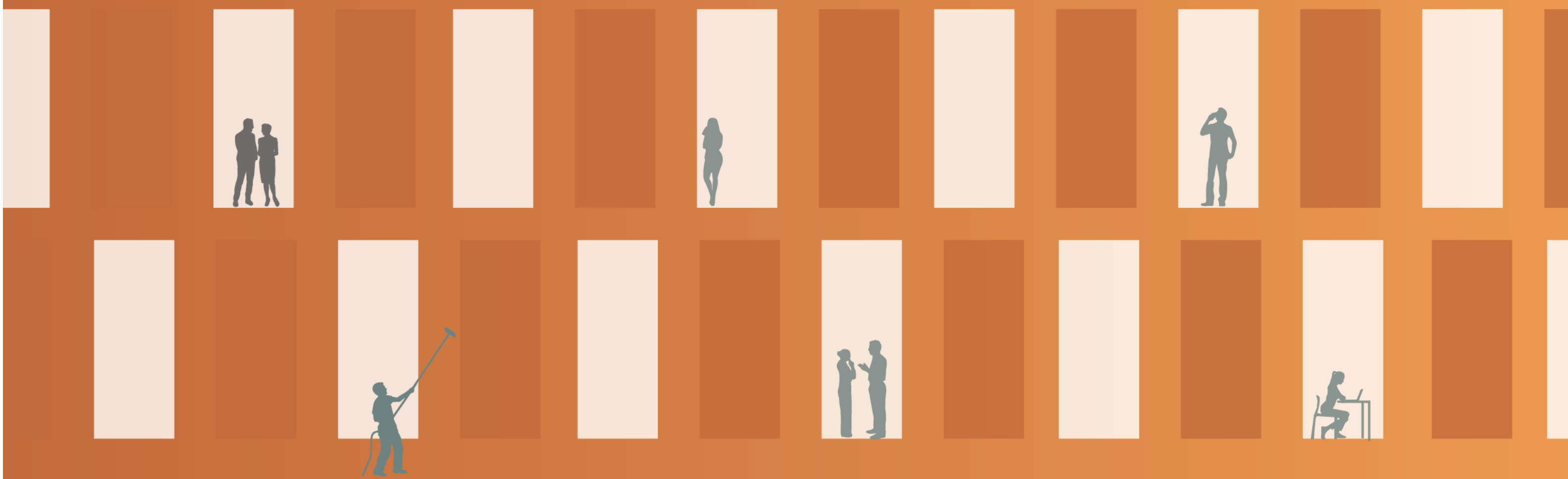
Digital Twin as Circularity Enabler of Façades in Maintenance

A Research into How a Digital Twin can Facilitate the Circular Maintenance of Façades



Master's Thesis | TU Delft
Management in the Built Environment
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Colophon

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Preface

In front lies the result of 10 months research of the master track Management in the Built Environment. This graduation thesis is the final part of this TU Delft master track. When commencing in September with the first part of the course ‘Graduation Laboratory’ I was interested by the issue on global warming, as I’ve always been interested in the earth and its processes. And this has been my motivator throughout the research. There are several ways to tackle global warming within the field of construction. However, circularity had drawn my attention the most.

Circularity has been addressed throughout the master track; however, it was only in September that it really had drawn my attention. During an interesting lecture the importance of circularity was addressed, alongside its possible effects on the construction sector. Also, the drivers in adopting circularity have been a large part of this lecture. The combination of circularity and technology has been tipped as the future and a huge enabler of circularity. I wanted to pick a topic that was really relevant, and in need of solving of solving.

This thesis is positioned within the domain *Design and Construction Management.* This domain aims to understand and develop new ways of how design and construction management can produce the future built environment and therewith reshape society, the environment and technology. This thesis entails a view on technology can shape buildings in the future.

Acknowledgements
Conducting research for an entire year is a tremendous task, mentally as well as physically. During this year I have received advice, guidance and support from various people. My mentors, family and friends have provided me with support to keep on going. Firstly, my first and second mentor Alexander Koutamanis and Berna Torun. You’ve helped me with your guidance and enthusiasm. You both have been so involved and were always available to answer any of my questions. You’ve made this process into very exciting. Secondly, my mentor from the Rijksvastgoedbedrijf Jille Koop. Even though COVID-19 changed the road of the internship tremendously, you were always looking for ways to get me to learn more of the RVB. You were very involved and looking for ways how to get the best out of this thesis. For this I want to thank you a lot. I did not only learn a tremendous amount on the topic, but also on the RVB as a whole. I would also like the interviewees and colleagues at the RVB who have helped me throughout the project. My colleagues did not miss any of the RVB drinks and have made my internship during the non COVID-19 times so pleasant.
I would also like to thank my friends and especially my family. During COVID-19 my social circle has been limited. This meant that I was most of the time doing research by myself in my room. During this special time, my friends, roommates and study mates made the moments during and outside conducting research great. Making the best out of this special situation. In particular I would like to thank my parents and brothers for their unconditional support and comfort at any given time.

This thesis is the final step of my seven years TU Delft education. A tremendous amount of knowledge gained throughout these seven years has been applied in this thesis.

Enjoy reading!

Abstract

Maintenance plays a vital part in the Circular Economy (CE). Repairing, upgrading and restoring façades extends their lifecycle and reduces waste. The European Union and Dutch government have set goals to reach a circular future: in 2050 the built environment must be 100% circular. However, this demands a tremendous change in the current maintenance system. Façades are often maintained for the service life of only 50 years. Therefore, the quality at end-of-life is usually low. Additionally, due to issues in information capture and management, the condition at end-of-life is also challenging to determine. Therefore, façades are discarded as waste, sometimes way before they are at their actual end-of-life. Furthermore, to increase the circular potential of façades, the existing maintenance system requires change. In this research, an investigation is done into how the current maintenance system can be facilitated towards circular maintenance utilizing digital technologies. Inspections on façade defects are currently carried out manually. Afterwards, this information is stored and maintained manually in real estate software. Visual inspections and information systems are prone to human errors. Therefore, a study is done into the automation of the existing maintenance system to facilitate communication between parties. The Digital Twin (DT) is a real-time computer-generated BIM-model of the mother building, using sensors and Internet of Things (IoT) to capture data. Existing detection technologies are compared with detection sensors from literature, like infrared thermography and fibre sensors. The influence of the recommended sensors on the existing maintenance process is determined. The output of this is a new maintenance system using a DT to increase the circularity potential of façades.

Keywords: [Circular Economy; Maintenance; Management; Information; Building Information Modelling; Digital Twins; Façades]

Glossary

Term	Definition
Circular economy (CE)	An industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models (Ellen MacArthur Foundation, 2013)
Façade	The shell of a building
Maintenance	The process of preserving or a condition or situation in order to guarantee the requested degree of functionality
Circular maintenance	Preserving the functionality and condition of a circular designed product or element into its desired level of performance. Securing its potential for reuse in another project.
Condition	The state of an element in regard to its quality or working order
Defect	An adverse consequence to a physical object, which can take form of a damage, a lack or an imperfection.
Management	Directing a process
Building Information Modelling (BIM)	A digital model of the physical building object consisting of a linkage between geometry and information
Digital Twin (DT)	A digital model of the physical building object consisting of a linkage between geometry and real time information measured directly from the physical object, by a sensor network
Real-time information	Direct communication of data on the current status of objects, including approximate locations. This communication occurs without delay
Sensor	Mechanical execution of 'sensing'. A sensor is a device which detects, measures or indicates a physical object or responds to it
Internet of Things (IoT)	The set of devices which are interconnected through the internet and can send data to computers

Executive Summary

Introduction

Motive 1: Required shift from the linear to the circular economy

The construction industry operates in a linear matter. This means virgin resources are extracted, produced, consumed and then discarded as waste, which impacts the environment substantially. In Europe, the construction industry is the largest consumer of resources and energy. This takes its full lifecycle into consideration: material extraction, manufacture, transport, construction, use phase and end of life. Their full impact counts for 50% of all energy use, 40% of all greenhouse gas emissions, 50% of the materials going into the economy and 30% of all water use (European Commission, 2019). The lingering environmental, economic and societal threats suggest that the linear economy must change.

CE is increasingly gaining acceptance as a method to tackle environmental, societal and economic problems produced by the linear economy. The circular economy is described as: '*[...] an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models* (Ellen MacArthur Foundation, 2013, p8). Waste and the need for virgin resources are reduced through reuse, repair, remanufacture and recycling of existing building components.

CE can be applied on several levels: site, structure, skin, services space plan and stuff (Brand, 1994). The skin of a building, a façade, is an interesting topic within CE, because its application in CE can have an impact in a buildings' use phase as well as the construction phase. Maintaining the performance quality of façades in the use phase can result in fewer energy leaks and thereby stimulate a buildings' energy efficiency. Additionally, when maintaining the performance quality of the façade, fewer new materials for repair or restoration are necessary.

CE is rarely adopted in practice, as it requires fundamental changes in the current workflow (Ritzén & Sandström, 2017). Buildings are not yet widely regarded as materials depots, which is one of the reasons a circularity gap has emerged. This circularity gap is depicted in Figure B.

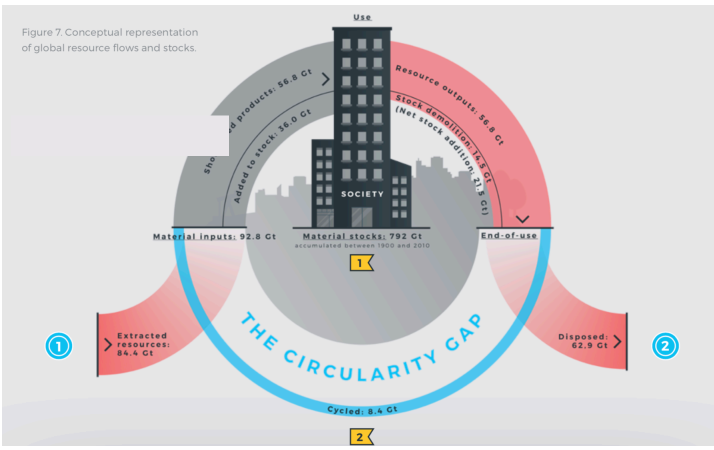


Fig B The circularity gap as described by Circle Economy (Circle Economy, 2019, p29)

Motive 2: Low quality at the end-of-life withholds circular façade demand
In current circular projects, the quality of components in 'donor buildings' is an issue. Stakeholders are often hesitant about the quality of façade components. Ritzén & Sandström (2017) state that reusing components of which the quality is low or unknown is a significant risk for companies.
Currently, building façades are generally designed to have a service life of 20 to 50 years, which reduces their reuse value and circular value at the end-of-life, turning them into mere waste (Interview A). Besides, of all building parts, façades are exposed to physical damages the most and require frequent reparations. Due to the long lifespans of buildings, maintenance management is an important topic to resource efficiency and closed-loop material cycles (Volk, Stengel & Schultmann, 2014).
Façade reuse is dependent on several other factors as well: the current architectural trends and how the user values the façade. Façade reuse is also reliant on future changes in building regulations. Future values of subjective factors are hard to predict because it is complicated to determine the trends of 30 years from now. However, it is possible to prepare a component for circularity by making sure its circular value and reuse value are high and constant (Interview A).

The implementation of circular façades is very relevant in commercial real estate. This is due to the fact commercial real estate is flexible and dynamic. Inflow and outflow of tenants occurs often, and the building is subject to renovation every certain amount of years (Interview C).

Motive 3: Rising project complexity through a lack of information withholds circular façade demand
Understanding buildings as material depots radically changes the way resources need to be handled. In buildings, it is necessary to keep track of the resource flow, to document and communicate which materials become available for reuse and recycling and in which quantities (Heisel & Rau-Obenhuber, 2019). Additionally, as façades are exposed to the most physical damages, tracking the quality of building façades elements is essential for ascertaining reuse potential and circular value (Androsevic, Durmisevic & Brocato, 2019). Due to the increasing complexity and the high number of materials and components in a building, there is need for information management, digitization, process automation and implementation of data standards to reduce project complexity (Heinrich & Lang, 2019). The large amounts of involved data require digital solutions to collect, process, store and utilize the information for this information to be reliable and easily accessible.

For CE in façades to function, it is necessary that this information is passed on and updated when changes are made. As buildings have long lifespans, this information needs continuous management (Heinrich & Lang, 2019). A buildings' DT gaining attention as a means to apply updated information. A DT is a virtual representation of the physical asset, connecting the physical and virtual worlds. This is managed through integration of sensors in the physical asset, measuring real time data, which is sent to the virtual asset.

Problem statement
Circular façades are an interesting topic to research, because proper maintenance can lead to fewer energy leaks and materials necessary for repair. This possibly produces favorable environmental effects, as well as resource efficiency. Its reuse potential depends on changes in architectural trends and building laws for example. However, it is possible to prepare a façade for reuse by tackling it performance quality. Currently, the following issues are barriers to circular façades: the low end-of-life quality and increasing project complexity due to lack of information on the condition of façades. Information on façade characteristics and condition is not widely available, and collection is time-consuming. Consequently, it becomes a significant risk for companies to reuse components of which the quality is uncertain. As a result, the chance that the façade will end up as waste becomes greater. Therefore, there is a need for transparent information on performance quality and assurance of this quality through effective maintenance. Scientific literature lacks the management of storing and

updating the condition information on façades during maintenance, and its use to improve the circular potential of the façade. This thesis will address this gap.

Research scope
This scope of this research is confined to the following topics:

- CE level: The skin, this encompasses the building façade
- CE characteristic: The thesis will address maintenance
- Positioning research: The research is positioned in the buildings' use phase
- Research perspective: Building owners
- Building type: Office buildings
- Façade connections: Both dry and wet connections.
- Digital measures: Digital twin, consisting of sensors and BIM
- Required data and information: 'technical performance' and 'maintenance details', as these are related to condition quality

Relevance
Societal relevance
This research adds new insights for addressing façade circularity. The United Nations, European Parliament and Dutch government have set aims to reach 100% circularity within various sectors, the built environment included. These aims will result in a shift towards circularity within design and production of elements, maintenance and business models. This research adds knowledge on design and maintenance. It provides an understanding on how to maintain a façade with digital measures, by providing insights on storing and updating information on façade condition, to diminish this barrier to CE. This research is necessary due to the need for strengthening of knowledge on circular maintenance, which is crucial for keeping materials in the loop and decreasing the pressure on the environment. Also, due to the future shift towards circular product, new knowledge needs to be generated. Therefore, this research is necessary.

Scientific relevance
In scientific literature, the concept of the circular economy is widely described. Literature extensively addresses barriers and enablers to the circular economy and the lack of adoption in digital solutions. However, circular enablers on a smaller scale – materials or components - have not been considered extensively. The same holds for research into the management of a circular process. Research into how the supply chain of the built environment should use digital solutions to determine the value of reuse in building facades can be improved. This research can facilitate the move towards decreasing the information gap on building façades and determining the value for further use.

Research questions
Main research question

How to facilitate façade circularity in maintenance using a Digital Twin?

Sub-questions
1. *What are current goals of buildings owners with respect to circular maintenance and condition of façades?*
2. *Which data is available on a facade's composition?*
3. *What is the current state of information management concerning façades?*
4. *Which data is available and necessary to map the condition of façades?*
5. *How to translate the minimum required data into a Digital Twin*
6. *How can the Digital Twin assist the circular maintenance management of the façade?*

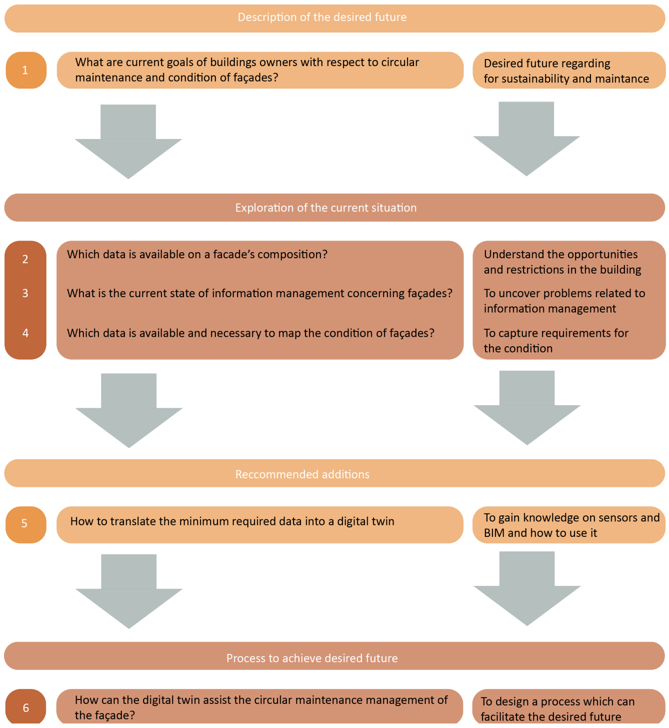


Fig C Thesis structure; Subcategorization of subquestions (Own ill.)

Aims and Deliverables
The aim of this research is (1) to design a process which informs façade owners on how to maintain a building façade in a circular fashion. (2) To support collaboration and communication between DT users by managing the accessibility of information. (3) To define the necessary data and specifications for the DT. (4) To stimulate project efficiency in circular projects, related to the future life of the façades.

The output of the research is a managerial process which guides involved actors of the maintenance process how to use the DT to guard the circular potential of façades. Additionally, specifications for the DT will also be given, which serves as input for the DT.

Literature review
Maintenance process
Maintenance combines all technical and administrative actions, in addition to supervisions which are also necessary to bring a façade component to the condition that meets its requirements (Madureira et al., 2017). According to Madureira et al. (2017), maintenance occurs in three steps: Detailed inspection, post-inspection maintenance actions and proactive maintenance actions. To plan adequate maintenance operations, an analysis must be made of the buildings' elements performance, their predicted service life, maintenance needs, degradation models and the most frequent anomalies. Besides, it is necessary to know the forces or agents exposed to the façade (Madureira et al., 2017).

Information management
Decisions regarding building maintenance demand integration of different types of information and knowledge created by different maintenance teams. When this information and knowledge is not captured, this results in additional costs and ineffective decision-making (Motawa & Abdulkareem, 2013).

Additionally, communication within the facility delivery process is often dependent on paper-based models. However, errors in this paper-based communication method often cause delay and unanticipated field costs between parties (Eastman & Sacks, 2011). This calls for effective communication between parties through improved forms of communication.

In BIM, stakeholders can store maintenance information in a structured way, which can reduce errors and facilitate communication between parties (Volk, Stengel & Schultmann, 2014). The use of BIM in the use and maintenance stages of a building's lifecycle aims to bridge the gap between operations and data; however, it lacks a real-time view state of the building. Therefore, BIM needs to be continuously updated, which is a labour-intensive project and needs accurate management (Stojanovic, Trapp, Richter, Hagedorn & Döllner, 2018). Graham and Bonacum (2004) describe the value of standardized tools and effective communication in complex maintenance systems, which prevent mistakes from being made. They can help bridge the differences in stakeholder communication in maintenance.
The DT application is a promising method to support circular maintenance of façades to ensure the quality of façade condition, and in addition to that the circular potential of façades. A DT is a combination between a virtual model and the physical object, designed to monitor, control and optimize the functionality of the physical object. In contrast to BIM, a DT comprises of real-time information: however, to overcome collaboration and communication problems, it requires a management process. This research will address this issue. The conceptual model of Figure 5 depicts the issue and its components within the research.

Methodology

Type of research

This research aims to develop a management process for the circular maintenance of façades, by means of a DT. The focus lies on improving the current situation and designing an additional dimension to it. This type of research can be considered problem-centred or practical research. The reason for this is that this research is aimed at investigating a practical problem, question or issue within an organisation or management context. The focus is directed at academic knowledge building as well as aimed at investigating and proposing solutions to real-life management problems (Lancaster & Crowther, 2005).

Data collection

Data collection has been carried out through primary and secondary data collection. Primary data collection involves information which is not yet widely available. Secondary data collection entails topics on which information is already available, this regards to data collected by sensors, documents on building passports and sustainability goals (Kumar, 2017).

- **Primary data collection:** Semi structured interviews
- **Secondary data collection:** Documentation and theoretical research

Methods and techniques

The applied methods are depicted in the research design, as shown in Figure E. The research design is divided into two parts. The first part consists of empirical and theoretical research. The second part consist of the synthesis: combining the derived information and knowledge. The synthesis forms the foundation for the research output.

Fig D Process design p1-p4 (Own ill.)

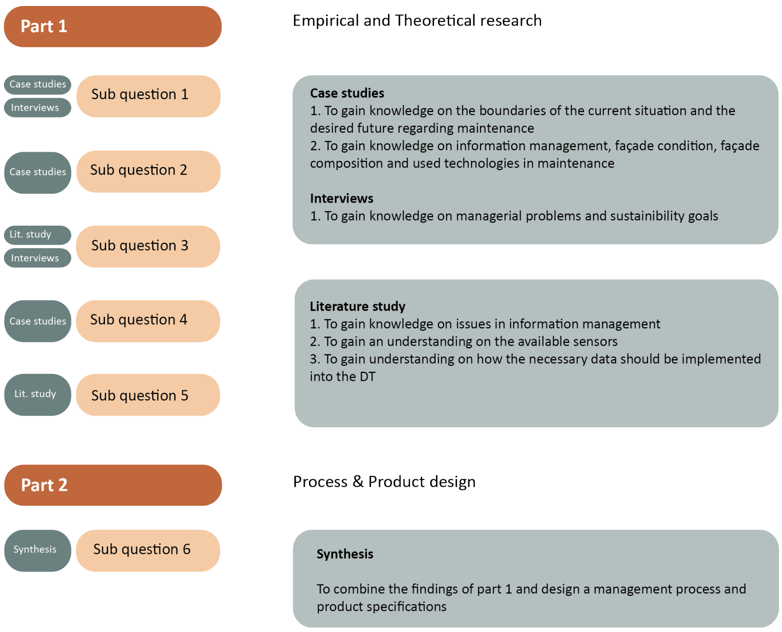


Fig E Research design with corresponding methods (Own ill.)

Empirical research

<u>Exploration of the current situation and desired future</u>

Interviews

Expert interviews have been conducted with actors from within the RVB, which expertise pertains to daily maintenance and larger maintenance projects. The aims of the interviews focused on understanding the process, products, involved stakeholders and their tasks. The outcome of the interviews describes the differences between the departments responsible for daily maintenance, and the department responsible for larger maintenance projects.

Case studies

Three case studies have been analysed in an in-case analysis, which are all part of the RVB portfolio. The aim for every case study is to gain knowledge on (1) the goals and issues of building owners of condition performance and circular maintenance. Also, (2) to investigate the maintenance process (3) analysis of building information and (4) information management.

Case study 1: JuBi Towers

The JuBi Towers is a high-rise office building situated in the city center of the Hague, built in 2012. The building provides 4000 workspaces for 5000 civil servants.

Façade condition: The goals for façade condition are compliance with building law requirements and providence of comfort for the buildings' activity. Also, the façade should not demand large maintenance tasks. However, the existing situation points out the façade has been showing several issues, such as cracking and crumbling bricks.

Maintenance process: The maintenance team of contractor Heijmans aims to solve the defects. Issues arise in detecting and describing defects in writing, as well as providing adequate information for a plan of actions are related to the fact that inspections are performed visually. Also, inspections are planned to be executed every year, this has a substantial disadvantage compared to real time inspections.

Information management: Computer systems are used to store and manage technical information and defects. However, its flaw is human-produced errors, as defects are often not signed out when solved in the physical object.

Case study 2: Rijkswaterstaat Building

The Rijkswaterstaat building is a mid-rise office building in Rijswijk, a suburb of The Hague. This building provides workspaces for 250 civil servants and was built in 2004.

Façade condition: Quickly after the buildings' delivery the façade showed severe defects, examples are falling cladding, wetted insulation and rusted window frames. Construction errors have been indicated as the responsible factor in the deterioration of the façade

Maintenance process: Barriers in the maintenance process are related to flaws of visual inspections and documentation of the defects. As well as lacking information on the characteristics of each defect. Strengths of the maintenance process is use of digital measures to expose the defects. Issues arise in detecting and describing defect, as well as providing adequate information for a plan of actions are related to the fact that inspections are performed visually.

Information management: Flaws in information management encompass poor keeping track of information.

Case study 3: Galileo Reference Building

The Galileo Reference Building is an office building and data center, situated in the flatlands near the Northsea. It is built in 2017 and the buildings' design is circular and sustainable.
Façade condition: The façade is made of interchangeable cassettes, which are detachable. The materials have been chosen to fulfil a long lifetime. The façade is situated in open flatlands, which is why the building is vulnerable to strong winds. Barriers of circular maintenance are flaws occurring through visual inspection of the building, overlooking in defects and the
Maintenance process: Barriers in the maintenance process are related to flaws of visual inspections and documentation of the defects. Issues arise in detecting and describing defect, as well as providing adequate information for a plan of actions are related to the fact that inspections are performed visually.
Information management: This building has up to date building plans and technical information. The building has an up to date BIM-model; however, this is not being used.

Findings

Recommended additions

The theoretical research comprises a literature review into sensor technology. The main building defects from the case studies formed the foundation for the research into sensor technology.
The influence on the existing maintenance processes are also described.

Case study 1

Main building defects	Current detection technology	Recommended detection technology	Recommended additions
Falling cladding and cracking	Visual inspections	Infrared thermography & piezoelectric actuators	Determine data purpose, data storage, educate employees,

Case study 2

Main building defects	Current detection technology	Recommended detection technology	Recommended additions
Falling cladding	Visual inspections	Distributed optical fiber sensors & piezoelectric actuators	Add new tasks, clearly allocate those tasks, ensure involved actors understand the technology
Leaks	Visual inspections	Infrared thermography	Add new tasks, clearly allocate those tasks, ensure involved actors understand the technology

Case study 3

Main building defects	Current detection technology	Recommended detection technology	Recommended additions
Leaks	Visual inspections	Infrared thermography	Ensure incentive to use new technologies is clear, involved people need to understand the technologies, data needs to be stored and managed
Damaged window frame coating	Visual inspections	Infrared thermography	

When striving for circular maintenance, the building in question should adhere circular prerequisites:

- Demountable façade
- High quality non-environmentally harming materials
- Request information valuable for reuse during design phase of the building.
    - Type of connections
    - Number of connections
    - Composition
    - Weight

- Currently, employees are not educated to work with new technologies, so they must be educated to work with them. Also, they need an incentive to work with the new technologies, otherwise they will return to their habitational processes.
- New departments should be created within the organisation
- Talent should be recruited, and have knowledge on
    - Data analysis
    - Data maintenance
    - Data storage
    - Programming
- Tasks should be allocated clearly, and a manager should guide the process. This person should ensure the tasks will be carried out.
- Sensor maintenance and replacement should be taken into account. This means the team should be prepared for sensor developments in the market, as well as sensor failure in the building.

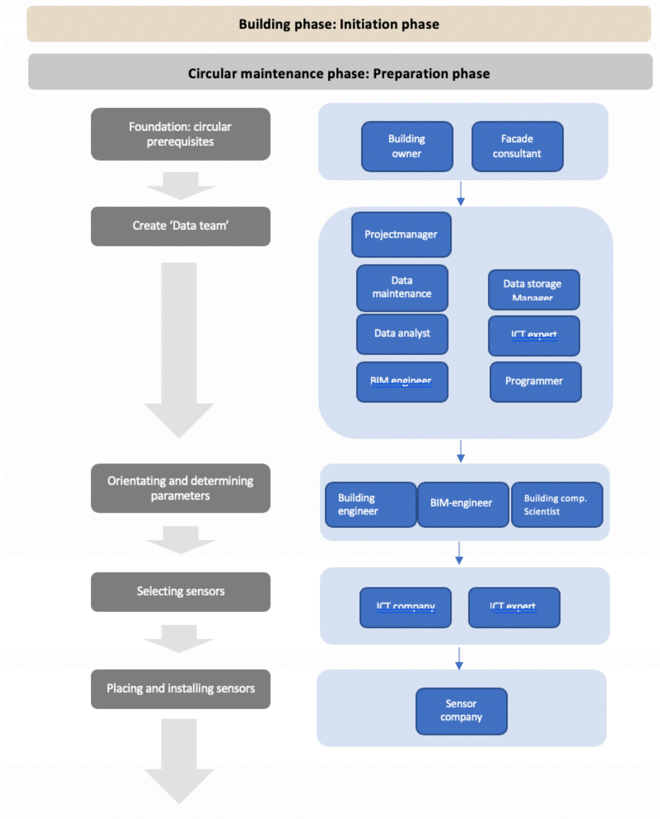
Conclusions

The conclusion describes the answer to the main question through a proposed process. The process is described on the next page.

Discussion

The following topics are addressed in the research discussion:

- *Discussion problem statement – research findings*
- *Discussion research findings*
- *Discussion beforehand expectations*
- *Discussion research methodology and research limitations*


Building phase: Initiation phase
Circular maintenance phase: Preparation phase
Foundation: circular prerequisites
Building owner
Facade consultant
Create 'Data team'
Projectmanager
Data maintenance
Data storage Manager
Data analyst
ICT expert
BIM engineer
Programmer
Orientating and determining parameters
Building engineer
BIM-engineer
Building comp. Scientist
Selecting sensors
ICT company
ICT expert
Placing and installing sensors
Sensor company

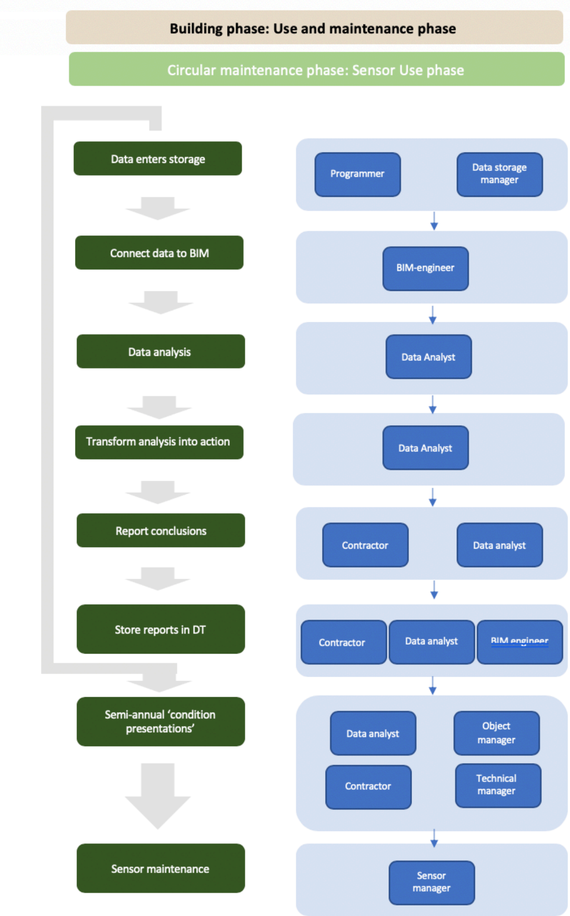

Building phase: Use and maintenance phase
Circular maintenance phase: Sensor Use phase
Data enters storage
Programmer
Data storage manager
Connect data to BIM
BIM-engineer
Data analysis
Data Analyst
Transform analysis into action
Data Analyst
Report conclusions
Contractor
Data analyst
Store reports in DT
Contractor
Data analyst
BIM engineer
Semi-annual 'condition presentations'
Data analyst
Object manager
Contractor
Technical manager
Sensor maintenance
Sensor manager

Table of Contents

Chapter 1
Introduction

Introduction

1.1 Research Analysis

Motive 1: Required shift from the linear to the circular economy

The construction industry operates in a linear matter, which means virgin resources are used and then discarded as waste. During the construction phase, the supply chain of the built environment uses a substantial amount of natural resources to produce components, which impacts the environment (Mulders, 2013). In Europe, the construction industry is the largest consumer of resources and energy. This consumption considers their full lifecycle: material extraction, manufacture, transport, construction, use phase and end of life. Their full impact counts for 50% of all energy use, 40% of all greenhouse gas emissions, 50% of the materials going into the economy and 30% of all water use (European Commission, 2019). The supply chain also produces a substantial amount of waste during the construction phase. When waste is not handled efficiently, this increases the take-up of natural or virgin resources (Mulders, 2013). The lingering environmental, economic and societal threats suggest that the linear economy must change.

CE is increasingly gaining acceptance as a method to tackle environmental, societal and economic problems produced by the linear economy. It is a promising method for combating the *greenhouse gas* (GHG) emissions and resource over-use in the built environment. The most renowned definition of CE originates from the Ellen MacArthur Foundation: 'A *circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models* (Ellen MacArthur Foundation, 2013, p8). Waste and the need for virgin resources are reduced through reuse, repair, remanufacture and recycling of existing building components. This stresses the need for designing for deconstruction, creating a high-value product and keeping the value as high as possible (Avraamidou, Baratsas, Efstratios & Pistikopoulos, 2019). Figure 1 describes how technological and nutrient-based products and materials cycle through the economic system (Ellen MacArthur Foundation, 2013).

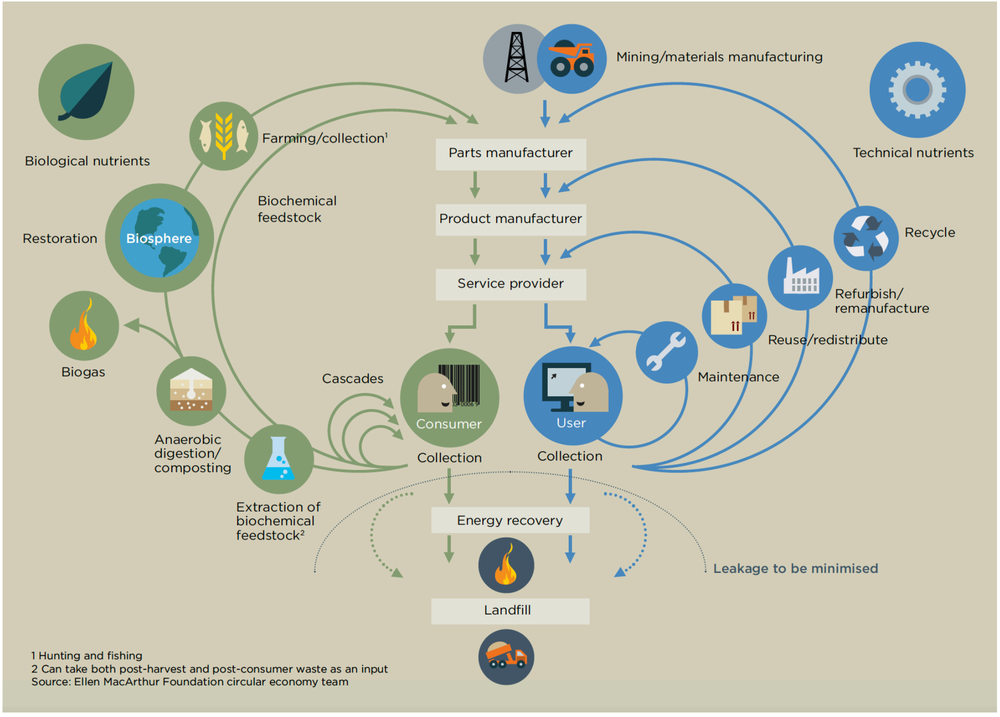


Fig 1. The circular economy – an industrial system that is restorative by design (Ellen MacArthur Foundation, 2013, p24).

CE reduces energy demand and subsequently, the emissions in a direct and indirect matter (Geisdoerfer, Savaget, Bocken & Hultink, 2017; Ritzén & Sandström, 2017). Indirectly, CE reduces the emissions of the construction phase as less energy is needed to manufacture new components from virgin resources (Ritzén & Sandström, 2017). For example, implementation of resource efficiency in the mobility, food and built environment through CE could reduce GHG emissions by 48 % by 2030. Besides, it could reduce GHG emissions by 83% by 2050; both compared to levels of 2012 (Ellen MacArthur Foundation & the McKinsey Center for Business and Environment, 2015). Directly, CE reduces GHG emissions in the use phase. Maintaining the quality of a façade during its lifetime in a building increases the embodied energy of the object, which is related to its energy efficiency. In this way, less energy is wasted, and fewer GHG is emitted to produce energy (Ellen MacArthur Foundation, 2019). Circular building practices have the potential to lower both GHG emissions and resource consumption (de Lange et al., 2018).

CE can be applied on several levels: site, structure, skin, services space plan and stuff (Brand, 1994). The skin of a building, a façade, is an interesting topic within CE, because its application in CE can have an impact in a buildings' use phase as well as the construction phase. Maintaining the performance quality of façades in the use phase can result in fewer energy leaks and thereby stimulate a buildings' energy efficiency. Additionally, when maintaining the performance quality of the façade, fewer new materials for repair or restoration are necessary.

CE also provides the opportunity to end the loss of valuable finite resources, to become less dependent on the global resource market and creating new job opportunities (Heisel & Rau-Obenhuber, 2019). However, despite its promising advantages, CE is rarely adopted in practice, as it requires fundamental changes in the current workflow (Ritzén & Sandström, 2017). Also, a low level of awareness concerning the preservation of natural resources restricts the circular material flow in construction (Zabek, Hildebrand, Wirth & Brell-Cokcan, 2017). Buildings are not yet widely regarded as materials depots, one of the reasons a circularity gap has emerged, in which more is disposed of than reused (Circle Economy, 2019). Figure 2 conceptualizes this gap.

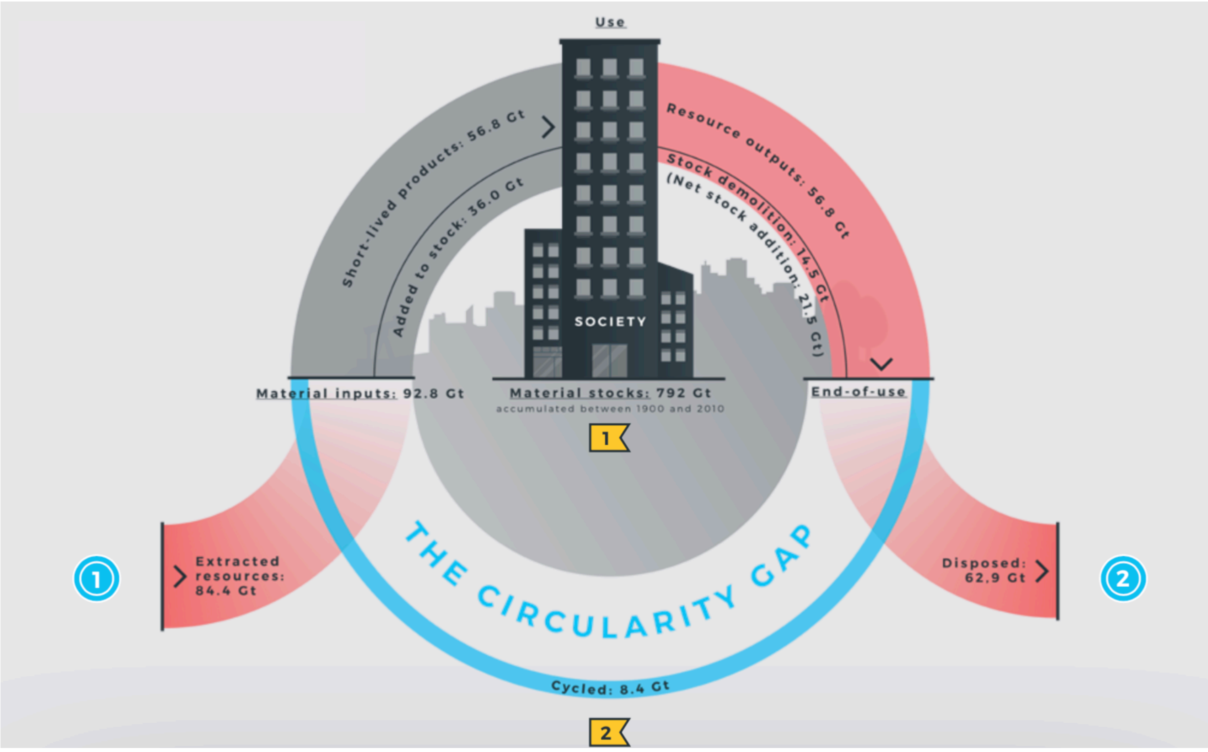


Fig 2 The circularity gap as described by Circle Economy (Circle Economy, 2019, p29)

Motive 2: Low quality at the end-of-life withholds circular façade demand

In current circular projects, the quality of components in 'donor buildings' is an issue. Stakeholders are often hesitant about the quality of façade components. Ritzén & Sandström (2017) state that reusing components of which the quality is low or unknown is a significant risk for companies. This restricts demand for circular façades. Besides, there is a poor understanding of the reuse potential of components (Hart, Adams, Giesekam, Tingley & Pomponi, 2019). Currently, building façades are generally designed to have a service life of 20 to 50 years, which reduces their reuse and circular value at the end-of-life, turning them into mere waste (Interview A). Due to the long lifespans of buildings, maintenance management is an important topic to resource efficiency and closed-loop material cycles (Volk, Stengel & Schultmann, 2014).

When reusing materials, it is vital to know their performance conditions. These days we are expecting more of building materials concerning the performance. A façade plays a major part in providing comfort within a building. Maintaining, retaining and restoring its quality is vital when reusing a façade in another project or when extending its lifetime (Zabek et al., 2017).
Of all building parts, façades are exposed to physical damages the most and require frequent reparations. Therefore, tracking the quality of building façades is essential for ascertaining reuse potential and circular value (Androsevic, Durmisevic & Brocato, 2019). Façade reuse is dependent on several other factors as well: the current architectural trends and how the user values the façade.

Façade reuse is also reliant on future changes in building regulations. Future values of subjective factors are hard to predict because it is complicated to determine the trends of 30 years from now. However, it is possible to prepare a component for circularity by making sure its circular value and reuse/disassembly potential are high and constant (Interview A).

The circular potential of façade components depends on (1) design for disassembly (2) design for adaptability, (3) the use of high quality, non-toxic, circular components, elements and materials (4) technical and aesthetical performance, (5) location, (6) component composition, (7) and maintenance details (Heisel & Rau-Obenhuber, 2019; Interview A; Interview B). Hart et al. (2019) state that measuring the quality and performance of materials along its lifecycle is a key enabler for CE. However, collaboration tools, information and metrics, able to facilitate this, are not being used efficiently (Hart et al., 2019). However, finding and accessing this data is difficult, even though it is vital for understanding the circular potential and residual value of a building component (Interview A). If it is not possible to ascertain the circular potential of a building component, the façade may be discarded as waste, because it is too costly and time-consuming to measure its value.

The priority of circular maintenance is directed at creating a maximum utility of the technology lifecycle and safeguarding the future value of the component. This derives from a maintenance system that performs continuous improvement. The system is subjective to the speed of the repair, the quality of the repair, guarding customer satisfaction, keeping track of waste streams on-site, and the preparedness to support maintenance (Ajukumar & Gandhi, 2013).

The implementation of circular façades is very relevant in commercial real estate. This is due to the fact commercial real estate is flexible and dynamic. Inflow and outflow of tenants occurs often, and the building is subject to renovation every certain amount of years (Interview C).

Motive 3: Rising project complexity through a lack of information withholds circular façade demand

Understanding buildings as material depots radically changes the way resources need to be handled. In buildings, it is necessary to keep track of the resource flow, to document and communicate which materials become available for reuse and recycling and in which quantities (Heisel & Rau-Obenhuber, 2019). Due to the increasing complexity and the high number of materials and components in a building, there is need for information management, digitization, process automation and implementation of data standards to reduce project complexity (Heinrich & Lang, 2019). The large amounts of involved data require digital solutions to collect, process, store and utilize the information for this information to be reliable and easily accessible. The highest level of information detail is provided at the delivery of the building. This information regards technical composition, location and ownership, among other things. However, building and material-related information are seldom passed on at its commission, as the real estate sector is not information minded. For CE in façades to function, it is necessary that this information is passed on and updated when changes are made. As buildings have long lifespans, this information needs continuous management (Heinrich & Lang, 2019). As mentioned in the previous section, façades are exposed the most to physical wear of all building components. Therefore, it is essential to track the quality of building façades to determine its reuse potential and circular value (Androsevic, et al., 2019).

For example, façade company Frener & Reifer have investigated the circularity potential of a Victorian building façade. They aimed to identify issues and possibilities for material and component reuse, to discover how easy it was to disassemble and to measure how long the disassembly took. They concluded that reuse was possible but limited. Also, the reuse potential, in general, is limited by changes in the users' taste and future regulation alterations. Disassembly was limited by having no accurate drawings and composition data on the components. Besides, disassembly was difficult due to the lack of standardization of elements, such as bolts. It was concluded that information on separation and disassembly, operation and maintenance were necessary to determine the reuse potential. In the end, having little information available on composition, connections and technical state makes it a time-consuming and expensive process. This could be stimulated by having such information available quickly (Arup, 2019).

1.2 Problem statement

Circular façades can reduce GHG emissions in the use phase. Due to the significant environmental impact of the built environment, there is a need to develop circular façades. However, there are barriers to the development of circular façades: the low end-of-life quality and increasing project complexity due to lack of information on the condition of façades. Information on façade characteristics and condition is not widely available, and collection is time-consuming. Consequently, it becomes a significant risk for companies to reuse components of which the quality is uncertain. As a result, the chance that the façade will end up as waste becomes greater. Therefore, there is a need for transparent information on performance quality and assurance of this quality through effective maintenance. Scientific literature lacks the management of storing and updating the condition information on façades during maintenance, and its use to improve the circular potential of the façade. This thesis will address this gap.

1.3 Research scope

This research addresses the literature gap around information capture in circularity maintenance of façades. The knowledge gap defined in literature is the management of updating and storing of information on a façades condition quality, and the use of this during maintenance.

As 'technical performance' and 'maintenance details' are related to condition quality, this will be the scope concerning the required data and information.

Also, it is of importance for a façade to be demountable. Façade connections can be either dry or wet. Dry connections refer to attachments to the building through bolts and nuts. Wet connections refer to attachments through glue, or when they stick to the building. It is of vital importance for circular façades to be quickly detachable. However, limiting the research to only demountable façades can be a constraint. In this thesis, the focus lies on both dry and wet connections.

Due to in- and outflow of tenants in office buildings, these types of buildings are flexible and dynamic. Office buildings are therefore subjective to renovation every specific amount of years. Maintenance in large office buildings is also a complicated matter. Thus, the implementation of circular façades is interesting. For this research, the focus will lie on office buildings.

Regarding the digital measures, the scope will be reduced to the use of a DT. This consists of BIM and IoT sensor data. The specific sensors will be chosen later in the research.

The positioning of the research within the circular building process is depicted in Figure 3. The research is positioned in the use phase.

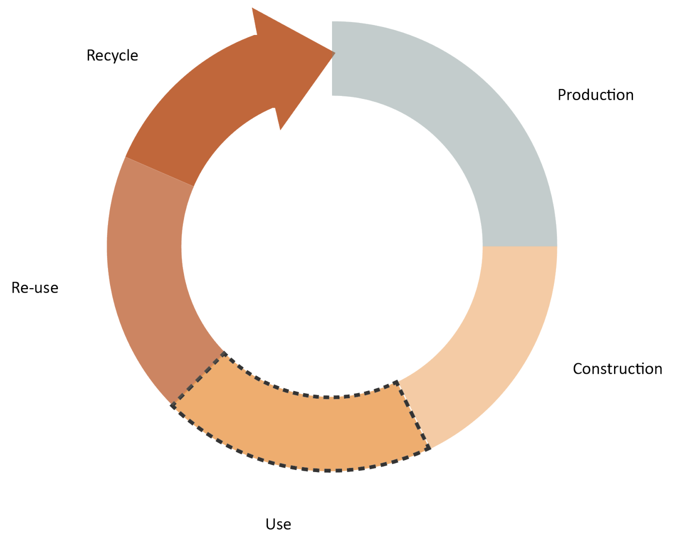


Fig 3. Positioning research within the circular building process (own ill.).

1.4 Relevance

In this section, the relevance of this research for scientific literature and society are explained.

Societal relevance

According to the 2015 Paris agreement, countries should curb emissions to keep global warming well below 2 °C above pre-industrial levels in this century, and to pursue efforts to keep global warming below 1.5 °C (IPCC, 2018). Currently, global warming already has shown its consequences, like the increase in precipitation and the subsidence of soil in many parts of the Netherlands (Dai, Wörner & van Rijswick, 2018; IPCC, 2018). If global warming continues to increase, this will pose dangers for the future as well. Core threats like sea-level rise will become even more dangerous for the Netherlands (IPCC, 2018). Adhering climate regulations is, therefore, of great importance. Developed countries play an essential part in this, as they have a higher chance to tackle climate-related problems, having greater availability to resources like money and knowledge (IPCC, 2018). So, the Netherlands has an opportunity and obligation to lead the way and develop methods to curb emissions for the construction phase.

According to the United Nations development goals, there is a great need to repurpose used materials (United Nations, 2019). Also, according to the Dutch government, circularity within the built environment is of great importance (Ministerie van Infrastructuur en Milieu & Ministerie van Economische Zaken, 2016). As mentioned before, the built environment counts for half of the materials going into the economy and produces large numbers of CO^2. Besides, CE strives for resource efficiency, as virgin resources are being depleted at this moment, and the built environment ought to be less dependent on them. CE facilitates the end of loss of valuable finite resources (Heisel & Rau-Obernhauer, 2019).
However, the adoption of the CE by the construction industry is infancy. Despite this poor adoption, the Dutch government aspires to be 50% circular in 2030 and 100% circular in 2050 within various sectors, among them being the built environment (Ministerie van Infrastructuur en Milieu & Ministerie van Economische Zaken, 2016). This requests the need for the Dutch construction industry to become circular to reach climate goals. It requires necessary changes to current construction management. Companies are already developing methods for becoming more sustainable and resource-efficient, as they are obliged to adhere to climate regulations (Interview A). Also, to be more resource-efficient, it of importance to implement circular measures. Therefore, companies start developing circular building methods to be able to remain their competitive position in the next 30 years (Interview A).

In today's rapidly changing environment, it does not take long for some of the knowledge to become outdated. Organisations change, ideas and knowledge change and circumstances change as well. The need for continued professional development is necessary and is done through knowledge development (Lancaster & Crowther, 2005). Due to the current issues among management of circular maintenance, there is a need to manage and stimulate communication and collaboration in maintenance to encourage its adoption. This research adds new insights to storing and updating information on façade condition to diminish this barrier to CE. This research is necessary due to the need for strengthening of knowledge on circular maintenance, which is crucial for keeping materials in the loop and decreasing the pressure on the environment.

Scientific relevance

In scientific literature, the concept of the circular economy is widely described. Literature extensively addresses barriers and enablers to the circular economy and the lack of adoption in digital solutions. However, circular enablers on a smaller scale – materials or components - have not been considered extensively. The same holds for research into the management of a circular process. Research into how the supply chain of the built environment should use digital solutions to determine the value of reuse in building facades can be improved. This research can facilitate the move towards decreasing the information gap on building façades and determining the value for further use.

Chapter 2
Research Questions

Research Questions

2.1 Main question

The research question of this paper is:

How to facilitate façade circularity in maintenance using a Digital Twin

2.2 Sub-questions

To be able to answer the main research question, several sub-questions will be considered. Besides these sub-questions, it is also important to consider the plan of action, or research method, on how to derive the answer. Choosing valid research methods have a considerable influence on the findings (Kumar, 2017). The sub-questions are as follows:

1. *What are current goals of buildings owners with respect to circular maintenance and condition of façades?*

   Method: Case studies (Scan of 'Program of Requirements') & interviews

   Goal: To uncover the problems to be solved or goals to be achieved related to façade-condition and circular maintenance.

2. *Which data is available on a facade's composition?*

   Method: Case studies

   Goal: To derive information on the composition, connections and materials of façade components.

3. *What is the current state of information management concerning façades?*

   Method: Literature review & interviews

   Goal: To uncover collaboration problems related to storing, handling and interpretation of information, that need to be solved. In general, and specifically for Rijksvastgoedbedrijf.

4. Which data is available and necessary to map the condition of façades?
Method: Case studies
Goal: To capture information flows, analysis of the dataset, combination of different data sources. Related to 'dynamic' datasets

5. How to translate the minimum required data into a Digital Twin
Method: Literature review
Goal: To understand how sensors work, which sensors to choose and how to include the necessary data in BIM.

6. How can the Digital Twin assist the circular maintenance management of the façade?
Method: *Synthesis*
Goal: The design of the process, in general and specifically for the Rijksvastgoedbedrijf.

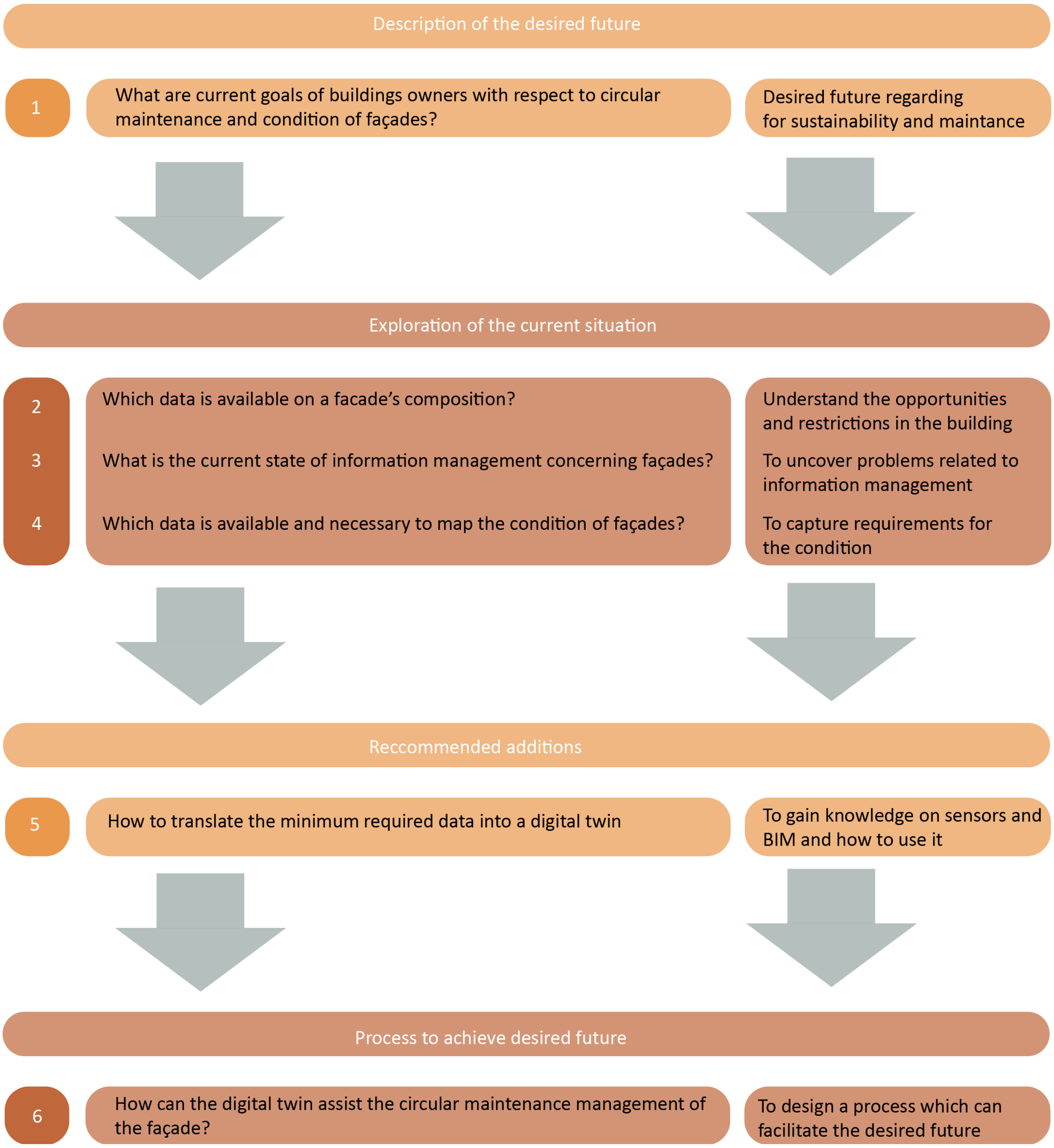


Fig 4. Thesis structure (own ill.)

Chapter 3

Research Aims and Deliverables

Research Aims and Deliverables

3.1 Goals and objectives

The aim of this research is (1) to design a process which informs façade owners on how to maintain a building façade in a circular fashion. (2) To support collaboration and communication between DT users by managing the accessibility of information. (3) To define the necessary data and specifications for the DT. (4) To stimulate project efficiency in circular projects, related to the future life of the façades.

3.2 Deliverables

The output of this research consists of two parts: the process and the product. The first part focuses on the users of the DT. These are actors concerned with façade maintenance, such as the facility manager and the property manager. This first part is (1) an information and process flow that guides involved actors on how to use the DT. It is a managerial output that describes how the building owner should maintain the quality of a façade, suitable for circularity using the DT. Secondly, the second part (2) 'the product' is directed at the developers of the DT. This deliverable entails the specifications for the digital twin, including which data should be added to a BIM model, which sensors are necessary for the building and the façade and what they have to measure.

3.3 Dissemination and audiences

Dissemination refers to the planned process of determining target audiences and the settings in which research results could be used. It also involves communicating and interacting with wider audiences in ways that facilitate research uptake in decision-making processes and practice (Wilson, Petticrew, Calnan & Nazareth, 2010). In other words, for the research to be useful, it needs to be disseminated to the people who can use it.

Circularity is currently at the beginning of its development. Barriers like knowledge on how to implement CE are holding the adoption of CE back. This research explains how circular maintenance of façades can be addressed, which is why the prospective audiences must be concerned towards the implementation of CE in their buildings. Additionally, they should have incentives for implementing circular façades. It is important they want to apply it or are already implementing it in their buildings. Also, maintenance of the façades should be part of the audience's duties. Or, the audience should have the incentive to be concerned with the maintenance of façades. Generally, audiences that are involved with maintenance depends on the contract made in the initiation phase of the building. They ought to be owners of the façades or have the duty to maintain the building. The latter can be possible in the form of a Design Build Maintain, Design Build Maintain Finance and Operate, or a different combination of which 'Maintain' or 'Operate' is part. These parties can be the building owners or owners of the façade, should it be leased out. Also, it can be the suppliers of the building owner as well. Building owners of offices can be the government, real estate investment firms, among many others.

This research is directed towards façade and building owners, on how they can address circularity maintenance. The settings in which the research should be received involves that this research output should be readable by the prospective audience. Possibly by providing the participants of the interviews and case studies with the summary of the final results.

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Chapter 4
Literature study

Literature Study

This chapter provides background information on the proposed problem of this research.

Façades are the face of a building. They determine its appearance, simultaneously working as a barrier to external forces and as a communication element between inside and outside, through light, visibility and ventilation. They play a fundamental role in the buildings' performance, all the while being a complex system to maintain (Madureira, Flores-Colen, De Brito & Pereira, 2017). As explained in the previous chapter, all building parts are a barrier and a risk factor in circular projects because the quality is often unknown or low. Due to its crucial role in a building's performance, assurance of a façades end-of-life condition is of vital importance. That is why maintenance is essential concerning the circular potential of façades. Capturing the condition quality of façades is a critical enabler of CE (Hart, et al., 2019).

Planning maintenance

To plan adequate maintenance operations, an analysis must be made of the buildings' elements performance, their predicted service life, maintenance needs, degradation models and the most frequent anomalies. Façades consist of walls, openings and cladding, identifying these façade components - in a building passport - and its associated needs and details is vital when determining the maintenance needs, as are the most probable anomalies and causes. Besides, it is necessary to know the forces or agents exposed to the façade (Madureira et al., 2017). It is also of importance to take the user's needs and expectations into account during maintenance. Determining this information is necessary for drawing up a maintenance plan, which anticipates proactive maintenance actions during different time ranges and with minimal interference with the regular functioning of the building (Madureira et al., 2017).

Maintenance process

Maintenance combines all technical and administrative actions, in addition to supervisions which are also necessary to bring a façade component to the condition that meets its requirements (Madureira et al., 2017). According to Madureira et al. (2017), maintenance occurs in three steps:

- ⇒ Detailed inspection
- ⇒ Post-inspection maintenance actions
- ⇒ Proactive maintenance actions

To minimize the direct environmental impact of façade maintenance, maintenance actions should only be performed when needed, leaving the components in good condition (Blom, Itard & Meijer, 2010). Reduced environmental impact of proper planning in façade maintenance is mainly related to a reduction of transportation movements of maintenance workers, due to lower activity frequency (Leonard, Graham & Bonacum, 2004).

Information Management

Maintenance activities cover the longest lifespan of buildings and also involve multiple stakeholders, who may be replaced over time. Therefore, detailed data of used products need to be tracked by authorities and clients. Consequently, it requires a system which captures and updates this data. Studies on integrated IT solutions have been conducted to overcome these problems. However, these problems were related more to information sharing and less to knowledge capture-and sharing (Motawa & Abdulkareem, 2013). Detailed information on the façade is a prerequisite to sharing this information.

Decisions regarding building maintenance demand integration of different types of information and knowledge created by different maintenance teams. When this information and knowledge is not captured, this results in additional costs and ineffective decision-making (Motawa & Abdulkareem, 2013). Maintenance already plays a critical factor in the total costs of a building. During a building's lifecycle, costs can occur at three stages: design, construction and use and maintenance. Design and construction costs are of great concern, but most of the costs occur in the use and maintenance stage. When a building has a service life of 50 years, 75%-80% of the total expenses arise in the use and maintenance stage. Besides the environmental impact, effective planning can also have a substantial economic effect (Madureira et al., 2017). Ineffective decision-making impacts this in a harmful matter.

Additionally, communication within the facility delivery process is often dependent on paper-based models. However, errors in this paper-based communication method often cause delay and unanticipated field costs between parties (Eastman & Sacks, 2011). This calls for effective communication between parties through improved forms of communication.

In Building Information Modeling (BIM), stakeholders can store maintenance information in a structured way, which can reduce errors and facilitate communication between parties (Volk, Stengel & Schultmann, 2014). Most functions are still done manually, even though facility managers know that adopting BIM can decrease the probability of errors and an increase in efficiency (Aziz, Nawawi & Ariff, 2016).

The use of BIM in the use and maintenance stages of a building's lifecycle aims to bridge the gap between operations and data; however, it lacks a real-time view state of the building. Therefore, BIM needs to be continuously updated, which is a labour-intensive project and needs accurate management (Stojanovic, Trapp, Richter, Hagedorn & Döllner, 2018). An updated BIM model with real-time data of the original building is the DT. Leonard, Graham and Bonacum (2004) describe the value of standardized tools and effective communication in complex maintenance systems, which prevent mistakes from being made. They can help bridge the differences in stakeholder communication in maintenance. Critical success factors in this process of maintenance are visible support and strong leadership.

Many research efforts have been made in maintenance and BIM-related topics; however, an industry-wide implementation is lacking. It requires accurate information on objects, relations and attributes in BIM. Maintenance and updating this information in BIM remain a huge challenge and an area of research (Volk et al., 2014).

The DT application is a promising means to support circular maintenance of façades to ensure the quality of façade condition, and in addition to that the circular potential of façades. It is a shared knowledge resource for information about a facility or object (Kaewunruen & Xu, 2018). A DT is a combination between a virtual model and the physical object, designed to monitor, control and optimize the functionality of the physical object. It comprises of real-time information, measured by building-integrated sensors, which is stored and cognitively analysed in order to facilitate operations. In contrast to BIM, a DT comprises of real-time information: however, to overcome collaboration and communication problems, it requires a management process. This research will address this issue. The conceptual model of Figure 5 depicts the issue and its components within the research.

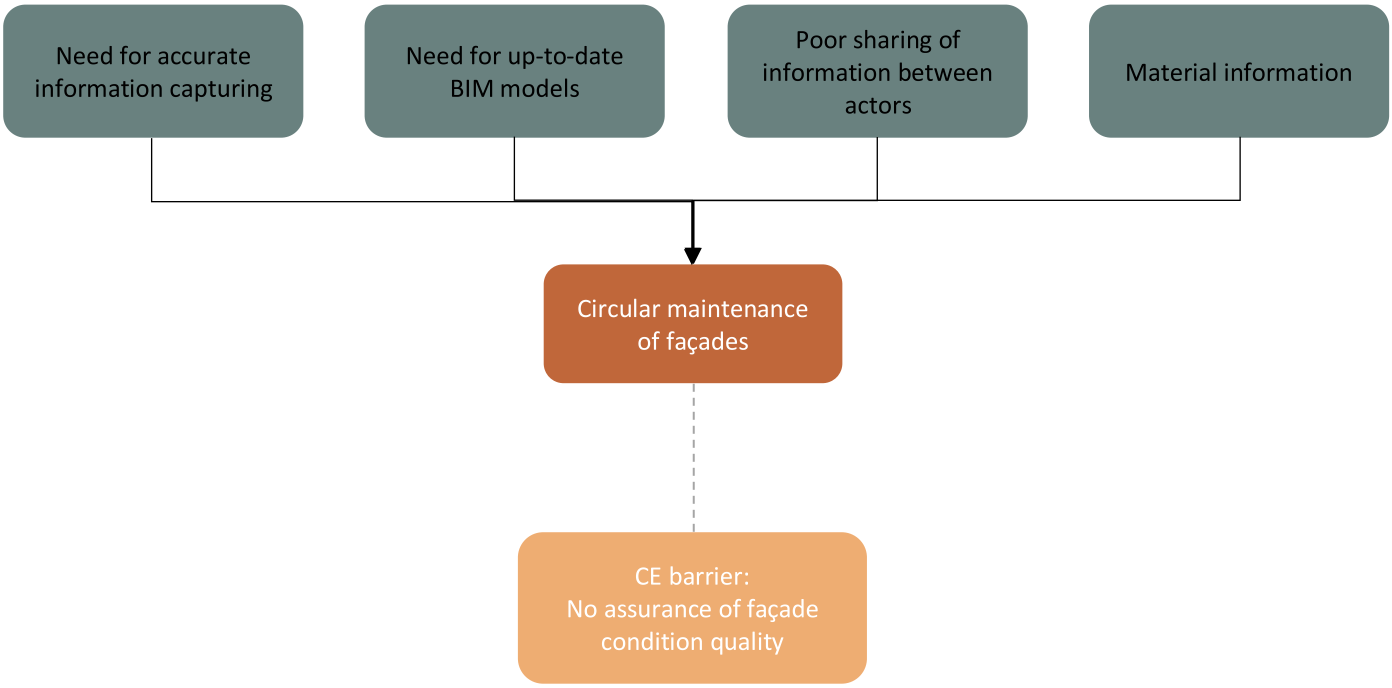

Fig 5. Conceptual model (own ill.)

Chapter 5
Research Methodology

Research Methodology

5.1 Type of study

This research aims to develop a management process for the circular maintenance of façades, by means of a DT. The topics of DT and circular façades are relatively new in practice, which is why this study has an explorative character (Bryman, 2012). The focus lies on improving the current situation and designing an additional dimension to it. Additionally, as the focus is to improve the current situation, this study has an operational character (Bryman, 2012).

This type of research can be considered problem-centred or practical research. The reason for this is that this research is aimed at investigating a practical problem, question or issue within an organisation or management context. It has a view of facilitating that problem and subsequently making recommendations for courses of action (Lancaster & Crowther, 2005). The focus is directed at academic knowledge building as well as aimed at investigating and proposing solutions to real-life management problems (Lancaster & Crowther, 2005).

This paper is investigating a management issue, and management research raises both theoretical and practical questions. Therefore, it is of importance to conduct theoretical and empirical knowledge (Lancaster & Crowther, 2005). If a large number of researches has been done on a particular topic, it is very useful to conduct a literature review. The reason for this that knowledge on this topic is varied and up to date. Regarding this research, theoretical research is relevant for the use and understanding of BIM, DT and façade maintenance. However, some topics pertinent to this research are fairly new. This calls for empirical research into those topics (Tharenou, Donohue & Cooper, 2007). Empirical research enables the necessary connection with the real world, gaining knowledge through experience from practice (Bryman, 2012). Empirical research can be done through case studies and interviews. Tharenou et al. (2007) state that the way a question is posed can say a lot about its research methods. Since the word ‘how’ is used in the research question, it will mainly refer to empirical research.

The output of this study aims to suggest a process and a product, which indicates an operational or managerial character. To be able to derive the operational output, the current situation has been analysed. The current situation refers to the existing methods and problems in information management, connections between actors and goals related to façade maintenance. To reach the desired future, new connections regarding information management, the use of DT and stakeholders should be suggested, as the aim is to improve the current situation. Data concerning the performance of façades needs to be analysed to understand which data is relevant to use. Alternative options will be explored to reach the desired future. Due to the data analysis of the façade condition, this study has a qualitative character. A quantitative research method answers the question 'how much' or 'how many' (Tharenou et al., 2007). The analysis of current connections and goals in the supply chain relates to qualitative research. The reason for this is that the purpose of qualitative research to provide detail, process, richness and sensitivity to the context (Tharenou et al., 2007). Therefore, this study has the characteristics of a qualitative study (Bryman, 2012).

5.2 Data collection

Regarding collection of the data, primary and secondary types of data collection have been taken into consideration. Primary data collection involves information which is not yet widely available. In this research, this information is related to problems in information management and collaboration, goals related to façade performance and goals related to circular maintenance. In order to gain access to this type of data, it is necessary to conduct interviews (Kumar, 2017). Secondary data collection entails topics on which information is already available, this regards to data collected by sensors, documents on building passports and sustainability goals (Kumar, 2017).

- Primary data collection:
  Interviews: Interviews are more appropriate for complex situation and useful for in-depth information (Kumar, 2017). Therefore, interviews are chosen to gain knowledge on problems in information management and the goals related to circular maintenance of façades. Interviews provide uniform information, which assures the comparability of the data (Kumar, 2017). This is useful in determining the most important problems in information management.

- Secondary data collection:
  ⇒ **Documentation:** Documentation is necessary to gain knowledge on sustainability goals, building information management, the building's composition and façade defects.
  ⇒ **Theoretical research:** The aim of the theoretical research is to gain an understanding on sensors, BIM and DT. It is important to understand how the DT can be used and what they are most useful for. In addition, to gain an understanding of the problems on information management on a general level.

In some cases, primary and secondary data collection may be combined. The case studies for example, involve large numbers of data and are complex. Multiple methods allow triangulation. A combination of methods is necessary to develop the clearest possible picture of the subject investigated (Tharenou et al., 2007).
Data collection regarding case studies can include systematic application of:

⇒ Interviews
⇒ Documentation
⇒ Attendance at meetings

This data is collected in four different phases. (1) The first phase consists of empirical research; this contains research on topics of problems in information management, façade composition and the maintenance process. Case studies have provided for data collection of buildings and documentation on the façade composition and condition. Data collection in this phase is done through semi-structured interviews and documentation. (2) The second phase is theoretical research. This regards to the investigation of sensor technology and DT's. The aim of this phase is to gain an understanding of available sensors available to use in the collection of building data and what a DT is. After finalising the second phase, and in addition to that P3, it is of importance to analyse findings from the data collection. The data collected from the existing situation is combined with the findings from the literature. (3) The third phase is related to the analysis and synthesis of these conclusions. Knowledge will be implanted and combined, as well as relevant conclusions, will be drawn as such. (4) The fourth phase consists of designing the operational method. Figure 6 depicts the process design.

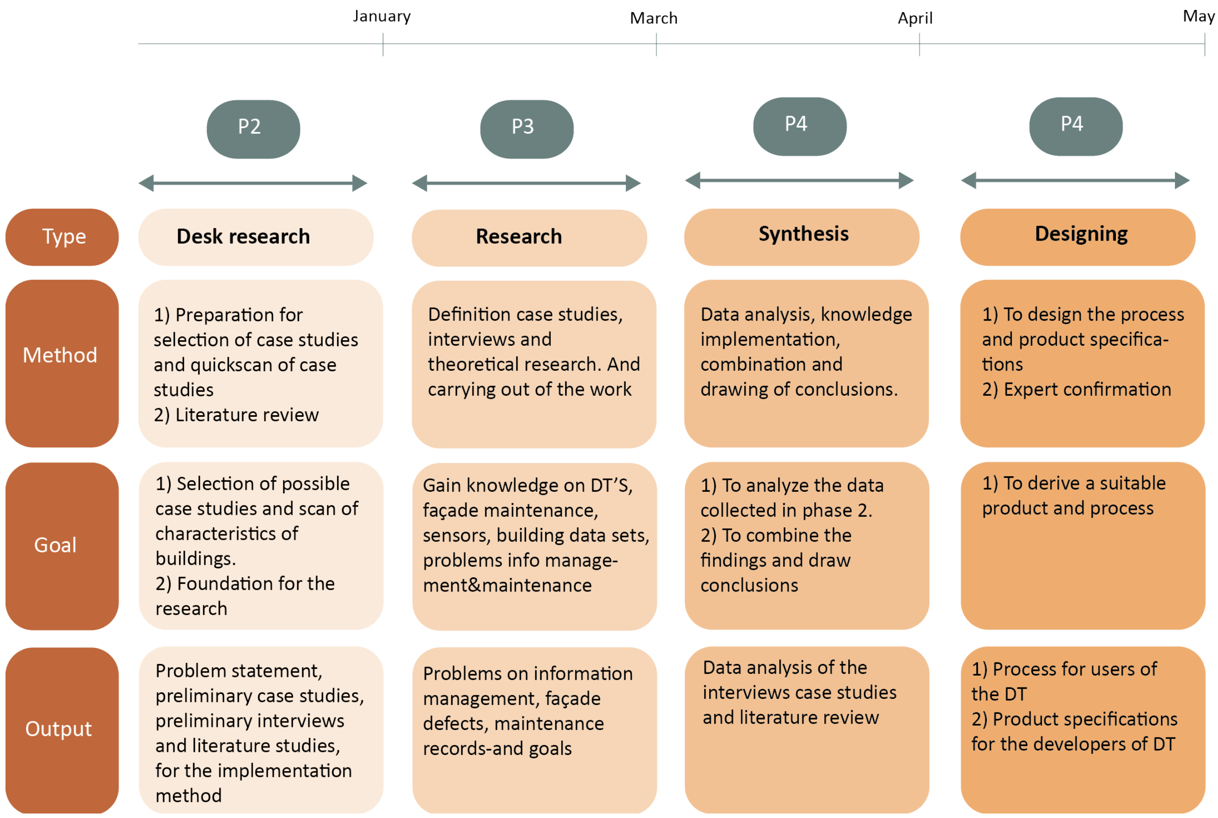

Fig 6. Process design of p2-p4 (own ill.)

5.3 Methods and techniques

Research methods are part of a strategy so conceived to obtain answers to research questions (Kumar, 2017). To come to a substantiated answer to this matter, it is of importance to collect empirical and theoretical knowledge and evidence. This paragraph will explain the chosen methods to uncover the relevant information, which is used to design the operational output.

The case studies are relevant in gaining knowledge for output 'the product', and interviews are interesting in gaining an understanding for the output 'the process'. Nevertheless, both methods can provide input for both deliverables. Figure 7 depicts the necessary methods and techniques.

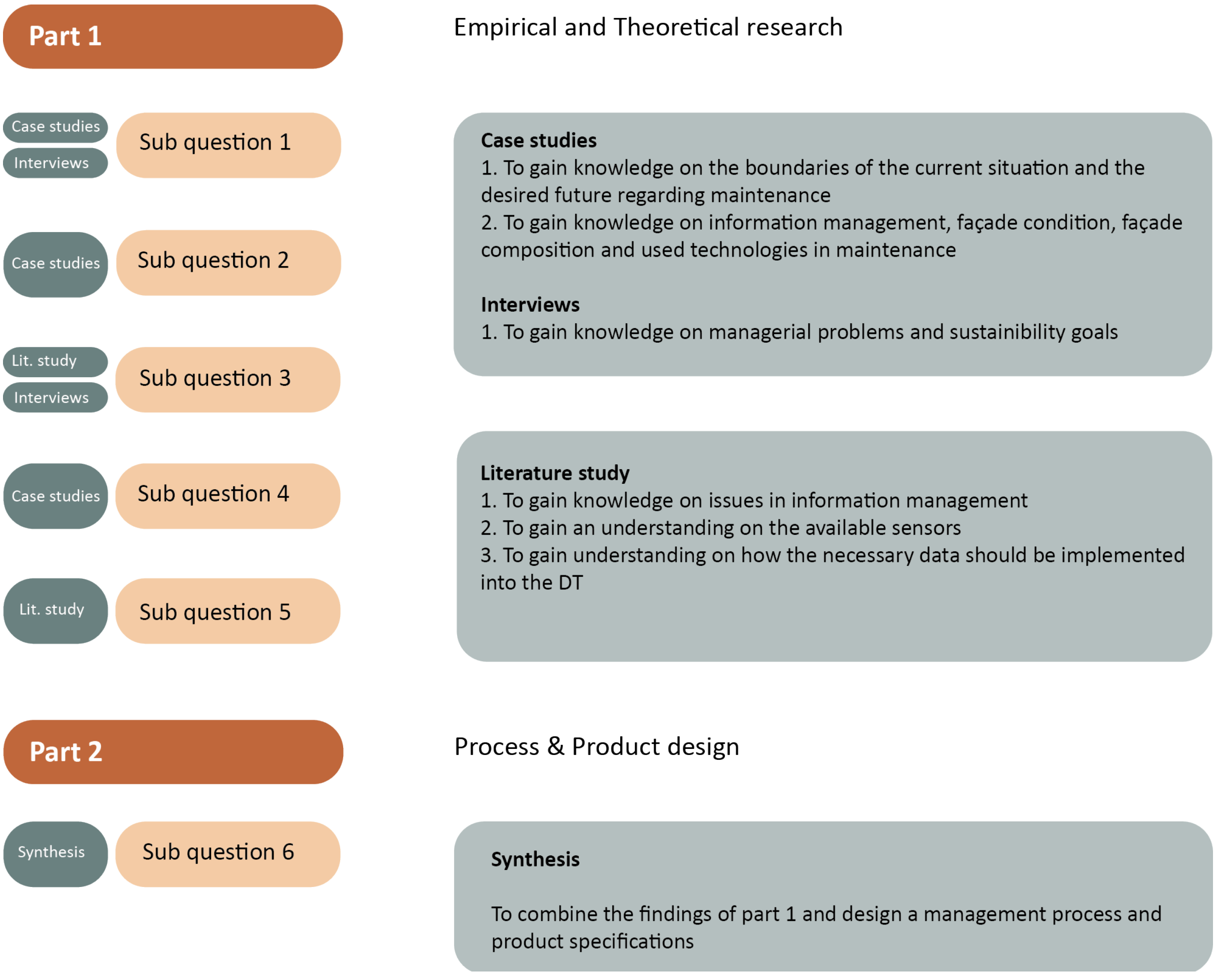

Fig 7. Research design with research methods (own ill.)

5.3.1 Empirical research

1. Case studies

Case studies are useful research methods when analysing and understanding complex organisational processes. They are helpful in management research of unique situations because they deal with multiple stakeholder considerations and multi-data sources (Tharenou et al., 2007). Case studies are useful when exploring an area on which little is known, or where it is necessary to get a holistic understanding of the situation (Kumar 2017). Kumar (2017) also states that case studies are relevant when the focus of the study is exploring and understanding rather than confirming. This fits this study because the research is directed at an area on which little is known.
Goals of the empirical research are to gain knowledge on (1) the goals and issues of building owners of condition performance and circular maintenance. Also, (2) to investigate the maintenance process (3) analysis of building information and (4) information management.

Through the case studies, problems will be discovered which will form a part of the operationalisation of the research. It is of importance to identify the most critical issues and test it to practice. This is helpful to review if the operationalisation is realisable and accurate.

Graduation organisation

The graduation organisation during this research is the Rijksvastgoedbedrijf (further referred to as ‘RVB’). The RVB is the central government real estate agency of the Netherlands which is responsible

for maintenance and conservation of an extensive diverse portfolio (Rijksvastgoedbedrijf, 2019). The total portfolio occupies approximately 12 million square meters, making it the largest portfolio of the Netherlands (Rijksvastgoedbedrijf, 2019). They are professionals in the field of maintenance, as well as large scale innovations, purchase and construction of new buildings, to name a few. But above all, the RVB is transitioning towards a sustainable future. Clear sustainable goals have been determined, together with a roadmap to reach the goals. Currently, they are improving and developing their knowledge on circularity and have several realised projects and project in the pipeline. They are looking for methods on how to transition the large and fragmented organisation towards better collaboration to support sustainability. Many problems with collaboration can be found, which is useful for this research.
The goals of this research align with sustainability goals of the RVB. Namely, how to reach circular maintenance through improving the current information capture in the maintenance process. Their current sustainability goals are clear, but a lot has to be done to achieve this. Therefore, the organisation has many interesting problems.
Also, the organisation consists of approximately 2200 civil servants and departments ranging from ICT to sustainability and maintenance. Therefore, the RVB provides a lot of inhouse information. Also, the organisation has an extensive network of market parties, which can be contacted.
The common goals, interesting problems, sustainability input is why this company is chosen as graduation organisation. It will provide data for the case studies and interviews.

Selection of cases

In order to derive relevant information from the empirical research, the case studies must meet some prerequisites. It is important that (1a) the maintenance team of the building has methods to gather information on the façade's materials and condition performance. Or (1b) maintenance and building composition information on the building is available. In addition, (2) the façade should have encountered defects and maintenance during the operational phase (3) one of the case studies must be designed for deconstruction. (4) It should be an office building or related to commercial real estate. (5) Some of the case studies should work with BIM. Lastly (6) the building and façade should be owned by the RVB.

Case study	Current owner	Relevant characteristic	Maintenance
1) Rijkswaterstaat building	Rijksvastgoedbedrijf	⇨ Building with sensor network ⇨ Active shell pilot ⇨ Façade with many defects ⇨ Insourced maintenance ⇨ Poor building information management	Traditional contract Rijksvastgoedbedrijf, Firma Hoogvliet and subcontractors
2) JuBi Towers	Rijksvastgoedbedrijf	⇨ Flexible office building/meeting spaces ⇨ Outsourced maintenance ⇨ Façade with defects ⇨ Problems identification defects due to height building ⇨ Pilot façade identification system	Design-Build-Maintain contract Heijmans, FM Haaglanden and Rijksvastgoedbedrijf
3) Galileo Conference Centre	Rijksvastgoedbedrijf	⇨ Demountable façade ⇨ 'No waste' building ⇨ BIM is made of this building, but not used	Rijksvastgoedbedrijf

Table 1. Case studies (own ill.)

Different subjects will guide the elaboration of the case studies. These questions are related to the goals of each individual sub question. These questions are:

- ⇒ How does the façade maintenance process work and what are its problems?
- ⇒ What methods are used to detect defects?
- ⇒ Which information related to maintenance can be conducted?
- ⇒ How does information management work and what are its problems?
- ⇒ Which data is available on composition of the façade is available?

a) JuBi towers

In 2012 this building was delivered to serve 5000 civil servants in their duties. The façade of this high-rise building has been showing unexpected defects. Due to its height these defects are difficult to locate. This case is relevant because it gains insight into façade problems, maintenance management, as well as information management since the building has a BIM.

b) Rijkswaterstaat building

In 2019, all new buildings of the RVB need to be energy neutral. The building in Rijswijk is being used as a test area, to test innovations related to energy efficiency. This case study is relevant because this building is full of sensors, measuring climate details, light, and used energy in the building. The building experiments with IoT, which means the sensors communicate with each other. This case provides insight in datasets of climate, light and used energy in the building and what sensors can be used. There have not been sensors implemented in the façade, however data on climate can also be relevant to determine the condition of the façades.

c) Galileo building

The Galileo conference centre is a building where data from the Galileo satellite system will be received. This case study is relevant because it is a circular building, the façade is demountable, it has a BIM through which also the demount ability index is developed. This case provides insight in circular maintenance of the façade elements and building information through BIM.

Analysis case studies

The case study data has been collected through documentation and semi-structured interviews. Mobilization of case studies occurs when case knowledge, compare and contrast cases, and so producing new knowledge (Kahn & VanWynsberghe, 2008). Therefore, the cases have been analysed and compared.

2.Interviews

Semi structured interviews have been used, this way it is possible to guide the interviewee during the interview (Bryman, 2012). Additionally, it is possible for the interviewer further questions on topics that seem relevant. These interviews are directed at one person in which in-depth questions can be asked. These interviews will consist of open-ended questions, where possible answers are not yet given, as well as closed questions (Kumar, 2017). Due to the novelty of the research subject, the preference lies to choose topics for interviews, instead of an interview consisting of predetermined questions.

Expert interviews have been conducted to gain an understanding in the company-wide processes.

Selection interviewees

People from the graduation organisation, their suppliers, and people from consortia that are involved in maintenance of the building and façade.

Possible persons to interview
RVB general information: maintenance processes
a) Daily maintenance and BOEI inspections
b) The project process within the RVB

Digital innovations
a) Technical manager digital information pilot Bruggebouw East
b) Technical manager pilot Rijkswaterstaat building
c) Project manager façade identification pilot Jubi Towers

Case studies
a) Object managers
b) Technical managers

Sustainability goals
a) Program manager circular building
b) Innovation experts

Information management
a) Department Vastgoedbeheer
b) Object managers
c) Technical managers

Guiding questions of the interviews are:
⇒ Which goals and desires companies have related to circular façades and the current state of their façades?
⇒ Which goals and desires do companies have, related to their current state of the condition and maintenance of the façade?
⇒ How can the façade contribute to this?
⇒ What are the current problems in information management?
⇒ What are the current problems in maintenance management?
⇒ How is information gathered and connected to the online database?

Data analysis
Data analysis will be done through thematic analysis of the interviews.

5.3.2 Theoretical research

2) Literature study

Theoretical knowledge is important to conduct on areas which more is known of. As mentioned in previous paragraphs, if a lot is written on a topic it means that the findings are up to date and relevant for use in a literature review (Kumar, 2017). The literature review will be directed at areas of the research question that is more well known. The literature review will be conducted to answer sub-question 5. The goal of the literature review is to gain an understanding of the following topics: DT and sensors. Journals that are useful for sensors are *Journals of Cleaner Production*, *Sensors, Construction and Building Materials, Measurement Science and Technology, ISPRS Journal of Photogrammetry and Remote Sensing, Future Generation Computer Systems, Journal of Manufacturing systems, Automation in Construction* and *Computers and Chemical Engineering* among many others.

Guiding topics in the literature study:
⇒ What are the external and internal threats of façade condition?

⇒ Which sensors can be used to measure aspects important to façade condition?
⇒ How can data be implemented into a BIM?
⇒ How does a DT work?
⇒ How can a DT be used?

5.4 Synthesis

The findings from the case studies, literature review and interviews will be combined, from which conclusions will be drawn. The conclusions from the research methods will form the basis for the operational output of the research.
For the validation of the operational output, expert validation is necessary. The reason for this is that the operational output must be valid and accepted by experts, for it to work in practice.

5.5 Data plan

There is a need to improve the infrastructure supporting the reuse of scholarly data. The FAIR guiding principles are a measurable set of principles that may act as a guideline for reusability of the data holdings. The FAIR principles (Findable, Accessible, Interoperable and Reusable) put specific emphasis on enhancing the ability of machines to find automatically use and find data. Good data management is a pre-requisite supporting knowledge discovery and innovation (Wilkinson et al., 2016). Therefore, it is important the data of this research is managed accordingly. The FAIR principles of the TU Delft will be taken into consideration in this research. This will not be elaborated further in this report.

5.6 Ethical considerations

Ethics is essential in research because it relates directly to the integrity of a piece of research and of the disciplines which are involved (Bryman, 2012).
Kumar (2017) explains that it is unethical to collect information without the knowledge of the participants, and without their willingness and consent. Seeking consent is one of the most common methods in social research (Kumar, 2017), which means that the participants are made aware of the type of information you want from them. Bryman (2012) describes that participants should be given as much information as possible to decide whether or not they wish to participate in the study. If participants are not informed thoroughly about the interview, there is a lack of informed consent. The participants will receive a letter beforehand, in which the research, its goals and the output of the data collection will be thoroughly explained.

Another dilemma researchers face is asking sensitive and intrusive questions. In social research, it is possible to harm the participants in such a way that they experience anxiety, discomfort or an invasion of their privacy (Kumar, 2017). When collecting data from respondents, it is of importance to consider if whether their involvement is going to harm them in any way possible. According to Kumar (2017) it is not unethical to ask sensitive questions if you inform the interviewee what is going to be asked—giving them the time to think if they want to answer the question. During the interviews, it will be specified in advance if sensitive topics are addressed.

Sharing information on the respondent for purposes other than the research is unethical. Also, it is unethical to identify an individual respondent and the information provided by this person. It is ethical to be confidential with the answers of the respondents and to ensure others do not have access to this information. Records and identities of participants should remain confidential unless consent is given (Bryman, 2012). Details on participants will not be shared; the participant will stay anonymous in the research.

Reporting findings in a way that changes them or is beneficial for one’s interest or someone else’s interest is also unethical. Reporting should be done correctly and unbiased to conduct ethical research (Kumar, 2017).

Ethical considerations also entail the appropriate use of the information received from respondents. When the use of this information directly or indirectly affects the respondent adversely, this is perceived as unethical. It may be possible to harm individuals to achieve benefits for other organisations; this behaviour, however, is also unethical (Kumar, 2017).

Chapter 6
Empirical Research

Empirical Research

6.1 Selected case studies

The first case addressed in this research is the JuBi towers, an office building providing workspaces for 5000 civil servants. This case is relevant because several defects have occurred into the façade. The façade of this high-rise building has been showing several shortcomings that are dangerous for passers-by and has been inspected (Interview 1A). During the maintenance process several problems have arisen, since several parts of this process have been slow and accurate management is lagging behind. The inspection reports are unreadable and unclear, and defects in the façade are hard to track (Interview 1B). Because of this, it gains insight into problems in the maintenance management process. This is also the reason the RVB has started a pilot project to inspect the façade using smart methods (Interview 1B). This case study provides insight into the tracking of defects in the façade, as well as insight into maintenance management and information management.

The second case addressed in this research is the *Rijkswaterstaat building.* This is an office building which houses Rijkswaterstaat. The façade of this building degraded quickly after the buildings' delivery and had been deteriorating since (DGMR, 2014). The problems occurring in this case study are relevant in understanding problems around communication, inspections and tracking of façade condition. Additionally, this building is currently serving as a *living lab* regarding sustainable innovations. One of these innovations concerns the façade and is still in its definition phase. Innovations related to the façade are the topics circularity, sustainable energy, biodiversity and climate adaptation.

The final case addressed in this research is the Galileo Reference Centre. This building adheres the requirements of a circular building. The architect's ambition is to make this building waste-free. Therefore, the façade of this sustainable building is interchangeable and designed demountable. Also, the materials are environmental-friendly. This building gains insight into the requirements for a circular building. It can also provide for insight into maintenance of a circular building. This case also provides insights into information management, as it has a BIM-model which is currently not being used.

6.2 Expert interviews

Maintenance Process RVB

Before discussing the case studies in-depth, the maintenance process of the RVB will be elucidated. The maintenance process is the same for all case studies; therefore, it is relevant to explain the maintenance process within the RVB first.

Interviews have been conducted with several experts, of whom the identify will remain anonymous.

Interviewee	Position	Department	Organisation
Interview 1C	Technical manager	Vastgoedbeheer	Rijksvastgoedbedrijf
Interviewee 2A	Manager	Transacties&Projecten	Rijksvastgoedbedrijf
Interviewee 2B	Contract manager	Vastgoedbeheer	Rijksvastgoedbedrijf

The RVB has two boards which are committed to maintenance. Firstly, department Vastgoedbeheer (English: Real Estate Maintenance, further referred to as VB) is responsible for daily maintenance which involves smaller deficiencies, like repairing broken windows or leaks. Transacties & Projecten (English: Transactions & Projects, further referred to as T&P) is responsible for more extensive maintenance projects, such as renovations or restorations (Interview 2A).

	VB	T&P
Core business	Reactive maintenance Corrective maintenance Preventive maintenance Small user demands	Larger maintenance User demands: ○ Functional demands ○ Program demands
Drivers for maintenance	Annual inspections, BOEI inspections, MJOP, Preliminary plans, clients wish	Clients wish A demand from VB
Job threshold	< €1000.0000	≥ € 5000.000
	Between €1000.0000 and €5000.0000 there is discussion who will take the assignment	
VB performs maintenance	When 'maintenance' is not integrated in the contract. *e.g. Design&Build contract; Design Build Finance contract*	Never
Responsible actor within RVB	Object manager and contractor	Never
Maintenance is outsourced	When 'maintenance' is integrated in the contract e.g *Design, Build, Maintain, Finance, Operate contract; Design, Build, Maintain, Finance contract; Design Build Maintain contract*	Never
Responsible actor within RVB	Buyer, contract manager and contractor	Never

Table 2. Description of differences between departments (Interview 2A; Interview 2B; Interview 1C)

VB sets up preliminary maintenance plans at the beginning of the use phase. This plan contains information on material degradation and when maintenance is due. This is called *planned maintenance*. A preliminary maintenance plan is based on previous experiences and standard materials degradation times. During the operational phase, this plan is updated trough *RgdBOEI inspections.*

RgdBOEI or BOEI inspections are a method of the RVB to map the condition of the building and its elements, among other things. BOEI is an acronym which stands for the following words in Dutch: fire safety, maintenance, energy and adherence to laws and regulations (Dutch: Brandveiligheid, Onderhoud, Energie & Wet en regelgeving). It builds upon the Dutch NEN2767, which is a which is the primary condition measuring method of the technical state of an element. BOEI, however, adds to this method a plan of action, as well as a new level of defects. BOEI inspections set *reactive maintenance, corrective maintenance* as well as *preventive maintenance* in motion (Interview 2B). An explanation of these types of maintenance will be given in the next section.

BOEI inspections are visual inspections, where inspectors use their senses to detect defects and photograph any outstanding parts (Interview 2B).
Inspectors analyse the defects on size, characteristics, location and create an inspection report subsequently. Generally, the RVB examines the information system every five years if the inspections were executed correctly. This information is used to update the preliminary maintenance plan made at the start, resulting in a 'Meerjaren OnderhoudsPlan' or *MJOP* (English: multi-year maintenance plan) (Interview 2B).
Appendix A describes the BOEI inspection requirements for condition score 3. This is the minimal score the façade should adhere.

Besides *planned maintenance,* reactive, corrective and preventive are also performed in buildings.

- ⇒ *Reactive maintenance:* When something occurs and needs immediate fixing. This can be due to a natural force, an incident or a change in law or regulation (Interview 2B).
- ⇒ *Corrective maintenance:* When something occurs but needs maintenance after a while. Defects are 'on the waiting list' (Interview 2B).
- ⇒ *Preventive maintenance:* Maintenance to prevent a defect from happening (Interview 2B).

The most applicable type of maintenance depends on the building use: if people use the building rarely, - like in storage buildings - only *reactive maintenance* is necessary. When frequently used and hygiene is important - like in hospitals - *reactive, correctiv*e and *preventive main*tenance are all important. In office buildings' the building is used frequently, so *reactive maintenance* occurs most often. The maintenance team is obliged to recover defects that should be fixed in the short term, such as a broken window or a leak. Each day 5 to 10 defects occur, from which the solve-rate ranges from 60 minute-defects, to 4-hour defects and 48-hour defects. Figure 8 depicts the communication diagram explaining the communication on how *reactive maintenance and corrective maintenance* starts.

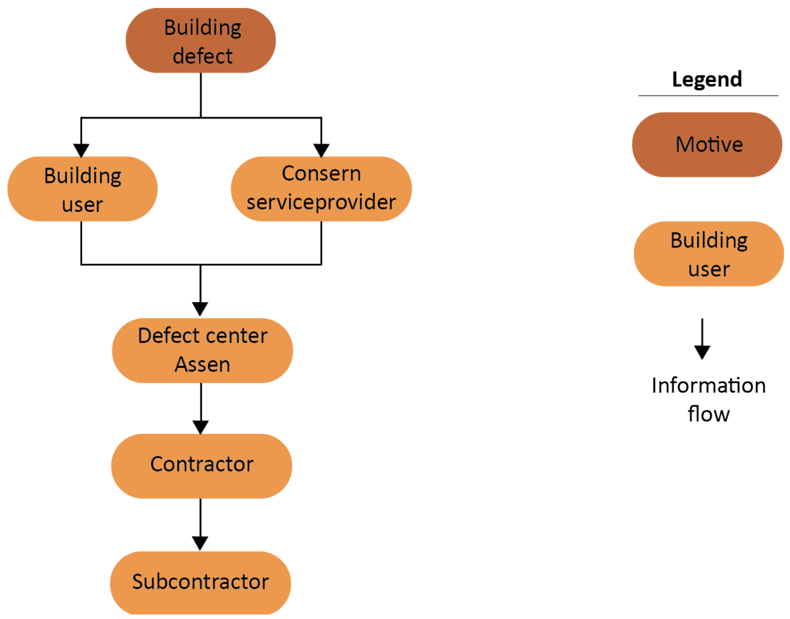

Fig 8. Reactive maintenance communication diagram (own ill, based on interview 2B)

Preventive maintenance is based on information provided by the maintenance plans or information passed on by the building user. The preliminary maintenance plan entails the expectations of the façade's maintenance needs and how long its elements will last. This maintenance plan is updated throughout the use phase, by BOEI inspections. During BOEI inspections, elements are inspected on fire safety, maintenance needs, energy and laws and regulations. This information is processed in the system of the contractor, but also in the information system the RVB uses: Condor. This information is used to update the preliminary maintenance plan made at the start, resulting in a '*Meerjaren OnderhoudsPlan'* or *MJOP* (English: multi-year maintenance plan) (Interview 2B).

Figure 9 describes the main stakeholders in the maintenance process of the RVB. The persons concerned with the maintenance within the RVB are the object manager - who is responsible for the users' comfort-, the technical manager/advisor - who advises the objectmanager on technical issues - , the contract manager – actor who checks if demands are included. (Interview 1C).

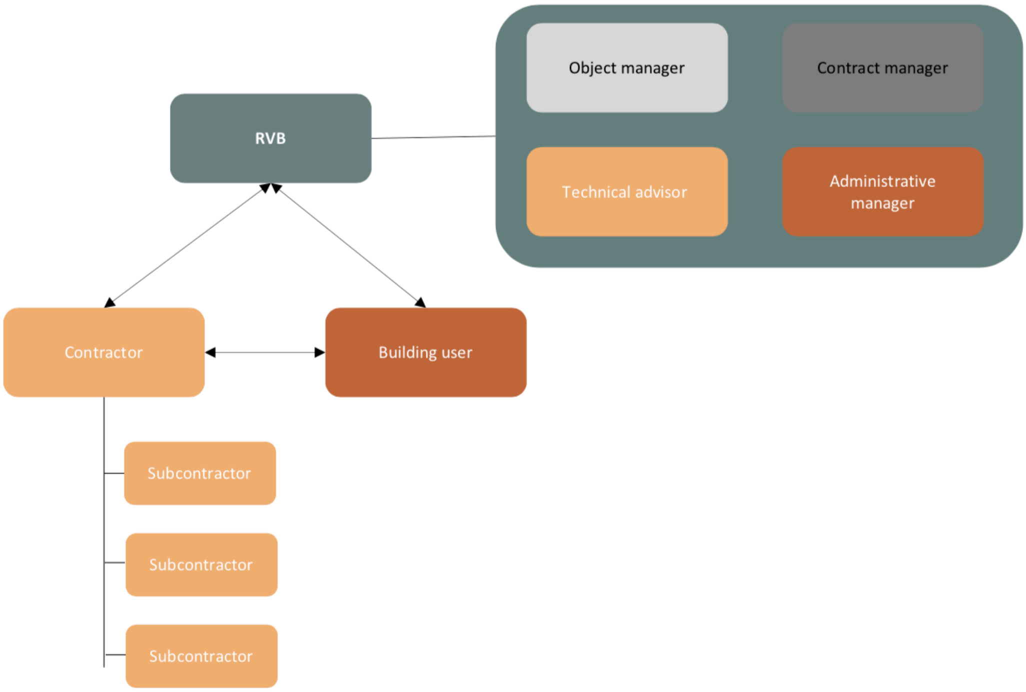

Figure 8. Stakeholders maintenance process (Interview 1C)

	Building user	Object manager	Contract manager	Technical advisor	Administrative advisor	Contractor	Subcontractor
Core task/ responsibility	To make use of the building.	To ensure the building users' welfare	To advise object manager when maintenance demanded is included in the contract	To deliver technical advice when necessary	Responsible for facilitating communication and assisting.	In charge of maintenance established in the contract.	To perform maintenance set out by the contactor
Frequent relations	Object manager	Building user, contract manager, technical advisor, contractor, administrative advisor	Object manager, technical advisor,	Object manager, administrative advisor, contract manager	Object manager	Object manager, sub-contractors	Contractor

Table 3. Main stakeholders and corresponding tasks

T&P handles greater maintenance demands, such as significant defects or large user demands. Appendix B describes the process of more extensive maintenance projects within the RVB. A project is set in motion when the client has a functional or programmatic demand, or when a large defect occurs. An example of such an error is when the entire façade leaks. Also, an assignment can be given by VB, when the defect is too large for this department (Interview 2C).

6.3 Interviews
Sustainability goals RVB

Fig. 10 Roadmap sustainability goals RVB (Rijksvastgoedbedrijf. Nd.)

In 2050 significant sustainability goals must be achieved. The aim is to adhere the aim of the government and the European Union to be 100% circular in 2050. Figure 10 depict the roadmap on how to achieve the goals. The entire real estate portfolio is sustainable and CO^2 neutral in 2050. In 2030, the RVB aims to party carry out circular maintenance as an organisation. This entails smaller tasks such as maintenance tasks which produce short-term output to feed the still developing knowledge. From 2019 all newly built governmental buildings must be nearly energy neutral (Rijksvastgoedbedrijf, n.d.).

Circularity is a comprehensive subject, which is in need of an improvement in communication. Also, information capture is necessary, and of importance to think what information is really necessary and valuable.
Many tools can be helpful in maintaining information; however, it is important to educate users in how to use it. Not just the BIM engineers, but all involved actors (Interview 2C).

Chapter 7
Case studies

Case studies

Case Study 1: JuBi Towers

7.1 JuBi Towers

Fig 11. The JuBi towers (Oppenheimer, 2019)

Interviewee	Position	Department	Organisation
Interview 1D	Facility manager	-	Heijmans
Interviewee 1A	Project manager	Transacties&Projecten	Rijksvastgoedbedrijf
Interviewee 2B	Contract manager	Vastgoedbeheer	Rijksvastgoedbedrijf
Interview 1E	Technical manager	Transacties&Projecten	Rijksvastgoedbedrijf
Interview 1B	Technical manager	Transacties&projecten	Rijksvastgoedbedrijf
Interview 1F	BIM Engineer	-	Heijmans

7.1.1 General information

The JuBi towers house the activities of the *Ministry of Justice and Security and the Ministry of Internal Affairs*. The nickname 'JuBi' applies to the users of the building as it abbreviates the former names of these ministries in Dutch: Ministerie van Justitie and Ministerie van Binnenlandse Zaken (Ju-Bi).

The building is located in the city centre of The Hague, the governmental heart of The Netherlands. This particular part of The Hague is full of high-rise buildings that house ministries, among other things. Close to JuBi are the Ministry of Health, the Ministry of Education, Science and Culture and the Ministry of External Affairs to name a few. The JuBi building consists of two towers, joined together by a 10-storey plinth (Rijksvastgoedbedrijf, 2019).

The JuBi building was delivered in December 2012. The RVB had a contract with parties to design, build and maintain the JuBi towers. RVB tested with *main contracting/integrated maintenance contracting* (Dutch: integraal beheercontracten (IBC)) for the maintenance of JuBi. In this type of contract, one contractor is responsible for the maintenance of several buildings (Heijmans, 2016). The duration of such a contract is 19 years. This is a long-term contract of the RVB where the information should be transparent for the client and contractor. Contractor Heijmans was appointed to be in charge of all maintenance of the building for 19 years. This also includes the maintenance of the façade during this period.

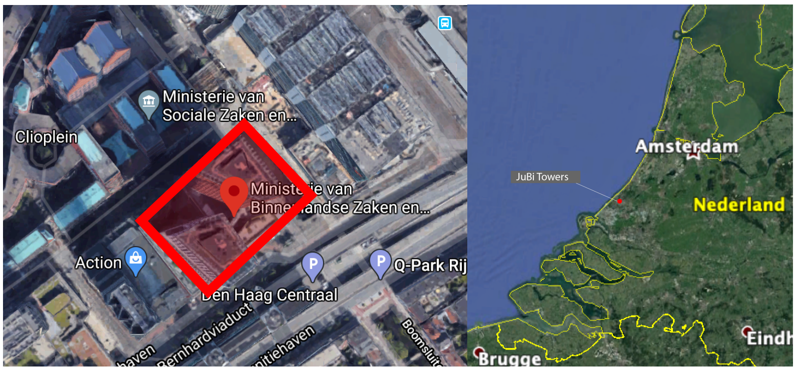

Fig 12. Location of JuBi Towers (Google maps)

JuBi Building Properties	
Location	The Hague
Composition	Two towers joined together by a low-rise building
Delivery year	2012
Building use	Office
Height	147 meters
Gross floor area	130.000 square meters
Employees	5000
Workspaces	4000
Building use	Office building

Table 4. JuBi Building Properties (Rijksgebouwendienst, 2013)

Fig. 13 Floorplan 6th floor JuBi Towers and corresponding functions near the façade (BIM-model JuBi towers)

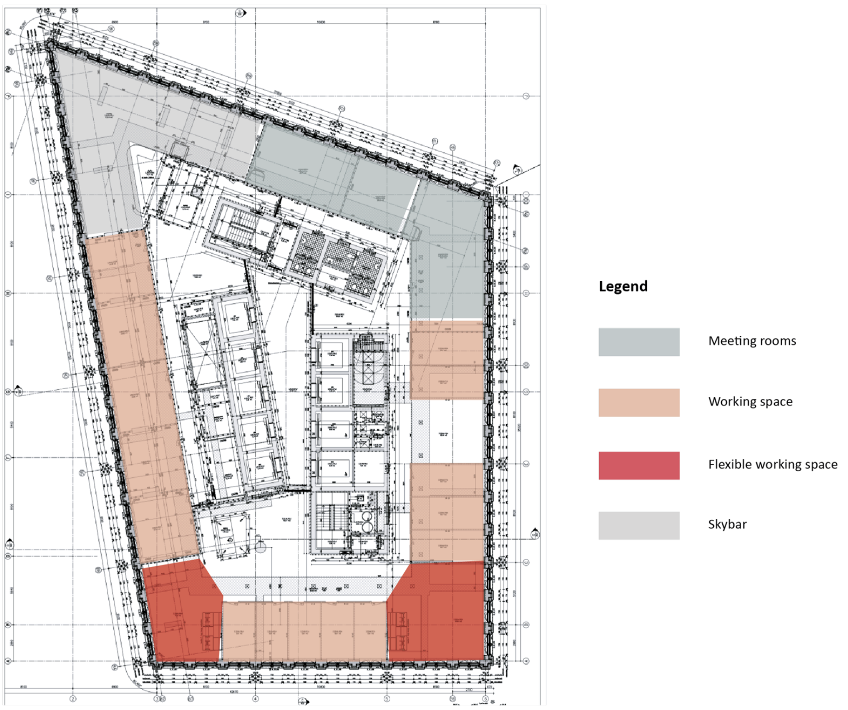

Fig 14. Floorplan 22nd floor JuBi towers and corresponding functions near the façade - north tower (BIM-model JuBi towers)

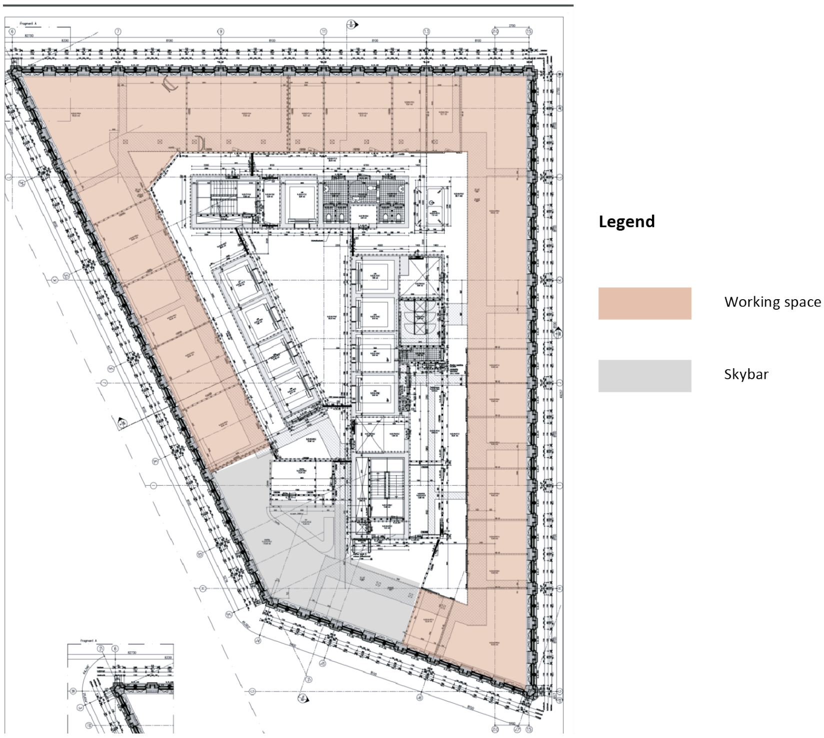

Fig 15. Floorplan 22nd floor JuBi towers and corresponding functions near the façade - south tower (BIM-model JuBi towers)

7.1.2 JuBi Façade

General façade information

The façade of JuBi consists of several elements. These elements, as described in the RgdBOEI maintenance plan, are the cladding, window frames, doors, sills, dilatations, joints, and grilles (Rijksvastgoedbedrijf, 2012). Appendix C shows the façade views and a constructive detail. Tables 5-9 describe the details of the façade.

Wall composition	
Cladding North tower	Prefab brick panels
Color	Red
Cladding South tower & low-rise	Prefab natural stone panels
Color	Grey
Connections	Brackets
Inner cavity leaf	Prefab concrete
Insulation	Mineral wool
Workspaces	4000
Building use	Office building

Table 5. Wall composition JuBi (BOEI inspection document, 2019)

Double window frame composition	
Outer window frame	Aluminum
Frame coating	Bronze anodized

Glass	Single glass
Remarks	Contains an air gap
Inner window frame	Steel
Frame coating	Bronze anodized
Glass	Double glass
Remarks	To open manually Integrated electric sun protection system
Insulation gas	Argon gas

Table 6. Window frame composition JuBi (BOEI inspection document,2019)

Door composition	
Door frame	Steel
Frame coating	Bronze anodized
Glass	Double glass
Insulation	Argon gas

Table 7. Composition doors JuBi (BOEI inspection document, 2019)

Grilles composition	
Material	Aluminum

Table 8. Composition grilles JuBi (BOEI inspection document, 2019)

Sills composition	
Material	Vary between natural stone and concrete

Table 9. Composition sills JuBi

Tables 5-9. Façade composition details (BOEI inspection document, 2019; Interview 1D)

Desired situation façade

The JuBi façade was reportedly delivered in very good condition (Interview 1D). The building and façade ought to represent a highly professional atmosphere since the JuBi towers are a high-profile building that serves the image of the government. Any severe problems concerning the JuBi façade (or building), can damage the image of the government. So, the façade was thoroughly designed, and delivered in high quality. It was explained the expected the façade should need little maintenance during the use phase (Interview 1D). This means the façade should not require major maintenance, besides cleaning the windows, cladding, grilles and doors, and other minor tasks. Other than that, the expectations were that the building wouldn't need extensive maintenance in the first years.

Current situation façade

When defects occur in the façade, poor design can be the cause. However, other factors also play a role, for example, weather forces. Currently, against the expectations, several problems are occurring within the façade of the JuBi towers. Due to the height of JuBi and the surrounding buildings, the winds surrounding the building become strong. This strong force has caused the gondola – used for window cleaning – to sweep against the façade, cracking the stone and brick cladding. Brick pieces fell off the façade, which resulted in safety risks around the building. The building is situated in a crowded and popular area. Additionally, in the south tower, a total of 72 other cracks have been discovered (Interview 1A). Tables 10-11 describe the current defects in the façade.

	North	South	East	West
Location	Station side	City side	City side	Seaside
Natural forces	Wind and rain	Heat Sunlight	Highway	Strong winds,

		Wind and rain	Wind and rain	rain
Cladding	Crumbling bricks	Dirt, discoloration	Dirt, discoloration	Dirt, discoloration
Sills	Algae, moss Growth	Algae, moss growth	Algae, moss growth	Algae, moss growth
Window Frame	Leaks on 36th floor, dirt and discoloration	Leaks on 36th floor, dirt and discoloration	Leaks on 36th floor, dirt and discoloration	Leaks on 36th floor, dirt and discoloration

Table 10. Maintenance details North tower (BOEI inspection document, 2019).

	North	South	East	West
Location	Station side	○ City side	City side	Seaside
Natural forces	Wind and rain	Heat Sunlight Wind and rain	Highway Wind and rain	Strong winds, rain
Cladding	Cracks, dirt and discoloration	Cracks, dirt and discoloration	Dirt and discoloration	Dirt and discoloration
Sills	Algae, moss Growth	Algae, moss growth	Algae, moss growth	Algae, moss growth
Window Frame	○			

Table 11. Maintenance details South tower and low-rise (BOEI inspection document, 2019).

7.1.3 JuBi Maintenance Process

General maintenance process

The maintenance contract gives Heijmans full control, and so, Heijmans and the building user are in frequent contact. The RVB is only in connection with Heijmans if defects deviate from the contract. When this occurs, only the contract manager, object manager and technical manager are in contact with Heijmans, their suppliers or the building user.

The JuBi towers are used frequently. The façade must ensure that the activity of the building is warranted. Besides this, safety is the highest priority. The RVB applies for office buildings reactive maintenance as the most frequent type of maintenance. They are to recover defects that should be fixed in the short term, such as a broken window or a leak. According to the maintenance contract, Heijmans is in agreement with the RVB to tackle every defect indicated as reactive maintenance. When a defect is noticed in JuBi this is communicated to the defects center in Assen. Depending on the size and gravity of the defect, it either solved by Heijmans or passed on to VB (Interview 2B).

The RVB also applies corrective maintenance in the JuBi towers' maintenance, which entails solving of defects that are 'on the waiting list' to be handled. Such as the cracks in the cladding. When defects are alarmed, they are inspected to determine its severity, price and priority (Interview 2B).

Every year Heijmans performs a BOEI inspection on the elements of the façade. This information is processed in the system of Heijmans, but also in the 'building information system' the RVB uses: Condor. This information is used to update the preliminary maintenance plan made at the start, resulting in a 'Meerjaren OnderhoudsPlan' or MJOP (English: multi-year maintenance plan) (Interview 2B). This information is processed in the system of Heijmans, but also in the 'building information system' the RVB uses: Condor. Every five years, the RVB checks the information gained by the BOEI inspections.

Preventive maintenance is the least performed in the JuBi façade, as this has not shown to be crucially necessary.

When performing reactive maintenance indoors, Heijmans uses a BIM model in order to work efficiently. The model is an efficient information model in terms of architectural and constructive information. The contractors have access to as-is models of the building, which are models or drawings that have been altered during the building and operation phase. uses these as-built 3D drawings in the maintenance of the JuBi towers. Currently, Heijmans uses this to quickly detect the location of a defect, such as a broken light (Heijmans, 2016).

JuBi Maintenance problems

As described above, the JuBi façade BOEI inspections are performed visually. The emerged cracks and crumbling bricks have been observed by sight. However, because of the enormous size of the facades, the determination of its causes took a long time. Additionally, during the inspection, it was not evident if the cracks had been there recently or since a long time. If this information is not stored effectively, it is not clear if this crack is due to be solved or has already been tackled. It is not immediately clear if it already has been indicated as harmful, or if it has been identified as not dangerous. Additionally, if the crack was there before, it is not clear if a decision on a plan of action has been made. Information on this matter is not stored sufficiently, which is an issue (Interview 1B; Interview 1E).

Additionally, technical managers/advisors of the RVB complain about the inspection report received from the inspectors. Often the reports are unreadable, and the photos are unclear. The location and severity of the defect are hard to understand (Interview 1B; Interview 1E).

Uncovering the cause of the cracks and crumbling bricks took a very long time. After a period of searching for its causes it was determined the gondola caused the cracking of the brick panels. This is why the JuBi is the current case used for the 'façade inspection pilot', which has been set in motion at T&P. In this pilot, cameras are attached to the gondola and photograph the entire façade. Employees check the photos taken of the façade and process its information. The photos are connected to a point cloud of the building, which shows the location of a defect immediately. The goal is to simplify the detection of defects (Interview 1B).

7.1.4 Information Management

General information on information management

The RVB uses the information management system ‘Condor’ to map the condition of the façade. Heijmans performs a BOEI inspection every year, and every five years the RVB receives a file in Condor and checks if the inspections are of adequate quality. This means that the defects, severity, location and price should be indicated clearly.

The interface of Condor contains tables in which the rows represent fire safety, maintenance, energy and laws and regulations (i.e. BOEI characteristics) of the building parts. The columns represent further characteristics on the rows: defect, priority, size, start and end, total costs and costs per year. It provides insight into the severity of the defect, the size, the required action, and the costs necessary to tackle the defect throughout the years. Also, a picture is provided showing the defect in the building (Interview 1C).

T	Defect	Priority	Size	Condition	Costs			
				Score	Start	End	Cycle	2020-2028
B								
O								
E								
I								

Table 12. Example of a Condor table on BOEI inspections

The JuBi towers have an existing BIM model. This model is used to generate drawings, inspect the surroundings when a defect occurs in the mother building, and to calculate surfaces.

The technical information adopted in BIM is depicted in Table 13. However, some of the variables do not have an entered value. The BIM-model follows the RVB-BIM standard, a document in which the RVB has formulated their demands for the BIM-models. It provides specifications on delivery requirements, such as what names families should have, NL/SbF-codes to classify elements, materialization and smoke-and fire safety (Interview 1F).

Element	Information
Cladding	Width, Height, Family Name, Type Name, Thermal Resistance, Fire Rating, Thickness, Heat Transfer, Cost, Assembly, Bulletproof
Doors	Width, Height, Family Name, Operation, Type Name, Self-Closing (1 or 0), Assembly
Window frames	Width, Height, Family Name, Operation, Type Name, Self-Closing (1 or 0), Assembly
Façade structure	Width, Height, Family Name, Operation, Type Name, Self-Closing (1 or 0), Assembly
Roof edge	Width, Height, Family Name, Operation, Type Name, Self-Closing (1 or 0), Assembly
Fencing and railing	Width, Height, Family Name, Operation, Type Name, Self-Closing (1 or 0), Assembly
Cladding	Width, Height, Family Name, Type Name, Thermal Resistance, Fire Rating, Thickness, Heat Transfer, Cost, Assembly, Bulletproof

Table 13. Technical information incorporated in BIM (Interview 1F)

The model contains as-is drawings, which means it is manually updated when changes are made in the building. This is a task specified in the DBM contract between the RVB and Heijmans. Manual updates do not occur immediately, but it often occurs after a certain amount of changes has taken place. This also applies to renovations, which are often incorporated in the model after it has taken place. However, sometimes, the renovation is included in the model during its execution. This is to optimize the renovation during execution.

Concerning the façade, certain information is incorporated into the model. However, the model is not used during maintenance for the façade. BIM does not contain information on maintenance needs or defects of the element types. BIM is primarily used to retrieve information on the surroundings on a reported defect. Additionally, BIM is used to generate drawings, calculate values and to search for optimizations (Interview 1F).

Information management problems

Information management problems often arise due to human errors. The defects found during BOEI inspection are supposed to be marked as ‘completed’. This does not happen often, due to mistakes by employees. The outcome of the BOEI inspection should also be incorporated correctly in Condor. Additionally, the MJOP is updated, however, when the Condor system is not correctly updated, the MJOP is based on incorrect information (Interview 2B).

7.1.5 Conclusion

- The desired situation of the façade deviates from the current situation: the façade is not maintenance free
- Visual inspections can result in false judgement of defects, and overlooking of hidden defects
- Large size of the façade makes it difficult to notice a defect
- Large size of the façade makes it difficult to track down the cause of a defect
- Corrective and reactive maintenance are performed the most. Preventive maintenance the least
- Inspection reports are unreadable and unclear
- Inspections take a long time
- Human error is common in information management, and results in incorrect information in the system

Case Study 2: Rijkswaterstaat Building

7.2 Rijkswaterstaat Building

Fig 16. Pictures of the Rijkswaterstaat building (Cobouw, 2019)

Interviewee	Position	Department	Organisation
Interview 3A	Object manager	Vastgoedbeheer	Rijksvastgoedbedrijf
Interviewee 3B	Technical manager	Transacties&Projecten	Rijksvastgoedbedrijf
Interviewee 2B	Contract manager	Vastgoedbeheer	Rijksvastgoedbedrijf

7.2.1 General information

Rijkswaterstaat building (Further referred to as RWS) is a government office which houses the activities of Rijkswaterstaat, which are part of the *Ministry of Infrastructure and Water Management*. The building lies in Rijswijk, in a neighbourhood predominantly used by firms and institutions. Its location is well accessible since it is near the A4 highway and the train station 'Rijswijk'. The building lies along the busy train track of the The Hague area, with trains passing each 5 minutes.

Figure 17 depicts the location of the Rijkswaterstaat building.

Fig 17. Location Rijkswaterstaat building (GoogleMaps, 2019).

The building is a square mass and each corner of the plan locates a black volume which locates the toilets, stairs and elevators. The ground floor occupies several meeting spaces as well as the cafeteria and the front desk. The other floors have a similar layout consisting of pantries, an office garden, meeting rooms and reading tables (Zorge & Spanjer, 2015).

Table 14 describes general information of the Rijkswaterstaat building.

Rijkswaterstaat building properties	
Location	Rijswijk
Composition	Square floor plan with black volumes on each corner
Delivery year	2004
Building use	Office
Height	34 meters
Gross floor area	7000 square meters
Workspaces	250
Floor layout	Pantries, office garden, meeting rooms, reading tables

Table 14. General information Rijkswaterstaat Rijswijk (Zorge & Spanjer, 2015)

In 2015 the building was transformed into a *test area*. A test area is a building where the RVB tests innovations and pilots regarding sustainability or unexplored territories. These are 'game changers' with a high-risk profile, but also with a more significant chance to reach groundbreaking innovations. The innovations which are currently being tested are related to climate, light and IoT. They occur on different floors inside the building. Also, the project team aspires innovations to be implemented into the façade. However, this project is still in the definition phase, formulating the Project Initiation Document (see appendix B). Which means specifications have not yet been determined. This project is called 'the active shell' (Vosmaer, Stolker & Schmull, 2020).

The goal of the active shell project is to stimulate innovations that lead to energy reduction and use of renewable sources; innovations should contribute to climate adaptation, circular building and strengthen biodiversity within the RVB portfolio (Vosmaer, Stolker & Schmull, 2020).

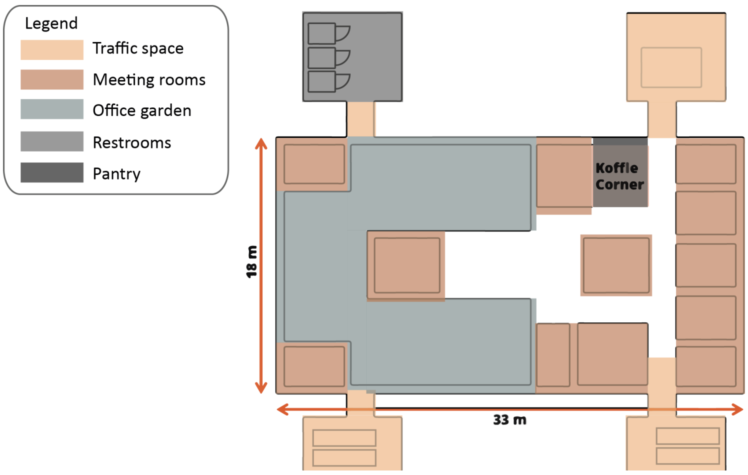

Fig. 18. Schematic drawing of the 1st-9th floor and the corresponding functions near the façade (Zorge & Spanjer, 2015)

7.2.2 Façade information

General façade information

The façade of Rijswijk consists of the cladding, window frames, doors, sills, dilatations, joints, and grilles. Tables 15-17 describes these elements in depth.

Façade Characteristics	Material
Cladding	Mosaic dark blue tiles
Joints (Dutch: Voegen)	Plaster mortar
Connections	Glue
Insulation	XPS-insulation
Inner cavity leaf (Dutch: binnenspouwblad)	Prefab concrete

Table 15. Façade characteristics (DGMR, 2014)

Window Characteristics	Information
Window frame 1	Aluminum
Ability to open manually	No
Glass	Double glass
Window frame 2	Aluminum
Ability to open manually	Yes
Glass	Double glass
Connection façade-window	Rubber sealing profile

Table 16. Window Frame details (DGMR, 2014)

Doors characteristics	Information
Door frame	Aluminum

Table 17. Door Frame details (DGMR, 2014)

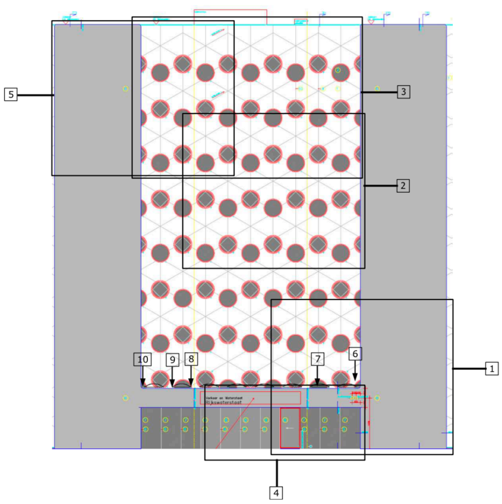

Fig 19. North east façade (DGMR, 2014)

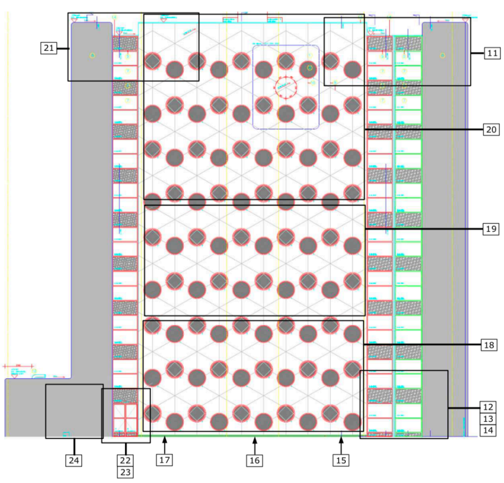

Fig 20. South east façade (DGMR, 2014)

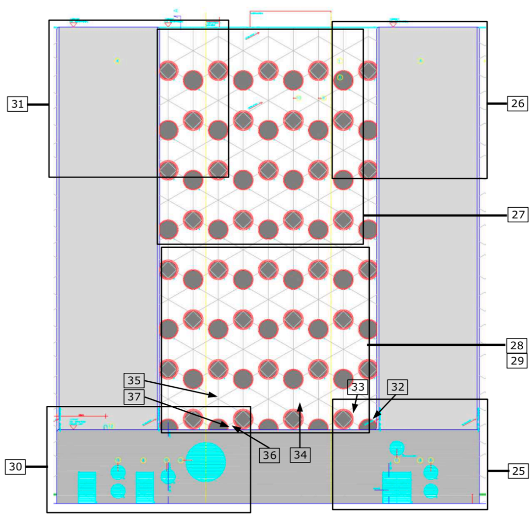

Fig. 21. South West Façade (DGMR, 2014)

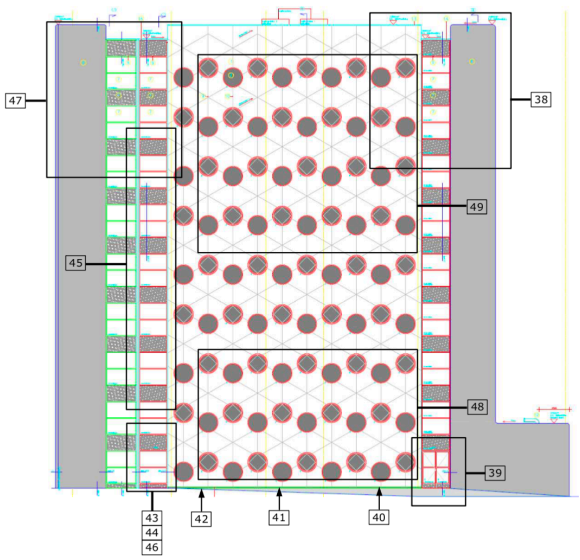

Fig 22. North West Façade (DGMR, 2014)

Desired situation façade

The main requirement for the facades' condition is to be waterproof and windproof. Additionally, the façade's elements should oblige the building laws and regulations, such as fire safety. The RVB also sets minimal condition requirements; the façade should adhere to 'condition 3' of the BOEI requirements (Interview 3A). The BOEI requirements set out condition scores on a scale 1-6. Condition 3 entails the façade has a 'decent' condition, see Appendix A.
At delivery of the building in 2004, the RVB expected the façade would perform decently in the next upcoming years. Maintenance expectations included tasks incorporated in the maintenance contract, including reactive, corrective and preventive maintenance. Additionally, demands not included in the contract, like user demands. However, expected was that maintenance mainly concerns cleaning and checking the grilles, cladding and window frames (Interview 3A).

The active shell project poses several requirements for the quality of the façade as well. Firstly, the new façade should adhere to the building laws and regulations. Therefore, the façade should be wind- and waterproof, it should be fireproof as well, for example. Also, it should have adequate thermal performance (Vosmaer, Stolker & Schmull, 2020). The façade should guard the comfort and use of the inside activities and the resistance of the façade shouldn't deteriorate. Finally, it should facilitate a hospitable environment for innovations. Additional requirements were not set, because the façade should have certain flexibility during the design phase (Interview 3B).

Current situation façade

The current quality of the façade is deferring from the desired situation. Quickly since its delivery in 2004, the façade has been showing severe defects (Memo, 2015). One of the first signs was leakage towards the inner side of the building (DGMR, 2014). On the long term, the mosaic cladding broke off of the façade, exposing the insulation on the inner part of the façade (DGMR, 2014). The presence of water in the inner cavity leaf and joints led to a decrease in attachments of the glue. The adhesive layer 'XPS on concrete' had gotten wet, as well as the adhesive layer between 'joint on XPS', causing the tiles to fall. All this is due to the presence of water in the materials (DGMR, 2014). After inspecting the building, it was concluded that the sun was a substantial hazard, causing cracking in the façade (DGMR, 2014).

In the last 15 years, many companies have inspected the façade, among them being the RVB and the construction company BAM - the original contractor of the building. In 2014 engineering company

DGMR had been appointed by the RVB to inspect the situation of the façade (DGMR, 2014). They have concluded the defects were caused by shrinkage of the XPS insulation boards, either due to thermal causes or birth shrink (DGMR, 2014).

The tables below describe the primary defects on each side of the building.

Element	Information
Cladding	Mosaic dark blue tiles are falling off the façade. Manual detachability is also easy.
Plaster mortar	In the plaster mortar /joints (Dutch: voeg) there are cracks. From these cracks white substance has emerged.
Insulation	The XPS insulation is exposed due to holes in the cladding. Due to rain some parts are wet.
Window frame	The window frames are leaking, and some of the frames are rusting.
Kit	Cracks, which also pursue leakage

Table 18. Southwest side façade (DGMR, 2014)

Element	Defects
Cladding	White substance from the cracks
Plaster mortar	Showing of cracks, white substance emerged
Insulation	Exposed and on some parts wet
Kit	Cracks, which also pursue leak

Table 19. NorthWest side (DGMR, 2014)

Element	Defect
Cladding	On some parts tiles have broken off
Plaster mortar	No cracks are showing in the material

Table 20. NorthEast side (DGMR, 2014)

Element	Defects
Cladding	Some tiles have broken off from the façade, mainly along the sealants (Dutch: kitvoegen). In some areas the tiles have slide over each other.
Plaster mortar	In the joints (Dutch: voegen) of the tiles there are no cracks.
Kit	Movement in the cladding is visible as the joints bulge.

Table 21. SouthEast side (DGMR, 2014)
Table 20. NorthEast side (DGMR, 2014)

In 2015, the poor quality of the façade motivated VB to set out a request for repairing the façade. Due to its high price, the assignment was offered to T&P. Department T&P were in the process of implementing innovations in the building. So, VB suggested implementing innovations in the façade. Due to the overlapping interest which came with a multitude of tasks, it was decided to combine all tasks into one project. This project is the 'active shell' project, and it is still running, leaving the building in its current poor condition (Interview 3A). Tiles are still falling off the building. Thus, the object manager is in agreement with the building user to solve façade defects that form a danger to safety. This is when cladding falls off because this can pose a danger for passers-by, or when there is a leak (Interview 3A). In order to protect the safety of passers-by, nets have been attached to the building to catch any falling tiles (Interview 3B).

7.2.3 Maintenance process

Maintenance process

Maintenance is not outsourced in the contract of RWS. This means VB is responsible for maintenance. In this case, the object manager is the primarily responsible actor.

In one of the interviews, it became clear that the function of a building determines the type of maintenance performed. Rijkswaterstaat building fulfils an office function, in which safety of the users has the highest priority and to ensure the activity of the building can function (Interview 2B)). This means reactive and corrective maintenance is performed most often. Preventive maintenance is also performed; however, it has a lower priority than reactive and corrective maintenance.

The RVB has a maintenance contract with the contractor Firma Hoogvliet. This company is in charge of façade maintenance and carries out the work together with appointed subcontractors (Interview 3A). The contractor's tasks are based on the agreements made in the contract, which in this case includes regular maintenance and defects. Regular maintenance is based on reactive and corrective maintenance and includes maintaining the condition of the façade in order for the activities to function normally. An annual cleaning duty is also included in the contract. This entails cleaning of the cladding, windows, window frames, grilles, sills and doors. Examples of defects is a broken window or a leak. Any additional demands are called Bijkomende Werkzaamheden (English: Additional Activities), for which a separate quotation has to be made by the object manager (Interview 3A). An example of additional activities is an inspection. BOEI inspections are also performed once every five years. However, this is not an additional activity as it is included in the contract.

The façade of RWS is inspected twice a year. This is a unique situation, as this normally happens once a year. The duration of inspections takes up to four weeks. The contractor receives the assignment and completes this inspection within 2 to 3 weeks. Thereafter, the report is sent to the object manager, who checks and judges the report (Interview 3A). During one inspection, a special company was hired to perform a thermographic inspection, exposing all areas where leaks were occurring. Inspections are generally performed by the same company (Interview 3A)
When inspections are carried out, a plan of action is made. However, it is not possible to tackle every defect, since the budget does not leave room for this. In determining the defects' priority, the use of the building is the guiding factor. In this case, Rijswijk is an office building, in which safety is the most critical priority (interview 2B). Therefore, the factors that pose a danger to the safety of the building users must be eliminated. In this case, falling tiles can pose a danger to users and passers-by (Interview 3A).

Rijswijk Maintenance problems

The external forces wind, sun and rain, have proven to be very damaging to this building. Specific maintenance plans for each façade had not been made. Moreover, the defects had not been solved sufficiently at the time. Therefore, the southwestern side of the building has been damaged severely.

This led to high expenses to solve all defects, so it was decided to combine the repair with the 'active shell' project. Money is the leading force in this case, and it was decided to combine all tasks in one project. This project has been going on for several years, leaving the building in its current state. The façade is still in poor condition, the only way the façade is maintained is when a tile breaks off, or a leak occurs. However, falling tiles can pose a danger for passers-by, which is why nets are attached to the building. A leak can be damaging for climate installations.

As described above, after the object manager requests an inspection, the inspection reports take up to 4 weeks to get back to the object manager. As a result, it takes a long time to repair the defect. Meanwhile, the façade is still exposed to external forces such as the wind and rain. At a certain point, it was measured how much water entered the building during rainfall. Half a tank of water was filled after the rainfall had occurred (Interview 3A).

The inspections performed are visual inspections, where subcontractors make use of their senses. So, it is easier to overlook a hidden defect (Interview 1B). Also, it is possible to underestimate or overestimate a defect during a visual inspection (Interview 2B).

7.2.4 Information management

General information on information management

Information on technical characteristics is stored in Condor. This regards information on dimensions, composition and fire safety among other things. Inspection documents are retrieved and stored by the object manager.
RWS is not modelled in BIM, instead the technical drawings are stored in the company's archive (Interview 3A).

Information management problems

Plan drawings, construction drawings and façade views are difficult to find (Interview 3A). These are large documents, which are not being maintained or stored in sufficient matter. Therefore, the RWS does not have as-is drawings.

7.2.5 Conclusion

- From request to delivery: inspection reports take up to four weeks to be received
- Defects were not tracked, in this case this led to the defects to worsen
- Leaving a façade in a poor condition substantially decreases its circular potential
- The repair of this project was combined with another project, leaving the building in its current condition. Tiles breaking off can pose danger for passers-by, but this is only tackled when it has already happened.
- Natural hazards can have a substantial effect on the building
- Building information like plans, façade views or construction drawings are difficult to find

Case Study 3: Galileo Reference Building

7.3 Galileo Reference Building

Fig 23. (De Architekten Cie, 2016); Van Rhijnbouw

Interviewee	Position	Department	Organisation
Interview 4A	Project manager	Transacties&Projecten	Rijksvastgoedbedrijf
Interviewee 4B	Object manager	Vastgoedbeheer	Rijksvastgoedbedrijf
Interviewee 4C	Technical manager	Transacties&Projecten	Rijksvastgoedbedrijf

7.3.1 General information

The Galileo Reference Center (further referred to as GRC) is an office building used for receiving data of the Galileo satellite system. GRC is part of the Global Navigation Satellite System (GNSS) and has emerged through collaboration between the European Union and the European Space Agency (De Architekten Cie, n.d.). The building is located in the Space Business Parc, in an open flatland near the dunes and the Northsea.
This building is unique due to its circular and sustainable design. Its quick construction has been possible due to the prefabrication of the buildings' parts. The prefabricated parts also ensure the building is modular and led to minimalization of waste. The ambition also is to ensure a waste-free and resilient building, and that the chosen materials have the potential for future reuse (De Architekten Cie, n.d.).

The building consists of two stories that locate several office-, computer and meeting rooms as well as a pantry. Table 22 describes the building properties.

Galileo building properties	
Location	Noordwijk
Composition	Rectangular floor plan
Delivery year	2017
Building use	Office building
Height	9.0 meters
Gross floor area	1500 square meters
Workspaces	20-40
Floor layout	Pantries, office rooms, computer rooms, meeting rooms

Table 22. GRC building properties (ArchitektenCie, n.d.)

Figure 24. Location GRC (Google Maps, 2020)

Fig 25. Floorplan ground floor and 1st floor GRC, and corresponding functions near the façade (X)

7.3.2 Façade

General façade information

The prefabricated façade has been made of interchangeable cassettes, which are either transparent, semi-transparent or closed. This allows for various levels of transparency and due to its modular ability, it grants a closed or transparent façade where needed. The rooms behind the façade can change function due to the interchangeable cassettes. Which facilitates flexibility and future resilience of the building (De Architekten Cie, n.d.).

Façade Characteristics	
Cladding closed panels	HR++ Glass
Cladding transparent panels	HR++ Glass
Window frames	Aluminum
Coating	Aluminum is anodized and powdercoated
Connections	Dry connections
Inner cavity leaf	Spruce wood
Entrance door frame	Steel
Cladding near entrance	Folded sheet aluminum

Table 23. Façade characteristics (Building specifications, De Architekten Cie, 2016)

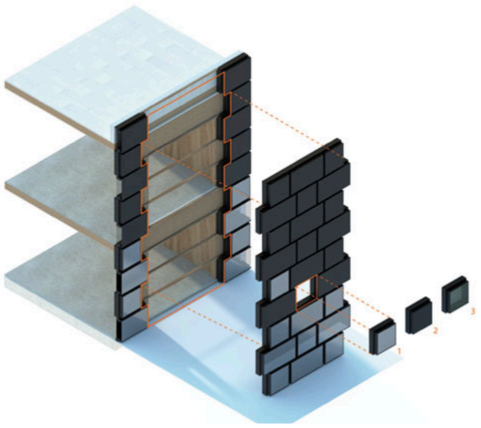

Fig. 26 3D view façade (ArchitectenCie, n.d.)

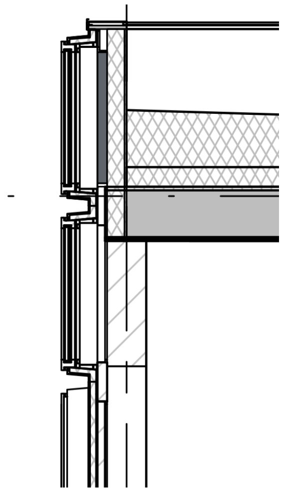

Fig. 27 Constructive detail roof (Building specifications GRC))

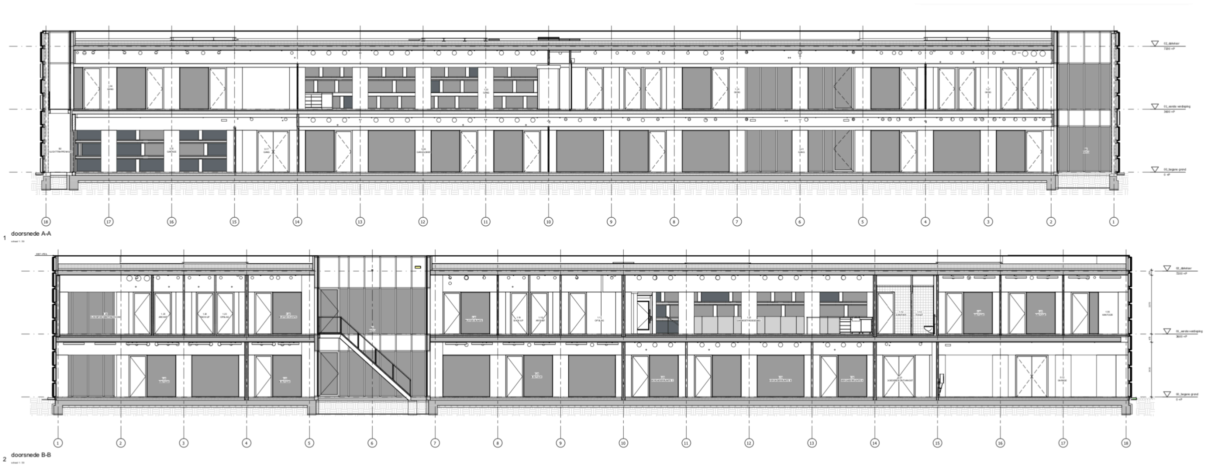

Fig. 28 Longitudinal sections (Building specifications GRC)

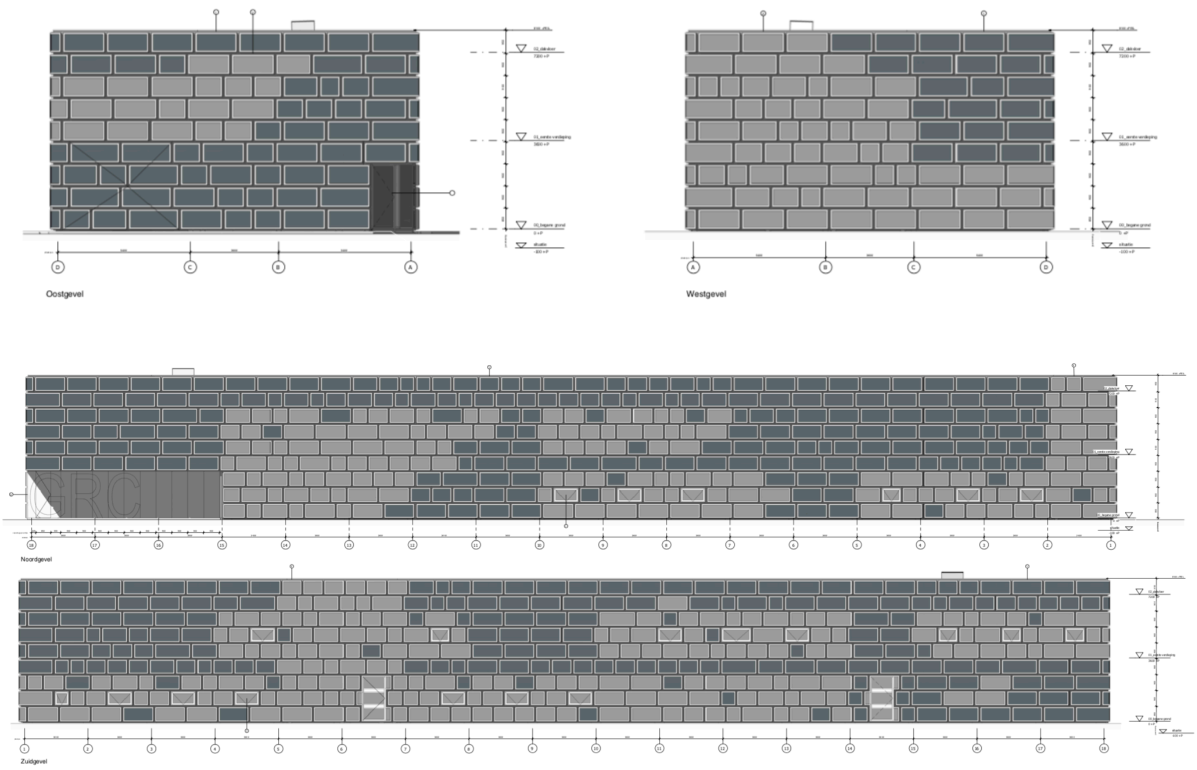

Fig. 29 Façade views (Building specifications GRC)

Desired situation façade

The building should be wind- and waterproof. Additionally, the façade should comply with the building laws, e.g. fire safety. As little maintenance as possible is desired (Interview 4A).
Additionally, it is desired as little waste as possible is generated. Also, the materials were chosen accordingly to create safeguard their future existence. Therefore, specific sustainability requirements were set for the materials to extend the lifecycle of the façade. The façade has a lower risk in strong deterioration (De Architekten Cie, n.d.).

Current situation facade

Due to the location of the building in an open flatland and near the sea, the building can experience strong and salty winds. Depending on the force and position of the winds, this sometimes leads to leaks (Interview 4A). The aluminium coating of the cassettes can be damaged by the sea wind, which can eventually lead to rust.

Element	Defect
Cladding closed panels	Dirt and discoloration
Cladding transparent panels	Dirt and discoloration
Window frames	Leaks
Coating	Fading of coating can lead to rust
Insulation	-
Connections	-
Inner cavity leaf	-
Entrance door frame	Dirt and discoloration
Cladding near entrance	Dirt and discoloration

Table 24. Façade elements and defects (Interview 4A)

7.3.3 Maintenance process

General information

According to the contract, maintenance is not outsourced to a third party. This means VB is responsible, and the object manager is the primary actor responsible. The object manager is in contact with the building user and the concern service provider, who notifies the object manager when a specific programmatic or functional demand is required. The user or concern service provider notify the defects center in Assen when an error occurs. The contractor is thereafter notified on the defect.

The façade is inspected visually by inspectors. They describe the defects on size, characteristics and possible causes. Inspectors use cameras to capture the severity and location of the defects.

Maintenance problems

Building is not being used at all times. This way, the contact person of the object manager is not able to pass on information on defects at all times (Interview 4B). This can pose problems when defects need to be alarmed to the defect centre in Assen by the user.

7.3.4 Information management

BLOEI is a tool designed to aid the RVB in implementing a circularity strategy in circular projects. Capturing information is an essential part of BLOEI, in which building passports are a crucial characteristic. These building passports hold essential information on the building which are relevant for reuse. Possible means to be used are BIM, excel or coded drawings. However, the last two options are difficult to keep up to date. Therefore, the mean used for building passports of GRC is BIM. Dependent on the ownership of the building and the façade, different information is available. The RVB is the owner of both the building as the façade. In 2016 the RVB specified information relevant for reuse of the façade, which is requested as content for GRC's BIM.

A BOEI inspection has not been performed yet at GRC, since the building was delivered in 2017.
The information specified in BIM is depicted in Table X.

Documents	Storage	Responsible
Façade drawings		
Plans		
Sections		
Maintenance details		
Maintenance needs		
Defects	Object manager	Object manager
Weight (kg)	BIM	Company Building 360
Composition	BIM	Company Building 360
Finishing Layer	BIM	Company Building 360
Dimensions	BIM	Company Building 360
Connections	BIM	Company Building 360
Constructive qualities	BIM	Company Building 360
Special specific qualities	BIM	Company Building 360

Table 25. Available information (Interview 4C)

BIM of GRC is not being used currently, which means the information is not being updated. The reason for this is that nobody was willing to use BIM (Interview 4A). Despite the possible future of high-quality building passports and exchange of information, there was no aspiration to maintain the BIM model (Interview 4A)

Information management Issues

BIM is not being updated since it is not being used. Therefore, the information on specific qualities are not updated.

7.3.5 Conclusion

- Materials need specific qualities to be able to have a long service life
- High quality materials have a longer service life
- A façade is not maintenance free, there are always natural hazards which can cause damage
- Materials should be demountable, to ensure the service life of the rest of the façade
- Specific information should be requested to determine the service life of building parts
- BIM is not used, involved actors need an incentive to start using BIM

7.4 Conclusions: case comparison

	Type	Case study 1: JuBi Towers	Case study 2: Rijkswaterstaat Building	Case study 3: Galileo Reference Building
General information	Delivery year	2012	2004	2017
	Location	City center	Suburb	Rural area
	City	The Hague	Rijswijk	Noordwijk
	Builiding type	Office	Office	Office
	Area (sqm)	130.000	7000	1500
	Height (m)	147	34	9
	Workspaces	4000	250	20-40
Circularity	Circular building	No	No	Yes
	Preservation of materials	Yes	Yes	Yes
	Harvest materials	No	No	Yes
	Biobased materials	No	No	Yes
	Minimalization of environmental impact	Yes	No	Yes
	Non toxic materials	Yes	Yes	Yes
	Design for demountability	No	No	Yes
	Circularity is included in project scope	No	No	Yes
	Ownership building	Yes	Yes	Yes
	Ownership facade	Yes	Yes	Yes
	Inventory materials on reuse potential	No	Yes	Yes
	Register materials in building passport	No	No	Yes
Facade information	Cladding	Prefab panels	Tiles	Prefab cassettes
	Material	Brick and stone	Ceramic and plaster mortar	HR++ glass
	Window frames	Steel and aluminium	Aluminium	Aluminium
	Insulation	Mineral wool	XPS boards	Argon gas and HR++ glass
	Inner cavity leaf	Prefab concrete	Prefab concrete	Spruce wood
	Main hazards	Sea wind	Sun, rain and wind	Sea Wind
	Main defects	Falling cladding, cracks, leaks	Falling cladding, cracks, leaks	Leaks
Maintenance	Integrated maintenance	Yes	No	No
	Maintenance contract	DBM	-	-
	Maintenance responsible	Contractor	RVB	RVB
	RVB responsible	Contractmanager	Objectmanager	Objectmanager
	Contractor	Heijmans	Unica	
	Inspection	Once a year	Twice a year	
	Defect detection	Facade inspection pilot	Visual inspection	Visual inspection
Information management	BIM	Yes	No	Yes
	BIM used for maintenance	Solely to obtain information on the surroundings, of a defect, drawing out quantities, looking for optimizations	No	No
	As-built plans	Yes	No	Yes
	As-built facade drawings	Yes	No	Yes
	Updating BIM model	Manually	-	Manually

The variety of cases studies provided for many insights. JuBi is a large building, in which maintenance is more complicated as a great deal of information is involved. Keeping track of the multitude of defects is essential to ensure the extension of its service life. Information systems are prone to human error, which is why it is important to prevent this from happening. Façade maintenance of such a large building is a time consuming and extensive process when visually inspecting this on defects. Visual inspections are prone to human error as well, because it can be difficult to determine the size, cause and characteristics of a defect. So, it is crucial to educate inspectors to be able to gain the right information.

This case has pointed out that BIM can be beneficial during the maintenance process. BIM is used for defects indoors, not including the façade. However, there seems to be a need for digital communication means of façade defects. This can be concluded because the façade identification pilot is set up, due to unexpected defects had happened. Additionally, the current inspection reports are unclear and unreadable; therefore, accurate judgement by technical managers is difficult.

Furthermore, this case has pointed out a façade cannot be 'maintenance-free'. Due to the exposure to natural hazards and materials' degradation cycle, façades are always in need of maintenance. However, it is possible to minimize the amount of maintenance a façade needs, namely, to incorporate high-quality materials in the design. To capture and maintain the façade's service life, accurate information and collaboration are necessary.

The RWS has also pointed out that high-quality and sustainable materials are vital for the façades service life. Also, to check the building on construction errors after delivery. It has also pointed out that natural hazards can have a substantial impact on the building. Leaving the building in its current condition has only increased the deterioration.

Besides, it exposed the value of technology in inspections. During an inspection, use was made from thermographic technology exposing all leaks. This provided evidence and supported determining a plan of action. RWS also revealed inspections could take up to four weeks, for an inspection report to get back to the object manager. This points out that technology can provide substantial evidence on defects. Also, it speeds up the inspection process.

GRC has pointed out that façade materials need more characteristics other than 'high-quality'. In order for a façade to have a long service life, it should be demountable, easy to maintain and consist of secondary materials, among other things.

This case has also pointed out that employees need an incentive to work with BIM. This model is currently not being used because of this, despite the potential of the model. GRC's BIM model did point out that it can serve as a handy source of information. It pointed out the great importance of requesting information which can be used to determine the future value. Examples of information are disassembly and weight per component.

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Chapter 8
Findings

Findings

The case studies have provided for extensive insights into circularity requirements, the maintenance process of façades, façade defects and information management. This chapter entails the next step towards the research output on facilitating circular maintenance by means of a DT. In this chapter, the insights from the case studies are combined with a comprehensive literature review on sensor technology, which is extensively described in Appendix D1 and D2. A comparison is conducted for each case study, which includes the most impactful façade defects, and their current detection technologies. These are compared with recommended detection technologies derived from literature. The influences of the recommended technologies on the current maintenance process are described as the main findings of the thesis.

The literature review comprises various sensors chosen on the basis of various façade defects derived from inspection reports of the three case studies. The façade defects can be detected on the basis of temperature, width, light and vibration among other things. Therefore, various sensors are applicable for a single defect. In this chapter the most impactful façade defects are discussed. These defects are falling cladding, cracking, corrosion and leaks. Appendix E, G and I describe a total overview of the façade defects present in each case study. However, the most impactful defects are featured in this chapter, because they form the highest threat to the quality of the façade element. Besides, they also pose safety issues, interfere with the buildings' main activity and lastly, they form the largest threat to the circular potential. Falling cladding (1) has resulted in acquiring new materials for repair, as well as safety issues for the activity in the surroundings. Cracking (2) has led to water infiltration and wetted insulation, threatening the lifecycle of the material. Preventing or quick handling of cracking can prevent harmful events from happening. Water leaks (3) may result in degrading of the material through growing of mold or mildew, or replacement of the element. Corrosion (4) can result in the loss of life span of metals, loss of efficiency of the material and lastly it can cause change in the physical appearance. Each case study entails a few of the mentioned defects, which are discussed in the tables below.

The case studies will thereafter be tested onto which level their characteristics resemble to a DT. In the corresponding table, the necessary characteristics of a DT will be explicated. Besides, the corresponding characteristics of the case studies are set out, presenting the lacking and present characteristics to achieve a DT degree. This provides for a good overview on the necessary additions to reach a higher DT degree.

8.1 Case study 1: JuBi Towers

Type (Cluster)	Material	Corresponding information in BIM	Circularity degree (based on Appendix F)	Defect	Force	Building Side	Type of maintenance	Current Defect-Detection Technology
Cladding	- Prefab brick panels - Prefab natural stone panels	**Entered value**: Width, Height, Family Name, Type Name **No entered value:** Thermal Resistance, Fire Rating, Thickness, Heat Transfer, Cost, Assembly, Bulletproof	-/+	Falling cladding	-Strong wind -Window cleaning gondola	South side, south tower	Corrective maintenance Reactive maintenance	**Visual inspection** **Pilot *:** Cameras are attached to the window cleaning gondola, capturing pictures of the façade. This results in a high-resolution 3D point cloud
Cladding	- Prefab brick panels - Prefab natural stone panels		-/+	Cracking	-Sun -Wind	South tower, south side	Corrective maintenance	
Outer Window frame	Aluminum		-/+	Leaks	-Rain	All sides	Corrective maintenance	

Legend	
+	Strong connection
+/-	Medium connection
-	Weak connection

Table 26 Factual information (Source: Façade Matrix in Appendix E; Circularity Degree table in Appendix F)

* The façade identification pilot is still in progress and is not being used at the moment.

Defect	Advantages current defect detection technology	Disadvantages current defect detection technology	Recommended Defect detection Sensors	Advantages recommended defect detection sensors	Disadvantages recommended defect detection sensors	Placement	Costs	Circularity
Falling cladding	**Visual inspection** -No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available **Façade Identification pilot** - High resolution image of all façades - The 3D pointcloud depicts the locations of all defects on the façade, which makes it easier to plan maintenance	**Visual inspection** - Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance **Façade Identification Pilot:** -The pictures and the corresponding severity and priority is a labor intensive and unpopular task. - Maintenance of output is labor intensive and prone to human errors. The severity and priority can be judged by students/interns, which may not be educated enough to take correct decisions - Lighting and weather conditions are very important, as differences can result in an inaccurate image	IR* *Infrared thermography PEAS *Piezoelectric Actuator Sensors	**IR:** Fast, safe clean method. Reduces guesswork **PEAS**: can visualize scattering locations and estimate size/location of several types of damages.	**IR**: IR needs a temperature difference to detect water, may produce possible errors during wintertime. Also, it is a complex technology which is in need of understanding **PEAS**: Major challenge in quantifying the damage based on sensor measurements. In need of people who understand the measurements	**IR:** IR is to be placed on a moving machine, in order to capture a complete image of the façade **PEAS:** The sensors should be attached to the façade	**IR:** Infrared cameras can be expensive. Several cameras are needed, to capture an image of the façade. **PEAS:**	-Fallen cladding should be prevented to decrease the use of new materials for repair - Sensors can help clarify severity and priority of the defect. It can even help to prevent the defect, by showing information on strain, vibration and temperature. -The following information in BIM should be integrated: constructive qualities, weight, composition, finishing layer, connections and certain specific qualities
Cracking								-Cracking should be prevented. PEAS aid in determining the façades behavior and helping to predict cracks -IR can help identify cracks
Leaking window frames			IR	**IR:** Fast, safe clean method. Reduces guesswork. IR is able to quickly detect water	**IR:** IR needs a temperature difference to detect water, may produce errors during wintertime. Also, it is a complex technology which is in need of understanding	**IR:** IR is to be placed on a moving machine, in order to capture a complete image of the façade	**IR:** Infrared cameras can be expensive. Several cameras are needed, to capture an image of the façade.	-IR can detect moisture quickly. In determining moisture within a building or insulation, it can help prevent from water infiltrating, posing danger to insulation for example

Table 27 Recommended technology (Source: Façade matrix in Appendix E)

Type	Defect detection technology	IoT	BIM-model	Impact on circularity	Digital twin degree
Current Situation	-Visual inspection -Thousands of pictures are made and accumulated into a 3D point cloud. This is a model which shows the location and number of defects	None	**Main use**: To generate drawings, obtain information on the surroundings, of a defect, drawing out quantities, looking for optimizations **Real time information**: the model is updated manually when changes are made to the building	The maintenance team is updated on the defects after it has already occurred. This way, additional materials are always necessary for repair. The facade is maintained with a vision in mind of a lifecycle of 50 years.	**-**
Recommended situation	Infrared thermography and piezo electric actuator-sensors, which collect information on temperature, strain, vibration, water. Through use of algorithms the data can be analyzed to make the process quicker, but human intervention is necessary to judge the severity and priority of the defects shown.	The (smart) sensor network is connected through the internet and thereby able to collect and exchange data across platforms, in this case BIM. The main purpose of IoT is to deliver real-time data, which can be analyzed and used to create better outcomes.	**Additional use:** It is recommended to use BIM in maintenance, to increase the circular value of the element. **Real time information** The sensor data is implemented into BIM to facilitate maintenance decisions. To increase the reuse potential of the component and to estimate the lifetime, the following information should be integrated: Constructive qualities, weight, composition, finishing layer, connections and certain specific qualities	Fewer waste is generated because the condition of the facade continues is stable. The maintenance team is notified when a defect occurs. Sensors show the behavior of the façade and are able to detect damages. This way fewer virgin resources are used for repair. Also, because the condition is stable, the energy efficiency of the building also continues to be stable The emissions generated by the logistics of maintenance also decreases, since maintenance is only carried out when necessary.	**+**

Legend	
+	Strong connection
+/-	Medium connection
-	Weak connection

Table 28 Digital twin degree JuBi (own table)

Defect Detection Technology

Current Defect Detection

In maintenance, defects are mainly sought after to maintain the safety and the comfort of the buildings' user and activity. To detect defects, visual inspections are performed annually by an inspector. The inspector analyses, tests and describes the defect based on the condition scores set out in the BOEI requirements, which is described in Appendix A. Defect analysis is based on experience, knowledge and interpretation. The inspector captures the defects with a camera. This information is thereafter combined into an inspection report. The contractor uses this information to create a plan of action for repair consisting of a planning, tasks and costs. This method of defect detection has favorable qualities. Namely that no additional costs for new technologies are necessary. Additionally, it is an easy way to detect defect which is very tangible for the inspectors, since inspectors have carried out this method for years.

However, this method of inspections also has several disadvantages. When comparing the annual inspections to real time inspections, there are differences. As inspections are carried out once per year, the defects can be often found long after its emergence. The severity of the damage could already have increased. Also, because the façade is inspected visually, defects can be overlooked, due to the size of JuBi building or the inexperience of the inspector. When a defect is not visible or hidden, it is not taken into consideration. Defects can be judged wrongfully through overestimating, underestimating or misunderstanding it.

Finally, the location and severity of the defect are difficult to determine in the inspection reports, due to poor image quality. This information is crucial in determining the plan of action to solve the defect.

As mentioned in §7.1.3, a façade inspection pilot has been set up for the JuBi building. This pilot allocates defects to a location by attaching pictures to a location in the 3D point cloud. Three cameras are attached to the moveable window cleaning gondola, which take pictures of the façade every 0,5 meters. This way the cameras visualize the façade of JuBi. This is favorable because is possible to determine the exact location of the defects. Also, it is possible to reach difficult spots and capture all visible defects. Besides, the time of emergence of the defect can be allocated better. And finally, it is

possible to conduct analyses from a distance and reduces the man hours of the visual inspections around the building.
However, the façade identification pilot also possesses several flaws. Lighting and weather conditions are crucial in the quality of the picture. Poor lighting and weather can lead to misjudgments of a defect. Besides, as the camera's do not acquire infrared characteristics, it is still a surface inspection. This means that hidden defects are not included, and the severity and priority are still difficult to determine from a picture. Finally, together the three cameras produce 800 pictures, which thereafter have to be judged by educated employees, which is a time-consuming process prone to human errors.

Recommended Defect Detection
The recommended technologies derived from literature for the specific façade defects described in Table 26 are infrared thermography (IR) and piezoelectric actuators-sensors (PEAS). Because they are able to contribute to circularity by showing evidence on defects characteristics. Defects can be better allocated to its causes; its characteristics can be better described and is priority can be better determined. Because sensors deliver factual information, the data analysis can lead to stronger input for plans of actions. This can aid in providing maintenance for the façade when necessary, maintaining its quality. Additionally, it can help in finding connections between defects. This facilitates circular maintenance because defects can be handled immediately, and repair can be better planned. Which ultimately impacts the facades' lifetime.

- IR can detect thermography above absolute zero, which is beneficial for leaks, cracking and falling cladding. IR can be used to quickly survey a building. The quality of the pictures is not prone to light or weather conditions. Also, it can reduce guesswork and identify 'hidden' defects not visible before. This partly eliminates the following current issues: overlooking defects, guesswork, locating defects, determining severity and priority. However, when the thermography drops below absolute zero IR cannot produce measurements, which can be an issue during winter. Also, it is a complex technology which demands understanding of the method.
- PEAS inject controlled diagnostic signals into structures and can interrogate a large area, which is advantageous with this large building. It can estimate the locations and size of several types of defects. Additionally, measures small motions extremely precise, which is advantageous for detection of cracking and falling cladding. This method eliminates the following shortcomings of the current method of working: determining severity and priority, overlooking defects and reducing guesswork.

Influences Existing Maintenance Process
The BOEI inspection process is described below. Step 1 entails the start of the BOEI inspections, the final step entails when sufficient information is received to perform an action. Also, the maintenance process also entails daily maintenance, which is described below as well.

BOEI Inspections

1. BOEI Inspection are scheduled to be performed annually
2. Visual inspection is carried out
    a. Using a regular camera to capture defects.
    b. The inspector describes the defect based on BOEI condition score 3
3. Pictures and information are collected into an inspection report
4. Information is collected in Condor
5. Inspection report is checked by contractor
6. Defects are prioritized
7. A plan of action is made
8. Action is performed

Daily maintenance

2. User / concern service provider notices defect
3. Information is passed down to the:

a. Object manager

3a. Object manager consults advisor and takes decision
4a. Object manager consults contractor and discusses decision
5a. Contractor carries out task

b. Defects center in Assen

3b. Contractor is consulted and notified on the defect
4b. Contractor performs tasks agreed upon

When including the new technologies in the current maintenance process, this process requires changes.

- It should be clear what data is captured by sensors
- Information to determine its future life is necessary, e.g. degradation, maintenance history and exploitation life
- The sensor data should be stored, filtered and analyzed
- Data analysts should be educated to read the data and produce readable data analysis reports.
- People need to understand the aim and outcome of the method
- All people involved need to understand the technology and what is being carried out
- Solutions to diminish human error should be implemented

Conclusion

Integration of the new technologies to facilitate circular maintenance requires changes in the current maintenance system. The existing maintenance system is not built to work with the recommended technologies, which is why additions to the current system are necessary. To ensure suitable sensors are chosen, a preparation phase should be included where parameters of the sensors are determined, sensors are chosen and installed. In this preparation phase, certain steps should be taken to prepare the façade for a circular lifespan. This includes collecting information to determine its future life, e.g. degradation, maintenance history and exploitation life. Additionally, it requires a circular design, such as implementation of dry connections.

During the use phase of the building - which is also when the sensors are begin used - the derived information from the sensors needs to be stored and easily accessible. Additionally, new tasks ought to be added to the existing process: data analysis, data maintenance, sensor maintenance and BIM maintenance. Data analysis should be done through a combination between algorithms and human analysis, the information from sensors needs to be easily readable by actors. The BIM model needs to be managed and updated accordingly.
Integration of the new technologies is something that concerns the entire supply chain of maintenance. In order to be able to provide input in the process, all involved people should know and understand what technologies are being used. Also, it needs to be clear what is being measured and for what cause. The most involved actors in maintenance need to know how to use the technologies.

8.2 Case study 2: Rijkswaterstaat Building

Type (Cluster)	Material	Corresponding information in BIM	Circularity degree (based on Appendix H)	Defect	Force	Building Side	Type of maintenance	Current Defect-Detection Technology
Cladding	Plaster mortar Ceramic tiles	None	-	Falling cladding	Wind Sun	South west side	Corrective maintenance Reactive maintenance	**Visual inspection**
Cladding	Plaster mortar Ceramic tiles		"	Cracks	Sun Wind	High south Southwest	Corrective maintenance	**Visual inspection**
Window frames	Aluminum		-	Leaks	Rain	All sides	Corrective maintenance	**Visual inspection**
Window frames	Aluminum		"	Corrosion	Wind Rain	All sides	Corrective maintenance	**Visual inspection**

Legend	
+	Strong connection
+/-	Medium connection
-	Weak connection

Table 29 Factual information (Source: façade matrix in Appendix G; circularity degree table in Appendix H)

Defect	Advantages current defect dection technology	Disadvantages current defect dection technology	Recommended Defect Detection Sensors	Advantages recommended defect detection sensors	Disadvantages recommended defect detection sensors	Placement	Costs	Circularity
Falling cladding **Cracking cladding**	**Visual inspection** -No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	**Visual inspection** - Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance	DOFS* PEAS *Distributed optical fiber sensor	**DOFS:** Reveals strain from any point along the line. Adequate when applications need multiple levels of coverage. **PEAS:** can visualize scattering locations and estimate size/location of several types of damages. It can measure small motions extremely precise.	**DOFS:** Works best if they are integrated into a façade. Labor intensive during installation and maintenance sensitive sensor. **PEAS:** Major challenge in quantifying the damage based on sensor measurements. In need of people who understand the measurements.	**DOFS:** In zigzag lines along the façade **PEAS:** attached to the façade	**DOFS:** High cost **PEAS:**	**DOFS:** These sensors can measure multiple variables in one fiber and the measurements are extremely precise. It can produce predictions, which are useful in predicting defects and save on new materials **PEAS:** Can also show data which can help with predict defects. This can also save additional materials necessary for repair.
Leaking window frames			IR	**IR:** Fast, safe clean method. Reduces guesswork. IR is able to quickly detect water	**IR:** IR needs a temperature difference to detect water, may produce errors during wintertime. Also, it is a complex technology which is in need of understanding	**IR:** Attached to a moving device, on an angle that captures the entire façade, or pictures taken manually.	**IR:** Infrared cameras can be expensive	**IR:** When water infiltration is detected in an early stage, this can prevent window frames from degradation
Corrosion on window frames			OFCS* *Optical fiber corrosion sensor	**OFCS:** It can detect aluminum cations from the early process of corrosion. The sensitivity of corrosion is good for the low thickness of corrosion	**OFCS:** High cost	**OFCS:** In zigzag lines along the façade	**OFCS:** High costs	**OFCS:** This sensor is able to detect corrosion in its early stage. This way, it can alarm the maintenance team to repair the frame, before corrosion accumulates over the frame.

Table 30 Recommended technology (Source: Façade matrix in Appendix G)

Type	Defect detection technology	IoT	BIM-model	Impact on circularity	Digital twin degree
Current Situation	The current defect detection method does not make use of technology. Only cameras are used to capture defect that are detected by inspectors.	None	Case 2 does not have a BIM model. The drawings have not been updated to the current situation. Also, retrieving the drawings is difficult.	Due to construction errors the building has degraded quickly after its delivery. The current defect detection method also makes it possible	**-**

New situation	Infrared thermography, optical fiber corrosion sensors and optical fibers provide to opportunity to quickly detect defects which are possibly dangerous or interfering with the buildings' main activity.	The (smart) sensor network is connected through the internet and thereby able to collect and exchange data across platforms, in this case BIM. The main purpose of IoT is to deliver real-time data, which can be analyzed and used to create better outcomes.	As there is no BIM model there is a need of one. The active façade project can lead to a BIM model for the façade. Otherwise, a laser scanner can be used for quickly converting the building into a 3D point cloud. Real time information measured by the sensors is implemented into the model To increase the reuse potential of the component, and to estimate the lifetime the following information should be integrated: Constructive qualities, weight, composition, finishing layer, connections and certain specific qualities	Less waste is generated because the condition of the facade continues is stable. This is done because the maintenance team is notified when a defect occurs. This way fewer virgin resources are used for repair. Also, because the condition is stable, the energy efficiency of the building also continues to be stable The emissions generated by the logistics of maintenance also decreases, since maintenance is only carried out if necessary	**-/+**

Legend	
+	Strong connection
+/-	Medium connection
-	Weak connection

Table 31 Digital twin degree (own table)

Defect Detection Technology

Current Defect Detection

In case 2, inspections are performed twice a year by an inspector. Similarly to the inspections at the JuBi building, the inspector does not use technologies to defects on the façade: the detection method are visual inspections. Defects are personally found and analyzed by inspectors based on experience, knowledge and interpretation. The BOEI characteristics are the manual by which the condition is determined. The inspector determines severity, priority and characteristics like age measurements. To capture the defects, cameras are used. The pictures and written analysis are combined in an inspection report, serving as a base for the plan of action.
The users are also a source to detect defects. The object manager has agreed with the users that information is passed down when a leak occurs or cladding falls.

Not investing in defect detection technologies has advantages as no additional costs for new technologies are necessary. Besides, it is a simple way to detect defect which is very tangible for the inspectors. The other way to detect defects is by notice of the users. They inform the defects center in Assen, which sends this information through to the contractor.

However, these defect detection methods also have several disadvantages. Inspections are performed once every six months, this poses disadvantages when comparing this to real time inspections. Namely that defects have the possibility to deteriorate in between those six months. This means repair can be more expensive, and the defects can cause more damage. Also, waiting until a natural moment has consequences for the circular potential of the building as the cladding is severely damaged, and the insulation has wetted.
The visual inspections also pose the possibility for defects to be overlooked, overestimated, underestimated. Additionally, visual inspections are surfaced inspections, so defects can be hidden in places which are not well accessible. Also, inspections take a long time. It can take four weeks from request to delivery of the inspection report. Finally, the location and severity of the defect are difficult to determine in the inspection reports, due to poor image quality. This information is crucial in determining the plan of action to solve the defect.

Recommended Defect Detection

The recommended technologies are distributed optical fiber sensor (DOFS) and piezoelectric actuator-sensor (PEAS) for falling cladding and cracking. IR sensors have been chosen to detect leaks, falling cladding and cracks, lastly, OFCS have been chosen to detect corrosion detection.

- DOFS are very sensitive and versatile. The fiber sensor can measure multiple variables in one fiber: it can measure stain, vibration, temperature among other things simultaneously. This technology shows when a defect is occurring, which enables maintenance teams to improve their planned maintenance. It reduces guesswork as it shows precise data on strain, vibration and temperature. It works best when integrated into a façade, it could be integrated in the active shell project. However, installation of the fibers is labor intensive. The fibers require maintenance. Also, people must be equipped with skills to be able to read and analyze the measurements, as they can be difficult to quantify.

- PEAS are extremely precise and can measure small motions. They can visualize scattering locations and estimate location and size of several types of damages. The precise measurements reduce guesswork of the visual inspections. However, the measurements are complex and hard to quantify.
- IR can be used to quickly survey the building on different thermography. IR can detect thermography above absolute zero, which is beneficial for leaks, cracks and falling cladding. Its outcome produces pictures indicating differences in temperature. This helps to judge defect correctly, to reduce guesswork, reduce in overlooking defects by exposing all defects. It also accelerates inspection times. However, IR is a complex technology, in which it is crucial the maintenance team knows how to read the information.
- OFCS can detect corrosion in its early stages and can thereby help in prediction of its occurrence. It can even measure thin layers of corrosion and can thereby identify all spots where corrosion is showing. This reduces guesswork, helps with correctly determine severity and priority, can help with prediction of its further development. However, this technology is expensive.

The relation between circularity and the sensors are that they can show evidence for occurrence or presence of defects. Furthermore, shows evidence for severity and can help to determine the priority. This all is a strong base for input in the maintenance plan, which can help to perform maintenance when necessary and keep the condition stable.

Influences Existing Maintenance Process

BOEI Inspections

1. BOEI Inspection are scheduled to be performed annually
2. Visual inspection is carried out
    a. Using a regular camera to capture defects.
    b. The inspector describes the defect based on BOEI condition score 3
3. Pictures and information are collected into an inspection report
4. Information is collected in Condor
5. Inspection report is checked by contractor
6. Defects are prioritized
7. A plan of action is made
8. Action is performed

Daily maintenance

1. User / concern service provider notices defect
2. Information is passed down to the:

a. Object manager

3a. Object manager consults advisor and takes decision
4a. Object manager consults contractor and discusses decision
5a. Contractor carries out task

b. Defects center in Assen

3b. Contractor is consulted and notified on the defect

4b. Contractor performs tasks agreed upon

In the current maintenance process the involved actors do not make use of technology to detect defects. However, technology is integrated in the building to test energy efficiency. The pilot which is currently running has produces lessons learned. Topics which need to be taken into account when implementing new technologies in current processes are:

- The organisation is not equipped for smart buildings yet, so new steps should be added
- Tasks should be allocated clearly on who stores, analyses and maintains the data
- Understanding of the new technology is crucial by people who work directly with this
- All people involved need to understand and be aware of the technology and what is being carried out
- All people involved need to know a little bit on the topic of ICT to be able to help with the situation, not solely the ICT engineers

Conclusion

Through integration of the new technologies in the current maintenance process, change is required. The following topics need to be taken into account. It matters what happens with the data after this is measured: it needs to be clear who analyses the data and where it is stored. Data input should be of high quality and data output should be maintained and easily accessible. It needs to be an incentive to maintain the data, otherwise it is not going to be used. Actors need to understand the sensors and its measurements. Finally, involved people need to be aware of the technology and what is being carried out

8.3 Case 3: Galileo Reference Center

Type (Cluster)	Material	Corresponding information in BIM	Circularity degree (based on Appendix J)	Defect	Force	Building Side	Type of maintenance	Current Defect-Detection Technology
Window frames	Aluminum	Components, dimensions, supplier information, assembly code, constructive qualities, weight, composition, finishing layer, connections Material, structural material, Fire safety	+	Leaks	Rain Wind	All sides	Corrective maintenance	**Visual inspection**
Window frames	Aluminum			Damaged coating	Wind Rain	All sides	Corrective maintenance	**Visual inspection**

Legend	
+	Strong connection
+/-	Medium connection

-	Weak connection

Table 32 Factual information (Source: Façade matrix in Appendix I)

Defect	Advantages current defect dection technology	Disadvantages current defect dection technology	Recommended Defect Detection Sensors	Advantages recommended defect detection sensors	Disadvantages recommended defect detection sensors	Placement	Costs	Circularity
Leakages **Damaged coating**	-No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	-Defects can stay hidden -Defects can get the chance to worsen, due to time -Defects can be discovered long after they happened -Making of a plan of action is more complex	**IR *** ***Infrared thermography**	Fast, safe clean method. Reduces guesswork. IR is able to quickly detect water	IR needs a temperature difference to detect water, may produce errors during wintertime. Also, it is a complex technology which is in need of understanding	In a position where a total image of the façade is possible	IR camera can be expensive	The sensors can detect defects and indicate necessary maintenance.

Table 33 Recommended additions information (Source: Table Appendix I)

Type	Defect detection technology	IoT	BIM-model	Impact on circularity	Digital twin degree
Current Situation	Currently, no use is made of technology to detect defects.	None	**Main use:** The model is not used **Real time information:** Overall the BIM-model is of high quality. The model has been produced by a separate party. The model includes information on various aspects, such as materials, fire safety, supplier information, dimensions. Also including information valuable for reuse. However, information on maintenance is not of high quality	The buildings' circular character, availability of plans, chosen materials and demount ability already provide an excellent base for circularity. However, maintenance of the façade can be improved, to ensure the quality throughout the years.	-
New situation	Infrared thermography collects information on temperature, revealing leaks and damaged coating. Through use of algorithms the data can be analyzed to make the process quicker, but human intervention is necessary to judge the severity and priority of the defects shown.	The (smart) sensor network is connected through the internet and thereby able to collect and exchange data across platforms, in this case BIM. The main purpose of IoT is to deliver real-time data, which can be analyzed and used to create better outcomes.	**Main use:** The model is currently not used. To make sure the model is used, the information should be valuable. The aim of its use should be clear. **Real time information** A separate party should be in charge of maintenance of the model. Information derived from the sensors should be attached to the corresponding element.	The real time information implemented into the BIM-model facilitates the maintenance team in making better maintenance plans.	+

Legend	
+	Strong connection
+/-	Medium connection
-	Weak connection

Table 34 Digital twin degree (Source: Own Table)

Defect Detection Technology

Current Defect Detection

In case 3, visual inspections are performed every five years. Surface defects are inspected by inspectors to predict the internal condition of the structures. Cameras are used to captures the defect. The inspector also judges and describes the defect, based on severity, age, cause and characteristics. Defects can also be detected visually by its users or concern service providers. This method to visually detect damages has several advantages. This method is tangible and easy to understand for many people. Also, it is cost beneficial, as no additional costs are necessary for the technologies.

However, because the defect inspection method is identical to the other case studies, the disadvantages are also the same. Defects can be overlooked, underestimated or overestimated. Visual inspections are time consuming, because it is labor intensive and lengthy from request to delivery of the inspection report. It also has disadvantages when comparing inspections to real time inspections.

Because inspections are performed once per 5 years, defects can deteriorate over time. This can lead to further damage of the element and expensive reparation costs.

Recommended Defect Detection
The recommended technology is IR (infrared thermography)

- IR detects temperatures above absolute zero. This is beneficial for leaks and deteriorating coating. The advantages of this technology are that it reduces guesswork, exposes hidden defects and exposes the severity. This can facilitate in producing maintenance plans. It can also reduce man hours. However, the disadvantage is that it is a complex technology which is in need of thorough understanding by all users and people involved.

Influences Existing Maintenance Process

BOEI Inspections

1. BOEI Inspection are scheduled to be performed annually
2. Visual inspection is carried out
   a. Using a regular camera to capture defects.
   b.The inspector describes the defect based on BOEI condition score 3
3. Pictures and information are collected into an inspection report
4. Information is collected in Condor
5. Inspection report is checked by contractor
6. Defects are prioritized
7. A plan of action is made
8. Action is performed

Daily maintenance

1. User / concern service provider notices defect
2. Information is passed down to the:

a. Object manager
3a. Object manager consults advisor and takes decision
4a. Object manager consults contractor and discusses decision
5a. Contractor carries out task

b. Defects center in Assen
3b. Contractor is consulted and notified on the defect
4b. Contractor performs tasks agreed upon

Case 3 is also not using technologies to detect defects. Including technologies into the process requires changes of the current process, such as:

- The incentive to use it needs to be clear BIM is available but not used, the reason for this is because there is not incentive to use it. This can be the same with the recommended new technologies.
- Users and involved people need to understand the technologies and should be up to date on what is being measured

- Tasks should be allocated clearly
- Data needs to be stored and managed

Conclusion

From the integration of the new technologies within the third case studies, conclusions can be made. The additional tasks to the current process should be allocated clearly. Also, it has been clear that actors need an incentive to use new technologies, this incentive should be clear. Also, in order for the data to be valuable, it needs to be clear what is going to be measured and for what use.
In order for the new technologies to be used properly, new tasks should be added in which actors are responsible for data analysis, data maintenance, BIM maintenance and sensor maintenance.
This case study has also pointed out that façade materials need specific characteristics to enable circular maintenance. This means the façade should be demountable, keeping the façade intact when a part is removed. Additionally, high quality materials are important. Also, during the design process an agreement must be made to provide technical information on the façade. In this way, information relevant to determine future use is available at the delivery of the building.

8.4 Chapter Conclusion

When comparing the conclusions of each case study in this chapter, this has given insights and requirements for the research output. These insights and requirements are as follows:

Defect detection technology

The case studies and interviews pointed out that new technologies lack further adoption after their initial start in practice. Therefore, it should be clear which data is capture and what its value is. Therefore, the preparation phase can be included where material hazards are determined, and specific parameters are chosen. The data must be reliable and of high quality, so determining parameters and choosing sensors plays an important part. The placement of the sensors should be investigated after choosing sensors.

Influences maintenance process

When using the sensors, tasks should be allocated to specific actors and clearly explained. Because, it matters what happens with the data, where this is stored and who analyses it. A data maintenance team should be in charge of data storage, data maintenance, sensor maintenance and data analysis. The BIM model should be managed as well. It needs to be an incentive to maintain the BIM model and the data output; otherwise, it will not be used.
Human error must be avoided during this process; however, relying on machine learning alone is also threatening. Therefore, a combination of algorithms and human analysis can derive adequate data output.
The involved actors should be able to read the data output; therefore, they must be educated. Additionally, not only the data team should know how new technologies work. Additionally, they should be up to date on what is being measured and for what cause. All involved actors should read the measurements, to be able to provide for valuable input.

The maintenance team should also have access to extensive material information on the façade. This way, future life can be better determined and safeguarded.

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Chapter 9
Validation

Validation

Expert Panel and Setup

Reliability and validity of research output are important factors when assessing research quality (Bryman 2012). As described in Chapter 5 'Research Methodology' the research findings have been presented to industry experts in order to validate the outcome. The consulted experts work in various sections: sustainability, real estate information and smart buildings. The findings of the empirical and theoretical research were presented during a one-hour meeting with the RVB section 'Duurzaamheid & Comfort'. The meeting ended with a 30-minute question round, where 15 colleagues made remarks and asked questions on the topic. The other experts have been questioned separately from this meeting, they were able to provide input by means of a video presentation and corresponding questionnaire. The experts involved in the validation of this research hold the following functions:

#	Function	Department	Organisation
1	Program Manager Smart Real Estate	Portefeuillestrategie & Portfeuillemanagement	Rijksvastgoedbedrijf
2	ICT Expert	Transacties & Projecten	Rijksvastgoedbedrijf
3	Expert Real Estate & Infrastructure (specialization: Real Estate Information)	Vastgoedbeheer	Rijksvastgoedbedrijf
4	Section 'Duurzaamheid & Comfort' - Consisting of 15 Experts holding the position of Real Estate & Infrastructure (specialization: sustainability)	Transacties & Projecten	Rijksvastgoedbedrijf

During the research validation the following topics were addressed to test the findings to reality and make alterations to the proposed method:

- *Relevance* of the topic and the proposed method
- *Phasing* of the implementation of the proposed method
- *Usability* of the proposed method
- *Feasibility* of the proposed method

Relevance

The relevance of the thesis subject was recognized by all experts. The implementation of a DT in maintenance to facilitate façade circularity is very relevant. Façades all over the RVB portfolio are showing unforeseen defects, which range from light defects to severe defects causing safety issues. Safety issues must be prevented at all times, it also has an additional consequence as it can damage the governmental image substantially. For example, ‘Rijnstraat 8’ is a governmental office adjacent to The Hague central station, underneath which thousands of people walk to work every day. Several façade panels have fallen off the façade in the last few years. So, smart solutions like the DT are very relevant in the large portfolio of the RVB.
Additionally, the RVB aims to transfer towards circular maintenance in 2030 and is looking for ways to develop their knowledge on this topic. Also, the organization is already working on the topic ‘smart buildings’, as two buildings house a pilot where sensors measure climate related information.
The topic of this thesis is something that is desired by the RVB, but the organization is not ready yet for a transition towards new technologies. Currently, there is too little in-house knowledge to start adopting the topic, too few experts, no section that is in charge of data analysis or maintenance, to name a few.

Phasing

- Creating a support basis: The real estate sector is a traditional sector, relying on traditional processes. As the proposed process of this thesis is deviating from the existing process, the value of the proposed process needs to be clear. In order for the new process to be supported, it is crucial for actors to understand the value the technologies. Actors want to know how it makes their work easier or quicker.

- Attracting the right people: It is also of great importance to attract the people with knowledge on the topic. It is crucial for the process to involve people with knowledge on data analysis, software and building engineering.

- Scaling: The RVB desires implementation of DT in maintenance to facilitate circularity, but the organisation is not ready yet for adoption of smart technologies. So, scaling is important when commencing such innovative projects. The experts mentioned to start with implementation of sensors in a single building, before implementation along the entire portfolio.

Usability

As mentioned in the previous section: real estate is a traditional industry, which is dealing with objects that have a long lifespan. Changes are therefore difficult to execute and implement. On the other hand, ICT is a developing industry which constantly changing due to the search for innovations and developments to keep up with the user/market demand or streamline the output. These two industries are very different in terms of development. So, implementation of innovations in the real estate sector can mean two different things. Adoption of new technologies will be slow or reluctant, it involves creation of new processes, tasks and additional investments. Or adoption will be successful: however, the implemented technology needs to go along with the innovation curve of ICT for it to work optimally. The sensor market quickly develops, so you need to keep in mind that sensors can be outdated, especially when working with the long lifespans of buildings.
Additional to sensor innovation, sensor failure and maintenance is also an important topic in usability of the system. It is important to be able to locate broken sensors and detach them easily from the building. During the expert panel it was mentioned that people need to be responsible for these tasks to increase productivity of the process.

During the expert panel it was mentioned it is important to avoid pitfalls. In this case they were referring to the involved actors falling back into their habitational processes, which occurs often.

Therefore, a person needs to be held responsible to guide the process. This person should have the responsibility that the tasks will be carried out. According to various experts, adopting new technologies is not so much a technical issue; it is more an organizational issue.
The experts also pointed out that in avoiding this pitfall the value of the new technologies must be clear to all involved actors. When the favourable characteristics of the technologies are made clear to actors, they are more willing to use them. Favourable characteristics can be simplifying work or fastening work.

Feasibility
Implementing new technologies also result in additional financial investments. The investments regard hardware, such sensors. Sensors are inexpensive, which will not regard the vast majority of the investment. The investment will be more related to the software- and computer systems which are expensive. For example, when dealing with a large amount of data, it is necessary to purchase a security system for information security. Finally, requiting people with necessary skills and knowledge, like sensor maintenance or data analysis is also part of the investment. In order for the project to be feasible, the total investments for the DT should earn itself back in the buildings' exploitation phase.

Additional remarks

- <u>Sustainable sensors:</u> What happens with the sensors after their service life is also an interesting side of the story. Senor failure or market innovations can lead to disposal of the sensors. However, it is interesting to think about what happens next. Perhaps you can be connected to a platform which collects sensors and ensures reusability.
- <u>Effect sensors on material:</u> It is also important to consider the effect of the sensor on the façade material when it will be detached. The sensor cannot harm the material and lead to excessive new materials for repair. It is important that the sensor is easy to demount and detach, in such a way that the material itself doesn't get damaged too much.

Chapter 10
Conclusions

Conclusions

10.1 Conclusions sub questions

1. What are current goals of buildings owners with respect to circular maintenance and condition of façades?

Goal: To uncover the problems to be solved or goals to be achieved related to façade-condition and circular maintenance.

Circular maintenance plays a critical part in extending the façade's utility and service life. Proper maintenance includes guarding personnel safety and preventing the façade from further damage and pollution. It also includes maintaining, upgrading and repairing of the façade to extend its service life. Circular maintenance also must be combined with circular prerequisites, such as design and information. Creating a maximum utility of the technology lifecycle and safeguarding the future value derives from a maintenance system that performs continuous improvement. The system is subjective to the speed of the repair, the quality of the repair, guarding customer satisfaction, keeping track of waste streams on-site, and the preparedness to support maintenance.

The RVB aims to achieve circular maintenance and has determined clear organisation-wide sustainability aims and a corresponding strategy for their portfolio. They aim to shift from consumption of raw materials and resources to the use of raw materials and resources. The focus lies on the prevention of waste and maximisation of value retention. They aim to operate 100% circular as an organisation in 2050 and work towards this aim fragmentary. The sustainability strategy is in motion, and RVB plans to meet circular maintenance by 2030. By this year, the RVB aims to carry out circular maintenance as an organisation partly, which entails simple maintenance tasks which produce favourable short-term outputs, feeding developing knowledge on circular maintenance within the organisation. In 2050 the organisation aims to carry out circular maintenance as an organisation fully. To achieve this goal by 2030, the RVB is working towards intermediate goals. In 2020, the governmental real estate should obtain a 25% CO^2 reduction, and they aim an average energy label 'B' for governmental office buildings. To achieve this, the RVB is currently developing requirements for building passports, which is also valuable for circular maintenance, as building passports serve as a manual to maintain each element.

The goals concerning façade condition are related to compliance with regulatory bodies, such as the building law and BOEI condition 3. From interviews with the object managers, it can be concluded that they aim a façade to be windproof, waterproof and fireproof. Also, it should adhere to the minimal Rc-value to create a sufficient indoor climate for users. The sustainability goals related to the façade condition consist of material -related goals and design-related goals. The materials should be used bio-based, non-toxic, and environmentally friendly and little use should be made of primary resources. Design goals are that the façade should be demountable and designed for the intended service life- and maintainability.

2. Which data is available on a facade's composition?

Goal: To derive information on the composition, connections and materials of façade components.

Composition means that a façade consists of several individual parts. A composition of a façade consists of the materials, building parts and connections. Departments VB and VI collect and store information on the façade composition of each office building. Technical information indicates the types of materials, characteristics, finishing layers, connections and dimensions of the composition. Technical information on materials and quantities of building parts are collected in the information system Condor. For building built after 2011, information is also stored in BIM; however, BIM is not often used to store information on composition. It has proofed to be useful for obtaining technical drawings, quantities or surfaces. Technical drawings provide information on the assembly and materials of building parts. Furthermore, in several buildings, technical information is also included in BIM.

The quality and completeness of information on composition differ per building, as shown by the case studies. This has to do with the delivery year, the information requirements present in that year and human errors. In case 1, BIM is used for obtaining technical drawings, quantities and surfaces, and the building information is updated whenever changes are made to the building. Little technical information is also included in BIM; however, this information is not complete because is not the platform where this information is managed. This has proofed to be different from case 2, from which the technical drawings are poorly accessible and technical information was derived from the inspection reports.
For circularity reasons, the BIM-model of case 3 includes additional technical information particularly useful in determining a façade's future value. This includes information such as types of connections, the total composition of materials and constructive qualities. This has proofed to be different from the other two case studies, which have not included this information. It can be concluded that a lack of availability of this information complicates the determination of the future value. From the expert panel, it became clear that this information should be requested during the design process, for it to be complete at the delivery of the building. All in all, technical information should be available, and additional information relevant for reuse should be requested during the design phase of a building.

3. What is the current state of information management concerning façades?

Goal: To uncover collaboration problems related to storing, handling and interpretation of information, that need to be solved. In general, and specifically for Rijksvastgoedbedrijf.

Information management encompasses the receiving, storing, maintaining and providing real estate information. The cases have pointed out that the quality and accessibility of information can differ per building.

Receiving information

At delivery of the building, the RVB obtains real estate information which is requested from the required parties during the design phase. This information can be technical information, drawings, BIM models, quantities or supplier information for example. What information is requested is dependant on the goals and tasks of the façade owner. Evident from case 3, it has pointed out to be crucial to request information relevant to determine the future value. Because failing to do so can complicate the reuse of an element in a future project.

The RVB also measures data during the use phase. In smart building pilots, data on lighting and indoor climate is collected. However, measuring this data and transforming it into is useable information can be improved. The RVB measures a lot of data; however, this is not being used to its fullest potential. It is not clear or what the added value of this data is and therefore, a driver lacks to transform the data into readable information. Additionally, currently there lacks space or knowledge within the organisation where this data is handled.

Storing information
Information is stored on several platforms, appropriate for the particular information. Condor is useful for information like quantities, inspection information and technical information. BIM is useful for obtaining drawings or calculating surfaces in case 1. Inspection reports are useful for allocating defects and are stored manually by object managers. From the expert interviews, it can be concluded that the accessibility of information is important. If the information is too difficult to track down, the chance it will be used decreases.

Maintaining information
In department VB, many people are responsible for maintaining information. Condor and BIM are maintained manually and thereby subjective to human error. This is the large contaminator of the system. For example, after repair, employees are obliged to mark defects as completed in the system; however, when this is not done, it provides an unreal image of the total defects. This also counts for drawings. From case 1, it became clear that the drawings were complete because the BIM model was well maintained. The BIM engineer was held responsible for this task. However, when the BIM model is not maintained, it produces drawings that are not in compliance with the physical object.

From the interviews, it can be concluded that information maintenance can be improved. Maintaining information is an important but unwanted task, which when not carried out with results in inaccurate drawings and datasets. This can be solved through assigning clear tasks or providing an incentive for updating information.

Providing information
Information is provided when information is requested by an employee or department. The right information can be provided to this employee when they have specified their goals and use for the particular information.

4. Which data is available and necessary to map the condition of façades?

Goal: To capture information flows, analysis of the dataset, combination of different data sources. Related to 'dynamic' datasets

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The condition of facades is specified through BOEI inspections, during inspection it is determined if the elements adhere to the technical requirements set by the RVB. Therefore, information on each component is necessary.
The essential requirement is in compliance with the building law. This includes technical specifications the façade should adhere, such as noise reduction and technical requirements to guard the safety of users.

The RVB also applies standard requests for a façade. The façade should be windproof and waterproof because infiltrating wind or water can damage insulation and other elements of the façade. This can ultimately result in repair or replacement. The Rc-value should also be sufficient. This means the façade provides a quality comfort to its users. If this is insufficient, it can result in repair or replacement.
The maintenance history, inspection reports and defects are important in determining the current condition and remaining service life.

In the future, the RVB will set sustainability requests for the façade as well. Materials should be non-toxic, environmentally friendly, demountable and designed for the intended service life. This is stated in the BLOEI strategy document.

To plan adequate maintenance operations, an analysis must be made of the buildings' elements performance, their predicted service life, maintenance needs, degradation models and the most frequent anomalies.

5. How to translate the minimum required data into a digital twin

Goal: To understand how sensors work, which sensors to choose and how to include the necessary data in BIM.

A DT is a BIM-model consisting of real-time information on the mother building. In this thesis sensors are chosen to provide real-time information to the DT. Sensors measure real-time, reliable and quick information and are an efficient way to obtain data. Sensors measure parameters and consist of a transmitting element and receiving element. The transmitting element sends out a signal, which is reflected against an object. The received signal determines the measurement.
To determine the data which must be measured, parameters must be determined. However, to come to valuable conclusions, a combination of sensors must be integrated onto the façade. The 'minimum' required data consists of various data inputs, which must be combined and analysed to find connections, causes and analyse the behaviour of the façade. A sensor is a mechanical version of the human 'senses', and to capture or predict a defect multiple 'senses' must be deployed. The sensors are part of a network, in which sensors communicate with each other if the parameters circumstances are suspicious. This lead can lead to complicated data analysis.

To translate the required data into the DT it is necessary to first determine the required parameters. Also, it is important to determine the cause for which the parameters are chosen. From sub-question 3 it has been concluded that information without a cause has a decreased chance to be used. Choosing the right parameters depends on what threatens the technical service life of the façade. From the case studies, it had seemed clear that high temperatures or strain can cause cracking. Water infiltration causes leaks and wetted insulation and elements near the façade can damage it, causing falling cladding. It was concluded from the case studies that these defects are threatening the technical service life the most.

Secondly, the data can be refined by use of algorithms. Through an algorithm, only the outstanding data is translated into the DT, making it favourable for the readers. To design the algorithm, a programmer should produce a code, which gives instructions on how the data input derives to the data output. Conclusions can be drawn from combining the data output.

6. How can the digital twin assist the circular maintenance management of the façade?

Goal: The design of the process, in general and specifically for the Rijksvastgoedbedrijf. Also, testing of the proposed process.

- *What is necessary for circular maintenance to succeed?*

Circular maintenance prevents a façade from further damage and pollution along with guarding personnel safety. As well as maintaining, upgrading and repairing the façade to extend its service life. Circular maintenance consists of a system which performs continuous improvement and is in need of buildings that are designed for extending its service life. In carrying out circular maintenance, a strong foundation is important. During the design process, sustainable materials must be chosen. The materials should be designed for the proposed service life and easy to maintain. Additionally, the materials should be demountable, leaving the façade intact if repair is due.

For circular maintenance to succeed, the façade must adhere circular prerequisites. This entails design for the intended lifespan- and maintainability, a design consisting of non-toxic and environmentally friendly. Also, the materials must be durable, because when materials are not of high-quality it can influence their technology lifecycle. Additionally, to provide accurate maintenance, certain information is necessary. A building passport should contain information on composition, maintenance needs, degradation expectations, toughest hazards. It should also contain information on the type and number of connections.

It is also important that maintenance is carried out when this is due. The speed of maintenance is herewith an important factor. When the repair has to be carried out, this should be of high-quality Location, size, characteristics and causes are important to provide quick and high-quality maintenance.

- *What are the current barriers to circular maintenance?*

In order for circular maintenance to succeed, its barriers must be tackled. Conclusions will be drawn from the prior findings and sub-questions to determine those barriers.

The case studies pointed out that building elements are interconnected. For circular maintenance, it is essential that elements are demountable in order for the repair to occur accordingly. In the case studies, it has shown that deteriorating of one part of façade can lead to the replacement of the entire façade when it is not demountable. It is also crucial building parts adhere other circular prerequisites, which means a circular mindset must be present at the start of the project. For existing buildings this is often lacking, however it does provide opportunities for new projects.

The case studies also pointed out that defects are handled when many have stacked up; therefore, maintenance can improve in its service speed. Additionally, inspections take a long time. Moreover, deteriorating building elements can pose problems for the circular value. False judgement and lack of expertise during inspections, lead to low-quality inspection reports.

Maintenance also lacks the availability of information. Unreadable inspection reports result in confusion, which has an influence on planning proper maintenance. Inspections are manually entered into the system; however, it has turned out human errors occur often. It provides for an unreal image of reality.

The RVB measures many data; however, little is done with this data. The value and purpose of this data are unclear, and this data is not maintained. The reason for this is that division of precise tasks is missing.

- *How can a DT assist circular maintenance?*

A DT provides for a real-time view on the hazards of the façade in the mother building. From the prior sub-questions, it had been made clear that complete, available and maintained information with a clear purpose increases its utility. The DT can provide for a real time view on hazards, and provide evidence on characteristics, causes and is location accurate. However, it does demand thorough data analysis to provide this information. Additionally, because the DT is a visual representation of the façade connections can be made between various defects. Also, because data is measured for a certain time period, the behaviour of the façade can be analysed and pursue predictive maintenance. This way, high quality and quick maintenance can be planned. Through a DT, maintenance workers are prepared on the maintenance which should be carried out. This deviates from the standard maintenance plans which are currently used, which is reacting on a standard degradation time. The DT can enable maintenance when necessary, instead of maintenance when planned.

Also, the DT creates a platform where types of connections and maintenance needs can be managed and stored. This way, information is easily accessible and stored in one platform.

However, implementing this new technology within the traditional real estate industry does demand changes to the current process. It is something that is relevant and desired by the RVB; however, it does require time and actions to implement it. From the expert validation it became new departments should be created within the organisation and new talent should be recruited to store, manage and analyse the data. To prevent the involved actors from falling back into the habitational processes it is crucial that this process is guided.
Also, during the expert panel it was mentioned that the sensor market is developing at a vast pace. Since buildings have long lifespans and new sensors are developed quickly, this must be taken into account. Sensors are connected to specific software, but when necessary changes have to be made, it is vital sensors are interchangeable and demountable. This is also vital when replacing broken sensors, which have to be removed from the network. The expert panel also mentioned the circularity of sensors. To ensure sensor circularity the façade owner must be connected to a platform where parts of the sensors can be reused for a different purpose.
Finally, the impact of the sensor in the materials must be considered. To ensure circularity of the façade material, the sensors cannot damage the material.

In the next section, the additions to the existing process will be shown.

10. 2 Main Conclusions

In this research an answer was searched to the main research question: *How to facilitate façade circularity in maintenance using a Digital Twin?* To answer this question, qualitative research has been conducted. One of the largest real estate companies in the Netherlands has served as the research field for this thesis. The desired circular future of the RVB has been analysed. Also, the current situation of information management, the maintenance process and corresponding detection technologies of the RVB has been investigated. Subsequently, the recommended additions to the current maintenance process have been investigated, the influence on the existing maintenance process was determined.

The RVB has defined clear sustainability goals, wanting to reach the first steps of circular maintenance by 2030. However, there are many problems to be solved. From the case studies it has been made clear the RVB does not have access to necessary knowledge, additionally, there is not space for the new technologies within the organisation. Investigation of façades is mainly done through visual inspections, and implementation of new technologies lack adoption, due to the little data maintenance afterwards, new technologies are seldom adopted. From the results, it became clear sensors provide similar information as investigations, however, they provide substantial evidence for maintenance decision-making. The implementation of the recommended additions in the current process demands for changes. Therefore, the conclusion takes the form of a process proposal, which serves as a tool to guide building owners when they begin to maintain façades in a circular fashion.

This process concerns a new building, and its daily maintenance process
Recommended Circular Maintenance Process- Building owners

1. Preparation phase - Circular maintenance process
New building: Initiation phase

a) Prerequisites façade

Involved actors: Building owner, façade consultant

Circular maintenance aims to extend the lifetime and creating maximum utility of the technology lifecycle. To perform circular maintenance, the façade must adhere circularity prerequisites:

- Selection of sustainable materials
  - Non-toxic, environmentally friendly
- Design specifications to be easily accessible for repair
  - Demount ability

Additionally, it is recommended to work with parties which have experience with circular projects.

Prerequisites information

Involved actors: Façade supplier, architect, contractor, buyer

To perform suitable maintenance and also to determine the future value, it is important to request information during the design phase. This means building passports should be requested consisting of:

  - Maintenance needs
  - Type of connections
  - Supplier information
  - Technical information
- BIM model
  - Plans
  - Constructive drawings
  - Façade views

- Action: Start of DT project. The project team is created for the preparation phase. The project manager leads this project execution.
- Action: creation of departments within the organisation for data storage, data analysis and data maintenance
- Action: Commence recruiting talent specialized in data analysis and data maintenance

b) Determination data team

Involved actors: project manager

From the interviews it became clear that it was of great importance to divide tasks when new technologies are implemented. Therefore, a data team can be set up, consisting of:

- Data maintenance
- Data storage
- Data analysis / inspector
- Programmer
- ICT expert
- BIM engineer
- Project manager

c) <u>Orientating and determination parameters</u>

Involved actors: Building engineer, BIM engineer, building computer scientist,

Implementing new technologies within the RVB is a field which has only gained attention recently. Often, employees fall back into habitational processes. One of its causes is data not being taken into proper maintenance. This is often because it is unclear what the purpose of the data is, and what the exact value of the outcome is. When choosing targeted parameters, the purpose of the data is clearer. By means of an algorithm, only the necessary information serves as output.

- Determination of building hazards
    - New building: Inspection of the surroundings, 3D modelled hazards, comparison with resembling buildings
- Determination degradation time of the elements
- Determination of the necessary 'senses' to measure the defects

The parameters which have the largest influence on the technical lifecycle have priority. This can be strain (wind), temperature (sun), degradation time (time). The parameters which are important for circularity are vital.

- Degradation time to be able to determine when materials are 'naturally due'
- Tough hazards

d) <u>Selection sensors</u>

Involved actors: ICT company, ICT expert

After the parameters have been determined, the sensors which fit the parameters should be chosen. Due the outstanding availability on sensors, it is important to consult expert knowledge during this phase. Consider:

- Placement opportunities in the façade
    - In a newly built building, sensors can be integrated into the façade.
- Combinations of sensors to derive a varied output

Action: Delivery of the new building

e) <u>Placing and installing sensors</u>

Involved actors: Sensor company

- The sensors are placed onto the façade by a separate company

The sensors need to be fed by electricity and connected to the internet. This way IoT can be enabled, the sensors are able to communicate reciprocally, and send the data output to BIM.

- Connection to the internet
- Storage in the building for sensor computer

2a. Use & Maintenance phase

In this process, maintenance managed by the organisation. This means maintenance is not integrated in the building contract. At the beginning of the use & maintenance phase, a preliminary maintenance plan is set up. Which serves as a starting point for this phase.

At the start of this phase, the sensors have been selected, installed and placed. In this phase they will be used.

a) Data enters data storage

Involved actors: Programmer, Data storage manager

To eliminate human error occurring during data analysis, programmers create an algorithm to filter large amounts of data into outstanding data. E.g. a hazard occurs which is in need of immediate fixing. The data enters the data storage and is filtered by the algorithm.

b) Connect data to BIM

Involved actor: BIM engineer

- The data output from the sensors must be connected to the corresponding element.
- BIM is connected to real-time data, which makes it the building's DT

c) Data analysis

Involved actor: data analyst

Data should be analysed and to make this possible, the data analyst should be properly educated to read the data. The analyst examines the raw dataset and determines:

- The severity
  - Size
  - Characteristics
- Type of defect
  - Is the defect a manifest defect?
- The priority
  - When should this be repaired?
- This together determines the type of maintenance:
  - Reactive maintenance
  - Corrective maintenance
- The location of the defect. Hereby the inspector can decide if one element should be detached and repaired.

d) Transform analysis into action

Involved actor: data analyst

The data analysis is transformed into readable actions

e) Report

Involved actors: Data analyst, contractor

The data analyst reports the contractor on his main findings from the DT. The contractor can make a plan of action for repair. The contractor can use the DT to examine the surroundings of the defect, and plan maintenance.

f) Store history of reports in DT

Involved actors: Contractor, BIM engineer, data analyst

The contractor must inform the BIM engineer on changes made in the building. The BIM engineer can alter the DT accordingly. The defect is signed out, and the information is attached to the corresponding façade part, and an update on its condition is determined. When attaching the defects and condition scores, its future life can be determined.

2b. use and maintenance phase – additional tasks

a) Semi-annual sessions

Involved actors: Data analyst, object manager, technical manager, contractor
After the sensors are implemented, and being used, the behaviour of the building will be analysed. Every quarter the main findings will be presented to the building owner and contractor. The largest natural hazards expected defects and expected moments when materials are 'naturally due'. Additionally, the current condition will be presented. This enables preventive maintenance to maintain high quality of the technology life.

a) Maintenance sensors

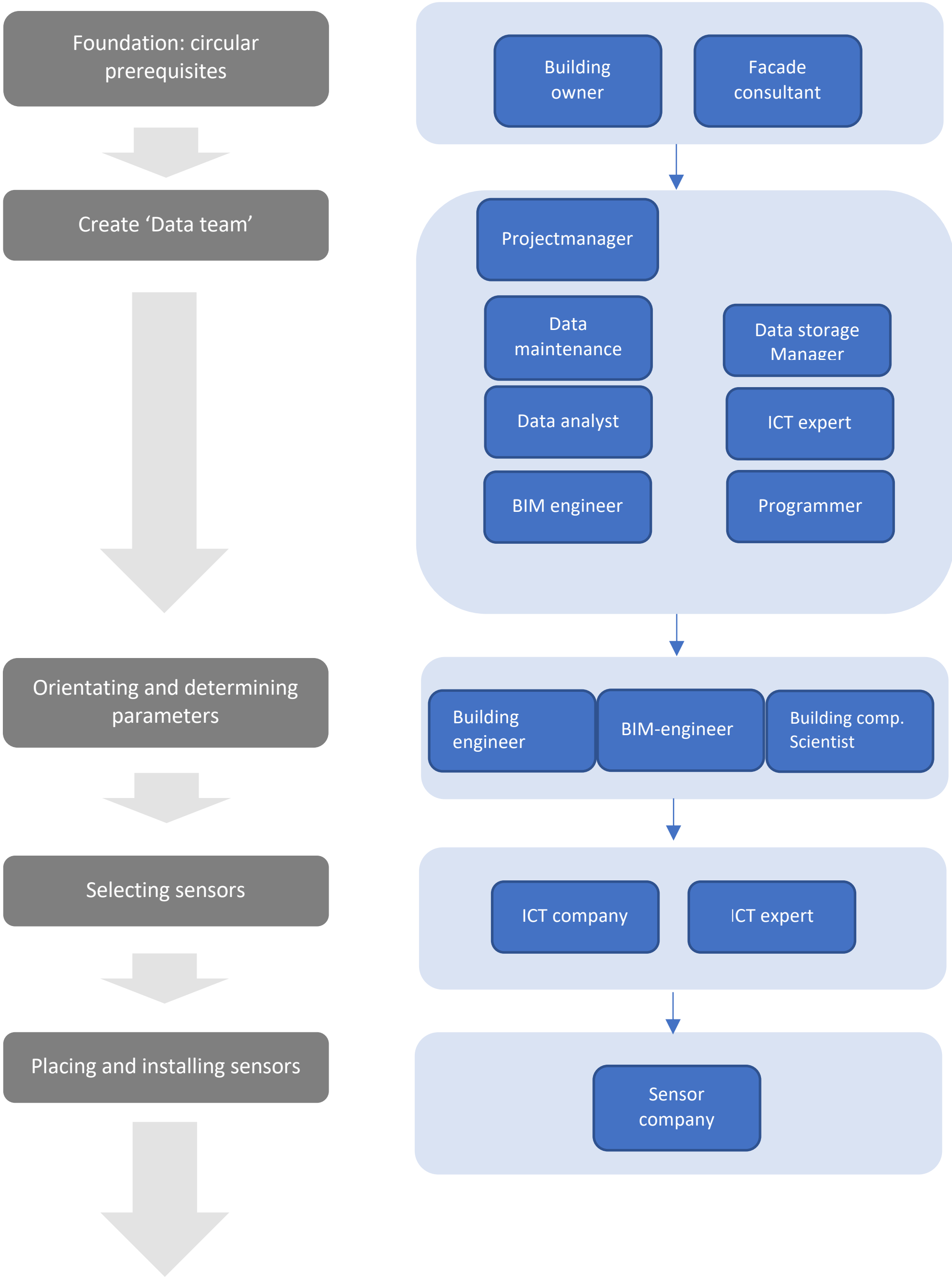
Involved actors: Sensor manager
The sensors need to be checked on their performance. Also, the sensors and software need to be checked on updates. If an update or repair is necessary, the sensor will need replacement.

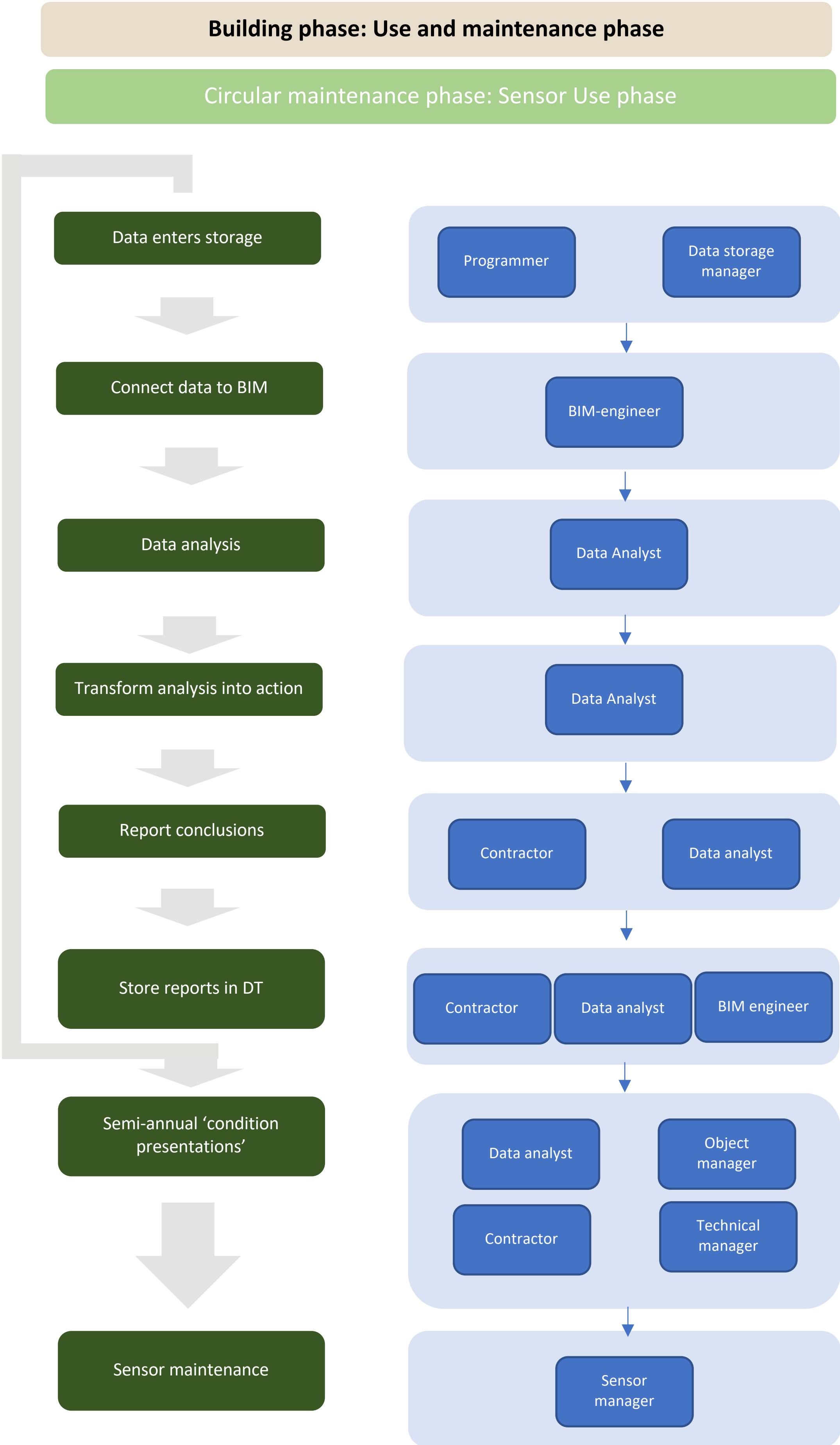
Repetition of this process facilitates the quality of the façades condition and thereby its technology lifecycle. Below, this process is illustrated.

Table 35. Circular maintenance process by means of a DT (own ill)

Building phase: Initiation phase

Circular maintenance phase: Preparation phase




Building phase: Use and maintenance phase
Circular maintenance phase: Sensor Use phase
Data enters storage
Programmer
Data storage manager
Connect data to BIM
BIM-engineer
Data analysis
Data Analyst
Transform analysis into action
Data Analyst
Report conclusions
Contractor
Data analyst
Store reports in DT
Contractor
Data analyst
BIM engineer
Semi-annual 'condition presentations'
Data analyst
Object manager
Contractor
Technical manager
Sensor maintenance
Sensor manager

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Chapter 11

Discussion

Discussion

The focus of this chapter is the discussion of the research. Firstly, the connection between the problem statement and the research findings will be discussed.

Discussion problem statement – research findings
The problem description specified in §1.3 stated the lack in management to provide accurate information on façade condition during maintenance, and the use of this, to improve the circular potential of façades. The research findings specified in chapter 8 are connected to problem statement; the findings form the foundation of the proposed circular maintenance system. This system is concerned with assigning precise tasks for capturing information and maintaining information. Subsequently, recommendations have been designed to proposing a manual to use this information to plan proper maintenance. The outcome is a process which facilitates the system to provide and use accurate information which aims to maintain façades circularly.

Discussion research findings
The findings pointed out that the design of a façade is an important part of the process. Façade materials should have specific characteristics to hold a lengthy service life. This includes for example, demount-ability, high-quality-and non-toxic characteristics. Also, it matters at what point the DT is adopted into the project. When stakeholders adopt the idea of a DT during the initiation process of a building, it provides opportunities. Implementing sensors during the design process, enables incorporation of sensors into the façade. Additionally, it enables more opportunities for the sensors – and their attachments – into the design. This provides more opportunities for which sensors can be applied and what they can measure.
Also, the findings pointed out that current maintenance teams are not equipped to work with new technologies, which also includes sensors and DT's. Additionally, the inspectors must be educated to read the data output. Moreover, the whole team must be aware of the sensors used in the building. If the value of the sensors is understood, their utility increases. The findings also revealed that sensors reduce errors in defect inspection, and can facilitate determinization of plans of action, by providing evidence.

Discussion beforehand expectations
When I compare these findings to my beforehand expectations, I realize that design does play an important part in this process. I expected that buildings which lack circular design characteristics were also able to be reused. In some cases, it has shown that non-circular façades can have a prolonged service life by proper maintenance. This is also circular in a way. However, the case 2 (RWS) made me

realize that when several parts all over the façade are deteriorating, it can result in replacement of the entire façade. If the façade had been demountable, comparable to case 3 (GRC), it would be possible to remove the deteriorating building parts—leaving the rest of the façade intact.
I also expected that the maintenance system, or the industry in general, to be more acquainted with the technology. At the TU Delft, the subject 'smart cities' is a popular topic, which gets a lot of attention. However, I have learned that in practice, this is not implemented at all. My findings pointed out that a lot has to change in the current system when implementing the proposed technologies.

Discussion research methodology and research limitations
During the data collection, expert interviews were conducted to gain knowledge on the maintenance process and project processes. The interviewees were carefully chosen, and all had a great experience within their fields. Thereby it is safe to conclude their input has been valid. However, the maintenance and project process of the RVB may deviate from processes at different companies. Therefore, the interviewees and case studies originate from a single firm, the findings of this research may not be generalized.

The novelty of the research topic has both been a driver, as well as a limitation. In the interviews many interviewees shared their opinion on the subject; however, the interviewees knew little about sensor implementation within maintenance systems. Therefore, many subjective opinions were involved during the interviews.
Another limitation of the research was that sensor technology was an entirely new topic for me as well. Therefore, it took a long time to find suitable sensors in literature. The sensors which I have found are technologies which already exist and are well-known. An interview with an expert in sensors could have been helpful in my investigation for sensors.

The outbreak of COVID-19 also posed new challenges for my thesis. Graduating from home required a considerable amount of discipline. Additionally, I was missing out on valuable information which I could have retrieved while working at the office. Before the COVID-19 outbreak, even the most casual conversations helped me to gain valuable information. This had led to invites to interesting lectures and conversations with colleagues involved in interesting pilots or projects. When I was required to work at home, I did not speak to as many people anymore, but only reached out to the necessary interviewees.

Future research

<u>Impact on construction- and real estate sector</u>
Further research can go into its consequences on the construction sector. If this system proofs to be valuable, it may lead to a building which is not deteriorating. When a building does not deteriorate, this has an impact on the number of new buildings to be built. It can also provide consequences for the amortization of a building since the value does not decrease substantially.

<u>Circular maintenance of a façade element</u>
This research can be conducted on a specific façade element, such as a window frame. Sensors can be chosen more specific to the needs of this element.

<u>Circular maintenance of Façade type</u>
Each façade type behaves in differently and is vulnerable to several hazards. In this thesis, a wholesome process was designed for façades in general. However, it also can be designed for a specific façade.

<u>Circular maintenance of specific building size</u>

Defects in large buildings are complicated, and labour intensive to detect. New research can also be conducted for larger buildings.

Circular maintenance of another building element

Maintenance of the sensors
Like the façade itself, the sensors also require maintenance. Especially when using fibre sensors, the fibres must be maintained in order for the sensor to deliver. Further research could be conducted into how sensors which are attached to buildings can be maintained.

Circular sensor platform
How to collect sensors that are exceeded their service life in the façade element.

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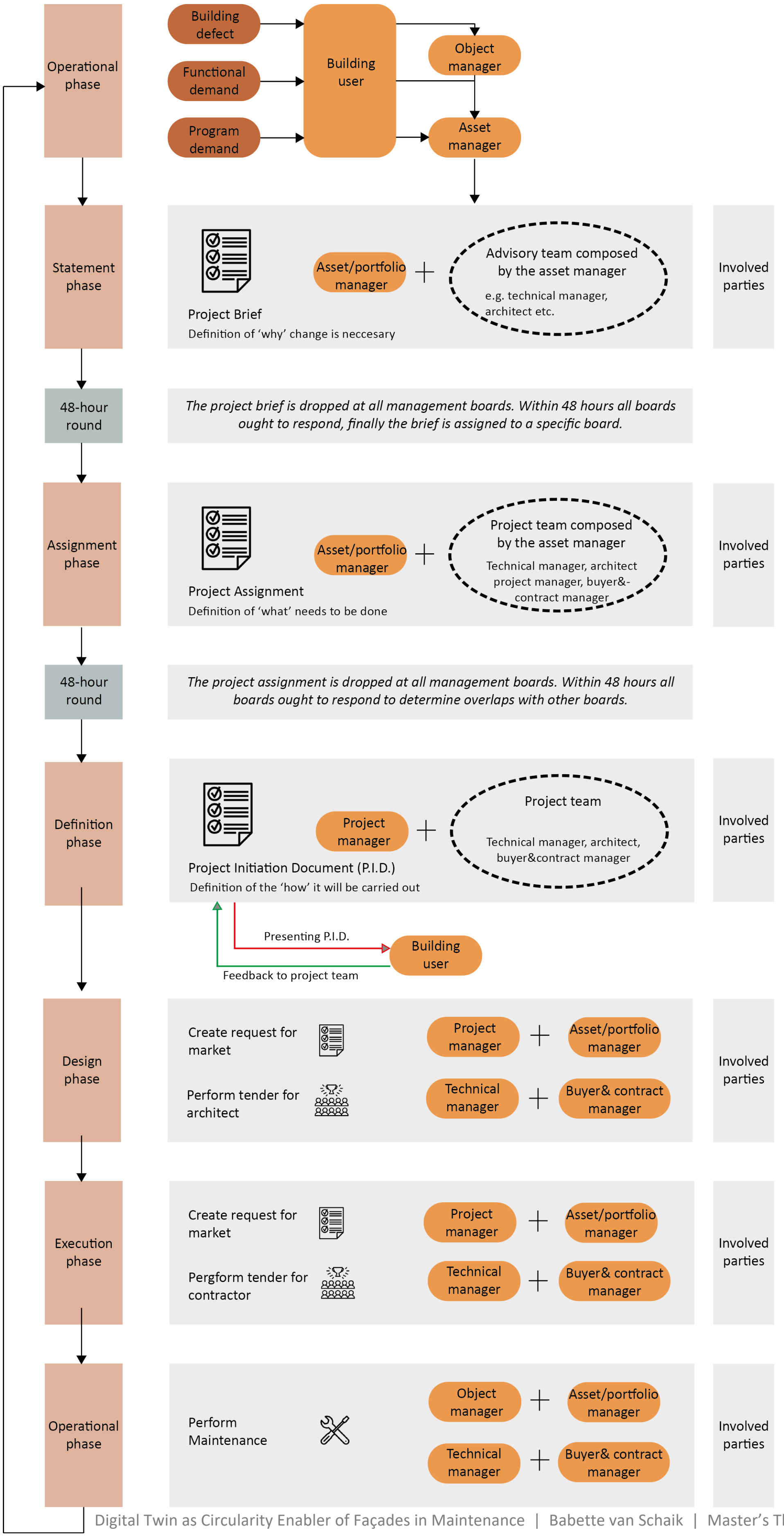
13. Appendix
Appendix

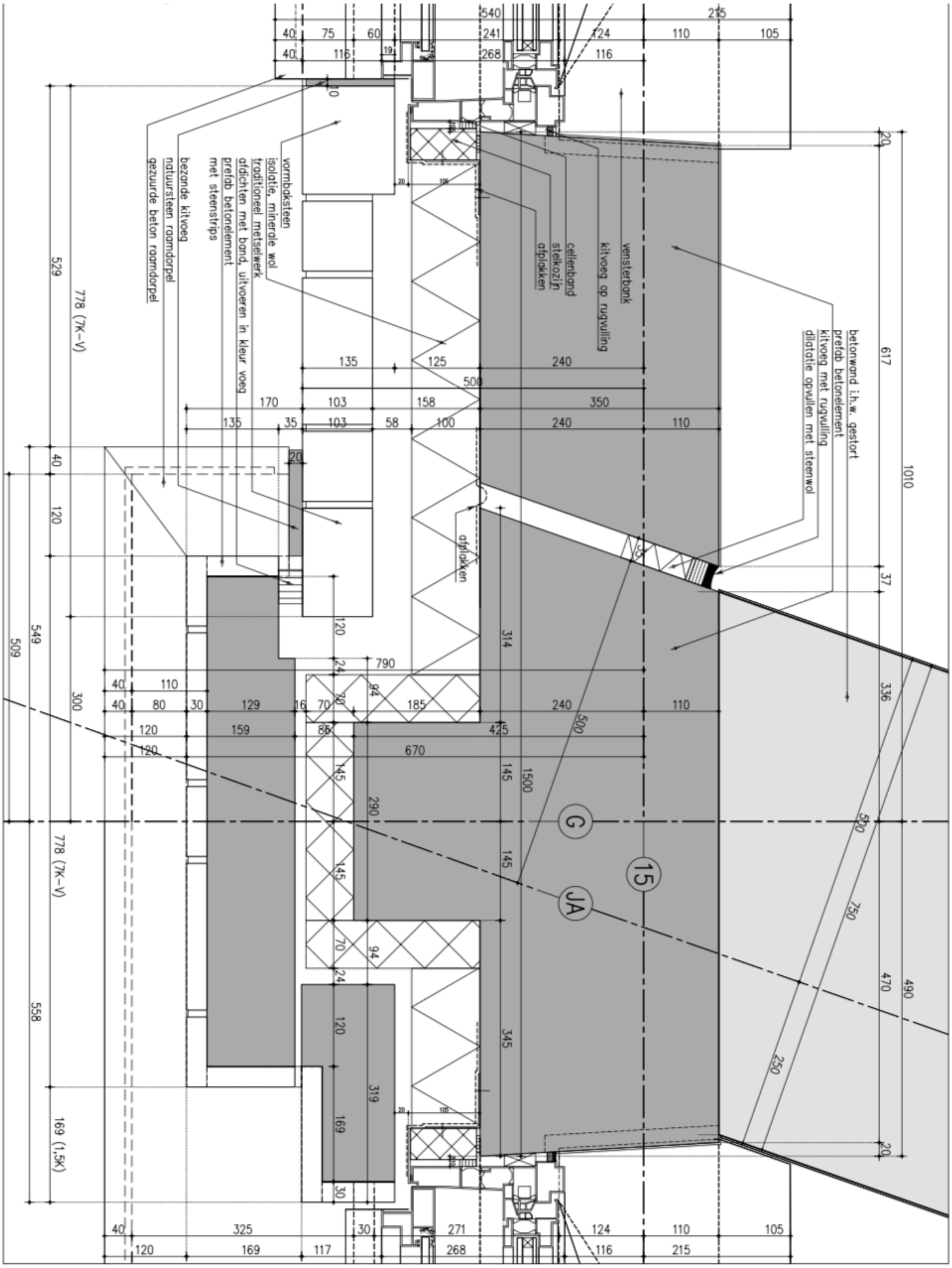
Appendix A. BOEI condition score scheme for cladding (Rijksgebouwendienst, 2012)

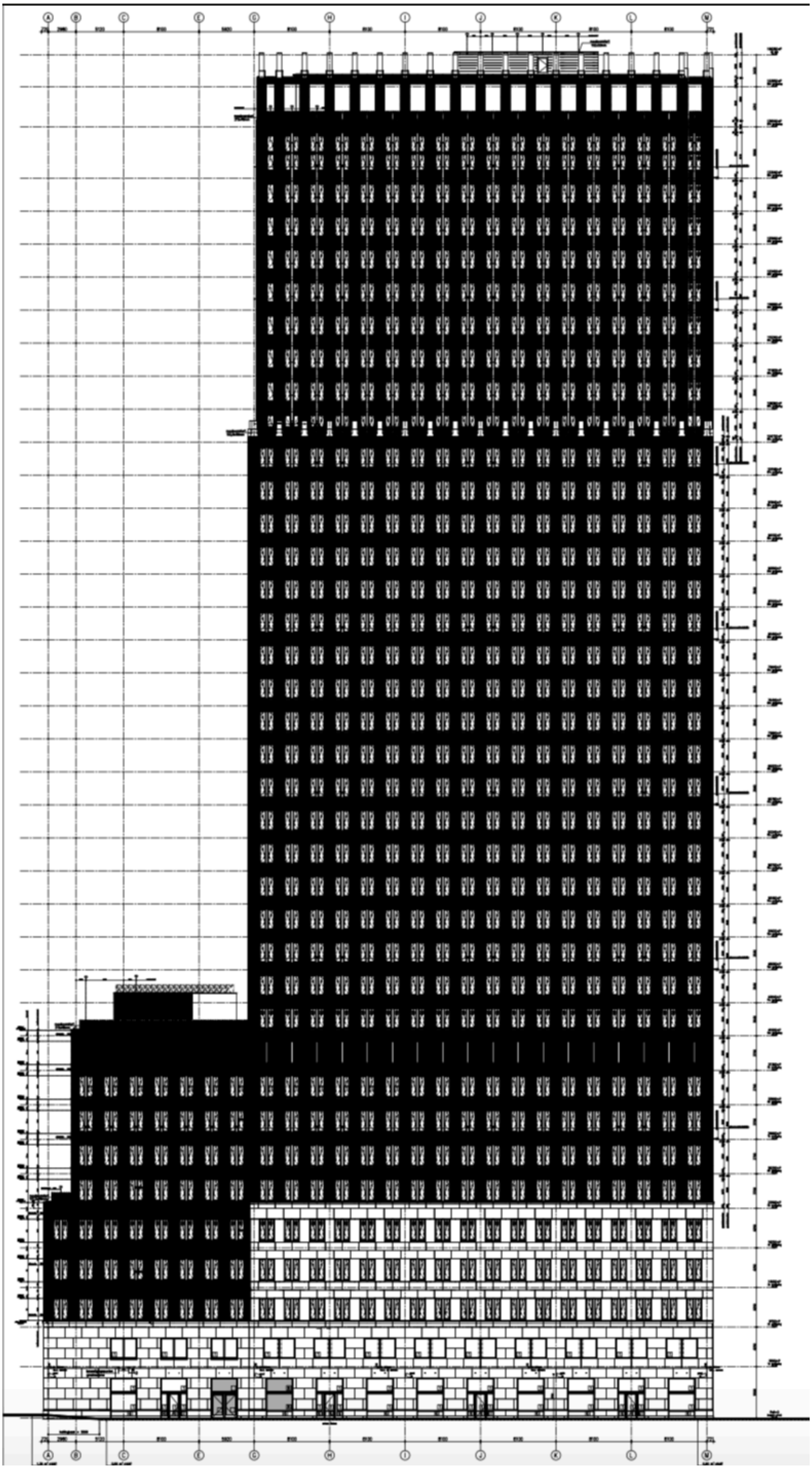
Façade condition	*Operation/construction*	*Material*	*Basis quality*
Condition 1: Excellent	Severe defects such as leakages, moisture, fungous through thermal bridges, cracks, distortions, anchorages, joints or other ways of defects regarding the surface may not occur.	Severe defects such as bulging, express pieces of façade, skew, exfoliation may not occur. Pollution, and presence of dust does occur on the façade. Light signs of cracks or loose stone is found. Incidentally there is signs of graffiti.	The material is good through implementation of sustainable and durable materials and a decent design, detailing and expert assembly and execution. Incidentally there is need for a sustainable reparation. Sufficient expansion joints to take in the thermal pressure.
Condition 2: Good	Severe defects such as leakages, moisture, fungous through thermal bridges, cracks, distortions, anchorages, joints or other ways of defects regarding the surface may not occur.	Incidentally a serious defect occurs, such as missing bricks. But serious defects such as exfoliation, cracking trough thermal expansion are occurring incidentally. Light defects such as moss and algae growth occur. Dust pollution shows a dark color on the façade. Incidentally there are signs of graffiti.	The material is good through implementation of sustainable and durable materials and a decent design, detailing and expert assembly and execution. Incidentally reparations are carried out. Small inconsistences occur.
Condition 3: Decent	Severe defects such as leakages, moisture, fungous through thermal bridges, cracks, distortions, anchorages, joints or other ways of defects regarding the surface occurs locally.	Locally severe defects occur, such as bulging and express pieces of façade. Light defects, such as moss and algae growth occur regularly. Due to dust- and soot the lightly colored stones changed color.	The work is decent due to application of meager materials and/or obvious defects in design, detailing and execution. This is reflected in: - cracks, skew and affected surfaces. - Good executed reparations occur frequently. - Expiring joints and brick works - Distorted bricks, in sight

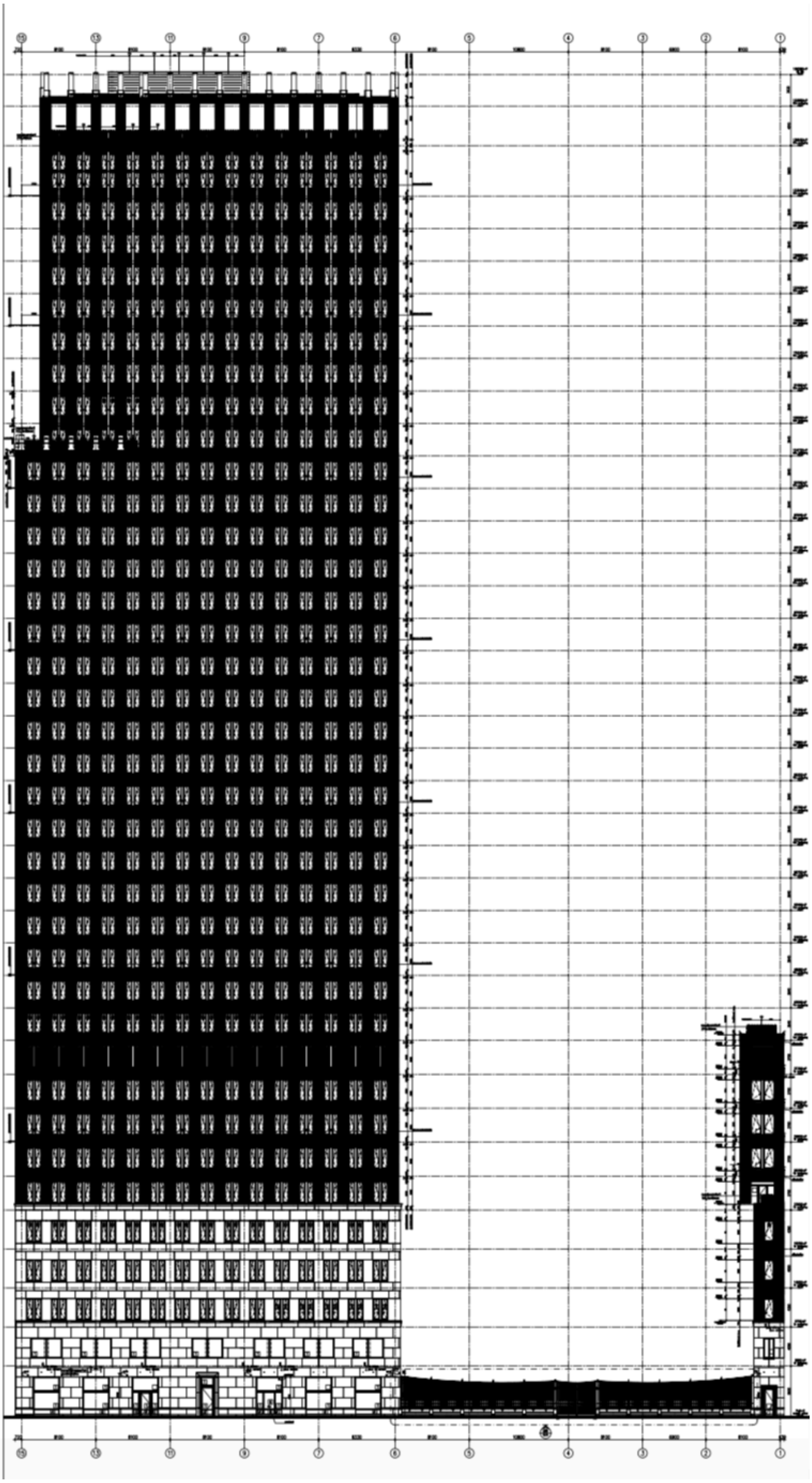
Appendix B. Project scheme Transaction & Projects board RVB (L. Kerpel, Bilateral consultation, 24 February 2020)



Appendix C. Constructive detail and façade view JuBi towers (BIM-model JuBi)







Appendix D1. Sensor exploration

Table 1. Overview sensor needs

Hazard	Building constraint	Application / Objective	To measure/detect	Sensor type
Rain	Leaks	Observation	Water, strain	Infrared Thermography, optical fiber corrosion sensor
	Dirt	Observation	Color	Image based defect detection
	Algae	Observation	Color	Image based defect detection
	Corrosion	Observation	Color	Vision based sensor, optical fiber corrosion sensor
Wind	Cracks	Observation	Strain, acceleration	UAV, Satallite based damage mapping, image based crack detection, fiber optic sensors, laser scanning, infrared thermography, piezoelectric actuator-sensor
		Damage detection	Displacement	UAV, Satallite based damage mapping, image based crack detection, fiber optic sensors, laser scanning, infrared thermography, piezoelectric actuator-sensor
	Falling stone	Observation	Displacement, movement	UAV, Satallite based damage mapping, image based crack detection, fiber optic sensors, laser scanning, infrared thermography, piezoelectric actuator-sensor
		Damage detection	Displacement	UAV, Satallite based damage mapping, image based crack detection, fiber optic sensors, laser scanning, infrared thermography, piezoelectric actuator-sensor
Sun	Cracks/expansion	Monitoring	Length, width, depth	optic sensors, laser scanning, infrared thermography, piezoelectric actuator-sensor
		Damage detection	Displacement, color, area	UAV, Satallite based damage mapping, image based crack detection, fiber optic sensors, laser scanning, infrared thermography, piezoelectric actuator-sensor
		Observation	Color, length, width, depth, temperature	UAV, Satallite based damage mapping, image based crack detection, fiber optic sensors, laser scanning, infrared thermography, piezoelectric actuator-sensor
Pollution	Dirt	Observation	Color	Image based defect detection
	Discoloration	Observation	Color	Image based defect detection
Human errors	Construction/ building errors	Observation	Water, airgaps	Infrared Thermography, optical fiber corrosion sensor
	Damages (e.g. Broken window)	Observation	Change in composition	Infrared Thermography,image based defect detection

Table 2. Characteristics case studies

Type	Case 1: Jubi towers	Case 2. Rijkswaterstaat office	Case 3. Galileo Reference Centre
Height	Tall building	Medium height	Small building
Function	Office function	Office function	Office function
Use	Frequently in use	Frequently in use	Less frequently in use
Façade	Bric, stone and concrete cladding	Ceramic tiles and plastar mortar cladding	Glass and aluminum cladding
Main hazards	Strong sea winds	Sunlight, wind and rain	Strong sea winds and sand
Main defects	Dirt, discoloration, cracks and falling cladding	Falling cladding, leaks, cracks	Leaks
Effect on circularity	Degrading material, need of new materials for repair		
Possibility on integration of sensors	Existing building	Existing building New facade project in the pipeline	Existing building

Appendix D2. Sensor Literature review

Defect	Type	Sensor	Characteristic	Advantages	Disadvantages	Applicable for
Cracks Fallng stone	Remote sensing	Unmanned Aerial Vehicle (UAV)	1) Flying machine which is coupled with an RGB camera to collect images of the building 2) The collected overlapping images can be translated into a 3D point cloud 3) Processing optical data is possible through human labor, but is in need of advanced machine learning algorithms.	1) Cost effective, stability and high reliability 2) Installation is not labor intensive 3) UAV's able to visit inaccessible or dangerous hazard areas	1) Most of the UAV's are not equipped to deliver data in 'real time': it takes time to process the large amount of images in multi-view surveys. Here sensors have a clear advantage. 2) Comparatively small operating range and flight duration 3) Fails to generate 3D point clouds for darker images such as shadows or smaller building openings 4) Can fail to capture images due to blocking elements, such as vegetation	Especially tall buildings, Good option, but in case of the JuBi building it is not possible.
Cracks Falling stone Algea Discoloration Dirt	Image-based crack detection	Raw image inspection	1) Basis defect detection. 2) Inspections performed by robots or unmanned aerial systems. The inspections are typically image based, meaning that the inspection platform captures images that are thereafter processed or reviewed by a human inspector.	1) High resolution can be achieved 2) Relatively cheap	1) Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors. 2) Lighting is very important, and can be crucial in determining the priority and severity	All cases
		Image enhancement	1) Inspections are performed by robots or UAV's/UAS's, but image processing is done though use of some image processing algorihtms	1) Through use of algorihtms cracks can be detected quicker, and human errors can be eliminated to some extent	1) Machine learning datasets must be of good quality 2) Datasets could be biased, machine learning is susceptible to errors 3) Imachine learning takes time to let algorithms learn	All cases
		Autonomous image processing	1) Insepctions are performed by robots or UAV's/UAS's, but image processing is done through use of algorihtms to detects cracks. Machine learning or artificial intelligence is used.	1) Quick solution for image processing 2) No human intervention necessary, human errors are eliminated	1) Machine learning datasets must be of good quality 2) Datasets could be biased, machine learning is susceptible to errors 3) Imachine learning takes time to let algorithms learn	All cases
Cracks Falling stone Construction errors	Fiber optic sensors	Distributed optical fiber sensor	1) Popular alternative to traditional electrical sensors 2) One fiber which replaces thousands of sensors 3) Reveals strain, temperature and vibration information from any point along an optical fiber through light scattering 4) Are adequate for applications which require high areas of coverage, with high location accuracy 5) Often used in determining the safety of a stucture, as it measures stresses inside concrete 6) Using in prediction of events 7) Any abrupt drop in the backscattered signal indicates a crack being formed at a certain location	1) Sensitive 2) Lightweight 3) Wide bandwith	1) Installation is labor intensive 2) bundles of wires that occupy space and which require regular maintenance (Barriás, Casas, & Villalba, 2018; Bao & Chen, 2012) 3) However, they also need a bulk and high-cost equipment for sensor interrogation as well as specialized equipment for the grating inscription (Leal-Junior, Frizera, Marques & Pontes, 2020)	Small buildings: case 2 and 3
		Fiber Specklegram Sensor	These sensors measure many parameters, such as temperature and vibration. The FSS only needs a laser and a camera, resulting in a low cost interrogation system			Small buildings: case 2 and 3
Cracks Falling stone	Laser scanner	Example: PTOF (Pulsed Time of Flight scanner), AMCW (i.e. Amplitude modulated continuous wave scanner)	PTOF: Technology for identifying damages. Uses a camera and infrared light to determine information. The sensors emits a light, which hits the subject and returns back to the sensor. The time it takes to bounce back is measured to provide information on the defect (depth/width) AMCW: Emit amplitude modulated continuous waves, and measure the phase difference between the emitted and returned signals.	1) Able to provide high coverage and accuracy at low ranges. 2) Eliminates human errors 3) Higher volumes of data can be collected over a shorter amount of time 4) AMCW: High accuracy 5) PTOF: longer scanning distances (>1 km)	1) Their sensibility is limited by the range they can measure AMCW: sensitive to erroneous mixed pixels: errors in measurements PTOF:	All cases
Cracks Falling stone Water leaks Algae Constructive errors	Infrared thermography (outdoor thermography)	Infrared camera	Infrared camera which can detect thermography higher than absolute 0 (Usamentiaga, Venegas, Guerediaga, Vega, Molleda & Bulnes, 2014). It can be used to quickly survey the entire building, and proof or support a problem (Balaras & Argiriou, 2002). It can detect where and how energy is leaking from a building envelope. A wet mass in a building envelope has a different thermal inertia which can be discovered by infrared thermography (Usamentiaga, Venegas, Guerediaga, Vega, Molleda & Bulnes, 2014). Infrared techniques provide a tool to indicate, measure and classify damage, and the energy-related conditions of building structures (Ljungberg, 1994) Camera has the size of a regular video cam recorder (Balaras & Argiriou, 2002).	Fast, clean and safe method when knowing how to use it (Balaras & Argiriou, 2002) Can reduce guesswork, identify abnormalities which weren't visible before (Usamentiaga, Venegas, Guerediaga, Vega, Molleda & Bulnes, 2014)	IR camera's can be expensive (Usamentiaga, Venegas, Guerediaga, Vega, Molleda & Bulnes, 2014) Interpretation of IR images requests good understanding of various principles of heat transfer, thermodynamics, optics and electronics. As a result, this technology may be complex and limit its applicability (Balaras & Argiriou, 2002) Highly dependent on the sensor selection and experimental set-up Defect can only be detected if enough temperature contrast is created (Usamentiaga, Venegas, Guerediaga, Vega, Molleda & Bulnes, 2014)	All cases
Cracks Falling stone	Piezoelectric actuator/ sensor	Single actuator-sensor pair / Multiple actuator-sensor pair	Active sensor (they stretch) which can be used as transmitters and receivers for monitoring local defects, by injecting controlled diagnostic signals into structures and can potentially interrogate a large structural area. Permanently attached to the structure, and generating elastic waves (e.g. Lamb waves) as well as measuring incoming elastic waves.	1) The diagnostic imaging method can visualize scattering locations and estimate size/location of several types of damages. 2) Extremely precise measurements of small motions	1) Major challenge in sensor-based health monitoring is quantifying the damage based on sensor measurements. Without this, residual life is difficult to detemine.	All cases
Corrosion Water leaks	Fiber optic sensors	Optical fiber corrosion sensors	Detect aluminium cations in the early process of corrosion. It is able to warn for corrosion.	The sensitivity of the optic sensors are good for the low thickness of the corrosion		All cases

Appendix E. Façade matrix, Factual information, part 1 | Case 1: JuBi Towers

Table 1.1 Existing situation

Element	Factual information								
	Material	RVB-BOEI Condition	Corresponding information in BIM	Circularity degree (based on 'Circularity Degree' Table)	Defect	Force	Building Side	Type of maintenance	Current Defect-Detection Technology
Cladding	Brick (north tower) Natural stone (South tower)	2	**Value entered:** Width, Height, Family Name, Type Name, **No value entered:** Thermal Resistance, Fire Rating, Thickness, Heat Transfer, Cost, Assembly, Bulletproof	-/+	Falling cladding	Sea wind Wind Window Cleaning Gondola	South (south tower)	Reactive maintenance Corrective maintenance	**Pilot:** Camera's attached to the gondola capture pictures of the façade, which results in a 3D point cloud with high resolution pictures
					Discoloration	Highway (Pollution) Train (Pollution) Sea wind Rain Sun	> 27th storey	Corrective maintenance	Camera
					Moss	Rain Sunlight Sea Wind	All sides	Corrective maintenance	Camera
					Algae	Rain Sunlight Sea Wind	All sides	Corrective maintenance	Camera
					Cracks	Wind Window Cleaning Gondola	South	Corrective maintenance	**Pilot:** Camera's attached to the gondola capture pictures of the façade, which results in a 3D point cloud with high resolution pictures
					Dirt	Highway (Pollution) Train (Pollution) Sea wind Rain Sun	> 27th storey	Corrective maintenance	Camera
					Damaged cladding	Human force Accidents	South, ground floor (North tower)	Reactive maintenance	Camera
Insulation	Mineral wool	2	-	-/+	None	-	-	-	-
Outer Window Frame	Aluminum Bronze anodiized	2	Width, Height, Family Name, Operation, Type Name, Self-Closing (1 or 0), Assembly	-/+	Leakages	Wind Rain	South West	Corrective maintenance	Camera
					Discoloration	Highway (Pollution) Train (Pollution) Sea wind Rain Sun	South West	Corrective maintenance	Camera
					Dirt	Pollution Sea wind Rain Sun	South West	Corrective maintenance	Camera

Façade matrix | Factual information, part 2| Case 1: JuBi Towers

Electric blind system			2	Non recorded	-/+	Stiff moving parts	Wear through usage	All sides	Preventive maintenance	
Inner window frame	Steel		2	Width, Height, Family Name, Operation, Type Name, Self-Closing (1 or 0), Assembly	-/+	-	Opening and closing	All sides	Corrective maintenance	-
Glass	HR ++ glass		2	Width, Height	-/+	Dirt	Wind Rain Sun Pollution	All sides	Corrective maintenance	Camera
Inner cavity leaf	Prefab concrete		2	-	-	None	-	-	-	-
Grilles	Aluminum		2	Width, Height, Family Name, Type Name	-/+	Dirt	Wind Rain Sun Pollution	All sides	Corrective maintenance	Camera
						Discoloration	Wind Rain Sun Pollution	All sides	Corrective maintenance	Camera
Sills	Prefab concrete		2	Width, Height, Family Name, Type Name	-/+	Dirt	Wind Rain Sun Pollution	All sides	Corrective maintenance	Camera
						Discoloration	Wind Rain Sun Pollution	All sides	Corrective maintenance	Camera
Door frames	Aluminum		2	Width, Height, Family Name, Operation, Type Name, Self-Closing (1 or 0), Assembly	-/+	Dirt	Wind Rain Sun Pollution	All sides	Corrective maintenance	Camera
						Discoloration	Wind Rain Sun Pollution	All sides	Corrective maintenance	Camera

Façade matrix | Recommended additions, part 1| Case 1: JuBi Towers

Table 1.2 Recommendations

Recommendations							
Advantages current defect detection technology	**Disadvantages** current defect detection technology	**Recommended Defect Detection Sensors**	**Advantages** recommended defect detection sensors	**Disadvantages** recommended defect detection sensors	**Placement**	**Costs**	**Circularity**
- High resolution image of all façades - The 3D pointcloud depicts the locations of all defects on the entire façade, which makes it easier to plan maintenance	- The pictures and the corresponding severity and priority is a labor intensive and unpopular task. The severity and priority are judged by students/interns, which may not be educated enough to take correct decisions - Maintenance of output is labor intensive and prone to human errors - Lighting and weather conditions are very important, as differences can result in an inaccurate image	1) Infrared thermography (IR) 2) Piezo electric actuator - sensor (PEAS)	1) IR: Fast, safe clean method. Reduces guesswork 2) PEAS: can visualize scattering locations and estimate size/location of several types of damages.	1) IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology 2) PEAS: Major challenge in quantifying the damage based on sensor measurements	1) On window cleaning gondola..... 2) Mounted on the façade	1) IR camera is expensice 2) -	- The following information should be added in BIM to better determine its reuse potential: Constructive qualities, weight, composition, finishing layer, connections and certain specific qualities - Repair of damaged cladding results in usage of new materials, which shuold be prevented - Sensors facilitate prevention of defects from expanding, preventing from usage of various new materials
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	Image enhancement (IE)	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.	...	Low cost	Regular cleaning to ensure high quality is necessary. Detecting areas where discoloration emerges is therefore necessary.
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	1) IE 2) IR	1) '- High resolution can be achieved ; Relatively cheap ; Through partly use of algoritms the process can be accelerated, and some human can be eliminated 2) Fast, safe clean method. Reduces guesswork	1) Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors. 2) Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology	1) Gondola 2) Gondola	1) Low cost solution 2) IR camera is expensice	Regular cleaning to ensure high quality is necessary. Detecting areas where moss emerges is therefore necessary.
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	1) IE 2) IR	1) '- High resolution can be achieved ; Relatively cheap ; Through partly use of algoritms the process can be accelerated, and some human can be eliminated 2) Fast, safe clean method. Reduces guesswork	1) Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors. 2) Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology	1) Gondola 2) Gondola	1) Low cost solution 2) IR camera is expensice	Regular cleaning to ensure high quality is necessary. Detecting areas where algae emerges is therefore necessary.
- High resolution image of all façades - The 3D pointcloud depicts the locations of all defects on the entire façade, which makes it easier to plan maintenance	- The pictures and the corresponding severity and priority is a labor intensive and unpopular task. The severity and priority are judged by students/interns, which may not be educated enough to take correct decisions - Maintenance of output is labor intensive and prone to human errors - Lighting and weather conditions are very important, as differences can result in an inaccurate image	1) Infrared thermography (IR) 2) Piezo electric actuator - sensor (PEAS)	1) IR: Fast, safe clean method. Reduces guesswork 2) PEAS: can visualize scattering locations and estimate size/location of several types of damages.	1) IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology 2) PEAS: Major challenge in quantifying the damage based on sensor measurements	1) On window cleaning gondola..... 2) Mounted on the façade	1) IR camera is expensice 2) -	1) Prevent cracks from emerging, to ensure safety and quality of the material
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	1) IE 2) IR	1) '- High resolution can be achieved ; Relatively cheap ; Through partly use of algoritms the process can be accelerated, and some human can be eliminated 2) Fast, safe clean method. Reduces guesswork	1) Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors. 2) Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology	1) Gondola 2) Gondola	1) Low cost solution 2) IR camera is expensice	
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	1) IE 2) IR	1) High resolution can be achieved Relatively cheap 2) Fast, safe clean method. Reduces guesswork	1) Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors. 2) Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology			
-			-				
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	IR	Fast, safe clean method. Reduces guesswork IR focuses on termperature differences and can locate water quickly	Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology	Gondola	IR camera can be expensive	leaks can damage the quality of the frame. Its detection enables an image of the defect. This can
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	Image enhancement (IE)	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.	...	Low cost	Regular cleaning to ensure high quality is necessary. Detecting areas where discoloration emerges is therefore necessary.
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	IE	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.		Low cost	Regular cleaning to ensure high quality is necessary. Detecting areas where discoloration emerges is therefore necessary.

Façade matrix | Recommended additions, part 2| Case 1: JuBi Towers

-		-	-				-
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	IE	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.		Low cost	Regular cleaning to ensure high quallity is necessary. Detecting areas where discoloration emerges is therefore necessary.
-		-	-				-
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	IE	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.		Low cost	Regular cleaning to ensure high quallity is necessary. Detecting areas where discoloration emerges is therefore necessary.
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	IE	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.		Low cost	Regular cleaning to ensure high quallity is necessary. Detecting areas where discoloration emerges is therefore necessary.
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	IE	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.		Low cost	Regular cleaning to ensure high quallity is necessary. Detecting areas where discoloration emerges is therefore necessary.
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	IE	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.		Low cost	Regular cleaning to ensure high quallity is necessary. Detecting areas where discoloration emerges is therefore necessary.
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	IE	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.		Low cost	Regular cleaning to ensure high quallity is necessary. Detecting areas where discoloration emerges is therefore necessary.
- Quick and easy way to detect defect, as every type of camera is possible to use - Depicts an image of the defect, which results in a plan of action	- The severity, priority and exact location is difficult to determine - The inspections are carried out once a year, due to costs and it being a labor intensive additional task	IE	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.		Low cost	Regular cleaning to ensure high quallity is necessary. Detecting areas where discoloration emerges is therefore necessary.

Appendix F. Circularity degree, part 1| Case 1: JuBi Towers

Source CE characteristics: Platform CB 23. (2019). Framework Circulair bouwen, raamwerk voor eenduidig taalgebruik en heldere kaders. https://platformcb23.nl/downloads
Source CE characteristics: Platform CB 23. (2019). Kernmethode voor het meten van circulariteit in de bouw, werkafspraken voor een circulaire bouw. https://platformcb23.nl/downloads
Source CE characteristics: Rijksvastgoedbedrijf. (2019). BLOEI - Instrument, Hulpmiddel voor een circulaire projectstrategie.

BLOEI : RVB - Tool for facilitating projects in a circular strategy	
B	Maintenance
L	Material sustainability
O	Designing with a circular strategy
E	Economic models for collaboration
I	Capturing information

	B				L					
CE characteristic	**1. Maintenance**				**2. Material sustainability**					
Specific Characteristic	Preservation of materials in own project	Repair and upgrade of element	Harvest of elements for - Recycling - RVB - or for other use elsewhere	**CE connection**	Reuse of products and raw materials (Secondary)	Use of natural raw materials (bio-based)	Avoided use of finite raw materials (primary)	Minimalisation of environmental impact (Milieu Prestatie Gebouw, MPG)	Avoided use of materials with toxic characteristics (banned list)	**CE connection**
Cladding	Yes	Yes	No	-/+	No	No	No	Yes	Yes	-/+
Insulation	Yes	No	No	-	No	No	No	Yes	Yes	-/+
Inner cavity leaf	Yes	Yes	No	-/+	No	No	No	Yes	Yes	-/+
Outer window frame	Yes	Yes	No	-/+	No	No	No	Yes	Yes	-/+
Electric blind system	Yes	Yes	No	-/+	No	No	No	No	Yes	-/+
Inner window frame	Yes	Yes	No	-/+	No	No	No	No	Yes	-/+
Glass	Yes	Yes	No	-/+	No	No	No	Yes	Yes	-/+
Grilles	Yes	Yes	No	-/+	No	No	No	No	Yes	-/+
Sills	Yes	Yes	No	-/+	No	No	No	No	Yes	-/+
m	Yes	Yes	No	-/+	No	No	No	No	Yes	-/+
Structure	Yes	Yes	No	-/+	No	No	No	No	Yes	-/+

Circularity degree, part 2 | Case 1: JuBi Towers

Efficient and lesser use of (environmentally harmful) materials	Design for separating biosphere and technosphere	Designing for demountability 1) Number of connections 2) Type of connections 3) Accessibility connections 4) Demountability time 5) Demountability costs 6) Residual value 7) Damage when demounting 8) Standardization / interchangeability 9) Accessibility for maintenance and replacement	Design for intended service (-life) and maintainability	**CE connection**	Calculation with a 'value model' - e.g. True pricing, capitalising of residual value, pay per use	Circularity is included in project scope - e.g. Façade leasing	Maturity of circularity in business operations 1) RVB 2) Contractor 3) Sub contractor 4) Supplier	A project demands a 'circular market demand' due to its innovative character	Ownership	**CE connection**
Yes	No	1) - 2) a) Brackets are mounted and glued between cladding and inner cavity leaf b) Panels are also glued together, to prevent water from infiltrating 3) The cladding will be damaged when accessing the brackets 4) Due to the different types of connections, it will take a long time te demount the cladding 5) High 6) Medium 7) High 8) ? 9) Yes	Yes	-	No	No	1) Medium 2) Medium 3) No 4) No	No	Yes	-
Yes	No	1) - 2) Brackets 3) Will be damaged 4) High 5) High 6) Low 7) High 8) ? 9) Low	Yes	-	No	No	1) Medium 2) Medium 3) No 4) No	No	Yes	-
Yes	No	No	Yes	-	No	No	'	No	Yes	-
Yes	No	No	Yes	-	No	No	'	No	Yes	-
Yes	No	No	Yes	-	No	No	'	No	Yes	-
Yes	No	Yes	Yes	-	No	No	'	No	Yes	-
Yes	No	No	Yes	-	No	No	'	No	Yes	-
Yes	No	Yes	Yes	-	No	No	'	No	Yes	-
Yes	No	No	Yes	-	No	No	'	No	Yes	-
Yes	No	Yes	Yes	-	No	No	'	No	Yes	-
Yes	No	No	Yes	-	No	No	'	No	Yes	-

Circularity degree, part 3 | Case 1: JuBi Towers

5. Capturing information									
Inventory materials on reuse potential	Register materials in a building passport 1) Source 2) Data on characteristics 3) Data on specified characteristics and supplier data 4) Information on all used materials during its lifecycle 5) Material scarce or generally available 6) Quantity	Create a 'user manual' on circular characteristic for maintenance plan	Sharing of innovation with parties and scale up	BIM	Plan drawings	Façade drawings	Construction drawings	**CE connection**	**Overall CE connection**
No	1) No 2) Yes 3) Yes 4) No 5) Generally available 6) Yes	No	No	Yes	Yes, and available in BIM	Yes, and available in BIM	Yes, and available in BIM	-/+	-/+
No	-/+	No	No	Yes	Non applicable	Non applicable	Yes, and available in BIM	-/+	-/+
No	-/+	No	No	Yes	Non applicable	Non applicable	Yes, and available in BIM	-/+	-
No	-/+	No	No	Yes	yes, and available in BIM	Yes, and available in BIM	Yes, and available in BIM	-/+	-/+
No	-/+	No	No	No	Non applicable	Non applicable	No	-/+	-/+
No	-/+	No	No	Yes	Non applicable	Non applicable	Yes, and available in BIM	-/+	-/+
No	-/+	No	No	Yes	Non applicable	Non applicable	Yes, and available in BIM	-/+	-/+
No	-/+	No	No	Yes	Non applicable	Yes, and available in BIM	Yes, and available in BIM	-/+	-/+
No	-/+	No	No	Yes	Non applicable	Yes, and available in BIM	Yes, and available in BIM	-/+	-/+
No	-/+	No	No	Yes	Yes, and available in BIM	Yes, and available in BIM	Yes, and available in BIM	-/+	-/+
No	-/+	No	No	Yes	Non applicable	Yes, and available in BIM	Yes, and available in BIM	-/+	-/+

Appendix G. Façade matrix, Factual information | Case 2: Rijkswaterstaat building

Factual information									
Type	**Material**	**RVB-BOEI Condition**	**Corresponding information in BIM**	**Circularity degree** (based on 'Circularity Degree' Table)	**Defect**	**Force**	**Building Side**	**Type of maintenance**	**Current Defect-Detection Technology**
Cladding	Ceramic tiles Plaster mortar	3	Non applicable	-	Falling tiles	Heat Cold Wind Rain	Southwest NorthEast NorthWest	Reactive and corrective maintenance	None
					Cracks	Heat Cold	Southwest NorthEast Northwest	Corrective maintenance	None
Insulation	XPS insulation boards	3	Non applicable	-	Exposed insulation	Falling cladding	Southwest	Corrective maintenance	None
					Wet insulation				None
Inner cavity leaf	Concrete	3	Non applicable	-					None
Window frame	Aluminum	3	Non applicable	-	Leakages	Rain Holes in waterdefense	All sides	Corrective maintenance	None
					Corrosion		All sides		None
Glass	Double glass	3	Non applicable	-	Dirt	Pollution	All sides	Corrective maintenance	None
Doors	Aluminum	3	Non applicable	-	Dirt	Rain Pollution	All sides	Corrective maintenance	None

Façade matrix, Recommended additions | Case 2: Rijkswaterstaat building

		Recommendations					
Advantages current defect detection technology	**Disadvantages** current defect detection technology	**Recommended** Defect Detection Sensors	**Advantages** recommended defect detection sensors	**Disadvantages** recommended defect detection sensors	**Placement**	**Costs**	**Circularity**
No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	- Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance	IR (Infrared thermography) DOFS (Distributed optical fiber sensor) UAV (unmanned aerial vehicle) IE (image enhancement)	- IR: Fast, safe clean method. Reduces guesswork - DOFS: Sensitive over entire fibre and able to measure different variables. Can be integrated in the new facade project - UAV: Reliable and stable	- IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology - DOFS: Requires maintenance - UAV: Short flight time, labor intensive output	- IR: On a moving vehicle along the facade - DOFS: integrated in zigzag lines in the façade - UAV: Flying vehicle	- IR camera can be expensive - DOFS: Fibres can be expensive - UAV: Low cost	Provides quick evidence for plan of action
No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	- Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance	DOFS IR	- DOFS: Sensitive over entire fibre and able to measure different variables. can be integrated in the new facade project - IR: Fast, safe clean method. Reduces guesswork	- DOFS: Requires maintenance - IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology	- DOFS: integrated in zigzag lines in the façade - IR: On a moving vehicle along the facade	- DOFS: Fibres can be expensive - IR camera can be expensive	1) Prevent cracks from emerging, to ensure safety and quality of the material
-No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	- Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance	IR Optical fibre corrosion sensor (OFCS)	- IR: Fast, safe clean method. Reduces guesswork - OFCS: Sensitive and reliable sensor	- IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology - Expensive technology	- IR: On a moving vehicle along the facade	- IR: infrared camera's can be expensive	When quickly detecting exposed insulation, the material can be protected before this is wetted
-No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	- Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance	IR Optical fibre corrosion sensor	- IR: Fast, safe clean method. Reduces guesswork - OFCS: Sensitive and reliable sensor	- IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology - OFCS: Expensive technology	'- IR: On a moving vehicle along the facade	- IR: infrared camera's can be expensive	-
-No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	- Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance	-	-	-	-	-	-
-No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	- Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance	IR Optical fibre corrosion sensor	- IR: Fast, safe clean method. Reduces guesswork - OFCS: Sensitive and reliable sensor	- IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology - OFCS: Expensive techology	- IR: On a moving vehicle along the facade - OFCS: Along window frames	- IR: infrared camera's can be expensive -OFCS: expensive	When leaks are prevented, further degradation of the element is protected
-No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	- Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance	IR OFCS	- IR: Fast, safe clean method. Reduces guesswork - OFCS: Sensitive and reliable sensor	- IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology - OFCS: Expensive technology	- IR: On a moving vehicle along the facade - OFCS: Along window frames	- IR: infrared camera's can be expensive -OFCS: expensive	When corrosion is prevented, further degradation of the element is protected
-No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	- Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance	IE	- IE: High resolution can be achieved; Relatively cheap; Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.	With distance from the facade, so a picture can be taken	Relatively low costs	Tecnical clean is required to optimize the aesthetic performance
-No additional costs are necessary for new technologies -Tangible method -e.g. phone camera can be used which are widely available	- Guessing, overlooking defects, hidden defects -Location, severity and priority are difficult to determine from the pictures, which leads to difficulties in determine the plan of action in maintenance	IE	- IE: High resolution can be achieved; Relatively cheap; Through partly use of algoritms the process can be accelerated, and some human can be eliminated	Manual identification of defects within thousands of images is time consuming, and prone to inaccuracy due to fatigue and human errors.	With distance from the facade, so a picture can be taken	Relatively low costs	Tecnical clean is required to optimize the aesthetic performance

Appendix H. Circularity degree, part 1 | Case 2: Rijkswaterstaat building

CE characteristic	1. Maintenance				2. Material sustainability					
Specific Characteristic	Preservation of materials in own project	Repair and upgrade of element	Harvest of elements for - Recycling - RVB - or for other use elsewhere	**CE connection**	Reuse of products and raw materials (Secondary)	Use of natural raw materials (bio-based)	Avoided use of finite raw materials (primary)	Minimalisation of environmental impact (Milieu Prestatie Gebouw, MPG)	Avoided use of materials with toxic characteristics (banned list)	**CE connection**
Cladding	No	No	No	-	Yes	No	Yes	No	Yes	-/+
Insulation	No	No	No	-	Yes	No	Yes	No	Yes	-/+
Inner cavity leaf	No	No	No	-	Yes	No	Yes	No	Yes	-/+
Window frame	No	No	No	-	Yes	No	Yes	No	Yes	-/+
Glass	No	No	No	-	Yes	No	Yes	No	Yes	-/+
Doors	No	No	No	-	Yes	No	Yes	No	Yes	-/+

Circularity degree, part 2 | Case 2: Rijkswaterstaat building

3. Designing with a circular strategy					4. Economic models for collaboration					
Efficient and lesser use of (environmentally harmful) materials	Design for separating biosphere and technosphere	Designing for demountability 1) Number of connections 2) Type of connections 3) Accessibility connections 4) Demountability time 5) Demountability costs 6) Residual value 7) Damage when demounting 8) Standardization / interchangeability 9) Accessibility for maintenance and replacement	Design for intended service (-life) and maintainability	**CE connection**	Calculation with a 'value model' - e.g. True pricing, capitalising of residual value, pay per use	Circularity is included in project scope - e.g. Façade leasing	Maturity of circularity in business operations 1) RVB 2) Contractor 3) Sub contractor 4) Supplier	A project demands a 'circular market demand' due to its innovative character	Ownership	**CE connection**
No	No	No	No	-	No	No	1) Medium 2) No 3) No 4) No	Yes	Yes	-/+
No	No	No	No	-	No	No	1) Medium 2) No 3) No 4) No	Yes	Yes	-/+
No	No	No	No	-	No	No	1) Medium 2) No 3) No 4) No	Yes	Yes	-/+
No	No	No	No	-	No	No	1) Medium 2) No 3) No 4) No	Yes	Yes	-/+
No	No	No	No	-	No	No	1) Medium 2) No 3) No 4) No	Yes	Yes	-/+
No	No	No	No	-	No	No	1) Medium 2) No 3) No 4) No	Yes	Yes	-/+

	5. Capturing information								
se	Register materials in a building passport 1) Source 2) Data on characteristics 3) Data on specified characteristics and supplier data 4) Information on all used materials during its lifecycle 5) Material scarce or generally available 6) Quantity	Create a 'user manual' on circular characteristic for maintenance plan	Sharing of innovation with parties and scale up	BIM	Plan drawings	Façade drawings	Construction drawings	**CE connection**	**Overall CE connection**
	No	No	Yes	No	No	No	No	-	-
	No	No	Yes	No	No	No	No	-	-
	No	No	Yes	No	No	No	No	-	-
	No	No	Yes	No	No	No	No	-	-
	No	No	Yes	No	No	No	No	-	-
	No	No	Yes	No	No	No	No	-	-

Appendix I. Façade matrix, Factual information | Case 3 : Galileo Reference Building

Factual information									
Type	Material	RVB-BOEI Condition	Corresponding information in BIM	Circularity degree (based on 'Circularity Degree' Table)	Defect	Force	Building Side	Type of maintenance	Current Defect-Detection Technology
Cladding	HR ++ glass Folded sheet aluminium	1	Constructive qualities, weight, composition, finishing layer, connections and certain specific qualities, Fire safety infrormation, supplier, material,	Heat Cold Sea Wind Rain Sand	Dirt	All sides	Corrective maintenance	Corrective maintenance	Camera
					Discoloration		Corrective maintenance	Corrective maintenance	Camera
Window frame	Aluminum Anodized, powercoating	1	Constructive qualities, weight, composition, finishing layer, connections and certain specific qualities	Stong winds	Leakages	All sides, dependent on the wind direction	Corrective maintenance	Corrective maintenance	Camera
					Corrosion	Sea wind Rain Sun	Corrective maintenance	Corrective maintenance	Camera
Door frames	Aluminum	1	Constructive qualities, weight, composition, finishing layer, connections and certain specific qualities	Sea wind	Corrosion		Corrective maintenance	Corrective maintenance	Camera
Inner cavity leaf	Spruce wood	1	Constructive qualities, weight, composition, finishing layer, connections and certain specific qualities	-	-	-	-	-	-

Façade matrix, Recommended additions | Case 3 : Galileo Reference Building

Advantages current defect detection technology	Disadvantages current defect detection technology	Recommended Defect Detection Sensors	Advantages recommended defect detection sensors	Disadvantages recommended defect detection sensors	Placement	Costs	Circularity
- Cost effective in terms of technology - Widely available, as workers can use the camera on their mobile phone	- Defects are discovered when an inspection is due. Therefore the defect can worsen in time, which has an effect on the costs and circular potential	IE (image enhancement)	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	1) Machine learning datasets must be of good quality 2) Datasets could be biased, machine learning is susceptible to errors 3) Imachine learning takes time to let algorithms learn	With distance from the facade, so a picture can be taken	Relatively low costs	Tecnical clean is required to optimize the aesthetic performance
- Cost effective in terms of technology - Widely available, as workers can use the camera on their mobile phone	- Defects are discovered when an inspection is due. Therefore the defect can worsen in time, which has an effect on the costs and circular potential	IE	- High resolution can be achieved - Relatively cheap - Through partly use of algoritms the process can be accelerated, and some human can be eliminated	1) Machine learning datasets must be of good quality 2) Datasets could be biased, machine learning is susceptible to errors 3) Imachine learning takes time to let algorithms learn	With distance from the facade, so a picture can be taken	Relatively low costs	Tecnical clean is required to optimize the aesthetic performance
- Cost effective in terms of technology - Widely available, as workers can use the camera on their mobile phone	- Defects are discovered when an inspection is due. Therefore the defect can worsen in time, which has an effect on the costs and circular potential	IR (infrared thermography) OFCS (optical fiber corrosion sensor)	- IR: Fast, safe clean method. Reduces guesswork - OFCS: Sensitive and reliable sensor	- IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology - OFCS: Expensive technology	- IR: On a moving vehicle along the facade - OFCS: Along window frames	- IR: infrared camera's can be expensive -OFCS: expensive	When leaks are prevented, further degradation of the element is protected
- Cost effective in terms of technology - Widely available, as workers can use the camera on their mobile phone	- Defects are discovered when an inspection is due. Therefore the defect can worsen in time, which has an effect on the costs and circular potential	IR OFCS	- IR: Fast, safe clean method. Reduces guesswork - OFCS: Sensitive and reliable sensor	- IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology - OFCS: Expensive technology	- IR: On a moving vehicle along the facade - OFCS: Along window frames	- IR: infrared camera's can be expensive -OFCS: expensive	When corrosion is prevented, further degradation of the element is protected
- Cost effective in terms of technology - Widely available, as workers can use the camera on their mobile phone	- Defects are discovered when an inspection is due. Therefore the defect can worsen in time, which has an effect on the costs and circular potential	IR OFCS	- IR: Fast, safe clean method. Reduces guesswork - OFCS: Sensitive and reliable sensor	- IR: Infrared camera's can be expensive, defects can only be determined if enough temperature contrast is detected, can be a complex technology - OFCS: Expensive technology	- IR: On a moving vehicle along the facade - OFCS: Along window frames	- IR: infrared camera's can be expensive -OFCS: expensive	When corrosion is prevented, further degradation of the element is protected
	-						

Appendix J. Circularity degree part 1 | Case 3 : Galileo Reference Building

CE characteristic	1. Maintenance				2. Material sustainability					
Specific Characteristic	Preservation of materials in own project	Repair and upgrade of element	Harvest of elements for - Recycling - RVB - or for other use elsewhere	**CE connection**	Reuse of products and raw materials (Secondary)	Use of natural raw materials (bio-based)	Avoided use of finite raw materials (primary)	Minimalisation of environmental impact (Milieu Prestatie Gebouw, MPG)	Avoided use of materials with toxic characteristics (banned list)	**CE connection**
Cladding	Yes	Yes	Yes	+	Yes	Yes	Yes	Yes	Yes	+
Window Frame	Yes	Yes	Yes	+	Yes	Yes	Yes	Yes	Yes	+
Door frames	Yes	Yes	Yes	+	Yes	Yes	Yes	Yes	Yes	+
Inner cavity leaf	Yes	Yes	Yes	+	No	Yes	No	Yes	Yes	-/+

Circularity degree part 2| Case 3 : Galileo Reference Building

3. Designing with a circular strategy					4. Economic models for collaboration					
Efficient and lesser use of (environmentally harmful) materials	Design for separating biosphere and technosphere	Designing for demountability 1) Number of connections 2) Type of connections 3) Accessibility connections 4) Demountability time 5) Demountability costs 6) Residual value 7) Damage when demounting 8) Standardization / interchangeability 9) Accessibility for maintenance and replacement	Design for intended service (-life) and maintainability	**CE connection**	Calculation with a 'value model' - e.g. True pricing, capitalising of residual value, pay per use	Circularity is included in project scope - e.g. Façade leasing	Maturity of circularity in business operations - RVB - Contractor - Sub contractor - Supplier	The project demands a 'circular market demand' due to its innovative character	Ownership	**CE connection**
Yes		Yes	Yes	**+**	?	Yes	1) Medium 2) Mediium 3) Medium 4) Yes	No	Yes	**-/+**
Yes		**Yes**	**Yes**	**+**	?	Yes	1) Medium 2) Mediium 3) Medium 4) Yes	No	yes	**-/+**
Yes		**Yes**	**Yes**	**+**	?	Yes	1) Medium 2) Mediium 3) Medium 4) Yes	No	yes	**-/+**
Yes		**Yes**	**Yes**	**+**	?	Yes	1) Medium 2) Mediium 3) Medium 4) Yes	No	yes	**-/+**

Circularity degree part 3 | Case 3 : Galileo Reference Building

5. Capturing information									
Inventory materials on reuse potential	Register materials in a building passport 1) Source 2) Data on characteristics 3) Data on specified characteristics and supplier data 4) Information on all used materials during its lifecycle 5) Material scarce or generally available? 6) Quantity?	Create a 'user manual' on circular characteristic for maintenance plan	Sharing of innovation with parties and scale up	BIM	Plan drawings	Façade drawings	Construction drawings	**CE connection**	**Overall CE connection**
Yes	Yes	No	No	Yes	Yes	Yes	Yes	+	+
Yes	Yes	No	No	Yes	Yes	Yes	Yes	+	+
Yes	Yes	No	No	Yes	Yes	Yes	Yes	+	+
Yes	Yes	No	No	Yes	Yes	Non applicable	Yes	+	+