify the expansion joint the measurements belong to. The link between the GUID in the sensor's metadata and the BIM asset ID is then be made. When also considering the OGC Web Feature services of using additional geo-datasets, such as weather and traffic loads, the integration between geo and BIM becomes more influential (Stoter, 2016). Important to note again is that the geo- and BIM-standards serve different goals. In case of the expansion joint, specifications for the integration of these data sources can be defined by focusing on the correlation and extrapolation.

In the basis, the publish-find-bind principle is used. This concept is known for its application within the service-oriented architecture (SOA), an architecture that provides an approach for building systems to deliver application functionality as services to the end-user (Joshi, 2005).

[9] GUID: Abbreviation for Globally Unique Identifier.

[10] Linked Data: The best practice for exposing, sharing and connecting pieces of data, information and knowledge on the Semantic Web using standards such as URI, RDF and OWL (Crapo et al., 2011).

[11] Service catalogue: The service catalogue is an organised collection of all business and information technology related services that can be performed within the application.

[12] Metadata: The metadata is data that describes the characteristics of other data.

[13] GUID is an acronym for "Globally Unique Identifier", which is a reference number used for identification purposes in software applications.

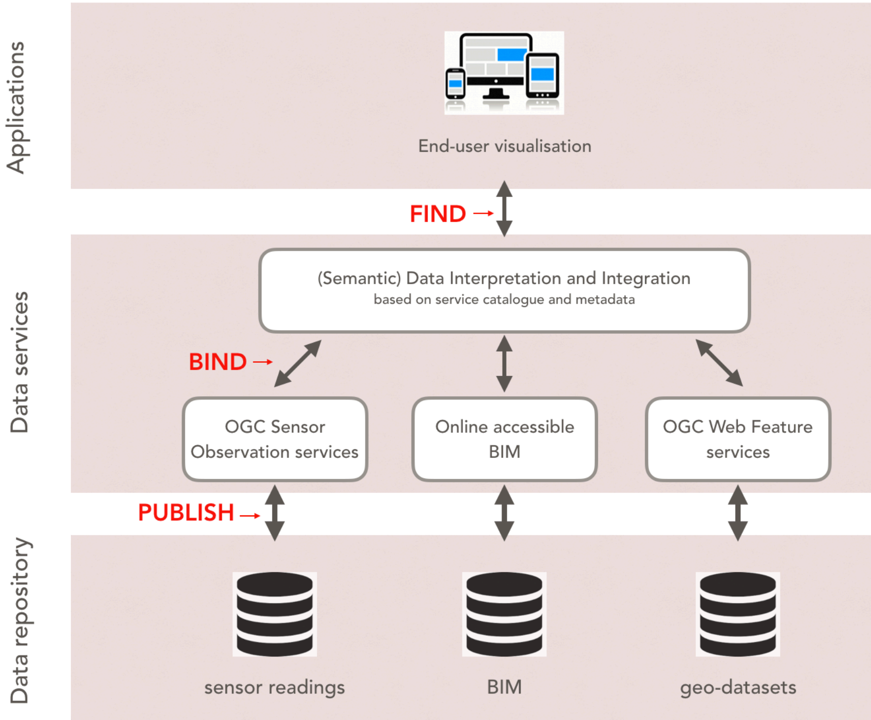

Figure 32: The publish-find-bind principle integrated in the conceptual system architecture.

The three layers – applications, data services and data repository – and three operations – publish, find and bind – are distinguished (Figure 32):

- Data repository (Service provider): The sensor publishes its measurements and metadata to the service broker so that the service requester can discover and assess the data.
- Data services (Service registry): It enables sensor data discovery. It contains a repository of available services and allows for the lookup of sensor data.
- Applications (Service requester): This is a software module that requests the sensor data. It collects - binds - the measurements via a SWE service.
- Publish. The sensor publishes its measurements and its service description metadata describing its capabilities and network address, so that is can be discovered and invoked.
- Find. Through a similar way as querying, the requester can locate the sensor, can determine its intra-correlation and its measurements.
- Bind. The (sensor) data and (sensor) metadata is combined based on ID's.

Together, these components and operations form the publish-find-bind pattern (Joshi, 2005). A sensor gives a description of its measurements it publishes to the service registry. The user conducts a find operation by querying a service that matches its criteria. These criteria are either to retrieve sensor data measurements such as raw data or inter-correlation or to determine the intra-correlation. The use of triggers and recipes known from the IFTTT (If This Then That) enable to perform actions in an automatic and systematic way (Fabry, 2015).

While most of the research work in sensor networks has focused on sensor engineering and communication and network questions, the near future is most likely to be concentrated on leveraging sensor network applications by Web services in a publish-find-bind service-oriented fashion (Bouguettaya et al., 2008; Simonis et al., 2010). This is where Semantic Web[14] and Linked Data become important subjects.

Research into smart grids of Crapo et al. (2011) emphasize that each device, when enabled with knowledge of its own capabilities and purpose expressed with the semantics and shared ontologies, will be able to "plug-and-play" at the semantic level. Through adopting semantic web and linked data, the interoperability based on devices enables to connect semantically and exchange data automatically.

3.4.2 USE CASE

A use case diagram helps to explain the context of the system and takes the requirements of the SAN into account. Use case diagrams belong to the Unified Modeling Language (UML), which enables the modelling as well as the visualisation of dynamic aspects of systems. It is applied to define a systems theoretical implementation (Booch et al., 1998). The use case diagram presents an outside view of how the elements can be used in context (Figure 34). It continues on the previously discussed principles of publish-find-bind and elaborates on the system architecture's components and data operations that are to be performed within these components.

The first part of the use case diagram is the find-principle and includes the users, user interface, client[15], the sensor alert service (SAS) and the web notification service (WNS). The asset manager interacts with the user interface, which can request information from the client. The client gains data from the Web Feature Service (WFS)[16] request. The SAS continuously monitors the sensor database, which is detecting and predicting asset performances. When the set threshold for performance is exceeded, the SAS alerts the client and the notification service enables to send a message to the user. A parallel process alerts a maintenance engineer when sensors are performing incorrectly. This can be due to (semantically) incorrect measurements or sampling problems. The messaging is performed through using Pub-Sub: A messaging pattern where senders of messages – publishers – do not program the messages but characterize messages into classes (Beres-Deak, 2014). Messages are sent to a topic, to which subscriber applications can subscribe. The main benefits are that unified messaging and data security, protection and reliability is realised (Google, 2016).

The data is requested from the sensor database, the BIM database, the traffic database and the base map geometry. Next to the three databases mentioned in the system architecture, the base map geometry has an important role in the use case where it enhances the user interface. The base map geometry provides an underlay for projecting data from other sources and can be used via open data sources as for example Open Street Map (OSM). The data request initiates the services that are at the core of the SAN. It is the bind-principle and includes the process from starting the data request at the client to providing the required data to the client. The client

[14] Semantic Web: The Semantic Web is an extension of the current web in which information is given well-defined meaning, better enabling computers and people to work in cooperation (Berners-Lee, 2001).

[15] Client: The client is a piece of computer hardware, which can access a service that is made available by a server. It relies on sending and retrieving information requests.

[16] WFS: The Web Feature Service is an interface for requesting and retrieving of data available from a server. It defines three types of requests: GetCapabilities, DescribeFeatureType and GetFeature.

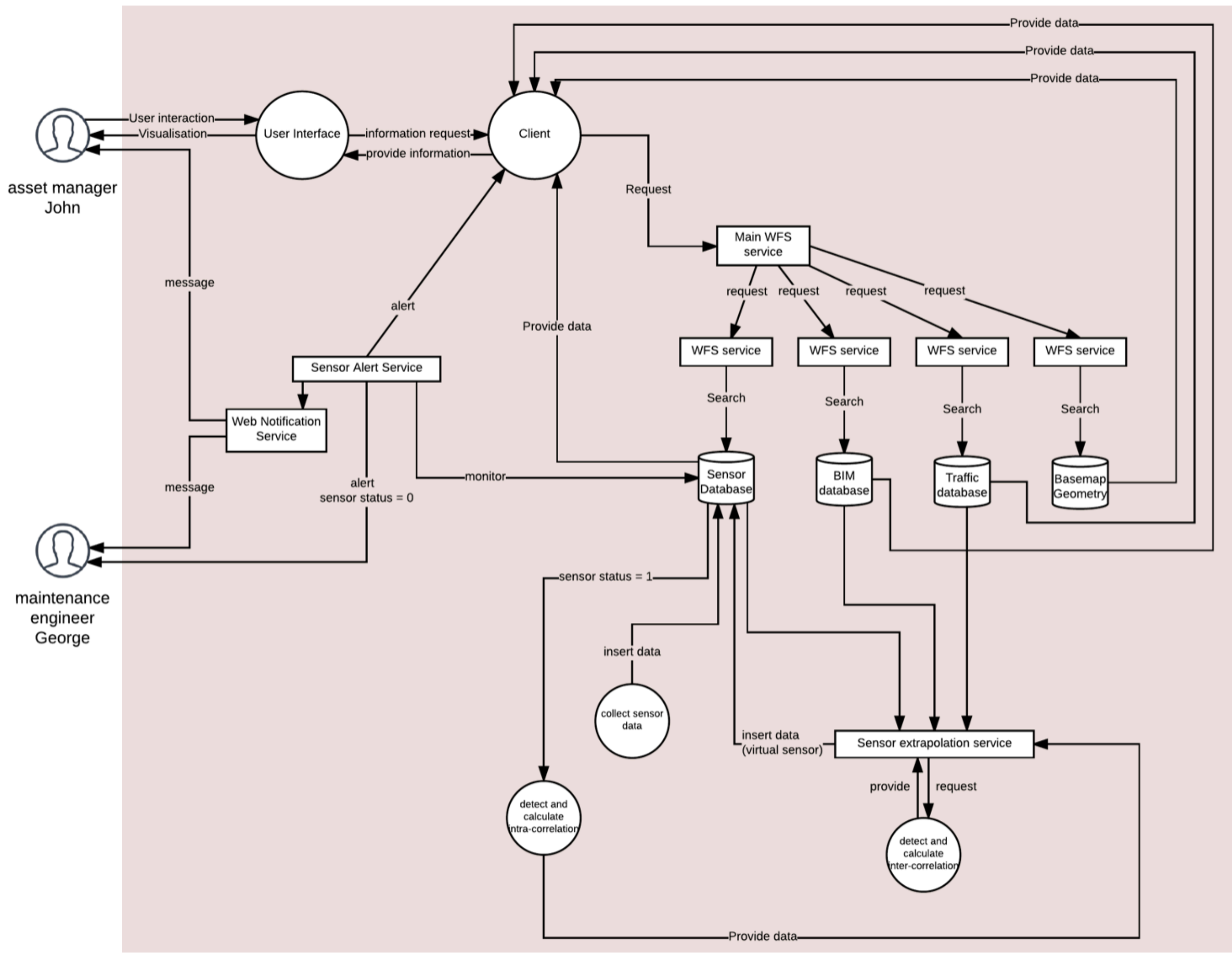

Figure 33: The use case diagram defines the components that are taken into account when the user requests information from the SAM system.

initiates the main WFS request, which is then split up into four separate WFS services that gather data from the distinguished databases that follow the publish-principle. The BIM database, Traffic database and Base map geometry provide input directly to the client. The sensor database contains the collection of all sensor data measurements and the detections and predictions of asset performances.

The collected sensor data is direct input to the sensor database. The intra-correlation is detected and calculated from the sensor database and provides data for the sensor extrapolation service. The sensor extrapolation service enables to detect and calculate the inter-correlation based on the gained input from the sensor database, BIM database and traffic database. Once the intra-correlation and inter-correlation are detected, correlation data is inserted into virtual sensors[17]. Resulting in a sensor database consisting of sensor measurements from physical sensors and correlation numbers for virtual sensors that enable on-the-fly calculation of virtual sensor data. Important to note is that the calculations are not performed on user request, but on a daily timed moment. This way, all required data is available on the server and the user does not have to wait for entire calculations. As just described, only small calculations of using correlation numbers for on-the-fly data input for virtual sensors are to be performed.

An important attribute in the sensor measurements tables is whether the sensor data is calculated via inter-correlation. This has an effect on the reliability in detection and prediction of asset performances. The performance prediction of an asset with all relevant sensors attached will be better than the performance prediction of the asset that used shared sensor data from the network. This additional metadata is necessary to be stored. The strength of the correlation influences this detection and prediction of asset performances. The use case diagram will be used in the subsequent section to define how the complete system operates when the proposed scenario of "Asset Manager of the future" of Braaksma (2016) is used as input.

3.5 THEORETICAL IMPLEMENTATION

With the system architecture and use case diagram in mind, this section defines the theoretical implementation for expansion joints. The theoretical implementation includes the data model and the application of a use case.

This section illustrates the data model for the expansion joint (§3.5.1) by adopting the class diagram UML model. As well, the use case for expansion joints (§3.5.2) serves as input for determining how the SAN can be deployed to enhance decision-making for the asset manager. The set scenario is tested through elaborating on the use case diagram for the application of managing expansion joints.

3.5.1 DATA MODEL FOR THE EXPANSION JOINT

To illustrate the data model for the SAN, an example for the application of expansion joints is shown in Figure 34. The figure is adapted from Figure 31 and shows how the data model for SAN is applied for expansion joints.

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[17] Virtual sensor: A sensor that is not physically attached to the asset, but in its digital representation fed by the shared sensor data over the network.

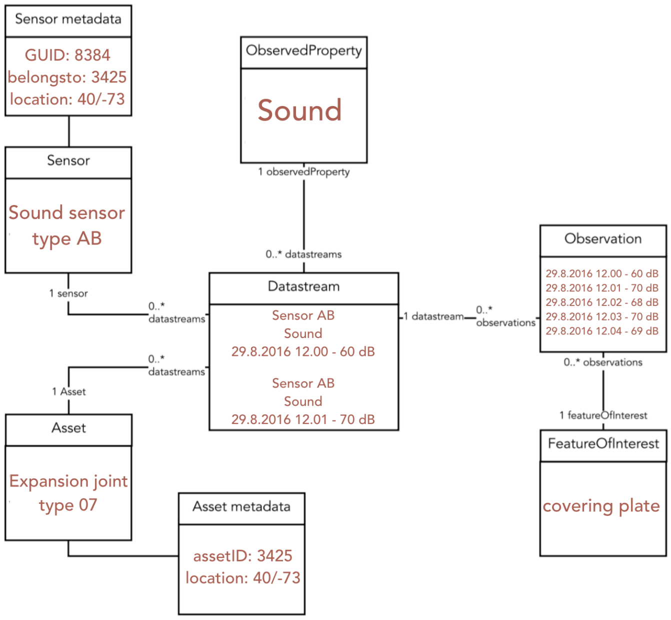

Figure 34: An illustration of the instance diagram of the Smart Asset Network when applied for monitoring expansion joints (based on Figure 31).

The example describes the situation where the expansion joint (*Asset*) retrieves sensor measurements via the *Datastream*, which is the collection of measurements (*Observation*) grouped by the same sound level (*ObservedProperty*) and *Sensor*. The *Asset* – expansion joint of type 07 – has its location and expansion joint ID stored in its *Asset metadata*. Similarly, the *Sensor* – sound sensor type AB – has its location and ID stored in its *Sensor metadata*. The connection between sensor and asset is also defined explicitly in the *Sensor metadata – belongsto: AssetID*. The attached sensor provides observations that are used for indicating the performance of the covering plate (*FeatureofInterest*). It can be seen that the *Datastream* connects the *Asset*, *Sensor*, *ObservedProperty* and *Observation*. This way, the connection between devices-to-devices and devices-to-applications is simplified and queries on the sensor data are more easily be linked to the asset (OGC, 2016b).

To illustrate how to model the observation data using available sensor standards, Figure 35 presents the central terms of the data model. The elements described in the instance diagram– *ObservedProperty*, *Sensor*, *Asset* – contribute to the *Datastream*. The expansion joint has sensors attached, in this case measuring the sound value. When requesting information of the asset (ID: 3425), the data from the associated sensor (ID:8384) is retrieved and used to provide an observation, which in turn can be used for data sharing and exploitation in the asset network.

Figure 35: Visual representation of how a sensor measurement can be described and linked within the instance diagram (Figure 34).

3.5.2 USE CASE: THE EXPANSION JOINT

The use case diagram, described in section 3.4.2, provides a technical basis for the data transformations that are required throughout the process. Since the use case diagram could also be applied to other areas of research, this section illustrates the case of expansion joints. Through focusing on the set scenario of "Asset Manager of the future", the perspective from asset manager John interacting with the data from the expansion joints is taken into account. The use case diagram is used to show the valid connection between the scenario and the developed theoretical system.

The user interface provides an overview of the project area and its assets. Through clicking on a single asset or demanding an overview of the multiple asset performances, a client request for information is initiated. The data to be retrieved considers the asset performance and the reliability of measurements.

John is interested in retrieving the detected and predicted asset performances and the associated reliability index. The reliability index of the detected and predicted performance of the individual expansion joint can be low, which is the case when John has requested this information from an expansion joints that does not have sensors attached. When requesting information from the expansion joint, the intra-correlation is calculated first. George, maintenance engineer, is alerted when the sensor is operating improperly. If the intra-correlation cannot be calculated, the inter-correlation is calculated through using the sensor extrapolation service. The sensor extrapolation service uses the input from the sensor database, BIM database and traffic database in order to provide virtual sensor data to the expansion joint' missing sensor. The extrapolation is thus based on a similar structure in BIM (expansion joint type), on a similar location (GIS) or through similar traffic loads.

The use case identifies that sensors can share data with other (virtual) sensors through using the asset-asset relation in terms of correlation. It continues on the defined hybrid network topology (see Figure 30) and the instance diagram (see Figure 31) that define the link between BIM and sensor models. The added value of the system is that John is now able to retrieve an overview of the performance of the expansion joints he has to manage. By applying intra-correlation, inter-correlation and extrapolation techniques, the data required to gain insight in the performance of expansion joints is gathered. This way, the SAN enables to provide a detection and prediction of the status of each expansion joint.

3.6 CONCLUSION: IDENTIFICATION OF INFLUENTIAL ASPECTS

This chapter provided an answer to the following sub-question:

SQ-2: Which aspects may be expected to be of determining influence on the incorporation of Smart Asset Networks in the construction sector?

There are four aspects distinguished of a determining influence on the successful realisation of a SAN. One is encouraged to identify aspects, through conducting additional research with the focus on a different monitoring system or different asset. The aspects relate to:

- The willingness of asset managers to work with and rely on a SAM system.

The use case indicates that the asset manager is in control of gaining information about the asset performances. Also, the extent to which the asset manager relies on presented information is important. An analysis of the user needs and its impact on the tasks to be performed by the network contributes defining the practical implementation. This relates to the step of defining the "goal" within the monitoring framework of SBRCURnet (2014) (see I in Figure 36). This research suggests the scenario where the user requests the performance of the individual asset or the collection of assets. The successful implementation of the SAN (in practice) depends on the role and attitude of asset managers. Is it fun to use and dare asset managers to rely on the data? The opportunities of sharing sensor data in a network for asset managers can be identified through a user-analysis. The added value for operational usage has to be acknowledged; otherwise the SAN will not be launched in real life.

- The application and interpretation of sensor and BIM data sources in order to provide information on the performance of assets.

The structure of a BIM database differs from the sensor database and the semantic linking of asset and sensor has to be addressed. The identified aspect relates to the step of "analysing data" within the monitoring framework (see II in Figure 36). Through linking the databases in a semantic model, the sensor extrapolation service will know how to draw information that it needs form the semantic model in which it exists (Crapo et al., 2011). Liu and Akinci (2009) define an approach to develop a model to integrate both sensor metadata and building information. This provides a way to further research the structure of sensor and BIM databases and link semantics.

- The successful detection of inter-correlation and further research into calculation techniques to achieve this correlation.

The inter-correlation depends on the extent to which two assets have a similarity in BIM, location, traffic etc. One individual expansion joint hereby detects the correlation with another asset in multiple ways. The use of case-based reasoning[18] (CBR) as a tool for determining correlation tends to be a good approach for the complex domain in where there are myriad ways to generalize a case (iesbeck & Schank, 1989). When large amount of assets arise, the system should be capable to handle all required calculations. The identified aspect thus relates to the step of "analysing data" within the monitoring framework (see III in Figure 36). Further research is required for this, because the correlation between assets changes over time (Aggarwal & Reddy, 2013, p. 362), the system should also be capable to update the values on a regular basis. Also, the explicit definition of correlation values has to be determined.

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[18] Case-based reasoning (CBR): The process of solving new problems based on the solutions of similar past problems (iesbeck & Schank, 1989). In this research, the method is seen as enabler for determining correlation through basing on similar past sensor measurements.

- The representativeness of sensor data to be used for extrapolation purposes.

Once the inter-correlations are determined properly, further research is required into the extrapolation of sensor data and the representativeness of this sensor data of one expansion joint to be used at other expansion joints. The focus hereby should be on the type of similarity and the strength of the detected correlations. The reliability is an important factor in the SAN. A high reliability of the inter-correlation will result in a relatively high reliability of the correctness of the predicted performance of the expansion joint. The asset manager will have more assistance in the decision-making process when the reliability is available. Effects of using extrapolation on the reliability of indicated asset performances are to be further investigated. The identified aspect relates to the step of "analysing data" within the monitoring framework (see IV in Figure 36). The extent to which the detected asset performance is a reliable representation of the real-world situation, determines the usability of information for the asset manager (Van Driel & Fan, 2013).

The four identified aspects relate to two steps of the monitoring framework (Figure 36): Defining goal and analysing data. This research is intended to explore SAN in the construction sector and to identify the contribution of sensor technology to realise this. Focusing on the capabilities of the SAN in this chapter resulted in identifying the "data analysis" step of the monitoring framework in three distinguished ways as an influential aspect to be considered. The theoretical implementation serves as basis for further studies. It was decided to develop a theoretical implementation, based a system architecture and use case to approach the real-world situation and used as a support to research findings in literature and case studies.

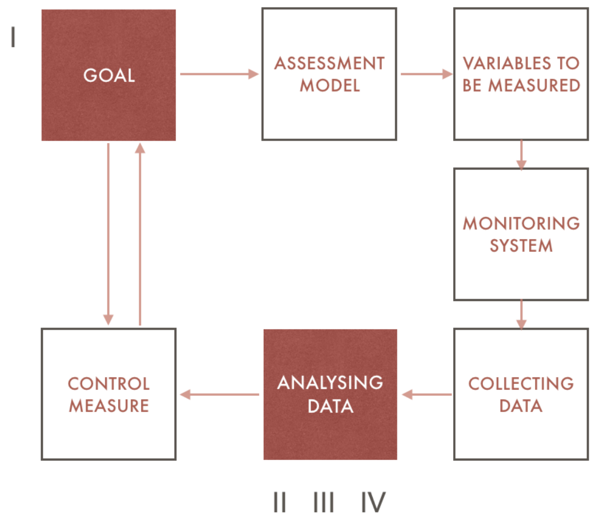

Figure 36: Overview of the identified aspects of the SAN associated to the steps of the monitoring framework of SBRCURnet (2014).

4 EVALUATION

This chapter provides an evaluation of the conducted research into the SA, SAN and evaluates the requirements set in the report of Braaksma (2016) used to realise the SA and SAN. Prior to this, the upcoming sections evaluate the results of the individual Smart Asset (§4.1) and evaluate the implementation of a Smart Asset Network (§4.2). The chapter concludes with the evaluation of the set performance, information and data requirements (§4.3) introduced in section 1.7.1.

4.1 SMART ASSET EVALUATION

The goal of the research into SA is to define what is needed for the individual asset that collects and analyses sensor data of attached sensors. The set of requirements in section 2.3.2 are based on the five data stages that relate to the collection, storage, analysis, sharing and exploitation of sensor data. The proof-of-concept has taken the requirements into account in the following way:

- The quality of collected sensor data is handled in two ways: By resampling sensor measurements and by filtering data using LSA.
- The data storage is pre-determined by selecting the measurement data from single runs to be saved on the computer.
- The data analysis is within the 95% confidence interval due to the set threshold of two standard deviations in the LSA filtering technique.
- The data sharing and exploitation refers to the amount of measurements sent to the computer for further analysis. This is limited to twenty measurements per run, which is considered indicative for evaluating the proof-of-concept.
- The link between sensors and BIM is made through elaborating on the ways of degradation of the asset, defining its associated indicators and defining which sensor measurements provide insight in these indicators.

The reliability of the proof-of-concept is analysed by considering the extent to which it includes accidental errors and its representativeness for the real-world situation. The validity of the proof-of-concept regarding the measurements and the identified relations considers the accuracy of the measurements and the results. The six combinations describe in general the increase in load and sound as the performance of the expansion joint decreases. The statistical significance however, as is when the observed correlation seems implausible that the effect of correlation is coincidental (Gallo, 2016) has to be further investigated.

Beside conducted case studies (see Braaksma (2016)) and a literature study, multiple experts were interviewed during the development of the proof-of-concept. This provides input for several design decisions:

- The incorporation of distinguished traffic loads. According to Peelen (2016) variations in traffic loads may effect measurements. This is why there was chosen at the van Brienenoord-bridge to focus on the right traffic lane where the greatest differences in traffic loads occur.

- The focus on sound and load sensors. Experts indicate that one could "hear" the expansion joint degrade (Doorn, 2016; Humpheson & Cenek, 2014; Mooyman, 2016). Both degradation types include the deformation of the expansion joint, therefore the increasing pounding of cars caused by wheel passages is likely to be detected (Doorn, 2016).
- The use of defining "fixed" performance states of expansion joints. This is in result due to the fact that simulating the actual degradation would be too expensive and elaborate for the intended goal.
- The use of a relatively simple micro-controller (Arduino MT Uno and Linkerkit system). The application of a monitoring system that allows transferring sensor data efficiently is challenging in the real-world situation. The proof-of-concept uses connection cables for data transfer. Although real-world cases exist where sensor applications are realised through cable connections (Steentjes, 2016; Van den Bos et al., 2013), wireless transfer of pre-processed sensor data is desired. The advantages of a wireless networks – easily accommodate new devices, wiring avoided, flexibility through physical partitions – outweighs the current low speed of communication and involved costs (Amruth et al., 2015).

The main recommendation is to improve the set-up to better represent the real-world situation by: 1) using improved prototypes in terms of real-world used materials of the expansion joint, 2) realising a true scale set-up to incorporate other applicable sensors such as strain gauges, and 3) using sensors and micro-controller allowing to collect more accurate sensor data and easier data resampling and transfer.

As the used set-up is a simplification of the real-world situation, the design decisions affect the extent to which the set-up is a proper representation. It can therefore not be concluded whether the proof-of-concept is representative. The indicator "load" is also difficult to include in the real-world situation, where expansion joints form an integral part with the infrastructural context without a fixed point of support. Indicators mentioned by Doorn (2014), Jang et al. (2013), Mageba (2015) and Timar (2013) (§2.3) could be further researched in future projects.

The proof-of-concept allows to collect and analyse sensor data of attached sensors. The performance of the individual asset is detected, although an adequate for real-world control measure cannot be provided. Therefore, no objective conclusion is drawn for operational implementation and improved set-ups are recommended.

Next to this, the relation between BIM and GIS was defined. The railway-monitoring project of VolkerRail uses an event server application server for this. The sensor data is linked through algorithms to distinguish events. With this, VolkerRail is able to link the event to the BIM component in the AM system (Steentjes, 2015). The linking of sensor data into events is manually performed in the proof-of-concept.

The added value for Smart Cities and Internet of Things is not evident at this point of development. When the data measurements are shared in an asset network, the sensor data could be exploited for Smart City and IoT applications.

4.2 SMART ASSET NETWORK EVALUATION

The theoretical implementation of the SAN is analysed by considering the extent to which the theoretical implementation can be used for operational purposes and is representative for the real-world situation. This section evaluates the set goals of the SAN, of which the alignment between BIM and sensor standards and the added value of extrapolation, and reflects on the following results: the system architecture, the SAN data model and use case diagram.

The alignment between BIM and sensor standards is investigated by discussing the existing standards and identifies a potential overlap. Seven sensor standards and four BIM standards provide the insight that there is no overlap in standards, since the standards serve different goals. However, the recently launched SensorThings API extension from the SWE collection is considered meaningful for the construction sector. The SensorThings API introduces the class *Thing* as adoption for IoT solutions. The developed SAN data model integrates the SensorThings API and BIM and is intended for further investigation. Following the Linked Data principles, the sensor standards contribute to provide additional BIM information, which can be used for SAM purposes. The BIM and sensor standards will aim at a "BIM-friendly-geo" for the construction sector. On the other hand, the solution is also "geo-friendly-BIM", where the BIM data is linked in the SAN system for determining means to share sensor data.

Subsequently, the requirements for the SAN were addressed on the basis of the conducted analysis. Through using the MoSCoW method, the requirements have been prioritised and have been used as basis for defining the further application.

The research into the SAN for expansion joints specifically resulted in a system architecture, the SAN data model and a use case. The system architecture consists of three data levels: data repository, data services and applications. The data repository discusses the network topologies. The hybrid star-mesh topology enables to position asset and sensor and defines the interconnections between them. Through using publish-find-bind and if-this-then-that (IFTTT) the actions are performed in an automatic and systematic way. The focus for further research should be on adopting semantics to address the data interpretation.

The SAN data model continues on the SensorThings API and includes the asset data via the class *Asset* and *Asset metadata*. The IoT concept is incorporated, because the initial OGC data model (2016c) was already suitable for IoT applications. This is beneficial when considering operational usage for an opt-in system for sensors.

The use case provides a theoretical basis for the application of expansion joints and describes the viewpoint of asset manager John and maintenance engineer George. The use case identifies the steps to be performed and makes the system approachable and understandable. It continues to build on available literature about sensor networks and defines a sensor extrapolation service, which allows to share and exploit sensor data. The use case shows that the application for expansion joints can be used in the construction sector and is recommended for further research.

The extent to which a theoretical implementation is representative for the real world situation is an important point of discussion. There was no theoretical basis for SAN in the construction sector available. The purpose this theory-developing research is to provide the theoretical basis that defines gaps in the construction of a theory for SAN and to develop a theoretical implementation as incentive for the construction sector. The results of this theory-oriented research into SAN does not constitute a full new theory, nor solve the theoretical problem entirely, but aims to contribute towards the (theoretical) discussion on this subject and towards the further development (Verschuren et al., 2010). Further development is directed to explore theoretical gaps and to conduct practical implementations such as pilot projects.

The added value for Smart Cities and IoT is hereby identified, where the SAN data model provides the opportunity to incorporate multiple devices and continues on earlier research of the SensorThings API of OGC (2016c). The application of the use case can be broader than expansion joints. The theoretical implementation can be applied for other infrastructural assets in the construction sector, can be an incentive for other industries, and can be useful for gaining insights in Smart Cities' processes.

4.3 REQUIREMENTS EVALUATION

The set of requirements for Smart Asset Management (SAM) that are introduced in section 1.7 will be evaluated through elaborating on the findings of the research into the SA and SAN. Important to note is that the results from the evaluation serve as input for the research of Braaksma (2016). The following section checks the performance requirements (§4.3.1), information requirements (§4.3.2) and data requirements (§4.3.3) with the results from the conducted research.

4.3.1 PERFORMANCE REQUIREMENTS

4.3.1.1 Provide insight into the reliability of assets

The SA that has all required sensors attached provide the insight into the performance of the asset. Assets that do not have all required sensors attached can through extrapolation still provide an estimation of the asset performance (§3.5). However, the practical application is yet to be researched.
Requirement satisfied.

4.3.1.2 Provide insight into the availability of assets

The research into SA and SAN focuses on the detection and prediction of performance, and the availability of the asset addressed as the probability of the expansion joints is operational functioning. The proof-of-concept indicates through using bounding boxes of the measurements the operational functioning of the expansion joint (§2.5), though the extent to which the proof-of-concept describes the real-world situation has to be researched. The theoretical implementation of the SAN explains how the use of intra-correlation and inter-correlation the extrapolation of sensor data provides insight in the availability of assets (§3.3).
Requirement satisfied.

4.3.2 INFORMATION REQUIREMENTS

4.3.2.1 Select applicable assets for monitoring purposes

The analysis of the current situation of expansion joints indicates three reasons for being applicable for monitoring (§1.3): The types of degradation, the increase in importance and the standardised applications. Additionally, the added value of sensor technology is to observe metal fatigue, which is not visible with the human eye.
Requirement satisfied.

4.3.2.2 Determine the need for information and therefore the needed data to be collected

The use of interviews and a literature study identifies nine indicators for the performance of expansion joints. The presumed relations towards performance reduces the number of indicators suitable to be included in the proof-of-concept into two: sound and load (§2.3.2). In order to provide the information about the assets' status, the subjects intra-correlation, inter-correlation and extrapolation address the need for data to be collected.
Requirement satisfied.

4.3.2.3 Store the data and information in an online server or database in order to be accessible at all times

The proof-of-concept stores the collected sensor data in an Excel-output (§2.5.1), which is accessible at all times. A practical implementation could store the sensor data output in an online accessible PostgreSQL database[19]. The theoretical implementation of the SAN introduces the separation of a sensor database, BIM database and traffic database and provides a theoretical solution to store the data and information in an online server (§3.4).
Requirement satisfied.

4.3.2.4 Define the performance pattern of an asset type

The results of the proof-of-concept show three bounding boxes, referring to the three distinguished asset status', which are distinguished as a performance pattern (§2.5.2). No hard conclusion about the proper identification of the performance pattern can be drawn from the proof-of-concept, because an improved (laboratory) test set-up that is more reliable to the real-world situation could better describe the exact performance pattern of, in this case, the expansion joint.
Requirement not satisfied.

4.3.2.5 Detect individual asset performance

This is proven in section 4.3.1.1. The proof-of-concept detects the individual asset performance, though with limited reliability. The theoretical implementation of the

[19] A PostgreSQL database is an open source object-relational database server, capable of storing the metadata and collected measurements in an online environment.

SAN describes the use of extrapolation to detect and predict the individual asset performance of assets that do not contain all sensors required (§3.3).
Requirement satisfied.

4.3.2.6 Predict individual asset performance

This is proven in section 4.3.2.5. The proof-of-concept however did not explicitly include the prediction of asset performance. However, measurements of sound and load collected over time can be used for predicting performances of expansion joints by positioning the measurements in the distinguished combinations and calculating the regression line.
Requirement satisfied.

4.3.2.7 Provide the reliability factor for the detected asset performance

The use case diagram indicates the reliability factor as an important attribute (§3.4.2). The asset manager has to perform the decision-making for maintenance activities and will have more certainty when the reliability factor is available (§3.6). The reliability factor also influences the willingness of asset managers to work with SAM applications. The reliability factor is defined theoretically, though the calculation of the factor itself is not included in the research.
Requirement not satisfied.

4.3.3 DATA REQUIREMENTS

4.3.3.1 Provide metadata and semantics

The theoretical implementation of the SAN appoints the metadata and semantics as necessary to be stored, because the data from sensors and assets is required for extrapolation purposes (§3.5.1). The data model further elaborates on the use of the asset metadata and sensor metadata for calculating correlations.
Requirement satisfied.

4.3.3.2 Serve interoperability between different data types

Sensor systems need to be robust and reliable for data collection, which is why there are standards needed to enable interoperability. The proposed data model for the SAN, based on the recently launched SensorThings API, takes the existing SWE standards into account. Therefore, the interoperability between different data types is addressed, which is included in the SensorML and O&M standard (§3.2.2).
Requirement satisfied.

4.3.3.3 Determine the connection between BIM data and sensor data

The SAN data model addresses the connection between BIM data and sensor data (§3.4.1). The class "Thing" from the recently launched SensorThings API from OGC enables to link BIM to the sensor domain. Through using the concepts of Linked Data and Systems Engineering, the BIM data can be used to detect correlations between assets and the sensor data can be extrapolated on the basis of these correlations.
Requirement satisfied.

4.3.3.4 *Ensure proper data collection*

In this, accuracy reflects on the data values to represent the considered piece of information and to be collected at a proper sampling rate. The proof-of-concept uses a sampling rate of 50 n/ms and resamples to 1 n/ms. This way, the amount of data to be transferred was reduced and the accuracy of the data collected secured. Similar adoptions can be included in real-world situations.
Requirement satisfied.

4.3.3.5 *Ensure data security and privacy*

The research into SA and SAN considers the collected data to be stored in a database with restricted access. The use case diagram illustrates that Asset Managers cannot access the raw data itself, but receive a visualisation about the asset performance (§3.4.2). Whether the sensor data is a violation of privacy is to be determined in additional (operational) implementations, because it was for this reason excluded in the current proof-of-concept.
Requirement not satisfied.

4.3.3.6 *Specify the method of sharing data order to be accessible at all times*

This has been discussed earlier in the requirement in section 4.3.3.4. The determination of resampling within the proof-of-concept and the elaboration on the needed data in the SAN gives means to the user in realising a practical implementation for SAM.
Requirement satisfied.

4.3.4 CONCLUSION ON THE EVALUATED REQUIREMENTS

The evaluation of the fifteen requirements for SAM indicates 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 further elaborated in the report of Braaksma (2016).

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. The two requirements are evaluated 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. It is appointed that security and privacy are covered by restricted access to the sensor databases for users and the use case indicates 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. An improved second set-up could contribute in satisfying the remaining requirements. Unfortunately this is excluded from the research due to time and investment constrains.

5 DISCUSSION AND CONCLUSIONS

This chapter reflects on the previous chapters in order to provide an answer to the research question: How can sensor technology be used in the construction sector to facilitate Smart Asset Management during the maintenance phase of road infrastructure projects? The related limitations in the context of the research into SA (§5.1.1) and SAN (§5.1.2) will be discussed as well as the contribution to other research (§5.1.3). The subsequent sections discuss the application of SAM and its relation towards emerging technologies (§5.1.4) and decision-making (§5.1.5). The chapter concludes with answering the main research question (§5.2).

5.1 DISCUSSION

5.1.1 RESEARCH LIMITATIONS ON SMART ASSET

The objective of realising a proof-of-concept of an individual asset that collects and analyses sensor data and detect and predict its own condition is achieved. One may be able to achieve results of improved accuracy however when improving the test set-up, possibly detecting a stronger correlation. This is achieved when certain areas for further development are investigated and current limitations are eliminated. The current set-up for the proof-of-concept has the following limitations:

- The expansion joints are eligible assets for monitoring purposes, but it is a complicated process to enable the measurability of indicators by means of a simplified representation. The used indicators provide an answer about the relations towards the asset performance over time, however with a limited reliability. No test and evaluation to determine the extent to which the simplification of the real-world situation affects the results were established.
- The expansion joints were handmade and therefore slight deviations occur in their dimensions. The extent to which measurements could be affected due to the instability of the expansion joint and due to the changing positions of the sensors throughout the runs could not be determined.
- The used micro-controller allows connecting and controlling physical sensors attached to the test set-up. The microcontroller works with 10-bit analogue ports and the used sensors provide an output in voltage. This means that a 5 Volt output is divided over 1024 values, resulting in measurable steps of 0.0049 V during testing. The extent to which mandatory data conversion within the microcontroller system affects the outcome of the test runs could not be determined with the test set-up.
- The research had to be carried out in a limited period of time. It was decided to develop an easy accessible test set-up applicable to measure performance of expansion joints, based on simplified sensor data and information.

Areas to improve the resolution of the test set-up are:

- Redesigning modelling parts, scaling the set-up to real-world sizes and using prototypes of expansion joints can result in improved measurements. Similarly, the use of a different approach in using micro-controllers, enabling to reduce the measurable step sizes and resampling rates.
- After analysing the dataset through filtering using the LSA method (see §2.4), the identified standard deviations of the sensor measurements indicate large differences. Further research is required, focusing for example on the specific sensor types and measurement capabilities of the microcontroller to improve the test set-up by increasing accuracy and precision.

5.1.2 RESEARCH LIMITATIONS ON SMART ASSET NETWORK

The objective of realising a theoretical implementation of an asset network that shares and exploits sensor data in order to provide an indication of asset performance is achieved. One is hereby encouraged to further develop this theoretical solution into a practical implementation. Since the research into the Smart Asset Network (SAN) continues on the performed research into Smart Assets (SA), the research limitations for the SAN also is likely to cover both subjects.

- The theoretical implementation of the SAN is limited to a single case: The expansion joint. The external validity in terms of the extent to which the theoretical implementation of the expansion joint can be generalised to other situations is not addressed. On the other hand, the use case diagram does not specifically address the expansion joint in its elements, but provides a generalised view of the functionalities of the system. The theoretical implementation is considered also applicable to other assets, although one is encouraged to further research this applicability.
- The results of the SAN are not based on a representative sample but on a single application of the test set-up and one theoretical implementation. No evaluation session for practical implementation could be performed in this research. One of the projects of the case studies is currently initiating a business case for practical implementation of monitoring expansion joints and other contractors are likely to conduct pilot projects as well.
- The SAN makes use of correlations to allow extrapolation of sensor data between assets. However, calculation techniques for the inter-correlation do not exist yet. A large challenge for the construction sector, which also applies to other sectors, is to define ways for computing these correlations. This includes determining factors that are involved and their degree of influence.

5.1.3 CONTRIBUTION TO OTHER RESEARCH

The research objective is to provide an understanding of how to realise a Smart Asset and Smart Asset Network through incorporating sensor technology in managing expansion joints. Until recently, the Smart Asset (SA) and Smart Asset Network (SAN) were not the subject of investigations. This research identified eight aspects to be taken into account when realising the SA and SAN. The aspects reflect on different steps of the monitoring framework of SBRCURnet (2014) and serve as boundary condition sector for the construction when implementing sensor technology for SAM.

The added value of sensor technology is properly recognised and understood by the construction sector (Benghi & Williamson, 2014; Brown, 2014; May, 2015; van den Beld, 2008). Expansion joints are increasingly seen as objects with added value which is defined within the analysis of this report; however, a theoretical solution for the SA and SAN has never been delivered. The results of defining a proof-of-concept for the SA and a theoretical implementation for the SAN prove that the expansion joint is eligible for further investigation for SAM purposes.

This research also included a view on the extent to which components of BIM relate to sensor technology. The analysed standards from the world of BIM and sensors provided the insight that the standards do not overlap, but serve different goals. Continuing on the developed SensorThings API data model, the connection between the two is found in the SAN data model. This research contributes to the theoretical definition of an asset network that utilises the sensor standards and BIM standards through a developed system architecture, SAN data model and use case.

The research into SA focused on the elements "collect and analyse" within the SAM definition. The subject intra-correlation is introduced to define the correlation of sensors contributing to detect and predict the individual asset performance. The research into SAN focused on the elements "share and exploit", hence introducing the subjects inter-correlation and extrapolation. In a theoretical way the sharing and exploitation of sensor data is defined and there is focused on distinguished real-world situations of asset-sensor appearances. Although multiple researchers and companies refer to the added value of extrapolation (Meijer, 2015; NedTrain, 2015; Peelen, 2016; Timar, 2013; Van Heusden, 2011), the use of intra-correlation, inter-correlation and extrapolation for performance monitoring in the construction sector is from a literature point of view considered a new concept.

Current research regarding incorporating sensor technology focuses on adapting sensors in a sensor network (Jang et al., 2013; Pasman et al., 2014; van den Beld, 2008). Complementary to existing research is this research' identification of an asset that collects and analyses sensor data in order to detect its performance – and when not properly detected gathers data from the asset network that shares and exploits sensor data amongst other assets.

This research provides from now on an insight in approaching assets - expansion joints in specific - in such a way that their individual performance can be detected and predicted and taken into account for SAM decision-making.

5.1.4 APPLICATION OF SAM: RELATION TO OTHER TECHNOLOGIES

This research focuses on the application of sensors in the construction sector, which is why other emerging technologies are not - or to a limited extent - being taken into consideration. However, other emerging technologies are noticed throughout the research. To address these, this section discusses a number of other technologies, serving as incentive for research by future students and indicating a potential contribution to the further development of SAM.

Asset monitoring can also take place by conducting aerial measurements – for example with unmanned aerial vehicles (drones) – or by collecting measurements from vehicles driving over the assets by user generated data (UGD). Drones and UGD provide an additional data source. However, these measurements are focused at the external changes of the asset. Because monitoring expansion joints also focuses on internal changes, this could be less relevant. However, it could be a valuable data source when focusing on for example crack detection in pavements. Relating to SAM, the data input will then originate from a different data source, but can possible also be adopted in future applications.

Cyber-physical systems (CPS) are the core technology of industrial big data, and are an interface between human and cyber world. The systems are often designed by following 5C: connection, conversion, cyber, cognition and configuration (Magesh et al., 2016). This research includes the connection and conversion stage by researching asset networks, smart analytics and data correlation. The higher levels seem to relate to IFTTT, by allowing triggers, additional data management capabilities and self-optimization. The system becomes more intelligent and, when relating to the SAM perspective, including decision-making.

Artificial intelligence includes the theory and development of computer systems able to perform tasks normally requiring human intelligence. Pattern recognition is a part of AI and is concerned with the classification of observations (Gang, 2016). The SAN could serve as artificial neural network, thereby including data analysis capabilities. Artificial neural networks are characterized by containing adaptive weights along paths between "neurons" that can be tuned by learning algorithms that learns from observed data to improve the model (Castrounis, 2016). Training samples of degrading assets are likely to be used for pattern recognition. The used algorithms are part of the broader field of machine learning and have potential for using in a future SAN application.

Lastly, an emerging technology, although not an IT technology, is the Semantics Web's Linked Data (see also §3.2.2). Following the principles of Linked Data allows linking the data sources from different satellite locations, which is the case when storing sensor data per individual asset or per collection of assets. Linked Data offers advantages with respect to storage, because data only is stored at a single location (Berners-Lee, 2006). Continuing on these principles contributes to the hybrid asset-sensor network as is described in Figure 30 (p.39). Additional research into Linked Data can explore the benefits for accessible, up-to-date and in context placed sensor data. This way, SAM includes a smart application of data storage and is able to link these satellite locations in its actual application.

5.1.5 APPLICATION OF SAM: RELATION TO DECISION-MAKING

The user perspective – in terms of analysing and mapping the user demand – is not included in the research scope. Nevertheless, the user is addressed multiple times throughout the research as important aspect to be taken into account.

In relation to the decision-making process for maintenance activities, most common AM approaches attempt to quantify value aspects. An example is the use of weighted multi-criteria analyses (MCA), resulting in one total numerical value (Triantaphyllou et al., 1995). Important AM decision-making is conducted on the basis of these quantified values. By using a MCA, a simple, clear and always applicable systematic is handled for determining maintenance activities to be performed.

However, this approach is also criticised (Van der Knoop, 2009; Wijnia & de Croon, 2013). Outcomes can be easily influenced by subjective ideas of asset managers, resulting in the desired maintenance action of the individual. The effect of this "human value" raises uncertainty about the objectivity of the decision-making process. The probability and impact of risks, weight factors and quality ambitions are hereby estimations and no longer objective. And if current decision-making is that much affected by subjectivity: What is the proper way for decision-making?

A first option is the application of sensors, which disables the asset manager to manually influence the incoming objective sensor data. Though, in general, this information is relative complex, because the data enters in large bulks – big data – and retrieving of asset performance from these measurements likewise.

A second option is the application of a theoretical foundation that describes the decision to be made. The problem with theoretical models however, is the abstractness and ambiguity, resulting in no human being able to recalculate these effects and theoretical solutions that seem "to good to be true".

A third option is to embrace subjectivity of Asset Managers and a central position in the process. Estimations based on intuition of employees through work experiences are useful. However, this remains a vague estimation and its influence on the applied Asset Management strategy will be either preventive or corrective.

The proposed application of SAM decision-making aims to combine the three options. The use of sensor data (option 1) is not a proposed definitive answer, but is a directive for indicating asset performance degradation over time. It contributes to more informed asset management decision-making in the near future, through visualising the complex information of assets. Theoretical models of asset degradation (option 2) and intuitive estimations of Asset Managers (option 3) can be used as starting point and can be corrected by the measurements.

This conducted research into SA and SAN focused on what is needed to collect, analyse, share and exploit sensor data. The subjectivity of asset managers is deliberately left out of the scope of this research. However, the identified aspects "willingness of the user" and "manage expectations" do indicate the importance of the "human value" in realising SA and SAN. The central position of asset managers in the process should be properly understood (Hastings, 2015; Pintelon & Gelders, 1991; Vanier, 2001; Woodhouse, 2007). Only then a successful practical implementation of the SA and SAN - contributing to SAM - can be achieved.

5.2 CONCLUSIONS

The research question in this research is:

How can sensor technology be used in the construction sector to facilitate Smart Asset Management during the maintenance phase of road infrastructure projects?

Until now, there has not been research into the potential of sensor technology for the SA and SAN within SAM in the construction sector. Currently, Dutch contractors reflect their policy for managing expansion joints by conducting visual inspections. The forecast in managing these assets by utilizing SA and SAN is a way to optimise AM. The objective of this research was to identify aspects to be considered when realising SA and SAN. To establish this, a developed proof-of-concept and theoretical implementation of SA and SAN demonstrate how sensor technology provides insight into asset performances and contribute to more informed decision-making.

The research is focused on the expansion joint due to: 1) the two types of degradation it is subjected to, 2) the increase in importance of the asset over the last years, and 3) the standardized application of the asset. The current main maintenance procedure for assessing asset performance is via visual inspections, which are inadequate for effective decision-making. The quality of visual inspections is arguable due to ambiguous boundaries for performance assessment and difficulty in detecting and predicting failures with the human-eye. In addition, costs for unexpected variable maintenance are high and result in undesired effects regarding the reliability and availability guarantee to the client.

The research defines a SA as an individual asset, which allows the detection and prediction of its own performance in context by collecting and analysing sensor data of attached sensors. The correlation of sensors to measure the individual asset performance is defined as intra-correlation. The application of the SA is researched through using the monitoring framework of SBRCURnet (2014) and designing a proof-of-concept. The proof-of-concept distinguishes two types of degradation of expansion joints and allows collecting and analysing sensor data by performing multiple runs of traffic loads. The collected sensor measurements are processed through using LSA filtering techniques and the filtered data identifies the degrading asset performance.

Afterwards, an analysis - including findings of the proof-of-concept, knowledge from experts and gained insights from conducted case studies - provides an overview of four aspects influencing the incorporation of sensor technology for SA:

- Collect relevant sensor data for asset monitoring through explicitly defining performance indicators and variables to be measured
- Define proper ways to transfer sensor data within the monitoring system
- Manage expectations of incorporating sensor technology in AM
- Adapt SAM systems to be capable of handling sensor data as data input

The research intends to explore the SA, as is part of SAM, and the contribution of sensor technology in this. The proof-of-concept serves as basis for further studies. It was decided to develop a practical test set-up, which has simplified the real-world situation and is used to validate research findings in literature and case studies.

The research defines a SAN as the collection of individual assets in a network, which is able to detect and predict the performance in context of individual Smart Assets by sharing and exploiting relevant sensor data. The application of the SAN is researched through: 1) defining the alignment between components of BIM to sensors, 2) defining how to share and exploit sensor data using extrapolation, and 3) describing a theoretical implementation. This theoretical implementation continues researching the expansion joint as an SA and illustrates the SAN application with a use case.

The current situation of adopting asset networks indicates developments in combining BIM and GIS applications. The first steps towards managing multiple assets in an online environment are taken, however, no formal asset network has been defined yet. The available standards of BIM and sensors serve different goals. The SAN has to combine the standards to allow data to be shared and re-used across application and domain boundaries. Recommended is to continue on Linked Data principles for linking assets and sensors, which allows realizing the proposed hybrid asset network.

Assets can have all required, a few or no sensors attached in the real-world situation. To define how the sharing and exploitation of sensor data allows measuring the performance of each asset, the research discusses inter-correlation and extrapolation. Inter-correlation relates to the correlation between assets and when detected, extrapolation of sensor values to other assets can be performed.

A theoretical implementation is designed to meet all previously established requirements for the SAN and consists of the system architecture and use case diagram. The system architecture consists of three layers: 1) the data repository, 2) data services and 3) applications. The data repository describes the hybrid asset-sensor network and provides the SAN data model – which continues on the recently launched SensorThings API model from OGC - identifying the link between BIM and sensor data. The use case defines the data services that are taken into account when the user requests information from the (SAM) application.

The main components are the client and its available databases, the sensor extrapolation service and the alert system. The client performs a WFS request to collect the required data from the databases. The sensor extrapolation service activates when the intra-correlation of an asset could not be detected. Through determining the inter-correlations, extrapolation can be performed and this way the performance of each expansion joint is measured. The alert system provides feedback on improper functioning of sensors or warnings when pre-set thresholds exceed. Although the reliability factor of the detected asset performances is to be further researched, this theoretical implementation of the SAN allows to detect and predict the status of each expansion joint, regardless of the number of sensors attached.

Afterwards, an analysis - including findings of the theoretical implementation, expert knowledge and gained insights from conducted case studies - provides an overview of four aspects influencing the successful realisation of the SAN:

- 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 to be used for extrapolation purposes

In this thesis a proof-of-concept and theoretical implementation of the SA and SAN are designed as response to the set scenario of Asset Manager of the future. The use of the SA and SAN allows to collect, analyse, share and exploit sensor data in such a way that the performance of each asset can be measured. The research introduces new concepts in the construction sector, such as intra-correlation, inter-correlation and a sensor extrapolation service. All find their basis in the application of sensor technology to assets. The sensor extrapolation service is the answer for real-world situations where individual assets do not have (all) required sensors attached in order to measure performance.

This research distinguishes itself from others in the focus on usability of sensor technology to collect, analyse, share and exploit data over unlimited employability of sensors. Since theoretically and technically seen a lot is possible, additional research into operational implementations of the SA and SAN is recommended. If the construction sector utilizes the identified potential of sensor technology, they can start maintaining their assets in a smart way.

In conclusion, this research identifies the potential of sensors technology for monitoring expansion joints and provides a way to go. It is the way of using sensors to measure performance of the asset it is attached to (SA) and re-using sensor data to contribute to measuring performance of assets in the network (SAN). Although the reliability of these measured asset performances is to be determined by future research, this research provides a promising way of imposing (and needing) a limited amount of sensors, and contributes to improving insight into asset performances to the construction sector.

6 RECOMMENDATIONS

The objective of this chapter is to provide recommendations for contractors responsible for maintenance of expansion joints for realising the future prospect of managing assets with sensor technology. This research has demonstrated that expansion joints are eligible to be monitored through using sensor technology, as well as a broader domain of assets. This chapter provides a helping hand in continuing on the research subjects and provides several directions for practical implementation (§6.1) and for further research (§6.2).

6.1 RECOMMENDATIONS FOR PRACTICAL IMPLEMENTATION

The research into SA and SAN initiates a performance-driven approach for managing expansion joints. Considering the conclusions and limitations of this research, the following recommendations are made to improve management of assets in the construction sector:

- Respond to the identified aspects that are to be considered when realising a SA and SAN in the construction sector. The *willingness of users* and *manage expectations* are the important aspects to be considered in the starting phase. Recommended is to initiate a pilot project in order to define a practical implementation, to identify possible problems in the organisation on the implementation of SAM and to stimulate and involve asset managers and other relevant stakeholders.

- Gradually design and implement a solution for the large-scale application. Start the development of SAM by focusing on a single asset; recommended is the provided research into the expansion joint. Through taking small steps, first design and implement the individual SA and second extend and develop the individual SA in the SAN. The three explained situations of assets and different amount of attached sensors that occur in real-world situation are used for defining the composition for practical implementation. The SAM system can be developed only after this has been achieved. And that is when the actual contribution of collecting, analysing, sharing and exploitation of sensor data to the decision-making process is to be determined.

- Throughout this research the monitoring framework of SBRCURnet (2014) provided a systematic approach for defining the SA and SAN. Its structured approach also helped to identify aspects to be considered. When contractors plan to take action for practical implementation, it is recommended to elaborate on the monitoring the framework to obtain insight in the information need and data need. Start with defining the goal and variables to be measured, before collecting data or taking premature control measures.

- This research focused on the variables load and sound for indicating asset performance. There are other indicators mentioned in the research (§2.3.1) that could be suitable for monitoring the performance expansion joints. These have been left out of scope in the remained of the research due to the focus on realising a proof-of-concept. For practical implementations however, the construction sector is recommended to elaborate on the measurability and application of these indicators for real-world monitoring purposes.

6.2 RECOMMENDATIONS FOR FURTHER RESEARCH

Due to the limited scope of the thesis, there are seven remaining topics for further research, which are prioritized by importance. The following recommendations are made to explore the future implementation of SA and SAN for asset management in the construction sector, and in particular for expansion joints:

- The standards of BIM and sensors both serve different goals. Proposed is to extend the BIM standards in such a way that sensor measurements are properly addressed. This link is not made yet. The recommendation is to continue on the findings of this research and previously conducted research of Berners-Lee (2006), who describes the use of Linked Data, which is concluded suitable to link assets (BIM) and sensors in this research. Taking into account the increasing usage of objects in buildings and infrastructure assets that can continuously generate data, it is imperative to create objects with data management capabilities.

- The proposed inter-correlation – the correlation between assets – can be calculated on basis of similarity in construction, location or usage of assets. The use of BIM data and traffic data are two examples of additional data for providing inter-correlation. In addition, the inter-correlation is likely to change over time (see §3.6). Causes are transformations in the asset structure and changes in traffic loads or climate conditions. It is recommended to develop an approach for determining this correlation and required calculation capabilities. Ultimately, further research can enable to fulfil the information requirements of Chapter 5, through improving the estimation the performance pattern of assets and calculating the reliability factor for detected asset performances. It includes to research the extent to which asset performance can be indicated correctly through using inter-correlation and extrapolation techniques as well.

- The introduction of the sensor extrapolation service addresses the need for defining a structure for transferring sensor data within databases. The correlation values are likely to be stored separately, but it is to be further researched how the correlation data is shared and where the virtual sensor values are to be calculated and stored.

- The ability to transfer sensor data directly to a server is concluded challenging in current practice (Steentjes, 2016). It is recommended to continue on current research into Wireless Sensor Networks (Heller & Orthmann, 2014) through focusing on the reliability of networks and data aggregation techniques (Sohraby et al., 2007; Williams, 2014). According to the described publish-find-bind principle, sensor data should be provided relatively simple. Contenders Sigfox and LoRa are operators for wireless networks aiming at the adoption of their technology for Internet of Things applications (Linklabs, 2016) and are developing solutions for wireless data transfer.

- Artificial Intelligence (AI) focuses on cognition and reasoning and is often used for pattern recognition. It is currently mainly used in consumer businesses, where companies improve customer support, through analysing their consumer behaviour (Kisaco, 2016). The use of AI could benefit SAM as well. By using training samples of degrading assets, the system can see multiple situations and can be taught to identify situations. Recognizing situations is important in revealing the functional value of assets, which is used for determining the available decision-making time interval. The application of AI for SAM in the construction sector is to be investigated.

- Requirements have been determined for SA and SAN on the basis of gathered information from experts, case studies and previously conducted research. It is recommended to further research the set requirements. Other researchers are encouraged to publish their findings and to adjust and complement the set requirements. The more accurate definition of a SA and SAN, the more clearly the application of SAM can be defined.

- The use of sensors on infrastructural assets, expansion joints in particular, can have a larger application than AM purposes. Examples of specific Smart Cities purposes to be explored are to contribute to develop a new understanding of urban problems and relations to environmental sustainability, social sustainability or economic sustainability (IEC, 2014). The recommendation is to continue on the findings of this research and previously conducted research of Batty et al. (2012), who addresses multiple areas of interest such as decision support as travel behaviour, transport and economic interactions and planning structures for the Smart City.

- The final recommendation is to always follow developments in the area of sensor technology and specifically the developments considering applications and research within and outside the construction sector. This research provides a state-of-the-art view, for further research recommended. In the end, all who research will have a turn to speak, one after the other, so that everyone will learn and be encouraged to continue learning (free interpretation of Corinthian 14:31).

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APPENDIX A: THE UNAVAILABILITY INDEX

The unavailability matrix (Dutch: "Niet-beschikbaarheidsmatrix") is defined by Rijkswaterstaat and addresses seven types of expansion joints. The index identifies fixed maintenance and variable maintenance and appoints an index scoring to these maintenance activities. The index score is used to support contractors in determining the proper expansion joint to be used in the project and is used to evaluate the performance of contractors on the RAMS (Reliability, Availability, Maintainability, Safety).

Rijkswaterstaat

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Bijlage 2 Niet-beschikbaarheidsmatrix voegovergangen

familie / concept	omschrijving familie / concept	vast onderhoud		vervangen constructie		vervangen onderdelen		overzicht variabel onderhoud (jaar na inbouw)																				indexscore			
		interval (jaar)	duur (cat)	interval (jaar)	duur (cat)	interval (jaar)	duur (cat)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	Uitgangspunten/opmerking	vast onderhoud	variabel onderhoud	totaal	score
1	**Nosing Joints**																														
1.1a	Rijroosters met stalen randprofielen en ingeklemde voegprofielen, type Enkele Grote Voeg (EGV).	1	1	25	5	10	2		1		1		1		5		2			5		2			5		Na 40 jaar modificatie met klauwprofiel, levensduur 25 jaar. Bij vervangen onderdelen tevens herstel conservering niet bereden delen en reparatie roostervulling / slijtlaag.	100	22	122	-
1.1b	Rijroosters met stalen randprofielen en ingeklemde voegprofielen., type kokerprofiel Maurer.	1	1	25	5	10	2		1		1		1		5		2			5		2			5			100	22	122	-
1.1c	Rijroosters met stalen randprofielen en ingeklemde voegprofielen, type Acmé.	1	1	25	5	10	2		1		1		1		5		2			5		2			5			100	22	122	-
1.2a1	In constructie verankerde stalen randprofielen met ingeklemde voegprofielen zonder geluidreducerende voorzieningen.	1	1	40	5	10	2		1		1		1		5		1			5		1			5		Conservering: thermisch verzinkt, onderhoudsvrij. Na 40 jaar modificatie klauwprofiel, levensduur 25 jaar, meerdere malen mogelijk. Extra tijd bij sinusplaten.	100	20	120	-
1.2a2	In constructie verankerde stalen randprofielen met ingeklemde voegprofielen met geluidreducerende voorzieningen.	1	1	40	5	10	3		2		2		2		5		2			5		2			5			100	25	125	-
1.2b1	Renovatiemodel volgens NBD 00400 zonder geluidbeperkende voorziening.	1	1	25	5	10	2		1			5		1			5		1			5		1			Conservering: thermisch verzinkt, onderhoudsvrij. Extra tijd bij sinusplaten	100	19	119	-
1.2b2	Renovatiemodel volgens NBD 00400 met geluidbeperkende voorziening.	1	1	25	5	10	3		2			5		2			5		2			5		2				100	23	123	-
1.4a1	Stalen randprofielen met ingeklemde rubberprofielen in onverankerde voegovergangbalken van polymeerbeton zonder geluidbeperkende voorziening	1	1	15	7	10	1			7			7			7			7			7			7			100	42	142	-
1.4a2	Stalen randprofielen met ingeklemde rubberprofielen in onverankerde voegovergangbalken van polymeerbeton met geluidbeperkende voorziening	1	1	15	7	10	1			7			7			7			7			7			7			100	42	142	-
1.4b	Stalen randprofielen met ingeklemde rubberprofielen en aangelaste deuvels of wapening in onverankerde voegovergangbalken van polymeerbeton.	1	1	5	5	10	1	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	Niet geschikt voor autosnelwegen	100	95	195	--
1.5a	Gelijmd voegprofiel in verankerde staalvezelbetonbalken.	1	1	25	5	10	1		1			5		1			5		1			5		1			Vast onderhoud betreft herstel van lokale schade aan de voegovergangsbalken en opnieuw verlijmen van het rubber.	100	19	119	-
1.5b	Gelijmd voegprofiel in verankerde kunstharsbalken.	1	1	20	5	10	1		1		5		1		5		1		5		1		5		1			100	25	125	-
2	**Vingervoegen (cantilever joints / supported joints)**																													0	
2.1a1	Uitkragende vingervoegen met vingers in de vorm van een rechthoek of parallellogram en een stalen onderbouw.	1	1	40	6	10	2		2		2		2		6		2		2		2		6		2		Conservering: thermisch verzinkt, onderhoudsvrij. Na 40 jaar vervangen hele constructie. .	100	26	126	-
2.1a2	Uitkragende vingervoegen met vingers in de vorm van een trapezium of driehoek en een stalen onderbouw.	1	1	40	6	10	2		2		2		2		6		2		2		2		6		2			100	26	126	-
2.1b1	Uitkragende vingervoegen met vingers in de vorm van een rechthoek of parallellogram zonder stalen onderbouw.	1	1	25	6	10	2		2		2		2		6		2		2		2		6		2			100	26	126	-
2.2a	Ondersteunde vingervoegen aan één zijde scharnierend vast en aan de andere zijde scharnierend transleerbaar. Vingers rechthoekig.	1	1	40	6	10	2		2		2		2		6		2		2		2		6		2			100	26	126	-
2.2b	Ondersteunde vingervoegen aan één zijde verend ingeklemd (vast) en aan de andere zijde scharnierend transleerbaar opgelegd.	1	1	40	6	10	2		2		2		2		6		2		2		2		6		2			100	26	126	-
3	**Mattenvoegen (mat joints)**																													0	
3.1	Gewapende mattenvoegen.	1	1	10	3	10	3		3		3		3		3		3		3		3		3		3		Vervangen rubbermat, verankeringen, rubberafdichtng en betonreparatie onderliggende constructie.	100	27	127	-
3.2	Geperforeerde voegovergangen.	1	1	40	6	10	2-4		2		2		2		6		2		2		2		6		2		Conservering: thermisch verzinkt, onderhoudsvrij. Na 40 jaar vervangen hele constructie	100	26	126	-
3.3	Gewelfde voegovergangen.	1	1	40	6	10	2-4		2		2		2		6		2		2		2		6		2			100	26	126	-
4	**Flexibele voegovergangen (flexible joints)**																													0	
4.1a	Traditionele bitumineuze voegovergang.	1	1	5	2	-	-	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2		100	38	138	-
4.1b	Bitumineuze voegovergang met een aangepast bindmiddel en wapening in de vorm spiraalveren.	-	-	25	4	10	1		1		1	4		1		1	4		1		1	4		1		1	Uitgangspunt voor vervanging is in situ aangebrachte voegovergang. Bij prefab voegovergang is een reductie op de uitvoeringstijd mogelijk.	0	20	20	++
4.1c	Bitumineuze voegovergang met verbeterd bindmiddel, wapening in de vorm van geogrid met aan weerszijden van de voegovergang een overgangsbalk.	-	-	10	3	-	-		3		3		3		3		3		3		3		3		3			0	27	27	++
5	**Verborgen voegovergangen (buried joints)**																														
5.1	Voegloze overgang van gemodificeerd gewapend asfaltbeton.	-	-	20	1	10	1		1		1		1		1		1		1		1		1		1			0	9	9	++

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familie / concept	omschrijving familie / concept	vast onderhoud		vervangen constructie		vervangen onderdelen		overzicht variabel onderhoud (jaar na inbouw)																				indexscore			
		interval (jaar)	duur (cat)	interval (jaar)	duur (cat)	interval (jaar)	duur (cat)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	Uitgangspunten/opmerking	vast onderhoud	variabel onderhoud	totaal	score
6	**Overgangsconstructies voor integrale kunstwerken**																														
6.1	Overgangsconstructie voor integrale kunstwerken.	-	-	-	-	-	-						1						1						1		Geen onderhoud nodig. Volgt in principe de levenscyclus van de asfaltconstructie op de aardebaan (reconstructie na 30 jaar)	0	3	3	++
7	**Lamellenvoegen (modular joints)**																														
7.1 a1	Lamellenvoegen met aan dwarsdragers vastgelaste lamellen zonder geluidreducerende voorziening	1	1	40	7	10	3		3		3		3		7		3			7		3		3			Conservering: thermisch verzinkt Na 40 jaar renovatie kast-in kast, levensduur 25 jaar Na 65 jaar volledige vervanging, levensduur 40 jaar	100	32	132	-
7.1 a2	Lamellenvoegen met aan dwarsdragers vastgelaste lamellen met geluidreducerende voorziening	1	1	40	7	10	6		6		6		6		7		6			7		6		6				100	50	150	-
7.2 a1	Lamellenvoegen met centrale dwarsdrager zonder geluidreducerende voorziening	1	1	40	7	10	3		3		3		3		7		3			7		3		3				100	39	139	-
7.2 a2	Lamellenvoegen met centrale dwarsdrager geluidreducerende voorziening	1	1	40	7	10	5		5		5		5		7		5			7		5		5				100	44	144	-
7.3 a1	Lamellenvoegen met zwenktraversen zonder geluidreducerende voorziening	1	1	40	7	10	3		3		3		3		7		3			7		3		3				100	32	132	-
7.3 a2	Lamellenvoegen met zwenktraversen met geluidreducerende voorziening	1	1	40	7	10	6		6		6		6		7		6			7		6		6				100	50	150	-

Figure 37: The unavailability matrix (Dutch: Niet-beschikbaarheidsmatrix) for expansion joints (Rijkswaterstaat, 2013).

APPENDIX B: PROOF-OF-CONCEPT: THE SET-UP

B.1 OBJECTIVE

The objective of the proof-of-concept is to realise a practical implementation of the individual Smart Asset. A Smart Asset is defined as an individual asset, which is able to detect and predict its own performance in context by collecting and analysing sensor data of attached sensors.

Therefore, the proof-of-concept basic aim was to realise a simplification of an expansion joint and provide the expansion joint (the asset) with sensors. Two variables were measured in the proof-of-concept: sound and load. The sound and load were generated by varying weights of cars passing over the expansion joint.

The proof-of-concept is a simplification of a real-world situation. In reality, cars of varying loads pass over the expansion joints. The expansion joint appears in different states of performance everywhere in the Netherlands. Simplifying the real-world phenomena enables to control other influencing factors besides the variables. For example, the influences of factors such as speed and temperature can be reduced compared to the real-world situation.

The generated sensor data with the proof-of-concept is filtered and analysed to see whether relationships between the factors sound, load and performance can be distinguished.

B.2 METHODOLOGY

The methodology within the proof-of-concept followed the steps as determined by the monitoring framework of SBRCURnet (2014).

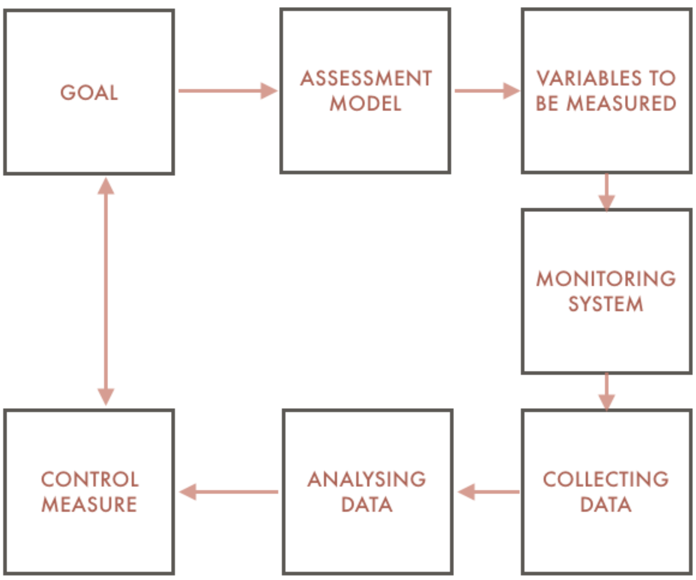


Figure 38: An overview of the monitoring framework developed by SBRCURnet (2014).

The seven steps of Figure 38 included the following tasks to be performed:

1. Goal
    a. Define asset of interest
    b. Define objective
2. Assessment model
    a. Distinguish the degradation types
3. Variables to be measured
    a. Determine variables to be measured (general)
    b. Determine variables to be measured (proof-of-concept)
4. Monitoring system
    a. Develop system architecture
5. Collecting data
    a. Perform multiple runs of varying traffic loads and varying performance of the asset
6. Analysing data
    a. Remove outliers
    b. Filter data
    c. Create graphs / histograms
7. Control measure
    a. Define relations between variables and performance
    b. Evaluate objective

B.2.1 DESIGN DECISIONS

The proof-of-concept is a conceptual rendition of the connection between a bridge and the embankment. The model consists out of multiple parts, which are model parts and electronic parts.

The model consists of a baseplate on which two columns are placed; signifying the water and the embankment. The road surface consists of multiple layers in order to be suited for the interchanging of expansion joints during the data collection stage. Model parts include (see Figure 39 and Figure 40):

- A baseplate with two main columns;
- Rendition of a road surface;
- Rubber rings for stabilisation of sensors;
- Multiple renditions of expansion joints. As can be seen in Figure 40, each expansion joint consist of an aluminium base plate (1), two mirrored Z intersection plates (2) and a cover plate (3) representing the deck plate.

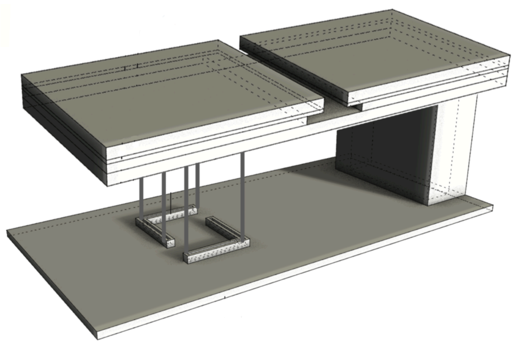


Figure 39: Overview of the simplification of the infrastructural context of the expansion joint.

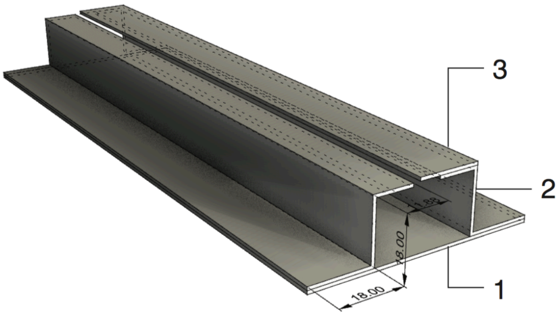


Figure 40: Overview of the simplification of the expansion joint.

Electronic parts include (see Figure 41):

- Arduino / Genuino Uno R3;
- Whiznet 5100 Ethernet Shield;
- Linkerkit Sensor Shield;
- Linkerkit Sound Sensor;
- Interlink Electronics FSR 402 Load Sensor.

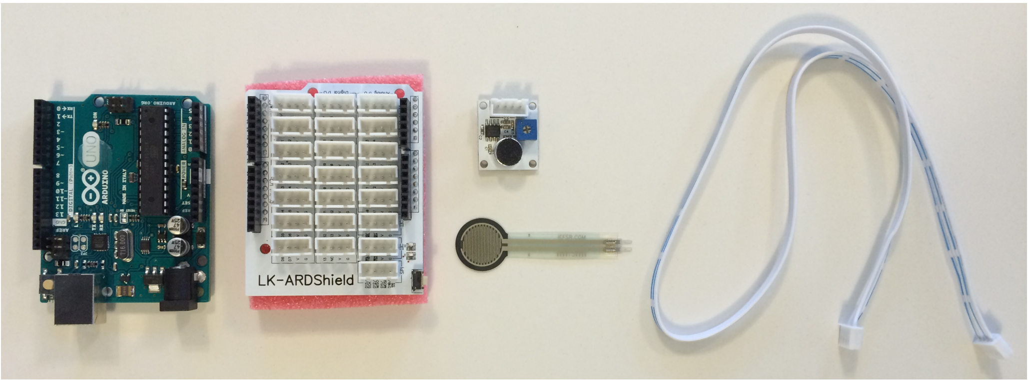


Figure 41: Overview of the used electronic parts. The Arduino (left), the Linkerkit Sensor Shield (mid-left), the sound sensor (mid-upper), load sensor (mid-lower) and the connection cable.

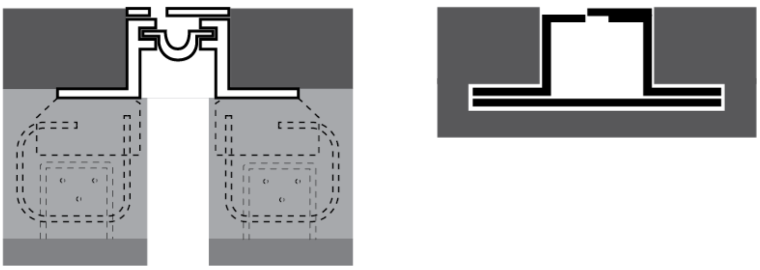


Figure 42: The real-world application of an expansion joint (left) differs from the simplification used in the proof-of-concept (right).

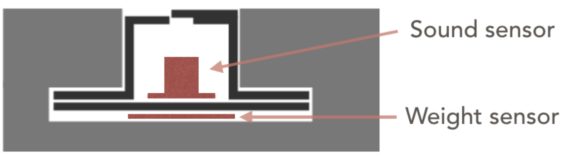


Figure 43: Overview of the location of the sound sensor and load sensor.

As mentioned, the proof-of-concept is a simplification of the real-world situation. The two simplifications, which can have an effect on the test results, are of the road surface and the expansion joints.

The road surface is simplified in the sense that it is created as one continuous part instead of two parts that are split up at the point where the expansion joint is situated (Figure 42). The road surface is created as one part, as it decreases external factors influencing the measurements later on. Next to this, the road surface is made of wood instead of using reinforced concrete, which was necessary due to the size of the proof-of-concept. The main reason for not splitting up the road surface is that a single road part allows enough space to position the load sensor beneath the expansion joint. The position and location of the sensors are shown in Figure 43.

The expansion joints are simplified to increase the ease of measuring with sensors. As shown in Figure 42, a difference exists between a real expansion joint and the simplified ones used in the proof-of-concept. As the simplified expansion joints used for the proof-of-concept could not be provided with reinforcement as in a real expansion joints (see Figure 4), there are no sensors used to measure these forces. However, this is likely to be done in real use cases.

The continuous plate simplifies the transfer of force from both beams to the load sensor. The plate also serves as a base for placing the rubber rings in order to make direct contact with the load sensor. The shape also enables to slide expansion joints into and out of the road surface, making the process of performing test runs with multiple expansion joints a simple action.

In the proof-of-concept, load and sound sensors are used to measure the load on the expansion joint and the sound of the traffic across the expansion joint. A third variable is taken into account in the proof-of-concept: Performance.

Directly measuring the performance with a sensor is impossible, the performance can only be detected based on other factors as load, sound or stress. Another difficulty with measuring the performance of the expansion joint is that the measurements would only be of value if the expansion joint degrades over the course of the test runs. It is chosen for fixation of the performances of the asset.

Two main types of degradation (Doorn, 2016) can be distinguished, each represented through the stages "new", "halfway life time" and "end of lifetime" (see Figure 44). The expansion joint itself can be deformed or the cover plate can come loose. Multiple expansion joints are created, each having a different performance. By introducing the asset performance in this way, the effects on the measured load and sound can be detected more clearly. As the "new" expansion joint is similar for the two types of degradation; five expansion joints were created (see Figure 45).

When the proof-of-concept is used to measure strain in the expansion joints in future projects, a redesign is needed. Then, the road surface and the expansion joints are then to be implemented more adequate.

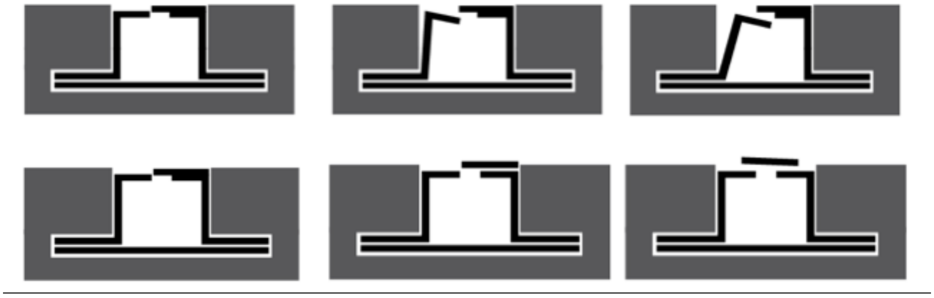


Figure 44: Two types of degradation can be distinguished: The expansion joint itself can be deformed (upper) or the cover plate can come loose (lower).

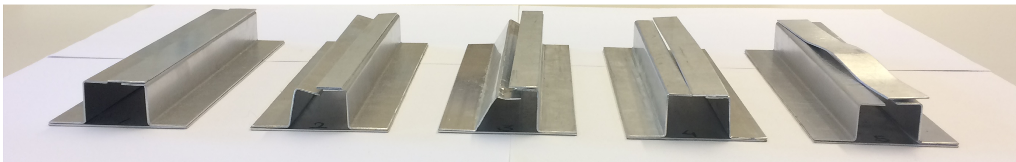


Figure 45: Overview of the five created expansion joints.

B.2.2 DATA PROCUREMENT PRELIMINARIES

The electronic parts listed in the previous section have to be connected together. The Arduino Uno R3, the Ethernet shield and the Linkerkit shield can be clicked upon each other. The data from the connected parts can now be passed through to the Arduino.

Before connecting the sensors to the shields, a proper understanding of this connection was needed. Shield with own special function, such as the Ethernet shield, use a part of the ports to communicate with the Arduino baseboard. Therefore, some ports will be unavailable on higher levels.

The Ethernet shield is directly connected to the Arduino. Before connecting the Linkerkit shield, the connector pins of the white ports as shown with red crosses in Figure 47 is soldered off to prevent conduction. The two connectors are removed from the shield because of the dimensions of the Ethernet connector below. The Linkerkit shield is connected to the Ethernet and the sensors can now be connected.

Sensors that have a range output, instead of maximum or minimum voltage, are to be connected to analogue ports. The connection of the load and sound sensor is shown in Figure 47. The load sensor consists of two pins; one for the 5 Volt input, one that sends through the reduced current. The load sensor is therefore a variable resistor, which changes based on the applied pressure.

B.2.3 SYSTEM ARCHITECTURE

An overview of the used system architecture is shown in Figure 46.

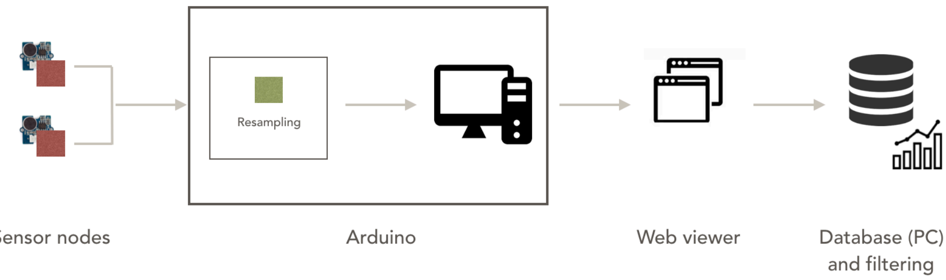


Figure 46: System architecture of the proof-of-concept.

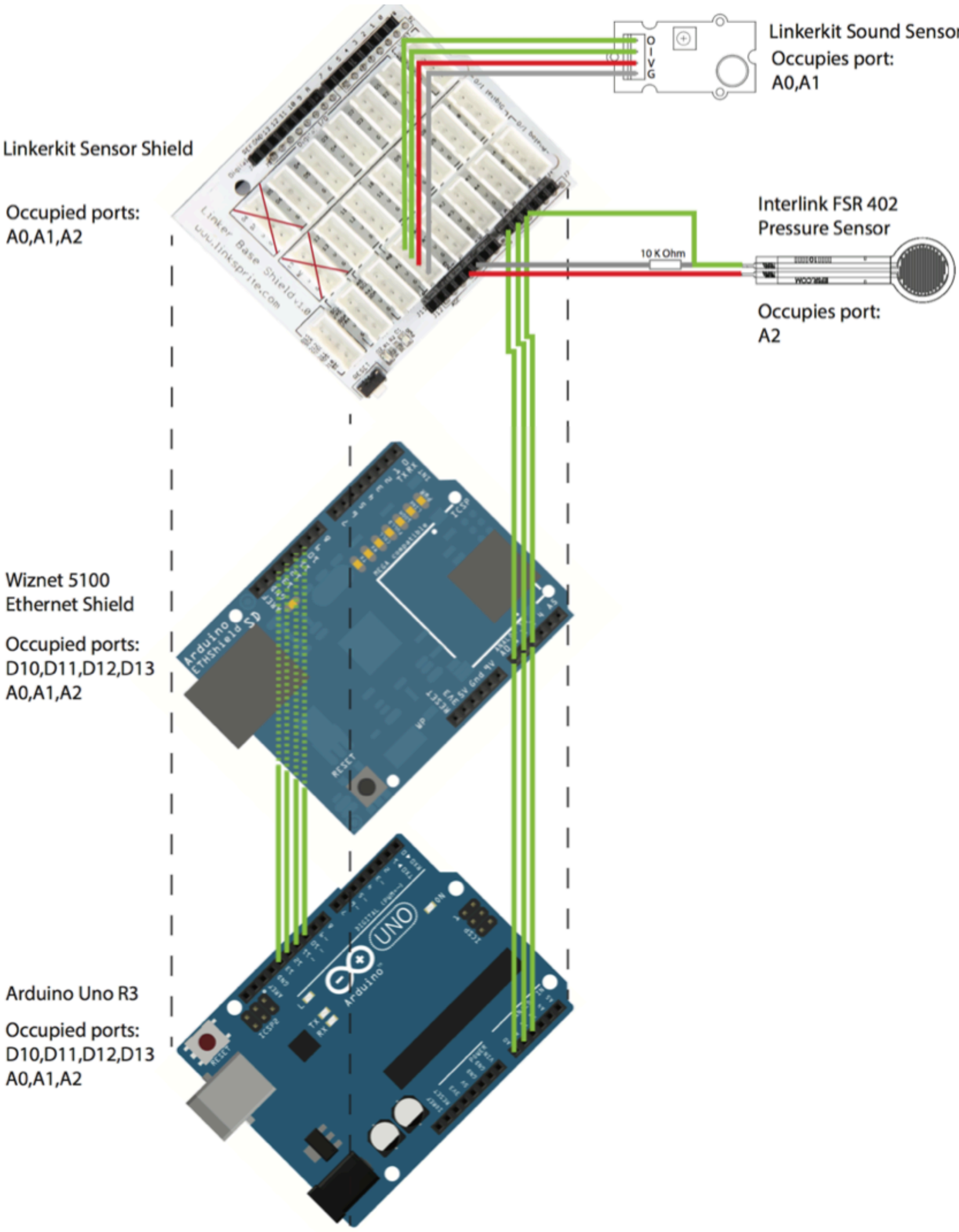


Figure 47: Overview of the connection schematics of the electronic parts (Ligtvoet, 2016).

B.2.4 DATA COLLECTION

Multiple runs

Two types of degradation of expansion joints are distinguished, represented through using a combination of three expansion joints with fixed performances. Five expansion joints are therefore created (Table 5). There are 50 runs performed for each expansion joint. A run is defined by one car that crossed over the expansion joint through manually pulling the cord that is connected to the car. By collecting 50 runs for each expansion joint, an indication for the load and sound for a fixed performance can be provided. Furthermore, different traffic loads are taken into account. Three traffic loads are used in the proof-of-concept to analyse the possible effects on the results.
In total 750 runs are performed. Table 5 and Table 6 provide an overview.

Subject / Object	[n]	Explanation
Degradation types	2	#1: Deck plate that comes loose #2: Distortion of the expansion joint
Expansion joints	5	1: Status "New" 2: Status "Halfway lifetime" of degradation type #1 3: Status "End of lifetime" of degradation type #1 4: Status "Halfway lifetime" of degradation type #2 5: Status "End of lifetime" of degradation type #2
Car / traffic load	3	A: 600 g B: 1030 g C: 1460 g

Table 5: Overview of the used degradation types, status and traffic loads for the data collection.

Combination	Explanation
1.A	Degradation type 1; Traffic load A [600g]
1.B	Degradation type 1; Traffic load B [1030g]
1.C	Degradation type 1; Traffic load C [1460g]
2.A	Degradation type 1; Traffic load A [600g]
2.B	Degradation type 1; Traffic load B [1030g]
2.C	Degradation type 1; Traffic load C [1460g]

Table 6: Overview of the combinations of interest. Combination 1.A for example relates to the first degradation type, which is represented by the expansion joints 1,2 and 3 (new, halfway lifetime, end of lifetime). The used traffic load is 600g. For each combination are 150 runs needed.

Sampling rate

Different sampling speeds are used for the sensors:

- Load sensor: 50 n/ms. Resampling for the load sensor searches out the highest value for every fifty measurements.
- Sound sensor: 10 n/ms. Resampling for the sound sensor searches out the highest value for every ten measurements.

This way, the sampling speed of the load and sound values is 10 ms. The maximum length of the arrays of the Arduino is set to 50 entries. This gives the user five seconds in the HTML page to see the measuring results before they are overwritten.

The resampling is performed due to the frequency of the measurements. Ideally, the peak of the sound wavelength is determined. This requires a sampling rate of ten times the frequency. The sampling speed of a measurement each 10 ms would therefore be able to reconstruct a signal of 10 Hz; a very low bass sound. Instead of reconstructing the signal, the highest value is stored with the assumption that the resampled highest 10 values per 100 ms will describe the peak of the sinusoid.

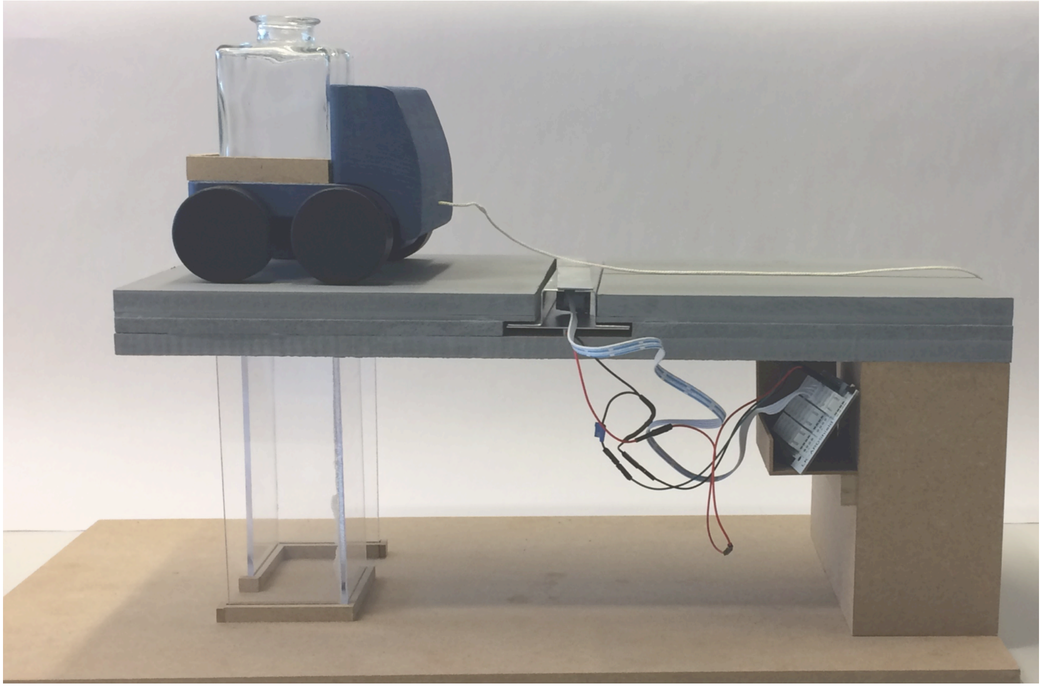


Figure 48: Overview of the test set-up.

Each individual run contains about 15 data values. As there were five expansion joints, three different traffic loads and a total of 250 runs; the collected data resulted in about 10.000 data values. An overview of the test-set-up is shown in Figure 48.

B.2.5 DATA ANALYSIS

The data analysis part consisted of the following steps:

- Remove outliers;
- Filter of the data;
- Calculate median and average.

The data filtering is performed through running a Python-script that uses the LSA to filter the data values. The script can be found in Appendix E.

B.2.6 DATA VISUALISATION

The data is visualised by using graphs and histograms. Below in Figure 19 two graphs show the sound and load that is measured during a single run. The sound is increasing until the car has passed the expansion joint and the front axle and rear axle of the car is detected by the load measurement.

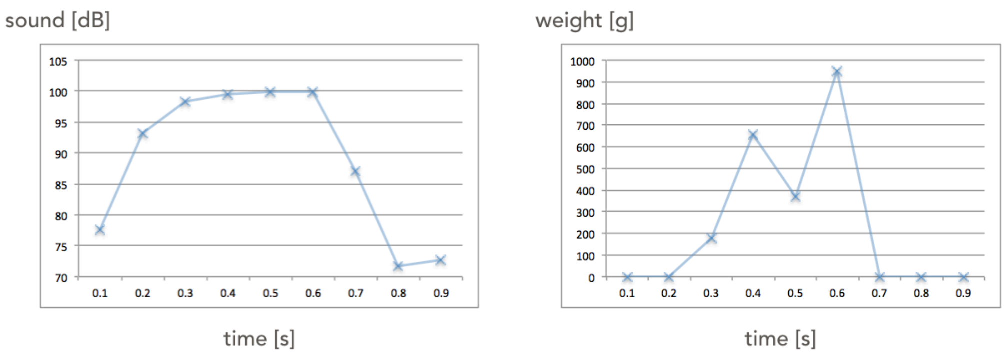


Figure 49: Overview of a single run. The peak of the sound (left) and the axle loads (right) can be seen.

B.3 TECHNICAL SPECIFICATIONS OF THE USED SENSORS

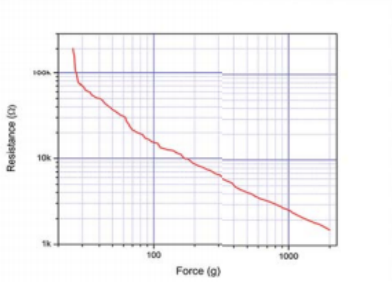
B.3.1 THE LOAD SENSOR: INTERLINK ELECTRONICS FSR 400

The Force Sensing Resistor (FSR) is a polymer thick film (PTF) device that exhibits a decrease in resistance with the increase in force applied to the surface of the sensor. Below the application information, sensor mechanical data and exploded view provided by Interlink Electronics is shown.

Application Information Force Sensing Resistors®

For specific application needs please contact Interlink Electronics support team. An integration guide and Hardware Development Kit (HDK) are also available.

FSR®s are two-wire devices with a resistance that depends on applied force. To the right is a force vs. resistance graph that illustrates a typical FSR® response characteristic. Please note that the graph values are reference only and actual values are dependent upon actuation system mechanics and sensor geometry.



For a simple force-to-voltage conversion, the FSR® device is tied to a measuring resistor in a voltage divider (see figure below) and the output is described by the following equation.

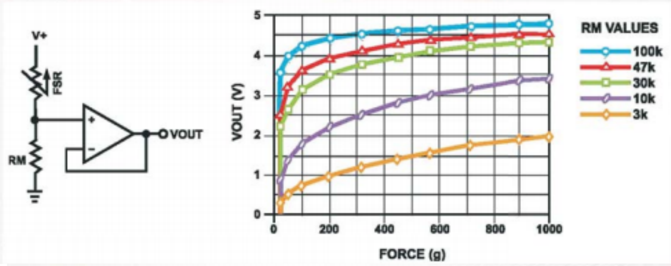
$$V_{OUT} = \frac{R_M V+}{(R_M + R_{FSR})}$$

In the shown configuration, the output voltage increases with increasing force. If R_{FSR} and R_M are swapped, the output swing will decrease with increasing force.

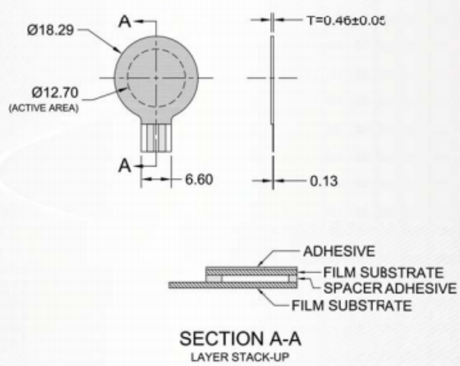
The measuring resistor, R_M, is chosen to maximize the desired force sensitivity range and to limit current. Depending on the impedance requirements of the measuring circuit, the voltage divider could be followed by an op-amp.

A family of force vs. V_{OUT} curves is shown on the graph below for a standard FSR® in a voltage divider configuration with various R_M resistors. A V+ of +5V was used for these examples. Please note that the graph values are for reference only and will vary between different sensors and applications.

Refer to the FSR® integration guide for more integration methods and techniques.



Sensor Mechanical Data



B.3.2 THE SOUND SENSOR: LINKERKIT LM386

The LinkerKit Sound sensor module is a simple type of microphone. Based on the power amplifier LM386 provided by LinkerKit, the sound strength can be detected. The value of the output can also be adjusted by a potentiometer. Below the sensor mechanical data and the circuit system provided by LinkerKit is shown.

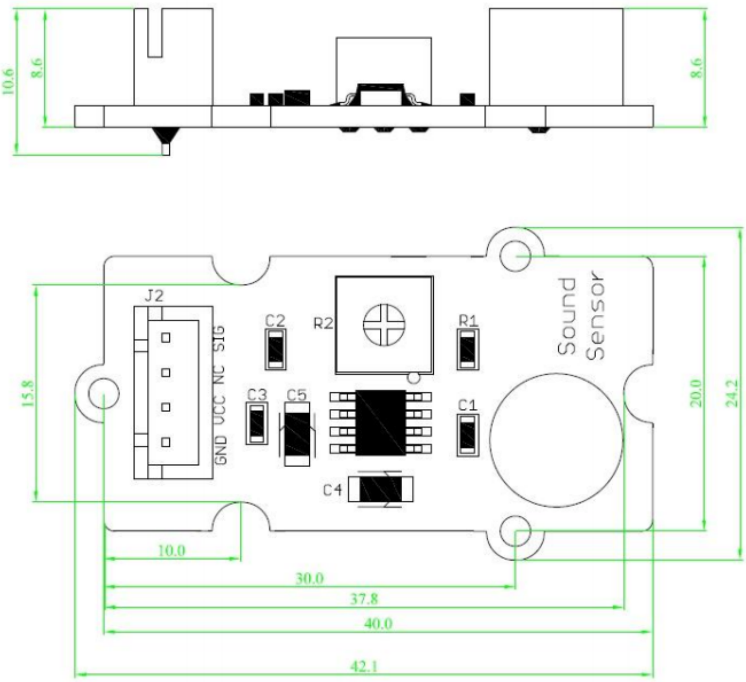


Figure 50: The mechanical specification of the sound sensor.

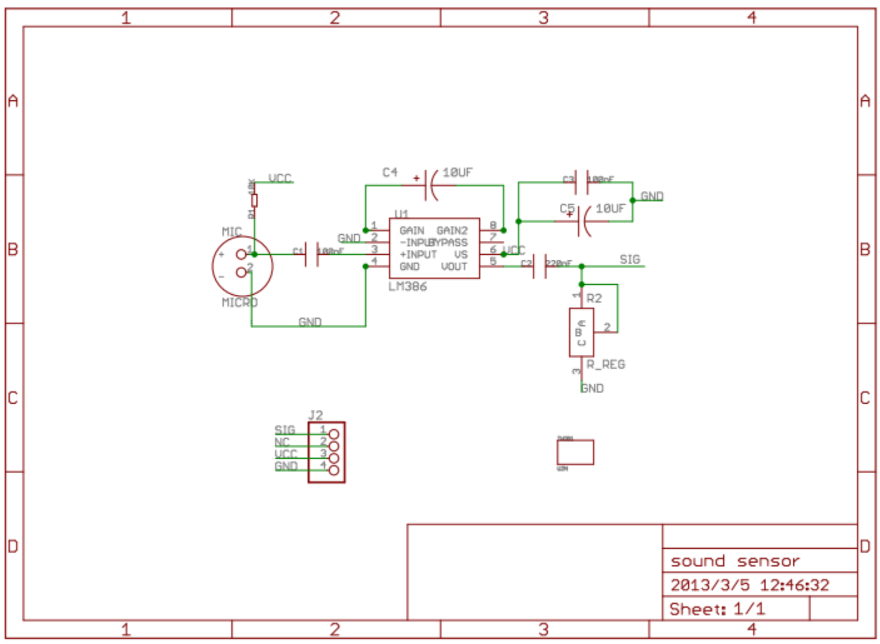


Figure 51: The circuit system of the sound sensor, explaining the wiring of the sensor.

APPENDIX C: PROOF-OF-CONCEPT: RESULTS

Below the results of multiple runs as described in Table 6 of Appendix 0 are shown. The filtered data of each combination is shown in a scatter plot and additionally a table is provided that includes the average and standard deviation of the measurements. For each combination a short explanation is provided.

Combination 1.A

Degradation type 1

Load A: 600 g

<u>Results</u>

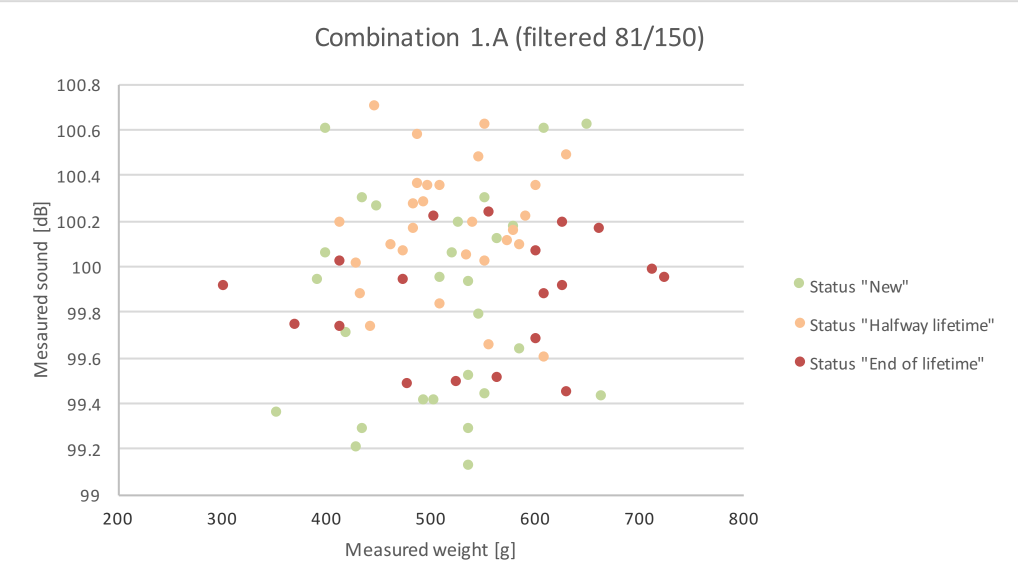


Figure 52: Overview of the results of combination 1.A.

Status	**Average load** [g]	**Average sound** [dB]	**SD load** [g]	**SD sound** [dB]
"New"	507,8	99,8	80,4	0,5
"Halfway"	519,0 (+11,2)	100,2 (+0,4)	60,2	0,3
"End of lifetime"	680,1 (+161,1)	99,9 (-0,3)	246,5	0,2

Table 7: Overview of the averages and standard deviations of the measurements of combination 1.A.

The scatter plot shows an overview of the load and sound measurements from multiple runs. The first impression shows that there are deviations between the measurements of the three different performance states of the expansion joint. When looking at Table 7, it can be seen that the average load increases when the performance of the expansion joint decreases. By looking at the average measured sound, it can be seen that the level of sound both increases and decreases. Therefore, no conclusion can be drawn about the sound. The standard deviation provides an indication about the distribution of the measurements and shows large deviation in the load measurements of the "end of lifetime" expansion joint.

It turns out that combination 1.A of this proof-of-concept does not provide an answer on either accepting or rejecting the presumption that the sensors can indicate performance of the expansion joint.

Combination 1.B

Degradation type 1

Load B: 1030 g

Results

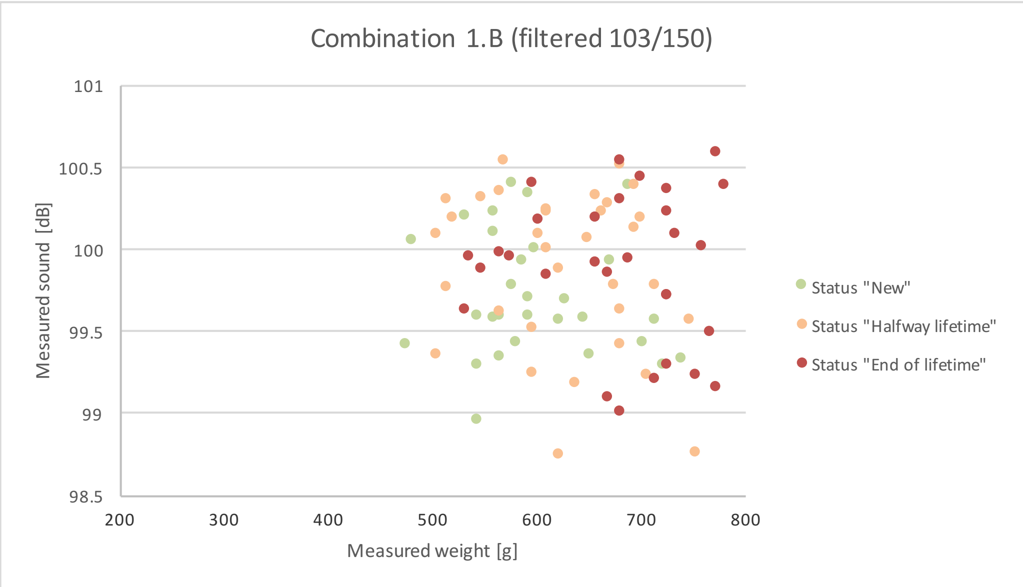


Figure 53: Overview of the results of combination 1.B.

Status	Average load [g]	Average sound [dB]	SD load [g]	SD sound [dB]
"New"	599,0	99,7	68,1	0,4
"Halfway"	626,3 (+27,3)	99,9 (+0,2)	71,0	0,5
"End of lifetime"	740,6 (+14,3)	99,9 (0,0)	127,9	0,4

Table 8: Overview of the averages and standard deviations of the measurements of combination 1.B.

In the scatter plot of combination 1.B it can be seen that the measurements intertwine and no clear indication can be stated. When looking at the average measurements in Table 8, it can be seen that the average load increases with 27,3g and subsequently with 14,3g as the performance of the expansion joint is decreasing. The average sound shows that it increases and stabilizes. The standard deviations are too high in comparison with the average loads and average sound of the measurements. Concerning the measured sound, no conclusion can be drawn, as the difference in the measurements is too little.

Combination 1.B therefore is not able to identify the performance of an expansion joint through the use of these two sensors.

Combination 1.C

Degradation type 1

Load C: 1460 g

<u>Results</u>

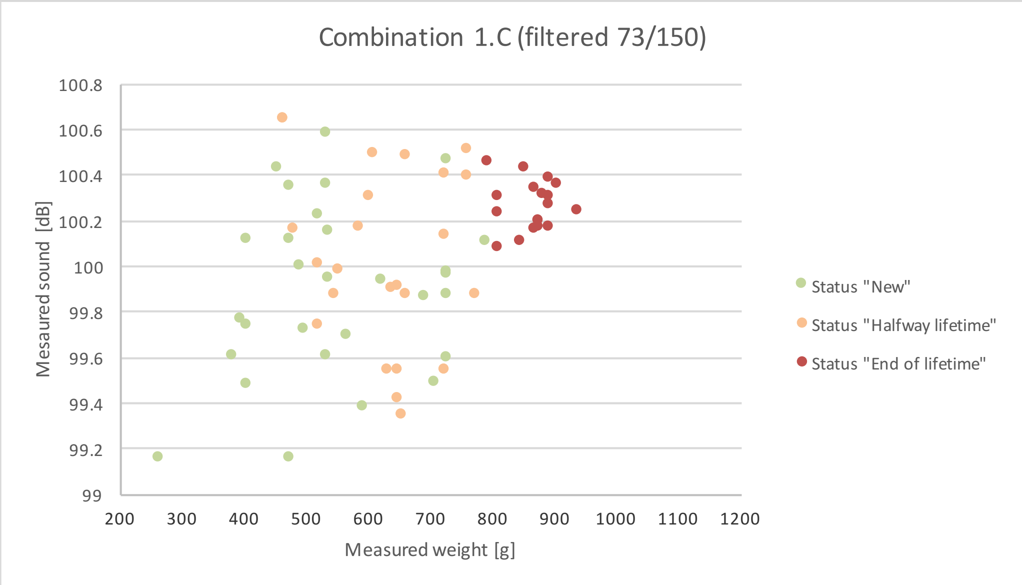


Figure 54: Overview of the results of combination 1.C.

Status	Average load [g]		Average sound [dB]		SD load [g]	SD sound [dB]
"New"	560,9		99,9		138,7	0,4
"Halfway"	625,7	(+64,8)	100,0	(+0,1)	93,6	0,4
"End of lifetime"	864,5	(+239,8)	100,3	(+0,3)	38,9	0,1

Table 9: Overview of the averages and standard deviations of the measurements of combination 1.C.

The scatter plot of combination 1.C clearly shows an increase in load and sound when the performance of the expansion joint decreases. The average measurements and the standard deviations in Table 9 also provide this insight. The average load increases in both stages, which is also the case for the measured sound. The more the expansion joint decreases in performance, the lower the standard deviations. It can be concluded that combination 1.C confirms the presumption that the sound and load increases as the performance of the expansion joint decreases.

Combination 2.A

Degradation type 2

Load A: 600 g

Results

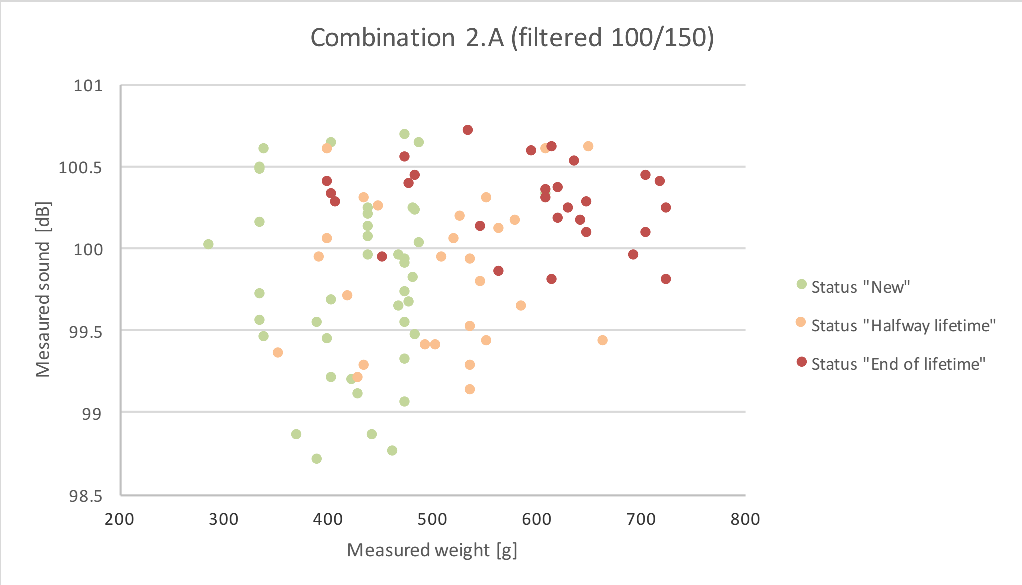


Figure 55: Overview of the results of combination 2.A.

Status	**Average load** [g]		**Average sound** [dB]		**SD load** [g]	**SD sound** [dB]
"New"	429,7		99,8		80,4	0,5
"Halfway"	507,8	(+78,1)	99,8	(0,0)	63,7	0,5
"End of lifetime"	590,3	(+82,5)	100,3	(+0,5)	100,6	0,2

Table 10: Overview of the averages and standard deviations of the measurements of combination 2.A.

The scatter plot of combination 2.A shows a slight shift in both the measured load as the measure sound the more the expansion joint's performance decreases. When looking at Table 3, it can be seen that the measured load increases. The average sound first indicates no change in average, but increases between the second and final performance state. The standard deviations of load indicate small deviations in in comparison to the differences in average loads. The standard deviations of sound are as high as the differences between the average measurements, which makes it difficult to draw clear conclusions about correlations.

Combination 2.A indicates that the measured load increases when the expansion joint decreases in performance. Despite the distribution in values, combination 2.A indicates a similar case for the measured sound.

Combination 2.B

Degradation type 2

Load B: 1030 g

<u>Results</u>

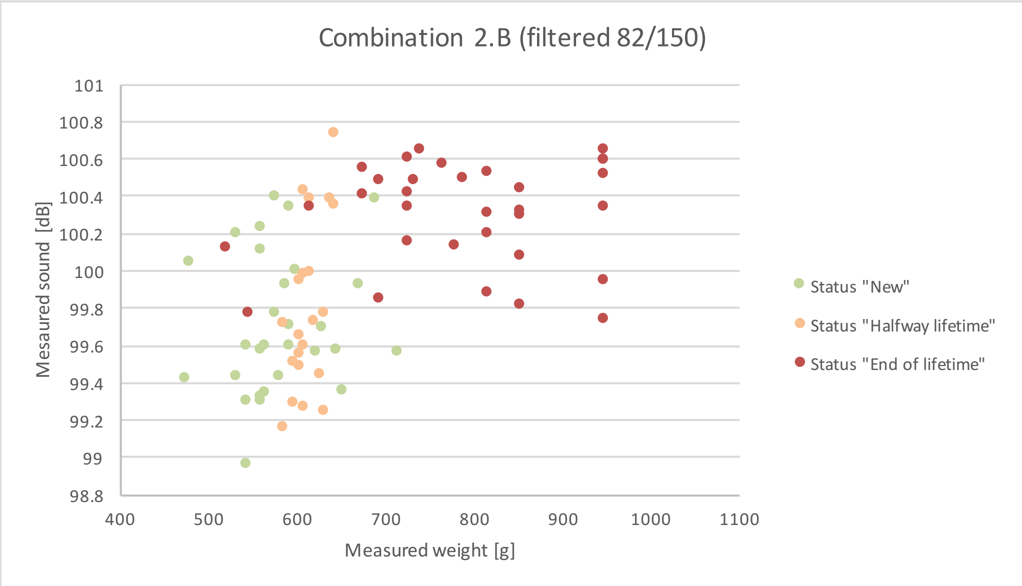


Figure 56: Overview of the results of combination 2.B; the second degradation type with the used traffic load of 1030g.

Status	**Average load** [g]	**Average sound** [dB]	**SD load** [g]	**SD sound** [dB]
"New"	581,4	99,7	54,9	0,4
"Halfway"	613,4 (+32,0)	99,8 (+0,1)	17,3	0,4
"End of lifetime"	789,8 (+176,4)	100,3 (+0,5)	117,1	0,3

Table 11: Overview of the averages and standard deviations of the measurements of combination 2.B.

The scatter plot of combination 2.B clearly shows the increasing load and sound when the expansion joint decreases in performance. In particular, the average load increases when the performance of the asset decreases. This way, the end of lifetime of the expansion joint can clearly be distinguished. When looking at Table 11 this can be seen again. The average load increases, and the associated standard deviations are rather small. The average sound increases as well, though the values relating to the first and second state are in close proximity.

Combination 2.B in this proof-of-concept is considered to be successful to indicate the status of the expansion joint by using load and sound. Nevertheless, the results of the new and halfway the expansion joint lifetime are in close proximity.

Combination 2.C

Degradation type 2

Load B: 1460 g

Results

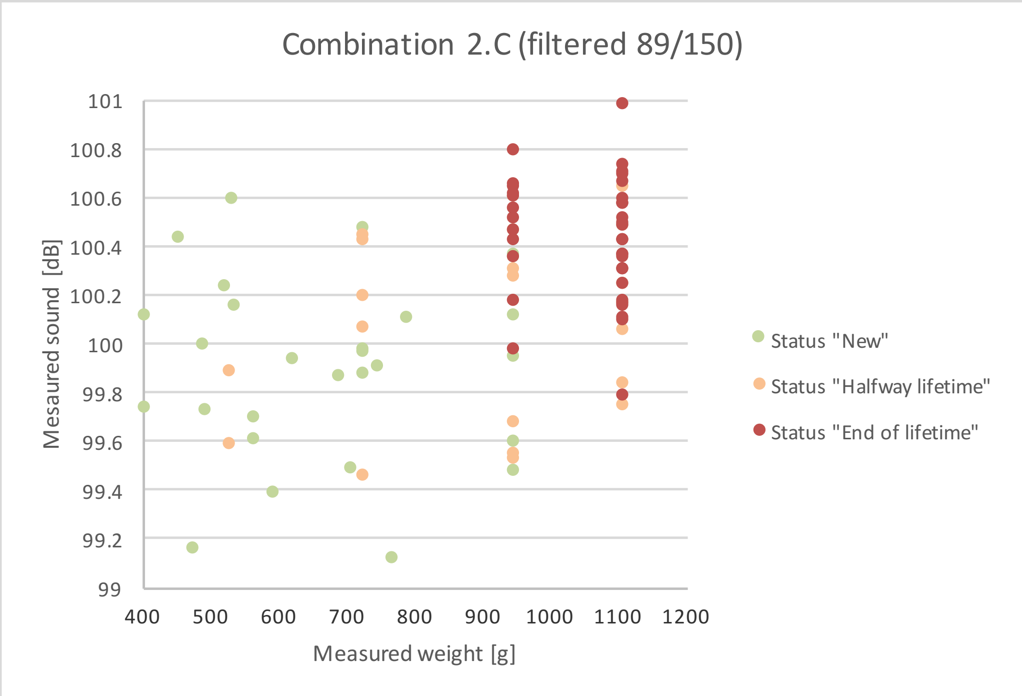


Figure 57: Overview of the results of combination 2.C. The measurements collected with the expansion joint that represents "end of lifetime" deviate greatly and are either false readings or blunder errors. This combination is taken out from further analysis as a re-run is to be performed.

Status	**Average load** [g]	**Average sound** [dB]	**SD load** [g]	**SD sound** [dB]
"New"	650,7	99,9	188,9	0,4
"Halfway"	908,2 (+257,5)	100,1 (+0,2)	192,7	0,4
"End of lifetime"	1055,8 (+147,6)	100,4 (+0,3)	76,4	0,2

Table 12: Overview of the averages and standard deviations of the measurements of combination 2.C.

The scatter plot of combination 2.C shows a clear distinction between the new status and the expansion joints in a later stadium of performance. The average values in Table 12 also indicate that the average load and average sound increases when the performance of the joint decreases. When looking at the distribution of values of both the load and sound, it can be seen that in the new and halfway lifetime of expansion joints the distribution is rather high. Considering the differences between the average sound and the standard deviation, it is difficult to draw conclusions. Combination 2.C shows that a new expansion joint can properly be indicated and that the halfway life and end of lifetime of the expansion joint are difficult to distinguish. The average sound provides an increasing result, but the distribution in values makes it impossible to state conclusions.

C.1 CONCLUSION

The proof-of-concept gives an insight in how sensors can be used to collect real-time data in context and use this data for analysis. The conclusions from the six cases are summarized in Table 13. The scoring (++, +, +/-, -, --) indicates the extent to which the indicator contributes the presumption to indicate the performance of an expansion joint.

Combination	Indicator Load	Indicator Sound
1.A	-	-
1.B	-	-
1.C	++	++
2.A	++	+
2.B	++	+
2.C	++	-

Table 13: Overview of the results from the six combinations.

The conclusions that can be drawn from the set-up are as follows:

- In general, the measured load of the car is increasing when the performance of the expansion joint decreases.
- In general, the sound is increasing when the performance of the expansion joint decreases.
- The provided standard deviations of measurements indicate that large differences between measurements occur. Further research is therefore needed to improve the proof-of-concept and to reduce the standard deviation by increasing accuracy.

By successfully collecting and analysing sensor data, the proof-of-concept shows a weak relationship between factors sound, load and performance. Further research should investigate whether this relation is also observable in the real-world situation.

C.2 LIMITATIONS AND RECOMMENDATIONS

The proof-of-concept has limitations in its use. The main improvements of results are expected by:

- Modifying the set-up (design) and redesigning some modelling parts.
    - During the procurement of data, problems were experienced with the positioning of the expansion joint on the load sensor. This explains the use of the rubber rings. If a rubber ring were misaligned it would result in false readings. This resulted in more time needed to collect the data.
    - The stability of the expansion joint could be improved. The joint could stagger inside the space of the road surface. The rubber rings decreased the impact, but it could still have an effect on the measurements.
    - The expansion joints were hand made and therefore slight deviations in their height exist. A model for 3D printing the joint is made, but due to time limitations not printed yet.
- Changing electronics, such as purchasing more advanced sensors.
    - The FSR 402 load sensor has a working range between 200-2000 grams. The sensor does not break when more pressure is applied; therefore measurements higher than 2000 grams are registered as 2000 gram and similarly for measurements below 200 grams.
- Adjusting the Arduino code.
    - The sampling speed could be changed to determine the sinusoid. The time needed for these kinds of calculations can be calculated, as more information can be found on: *http://www.microsmart.co.za/technical/2014/03/01/advanced-arduino-adc/*
    - The Arduino works with 10-bit analogue ports. This means that the 5 Volt output is divided over 1024 values, therefore resulting in measurable steps of 0.0049 V during the testing.

The proof-of-concept is a simplification of the real world situation in such a way that these results should be handled carefully. This means that the phenomena described and measured by the proof-of-concept can be used as an indication for the real-world purposes, but the specific relations of sound and load values could differ in real-world applications.

However, the proof-of-concept is still useful. The intention of the proof-of-concept was to develop a set-up able to measure the defined performance indicators and to analyse these sensor measurements for identifying asset performance. The proof-of-concept shows that it is able to measure variables, and through analysing the sensor data it can identify asset performance (though with limited accuracy and precision).

APPENDIX D: MICRO-CONTROLLER CODE[20]

The complete code to retrieve the sensor data can be retrieved until 16 December 2017 via the following link:
https://www.dropbox.com/s/lv0fxlo73h8im3u/ProofOfConcept_SmartAsset_Arduino.ino?dl=0

The Arduino code is written in C/C++. The code contains five main functions, which are all marked with the <<def>> tag:

- void setup(). Used to execute statements, which only need to be executed once.
- void loop(). An indefinitely loop on the Arduino, which can be described as the body of the code from other functions are hailed. The function contains two loops which control the sampling rates of the two getData functions.
- getData_1(). The function monitors the A0 pin, and converts incoming bits to volts, to dB. The formula is created by calibrating the sound sensor through fitting a logarithmic function.
- getData_2(). The function monitors the A2 pin and converts the incoming bits to volts, to load. The relationship between pressure and voltage is in the sensor specifications and could be calibrated based on this.
- ListenForEthernetClients(). The function creates aHTML page on which the results stored in the global variable arrays are printed as a table.

The Max Weight and Max Sound parts of the code are used to re-sample the incoming data. The re-sampled values and the time are appended to global variables of the type array. The time is measured as milliseconds after the powering on of the Arduino. The maximum size of the arrays depends on the memory of the Arduino. After testing it was concluded that the maximum size of the arrays is 70-100 entries for each array. The arrays are used to remember old measurements when publishing a list.

[20] The Arduino code for this proof-of-concept is co-authored by MSc student B. Ligtvoet.

APPENDIX E: PYTHON-SCRIPT

The complete code for filtering the sensor data can be retrieved until 16 December 2017 via the following link:
https://www.dropbox.com/s/9scbp9yl0ffrgp4/ProofOfConcept_SmartAsset_Python.py?dl=0

There are six functions defined in the script:

- Mainfunc(). The main function starts the loop for adding outliers to either a list for sound or load values. The main function calls the other functions.
- Write_to_excel(). The function calls the filtered data in specific order and exports this to an Excel file.
- Filterfunc(). The filter function includes the different lists that are created throughout the process. The lists that are exported to Excel after completing the data filtering are created as well. Also the outliers are removed, which are the load values below 201 or above 1999 grams.
- Filter_dB() and Filter_weight().
  The sound and load values are filtered through removing outliers based on the standard deviation of the dataset and set threshold for significance. Per loop, the identified outliers are stored in an outlier list and the outlier with the highest deviation is removed until no outliers are detected.
- Graph(). The graph function manages the visualisation of the data procured in the filtering function and the main function. The input data for the function contains the lists from the earlier functions that can be used to create graphs.
- Histo(). The histogram function uses the input data from the earlier function to create a histogram of the results.