MASTER THESIS

BIM and AR based construction supervision for underground utilities

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Foreword and acknowledgements

The report in front of you presents the result of the master thesis "BIM and AR based construction supervision for underground utilities". This thesis has been made in collaboration with TAUW and is the final part of my master's program 'Construction Engineering and Management' at the University of Twente.

Given the increasingly popular BIM and AR technologies, this thesis was designed to investigate the potential of these concepts for quality control in the underground utility domain. Over the past months, I studied what these digital concepts entail and how they can support the quality control during underground utility construction. Although challenging at times, the input and guidance from both TAUW and the University of Twente has helped shaping the research to its final form.

At first, I would like to thank Farid Vahdatikhaki and Léon olde Scholtenhuis for their weekly supervision. Their guidance and constructive feedback have really helped me to stay on track. Furthermore, I would like to thank Hans Voordijk for his comments and recommendations at the end of each phase. Besides, I would like to thank my weekly supervisor from TAUW, Niels Vossebeld, for his input and guidance, especially during the early stages of the research. All supervisors contributed significantly for which I am grateful for. In addition, I would like to thank Sybren Boukema and all other TAUW colleagues for their input and enthusiasm. I enjoyed the extensive interviews in which you gave me valuable and interesting insight into daily practices. At last, I want to thank my friends and family for the necessary distraction and motivation throughout the project.

I hope you enjoy reading my thesis.

Tim Terwisscha van Scheltinga

Amsterdam, September 2021

Glossary

3D-data
Virtual three-dimensional data to visualise object geometry

As-planned environment
The design that represents how the assets are supposed to be built

As-built environment
The physical environment with assets that represents how it is actually built

As-planned model
The as-planned environment represented as BIM model

As-built model
The as-built environment represented as BIM model

Augmented reality
A user view in which virtual three-dimensional virtual objects are projected onto the physical environment (Satoh et al. 1999).

BIM
A set of interacting policies, processes and technologies generating a methodology to manage the essential project design and data in digital format throughout the projects' life-cycle (Succar, 2009)

Deviation
A misalignment between things, in this report used to refer to the misalignment between as-planned and as-built

Inspection item
Attributes of construction objects that should be inspected during the construction phase to make sure that it is in accordance with the construction specification

Inspection process
The act of making sure the construction progress is in accordance with the design

Meta-data
The attribute data (in tabular form) attached to objects in a BIM environment

Object
A physical or virtual (construction) element, mostly refers to a pipe or cable in this report

Ontology
A formal and explicit model of shared conceptualizations about reality (Studer et al. 1998)

Quality control (QC)
The inspection and verification process of finished products (Pellicer et al. 2013), in this report mostly referred to as the inspection process to identify deviations and design clashes

Quality management (QM)
The act to deliver products and services that meet the customers' requirements

Supervisor
The person responsible for the inspection process

System component
A hardware or software component of a system

Underground utility network
Network of utility objects (i.e. cables and pipes) in the underground, in this report also called underground infrastructure

Unified Modelling language (UML)
A standardized modelling language in the field of software engineering

Abbreviations

3D
Three dimensional

AR
Augmented Reality

BIM
Building Information modelling

CQ
Competency questions

QC
Quality control

QM
Quality management

UML
Unified Modelling Language

VR
Virtual Reality

Summary

As project delays and cost overruns due to reworks remain a prominent issue in the construction industry, practitioners keep looking for new ways to improve conventional quality control practices. With the increasingly popular BIM and AR technologies, this research was designed to investigate whether those digital concepts have potential to uplift current practices. Because a limited number of studies considered underground utilities, this research specifically focussed on that domain.

It was also found that earlier studies applied a technology push strategy. Instead, this study applied the principles of end-user engagement in which end-user were involved at an early stage of the research. As a result, the outcomes are tailored more to the end-user needs and goals. Hence, the purpose of this study was to structurally develop a list of requirements and a system ontology that uses the principles of BIM and AR for QC that meet the needs of end-users.

To do so, the end-users (i.e. designers and supervisors) were interviewed and their current practices and issues were mapped. The current QC practice in the underground utility sector is characterized by manual measurement techniques, information exchange that is mainly document based and a low inspection frequency. Out of that analysis, four end-user goals were distinguished. The first end-user goal is about the ability to efficiently and accurately identify the six possible deviations (between as-planned and as-built) that can occur during the construction of underground utilities. The second end-user goal is about the improvement of design understanding among fieldworkers. The third one addresses the identification of design clashes. The last end-user goal is the possibility of real-time off-site access to latest on-site developments.

The end-user goals provided input for the functional requirements. The list of functional requirements considered three domain levels (from business operation level to system component level) and was developed by using existing literature and consulting BIM and AR experts. Furthermore, the four end-user goals also provided input for the goal-modelling approach (Fernandes et al. 2011) that was used to elicit competency questions. Competency questions justify the choice of concepts in the ontology and is therefore a useful tool for ontology engineering.

To create a system vision, a technical and functional design was made that describe the intended behaviour and required system components. The technical design include the necessary hardware and software components to meet all functional requirements. Multiple AR features, a data integration between BIM and AR, a localization mechanism and the conditions for the BIM environment were described. The functional design depicted the behaviour of the system by means of two diagrams. The Use Case Diagram conveniently illustrates the possible interactions the end-user is able to do with the AR and BIM environment, respectively. The Activity Diagram depicts the step-by-step actions while using the envisioned system, thereby providing an overview of the envisioned workflow

The system ontology conceptually represents the reality the system is built upon. It was developed by synthesizing the system components and behaviour diagrams. In addition, the list of competency questions was used to elicit initial concepts. As a result, a class-based ontology was developed (in UML) that describes the system from four different viewpoints, being the Physical environment, the BIM environment, the AR environment, and the Process model. The system ontology illustrates a variety of conditions to be met in order to bring the envisioned system into practice. For example, the ontology depicts what BIM models are required and what virtual objects and attributes should be modelled within. Also, the GUI of the AR environment and its required interface components such as the move object feature and distance measurement feature are described. Furthermore, the ontology illustrated the relation between the different environments. For example, it indicates how and what AR

components identify (or measure) each of the as-planned vs. as-built deviations that can occur during the construction phase.

The requirements set and system ontology were positively evaluated by domain experts. As a result, the envisioned system shows a wide range of possibilities uplifting current practices. Ultimately, the requirements set and ontology can help innovators and programmers in the underground utility sector understand the potential of and develop a system for QC that uses BIM and AR. Therefore, this research offers support for the transition from conventional QC methods to innovative methods using digital technologies

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1. Introduction

Proper quality management is vital to any construction project's success. According to McKinsey (2015) 98% of all large infrastructure projects incur cost overruns or delays, with an overage cost overrun of 80% of original value and an average delay of 20 months. Memon et al. (2014) assessed factors influencing cost and time overruns of construction projects and found a high correlation between schedule delays and inadequate quality control. Quality control is part of quality management and is often referred to as the inspection process by supervisors. Quality control during the execution phase of a construction project can prevent many defects that lead to reworks that can otherwise be very costly and unsafe if not resolved. Love et al. (2019) reported in a study involving 19,605 rework events among 346 construction projects conducted between 2009 and 2015 that rework cost (cost endured by re-doing a process or activity that was incorrectly implemented the first time) on average make up for 0.39% of the original contract value. For these contractors, the yearly profit was on average reduced by 28% due to these rework events. Likewise, Hoonakker et al. (2010) reported that through improving quality through better quality management, contractors have lots of benefits including reduced reworks and improved safety and schedule performance.

During a construction project, the site supervisor is generally responsible for carrying out regular inspections to make sure that the works, in terms of quality, progress as intended. In the context of this research, quality control (QC) is defined as the inspection and verification process of finished products (Pellicer et al. 2013). During inspection, the supervisor analyses the differences between the results obtained (as-built) and the desired results (as-planned) in order to make decisions which will correct these differences. This research considers the documentation of the as-built progress as part of the inspection process.

An effective quality control system is crucial in order to prevent costly errors and project delays. Figure 1 outlines the typical information flow during quality control. First, data is generally gathered through measuring and inspecting the construction site (also called 'as-built environment'. Thereafter, the decision makers (client or contractor, depending on the issue at stake) need to process the inspection data for which he compares it to the design (also called 'as-planned environment') and they should, in the case of a defect or deviation, act accordingly. This results in change orders during the construction phase, or, if not timely discovered, reworks afterwards. When a new QC method allows for more effective and/or efficient comparison between as-planned and as-built, deviations can be identified faster and with more accuracy, potentially reducing much of the rework costs.

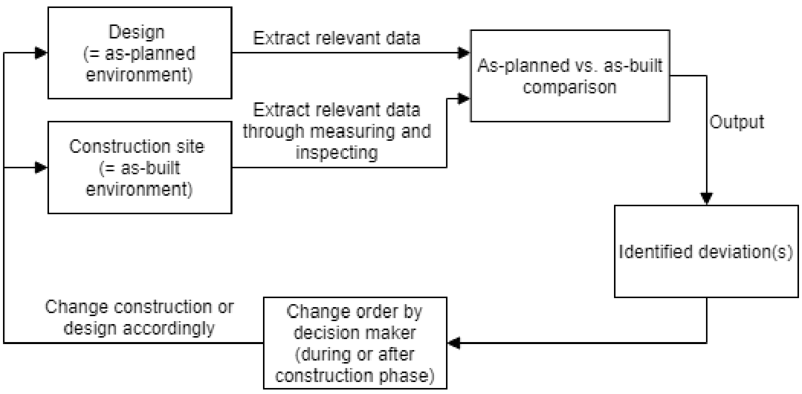

Figure 1. Basic concept of QC information feedback loop

In this era of digitization, there are many possibilities to improve the entire value chain of the construction process, starting from urban and land use planning and ending up with management of built environment assets (Leviäkangas, 2017). Hence, in the last decade multiple concepts and ideas are established to improve quality control in construction using digital technologies. These studies found that the use of Building Information modelling (BIM) and Augmented Reality (AR) can improve the efficiency and accuracy of detecting construction defects by facilitating an efficient as-planned vs. as-built comparison (figure 1), thus reducing rework cost and project delays. These studies are further described in section 1.1 Research Background.

BIM is a set of interacting policies, processes and technologies generating a "methodology to manage the essential project design and data in digital format throughout the projects' life-cycle" (Succar, 2009). BIM uses software that models an asset as objects, using object-oriented logic. Such models include geometry, the relative position of objects, and information like the material and costs (also referred to as meta-data). The object-oriented data can also be linked to a variety of things like phasing, functions, and simulations. Within the construction process, BIM software further allows for data centralization and stakeholders' collaboration (Raimbaud, 2019), since it can simply generate views and project-related data based on one central model. This, in turn, enables a centralized approach to construct and control the building project environment such that is complies with the initial design. The transition to the BIM paradigm is currently prominent in the construction industry. Consequently, Tsai et al. (2014) demonstrated that enabling BIM could improve inspection tasks and, therefore, the quality of construction work. Furthermore, Ma et al. (2016) pointed out that the new means of information management with BIM allows for improvement in the construction quality supervision.

Besides BIM, 3D visualization approaches such as Augmented and Virtual Reality become implemented in the construction industry (Behzadi, 2016). Virtual reality (VR) is a computer-generated simulation of three-dimensional (3D) environment, in which the user is able to both view and manipulate the contents of that environment (Goulding, 2012). Augmented reality (AR) shares the same concept, but instead of a full virtual environment, virtual elements are projected onto the physical environment (Satoh et al. 1999). This allows to transfer the semantic information of BIM to AR (Chen et al. 2020) and visualise on site. Augmented Reality has plenty of applications in the construction industry, including construction equipment operator training (Wang, 2007), project progress monitoring (Zollmann et al. 2014) and, more importantly, improved detection of construction defects (Park et al. 2013). Although practical examples of augmented reality technologies in construction projects has tremendously increased in recent years, these technologies are still in the research stage and their practical potential is not fully achieved (Behzadi, A. 2016).

For the construction industry, the foremost feature of AR is the ability to present digital information, on-site, onto the physical world. The AR interface is displayed most often on a mobile display, which combines a user's view (often a video feed of their physical surroundings) with spatially aligned digital information (Zollmann, 2014). To this end, as-planned digital models can be superimposed onto the physical environment during different stages of the construction phase.

1.1 Research background

As described earlier, existing studies have shown that BIM and AR can improve the detection of construction defects during inspection, thus reducing rework cost and project delays. Here, the studies are shortly explained. Table 1 provides a summary and comparison between the studies. Thereafter, the value of this study is explained.

Park et al. (2013), for example, analysed the issues with current field inspection practices based on literature and proposed a conceptual system framework for identifying omission error and dimension deviation during facility construction using BIM, augmented reality, and ontology-based data collection template. The framework could be used to identify core control time points and measures beforehand, enabling a proactive defect management.

Additionally, Tsai et al. (2014) considered the possibilities of BIM models and the increasing functionalities on mobile devices, and based on these positive developments, they put forward a BIM-enabled approach that facilitates offline construction supervision with mobile devices which is believed to improve the quality management of construction work for facility construction.

Zollman et al. (2014) shortly addressed the importance of construction defect detection and based on that motivation proposed a system approach that describes how AR can be used to support monitoring and documentation of construction site progress.

Next, Ma et al. (2016) focused also on facility construction and argued that too many inspection items specified by the relevant standards have led to inefficiency of the inspection work. Therefore, he performed a basic requirements analysis and used it for the development of an IFC-based information model and an algorithm which automatically generates inspection points for construction quality supervision based on BIM and implemented and tested the proposed system. This aids inspectors in identifying relevant inspection items used in quality standards, and therewith streamline their work.

Further, Achkar (2017) identified problems of current QC practices for building construction based on literature and argued that the main weakness is poor information management. He proposed a quality management system that incorporated BIM concepts in order to reduce quality defect occurrences on facility construction projects.

Also, Raimbaud et al. (2019) argued together with BIM experts that the current method of on-site inspections could be improved by superimposing planned design on the real current state of building construction preventing the need of going back and forth between on-site and the BIM model to make changes. They described the functional behaviour of a mixed reality system based on BIM data and drone videos, allowing off-site construction supervision, and validated the system with experts consisting of civil engineering students and young civil engineers that lead construction projects.

Last, Ratajczak et al. (2019) took a broader view and investigated, by means of literature, how BIM and AR can improve the construction performance of facility construction in general. They developed and evaluated a system that provides on-site information and performance indicators on the progress and performance of construction tasks which provides (among other) the opportunity to efficiently identify design deviations.

Table 1, Comparison between and overview of existing studies

Study	**Goal**	**Asset type**	**System architecture**	**End-user engagement**	**Requirement analysis**
Park et al., 2013	To find an innovative way to change current defect management practices from reactive to proactive by means of BIM and AR	Facility construction	✓	×	×
Tsai et al., 2014	To develop a BIM-enabled construction inspection system	Facility construction	✓	×	×
Zollman et al., 2014	To describe how to use AR to support monitoring and documentation of construction site progress	Facility construction	✓	×	×

Ma et al., 2016	To propose a BIM based approach that improves the quality supervision	Facility construction	✓	×	✓
Achkar, 2017	To develop quality practices and tools that reduce construction quality defects	Facility construction	✓	Only during test phase	×
Raimbaud et al., 2019	Propose a mixed reality application based on BIM and drones to allow off-site supervision	Facility construction	✓	Only during test phase	×
Ratajczak et al., 2019	To propose a BIM and AR-based application that can improve construction performance	Facility construction	✓	Only during test phase	×

One of the few cases that could be extended from AR-application in the facility construction towards the deployment of buried infrastructure, is demonstrated in Park et al, 2013; Zollman et al, 2014; Raimbaud, 2019. These studies showed that AR could be used to check whether a constructed pipe comprised of the 'right' material and dimensions, and whether it was deployed at a proper location and depth.

In sum, existing studies have focused on the relevance of digital technologies, such as BIM and AR to improve quality control. However, a limited number of those studies have actually identified the needs and requirements from the end-users that would eventually need to use those systems in the field. When doing so, it is ensured that the technological propositions are of real practical value. What is lacking, therefore, is a specification of requirements that a digital QC system should meet. This specifically holds for the domain of buried utilities, since many of the studies predominantly give examples of the value of AR/BIM for the management of a facility construction project. To find how the potential of BIM and AR to improve QC can be expanded, this research focussed on the practical domain of underground utilities.

The goal of this research was, therefore, to identify the goals and needs of the end-users of digital quality control systems, using a bottom-up approach. To this end, it first developed a list of requirements for a BIM/AR system. This should come with overview of envisioned system components and relevant objects and attributes required to conduct adequate quality control.

The second goal of this study was hence to develop an ontology that represents the reality the system is built upon, incorporating different viewpoints including the viewpoint of the BIM and AR technologies. An ontology is defined in this research as a "formal and explicit model of shared conceptualizations about reality" (Studer et al. 1998).

1.2 Problem statement and Research objective

The literature study showed that there is a lack of a clear requirements analysis among previous studies. When this is done in a structural manner, the needs of end-users (i.e. supervisors and designers) can be better incorporated. Based on the former, the research aims to develop a class-based ontology that conceptually represents the reality the system is built upon. Additionally, it was found that previous research involving BIM and AR to enhance quality control practices focussed only on facility construction. This research will focus on underground utilities, although findings may also be of use in other domains. To summarize, the following problem statement was identified:

"There is no clear generic list of functional requirements for a BIM and AR integrated system for quality control during underground utility construction and there is an absence of a class-based ontology that conceptually represents the reality the system is built upon"

The research objective is strongly related to the problem statement and is formulated as follows:

"This research aims to develop (1) a generic list of functional requirements for a BIM and AR integrated system for quality control during underground utility construction and (2) develop a class-based ontology that conceptually represents the reality the system is built upon."

The research questions are formulated based on the research objective. In order to reach the research objective, the following research questions were answered:

[1.] How do current QC practices in the underground utilities sector look like and what are the goals and needs of the end-users?
[2.] What functional requirements must be captured in a BIM and AR integrated system to achieve the end-user goals?
[3.] How can the domain-related data and functional requirements for quality control with BIM and AR in the underground utilities sector be captured and structured as class-based ontology?
[4.] Is the list of requirements and the proposed system ontology valid according to practitioners?

1.3 Research Context and Scope

TAUW is a Dutch consultancy and engineering firm with a strong footprint in the underground domain from several perspective. TAUW provides the platform to conduct this research. Thus, the study will be done in the context of the Dutch construction industry. Typically, TAUW combines a broad spectrum of environmental consultancy services and a role of engineering consultant on infrastructural projects. The company offers specialized knowledge for which an effective information feedback loop between the field and the office can potentially be of great value. Especially given TAUW's experiences regarding projects whereby either BIM models were not used after the Final Design stage or on projects whereby BIM as-built revision was requested after site supervision was conducted and registered in traditional manner by the contractor. More specifically, the as-built environment is often still registered in various formats and locations ranging from documentation to scan models and inspection databases from the client, contractor, or at TAUW. Thus, integrating a BIM model with rich meta-data with an AR environment, could potentially have significant benefits.

Therefore, this research tried to close the knowledge gap by providing a requirement list and system ontology for the use of BIM and AR for QC. Irrespective of who plays what part, in the long run TAUW wants to play a positive part in improving the information feedback along the supply chain and over the lifecycle. This research can provide TAUW insight into workflow and requirements as relevant for a BIM model with AR integration as an input for further methodology improvements to be conducted by TAUW.

This study focused on expanding the use of BIM and AR for underground utilities, so that AR is applicable for efficient quality control practices. By integrating AR and BIM, an effective information feedback was obtained with a variety of functionalities that helps the inspection process. Data gathered from practitioners is based mainly on experiences gained in the Dutch construction industry. More specifically, the experiences of TAUW are used as basis for this research, as they provided the research platform, so the findings are suited to their main field of work which is the role as engineering consultant on infrastructural projects.

This research will focus on underground utilities. Underground utilities are considered cables (i.e. electricity, telecoms) and pipes (i.e. gas, water, and sewer).

2. Research methodology

In this section, the research strategy is outlined. The research strategy lays out a step-by-step approach that was followed during the research period. In phase 1, the current practices (i.e. workflow methods and typical issues) are explored by means of interviews with end-users. Based on that, a classification of end-user goals was composed. In phase 2, the end-user goals and an additional input from BIM and AR experts were used to form a list of functional requirements. In phase 3, a vision of the system is created, thereby describing the technical and functional design, and subsequently presenting the system ontology. In phase 4, the requirements set and ontology were validated by means of two validation techniques: competency questions validation and expert panel validation. Figure 2 shows the framework of the research strategy.

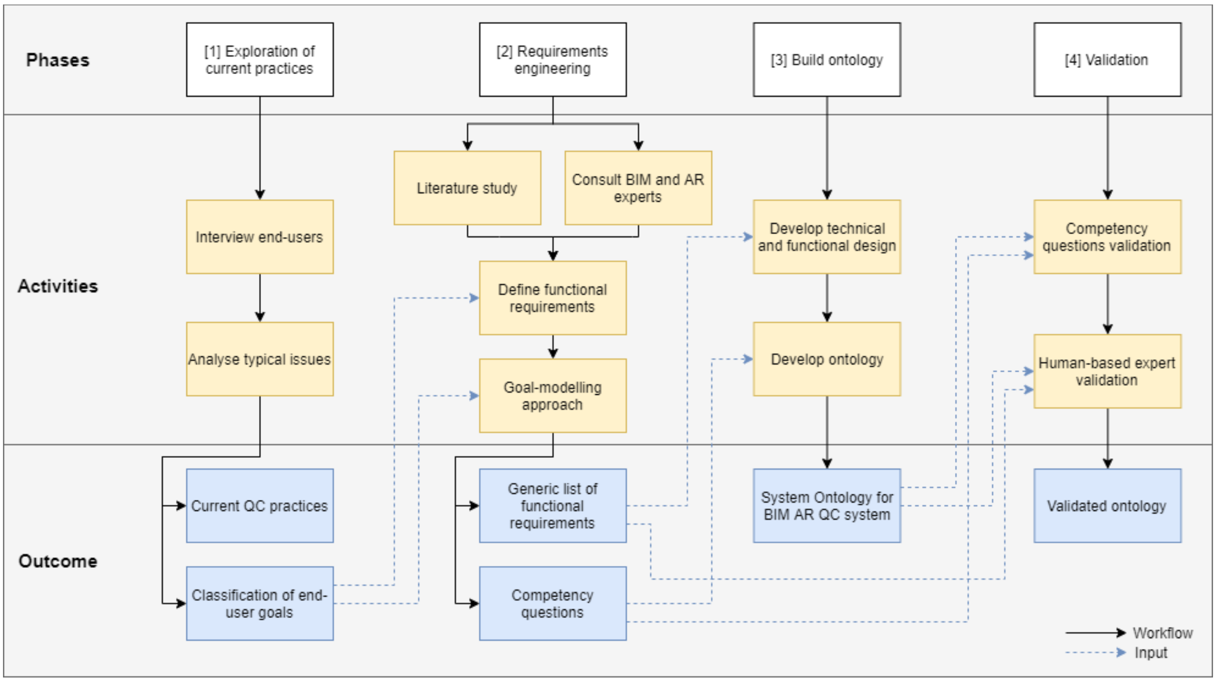

Figure 2. Research Strategy Framework

2.1 Phase 1 – Exploration of current practices

The research question answered in phase 1:

How do current QC practices in the underground utilities sector look like and what are the goals and needs of the end-users?

This phase was divided into three steps, each applying methods and strategies, as described below:

Step 1: Describe current QC practices during underground utility construction

In order to outline current practices the principle of end-user engagement was used. This was applied to assure that the research outcomes consider all information and functionalities as required by the end-users.

First, interviews with end-users were conducted to outline the current QC practices of underground utilities, specifying (1) the methods for information exchange, measurements, and inspection frequency, and (2) typical (most common) issues (e.g. wrongly constructed, misalignments, reworks). The format of the interviews was semi-structured and open-ended. The criterion for selecting interviewees was based and prioritized on experience within the domain of utility quality management of construction projects; people with practical knowledge were prioritized above people that pursue higher level managerial or advisory roles. End-users include quality control practitioners (i.e. inspectors and/or supervisors; this report uses the term 'supervisors') and (digital) designers/design experts.

During the interviews, the respondents were asked to explain their regular work process concerning either actual QC practice (i.e. inspection process by supervisors) or their design activities. Supervisors were then asked to explain the most common issues or inefficiencies in their daily work. Likewise, designers were asked to formulate potential issues in their usual way of information exchange between the field and the office. Thereafter, the observed phenomena/issues were structured with the use of a cause-and-effect diagram to analyse the current practices with more detail.

The interviews were recorded and transcribed. The transcripts were analysed by mixing two of the four approaches described by Kvale (1996), being (a) meaning condensation, and (b) meaning categorisation. The aim is to have transparency and consistency throughout the analysis. Kvale states that 'Control of Analysis' (i.e. transparency) can be achieved by the explication of the procedure. Therefore, a sample of quotations from the interviews that were used in the analysis are included in appendix C, together with the applied meaning categorisation (i.e. typical issues or failure).

Appendix A provides the complete interview structure, including the list of questions asked during the interview. The respondents were selected based on their experience as supervisor or designer on utility related projects (e.g. sewer replacements, site preparations, area redevelopments).

Step 2: Classification of end-user goals
The outcome and analyses by means of a cause-and-effect diagram were used to formulate end-user goals. To this end, four end-user goals were defined (section 3.6) that will contribute to solving the observed issues if those goals are met with a new QC system.

Outcome phase 1:
Description of current QC practices and classification of end-user goals

2.2 Phase 2 – Requirements engineering

The research question answered in this phase:

What functional requirements must be captured in a BIM and AR integrated system to achieve the end-user goals?

This phase consisted of two steps. The method and strategies applied within this step are explained below:

Step 3: Define functional requirements
In order to elicit functional requirements, (1) the end-user goals were translated into (high-level) functional requirements, (2) BIM and AR experts were consulted to help identify technical capabilities of BIM and AR, and (3) BIM and AR literature was explored.

The end-user goals were initially used to develop high-level functional requirements. Following the principle of end-user engagement, the end-user goals could be used as guidance to move from tacit knowledge obtained from the interviews to explicit knowledge in the functional requirements.

Secondly, two consults with BIM and AR experts were conducted to explore capabilities and opportunities of BIM and AR technologies for the system. The identified goals of end-users were showed to the expert in order to acquire knowledge of BIM and AR opportunities to achieve those goals. Based on this input, more functional requirements could be defined.

thirdly, the use of literature in which frameworks were described to use AR and BIM for a variety of construction use cases, provided the required information to find the practical use cases for these technologies to apply to the domain of underground utility construction. This literature is described in section 1.1 Research background.

The requirements were written according to the method proposed by INCOSE (2019). This method outlines rules, characteristics, and attributes to structure and to facilitate (by means of criteria) the transformation of goals to requirements. Within this method goals and requirements exist at five levels: (1) enterprise level, (2) business management level, (3) business operation level, (4) system level, and (5) system component level. The method proposed by INCOSE is in accordance with ISO 15288 - the systems engineering standard developed by the consensus of SE experts from government, industry, and academia. Because the focus was on end-users, requirements on enterprise and business management level were not analysed. Hence, those domain levels were not included in the requirements table.

To smoothen the transformation of goals to requirements, system goals and system element goals were also defined in the process. Those goals impose requirements to the system directly and belong to the lower-order domains following the INCOSE method. Besides, the system goals and system component goals are used in next step (step 4) for the goal-modelling approach to acquire competency questions.

Following the INCOSE method, the criteria I used to structure the development process of the requirements were completeness and consistence. Completeness indicates if the requirement set sufficiently describes the necessary capabilities, characteristics, constraints, and/or quality factors to meet the end-user needs without requiring other requirements at the appropriate level of abstraction. Consistence indicates if the set of requirements contains individual requirements that are unique, do not conflict with or overlap with other requirements in the set. These two criteria were also used to subsequently validate the requirements set during the expert panel validation.

Step 4: Define competency questions

The use of competency questions (CQs) is a well-known method in ontology development. CQs is defined as a set of questions stated in natural language, that the ontology must be able to answer according to a particular community of users (Noy et al., 1997). CQs justify the choice of concepts and relations in the ontology and thereby defines its objective, scope, and expressive requirements (Fernandes et al. 2011).

This research applies the goal-modelling approach to capture competency questions for ontology-based systems put forward by Fernandes et al. (2011). This approach (figure 6, section 4.2) uses the goal model methodology of Tropos (Bresciani, 2004) and modified it to capture and link competency questions to actor goals to help the ontology engineer reason and model competency questions. Within this approach goals are modelled from the user and system perspective respectively. The approach is described in detail in section 4.2 of this report.

Outcome phase 2:

List of functional requirements and competency questions

2.3 Phase 3 – Build ontology

The research question answered in this phase:

How can the domain-related data and functional requirements for quality control with BIM and AR in the underground utilities sector be captured and structured as class-based ontology?

This phase was divided into two steps. For each step the applied methods and strategies are explained.

Step 5: Develop technical and functional design
To create the system vision of the intended BIM AR QC system, a technical and functional design is first made. The technical design consists of the system components, which are the necessary hardware and software elements to meet all functional requirement as identified in previous phase. Therefore, for each system component it was specifically stated which functional requirement is fulfilled. To this end, multiple AR features, a data integration between BIM and AR, a localization mechanism and the conditions for the BIM environment were described.

Next, a functional design is made that outlines the behaviour of the envisioned system. To this end, a UML (Unified Modelling Language) Use Case Diagram and Activity Diagram was made. The Use Case Diagram depicts the possible interaction end-users are able to do with the AR and BIM environment, respectively. The Activity Diagram depicts the step-by-step actions while using the envisioned system, thereby providing an overview of the envisioned workflow.

Step 6: Develop system ontology
In this step, the system ontology was developed based on the competency questions and technical & functional design of previous step, with special care to the system components. The aim of the ontology was to represent the system conceptually thereby describing the system from four viewpoints, namely the physical environment, BIM environment, AR environment, and processes. Also, the relationship and data integration between the different layers/elements is depicted. The system ontology is formatted as a UML class diagram, because that enables to depict concepts as classes while describing the relationship between the different concepts from different viewpoints.

Outcome phase 3:
Designed system ontology

2.4 Phase 4 – Validation

The research answered in this phase:

Is the list of requirements and the proposed system ontology valid according to practitioners?

This phase was divided into two steps. For each step, the applied methods and strategies are explained.

Step 7: Assessment against competency questions
First, the ontology is also held against the CQs developed in step 3. CQs represent a set of questions that the ontology should be able to answer. Because the ontology is also partly developed using CQs, this validation method is done in an iterative manner. More specifically, for every iteration during the ontology development, the ontology is expanded based on one or multiple CQ('s) and validated at the same time. The aim was to change the ontology accordingly, so that all concepts and relations implicitly represented by the set of CQs are covered in the ontology.

Step 8: Assessment against expert panel
During this step a human-based validation was performed by means of an expert panel. The expert panel consisted of domain experts, divided into three domains, namely (1) supervisors, (2) designers/BIM experts and (3) AR experts. The goal was to validate the list of requirements and the

ontology. During the validation sessions, the two items were presented first alongside with some examples of the system components that are supported by the envisioned system. Afterwards, the domain experts were asked to fill in a questionnaire that consisted of several evaluation criteria. For every criterion, the participant was asked to give a score between 1 and 5. The lowest score means the criterion is not satisfied and the highest score means that it is perfectly satisfied. Additionally, they were asked to explain their assessment and if they had any recommendations or possible improvements.

The first item was the list of requirements. The list of requirements was validated based on two criteria following the method proposed by INCOSE (2019): completeness and consistence. Completeness indicates if the requirement set sufficiently describes the necessary capabilities, characteristics, constraints, and/or quality factors to meet the end-user needs without requiring other requirements at the appropriate level of abstraction. Consistence indicates if the set of requirements contains individual requirements that are unique, do not conflict with or overlap with other requirements in the set.

The second item was the system ontology. The ontology was evaluated based on five criteria as defined by Degbelo (2007). The criteria used are accuracy, clarity, completeness, conciseness, and practical usefulness. The criterion of accuracy indicates whether the ontology correctly captures the real-world concepts and relations. The criterion of clarity expresses whether the ontology has effective communication of the intended meaning of defined terms. Completeness indicates whether the ontology has the appropriate coverage of the domain of interest. Conciseness assesses whether the ontology has an absence of unnecessary or useless definitions or axioms. The last criteria, practical usefulness, expresses the number of practical problems to which the ontology can be applied.

Outcome phase 4:
Validated system ontology

3. Current practices and end-user goals

The purpose of this chapter is to explore the current state and practices of supervision in underground utility projects, in order to (1) identify opportunities for a BIM and AR integrated system, and (2) provide necessary details – e.g. shortcomings, responsibilities, and end-user goals – to create appropriate requirements in next chapter. To achieve this purpose, first, the position and responsibilities of supervisors are outlined. Second, the inspection items relevant to underground utility projects are listed and explained in detail. Third, the most used quality control methods currently used by supervisors are given. Fourth, the typical failures occurring in underground utility projects are presented. Last, the end-user goals and needs are composed and presented as a list.

A lot of the material included in this chapter was extracted from the interviews with end-users (i.e. supervisors and designers). In total, six experts with a relevant background in underground utility projects were interviewed. Table 2 provides an overview of the interviews, including the end-users' background, type of firm, years of experience and type of projects.

Table 2. Overview of interviewees

#	Background	Type of firm	Years of experience	Type of projects
1	Supervisor	Engineering firm	35 years	Mainly soil remediation projects
2	Designer & supervisor	Engineering firm	4 years (designer) 25 years (supervisor)	Wide range, e.g. sewer remodelling and replacement, road construction, site preparation for construction
3	Designer	Engineering firm	13 years	Wide range of projects, e.g. sewer remodelling and replacement
4	Supervisor	Engineering firm	40 years	Mainly below and above ground facility construction projects
5	Supervisor	Engineering firm	22 years	Wide range of projects, e.g. water utilities
6	Supervisor	Engineering firm	25 years	Wide range of projects, e.g. inner-city redevelopment, site preparation for construction

3.1 Position and responsibilities of supervisors

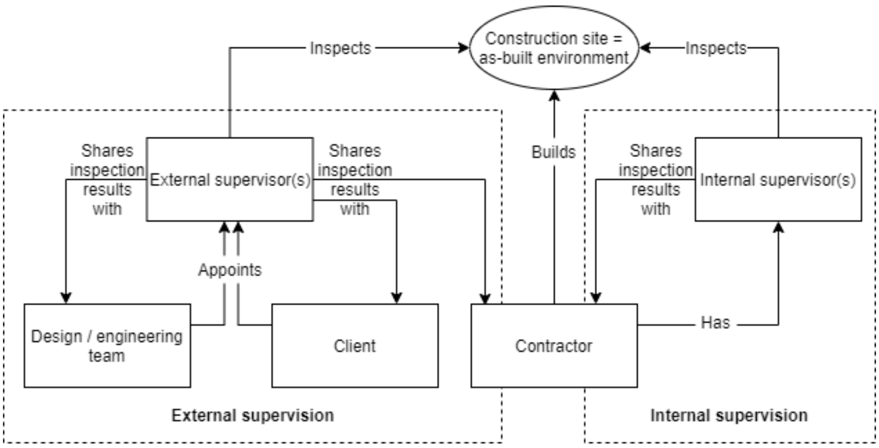

Figure 3. Position of external and internal supervisors in the project organisation

Two kinds of supervisors can be distinguished; the ones working for the client/design team and the ones that work for the contractor. Supervisors that work for the client are referred to as external supervisors. The supervisors that work for the contractor are referred to as internal supervisors. The difference is schematized in figure 3. Although external supervision and internal supervision have a different position within the project organisation, their main task remains the same: inspecting whether the as-built environment is similar to the design. Hence, a new QC method using BIM and AR that focusses on improving as-built vs. as-planned inspections can be used by both kind of supervisors.

Furthermore, external supervisors have two additional responsibilities that are (indirectly) related to quality control of underground utility projects. The first responsibility involves informing the design/engineering team. More specifically, external supervisors are responsible for identifying design clashes with existing infrastructure and share them with the design/engineering team as input for design. The second responsibility involves is the registration and communication of as-built progress data. When this is done in an efficient and accurate manner, the information provision towards all project members is improved, potentially streamlining the decision-making process. An efficient feedback loop (e.g. with the use of BIM and AR technologies) to share identified design clashes and as-built progress would therefore be an additional benefit for external supervisors.

3.2 Inspection items

Here, the inspection and verification process that ensures the project is built (as-built) according to the construction specification (as-planned) is described. To this end, six inspection items were identified based on the interviews. Inspection items are considered the attributes of construction objects that should be inspected during the construction phase to make sure that it is in accordance with the construction specification. The construction specification is a document composed by the designer(s) that describes the scope of work, materials, technical (design) drawings, method of construction and permits. Right after the contract agreement, the assigned supervisor collects all these materials in order to use during his subsequent inspections during the construction phase.

During the interviews the supervisors described a whole range of inspection items. Considering the literature on the possibilities of BIM and AR to accurately compare as-planned vs. as-built during inspection (Park et al, 2013; Zollmann et al, 2014; Kopsida et al, 2017; Raimbaud, 2019; Ratajczak et al, 2019), a list of six inspection items for underground utilities is made that can potentially be improved with these technologies (table 3). For each inspection item, the responsible party/parties, the as-planned data source, and data type is given. Each item is also explained in more detail below.

Table 3. Overview inspection items for underground utilities

#	Inspection item	Applies to which underground objects	Responsible party for correct processing	Data source (as-planned)	Data type (Real = number, string = text)	Data type description
1	*Location*	Cables, pipes	Contractor	Technical drawings	Real	X, Y coordinates per utility segment
2	*Depth*	Cables, pipes	Contractor	Technical drawings	Real	Depth values (Z coordinate)
3	*Dimensions*	Cables, pipes	Supplier or contractor	Technical drawings	Real	Dimension values (object geometry), e.g. length, width, height, diameter
4	*Material use*	Cables, pipes	Supplier or contractor	Material section in construction specification	String	Materials, e.g. concrete, steel, PE

5	*Gradient (inclination)*	Pipes	Contractor	Technical drawings	Real	Gradient values, generally derived from coordinates
6	*Damage occurrence*	Cables, pipes	Supplier or contractor	Technical drawings	-	as-planned drawings used to compare to as-built

Inspection item 1: Location – The location of underground utilities is inspected by the supervisor(s) during the installation of objects (i.e. cables, pipes, and other construction objects like foundations). The contractor is responsible for the placing the objects on the right location. Usually, the site is prepared with marks on where to dig and place objects. Either reference points in the existing environment (e.g. existing infrastructure or buildings) or GPS with coordinates is used to figure out the right location on where to place objects. The as-planned location of the objects is included in technical drawings - which are included in the construction specification. When the location of the constructed objects differs from the technical drawings, the supervisor will first approach the contractor directly in order to rectify the deviation. If that fails, the supervising party will involve the client because ultimately the contractor works directly for the client. This applies to all inspection items.

Inspection item 2: Depth – The depth of underground utilities is inspected by the supervisor during the deployment of objects (similar to location). The contractor is responsible for applying the correct depth. Usually, manual measurement devices (e.g. levelling rods) are used to figure out the right depth. The as-planned depth values are usually based on standard regulation (i.e. NEN 7171) and are included in the technical drawings in the construction specification.

Inspection item 3: Dimensions – Dimensions of utility objects can be inspected before placement individually or after placement as a whole. The dimensions of underground objects are captured in the technical drawings. Placing or constructing objects with the right dimensions is the responsibility of the supplier or the contractor, depending on where the object is composed. Cables and pipes are the responsibility of the supplier because they are composed beforehand by the supplier. Concrete foundations can be composed at the construction site and are therefore the responsibility of the contractor. The inspection of the correct reinforcement profile within concrete also falls under this category. When dimensions deviate from the technical drawings, the supervisor will hold the associated supplier or contractor responsible.

Inspection item 4: Gradient – The supervisor inspect the gradient of pipes in construction projects such as underground sewer or drainage systems. The correct gradient is important to let flow wastewater. Modern techniques (e.g. lasers) are used to accurately apply the correct gradient.

Inspection item 5: Material use – The materials of objects can be inspected before placement. The construction objects should be composed with right material, i.e. similar to the as-planned materials in the construction specification. Cables and pipes can be made of different materials. Among the most used materials are concrete (e.g. for sewers and foundations), metal (e.g. for gas pipes) and Polyethylene (or PE). When concrete is poured on site, the composition of the concrete mixture is an important issue to be inspected by the supervisor.

Inspection item 6: Damage occurrence – The supervisor is also there to check whether nothing is damaged during the construction process. For example, cracks and coating damage can occur during the placement of cables and pipes. Damage inspections are generally done through visually comparing the as-built (real-world) environment with the as-planned drawings of the products/designs.

3.3 Typical issues and failures

Here, typical issues and failures identified and observed by supervisors are presented. This list of typical issues and failures functions (only) as a list of observed phenomena. This implies that an issue can be the effect or cause of another issue. Therefore, the typical issues and failures, also called the 'problem mess', should be structured and is analysed in section 3.5 by means of a cause-and-effect diagram (Van Aken, 2018).

The interviewees indicated eight issues and failures in total, being: (1) wrong placement, (2) wrong installation, (3) pipe damages, (4) design clashes with existing infrastructure, (5) poor data from existing infrastructure, (6) difficult to interpret design, (7) high-time pressure, (8) lack of insight into latest developments.

Figure 4 presents a quantitative overview of interviewees indicating each issue or failure. The thickness of the link represents the number of indications. Each issue or failure is also explained more in depth below. A sample of quotations (the qualitative data) from the interviews from which the typical issues or failures are derived is included Appendix C.

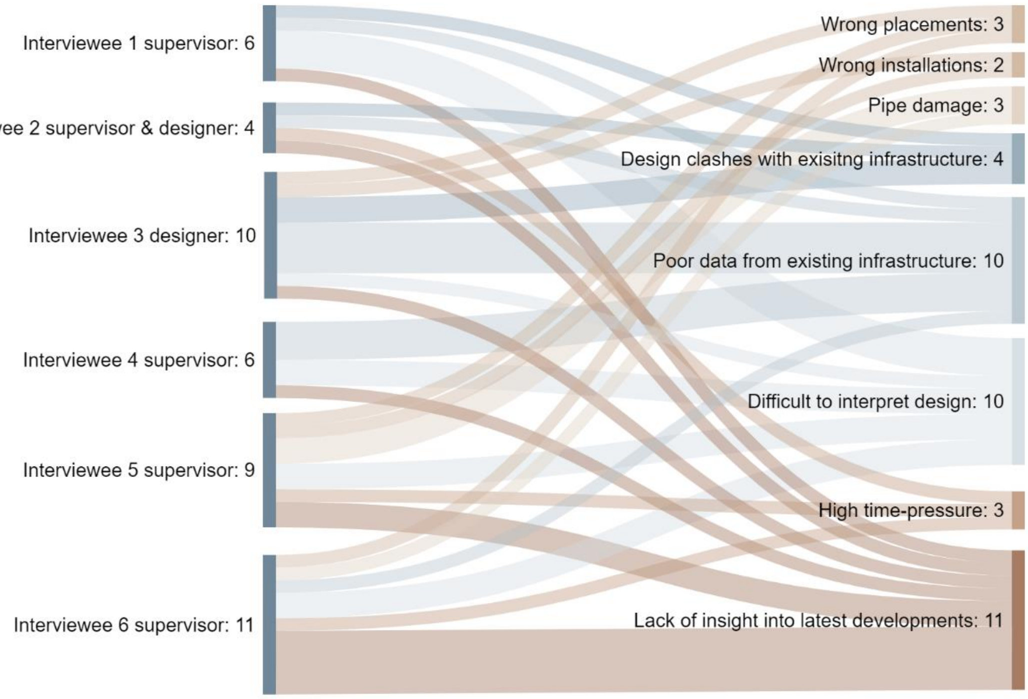

Figure 4, quantitative overview of typical issue/failure indications by each interviewee

[1.] Wrong placements

It was indicated by three interviewees that wrong placements of the utility network happen. One supervisor had an incident (*see quotation 1 appendix C*) in which multiple storm drains were wrongly placed, resulting in an unnecessary complex network underneath. Initially this deviation from design was thought to be acceptable, but it had to be changed afterwards with major financial consequences. In this case, the wrong placement was not communicated with the client and/or engineers. It was only days later accidently discovered by the supervisor of the project. When the deviation from design would have been evaluated by the client or engineers immediately after placement, big rework costs could have been avoided.

[2.] Wrong installations

It also happens that underground utilities are not installed properly, according to two interviewees. For example, in one instance (*see quotation 3 appendix C*) it was stated that multiple connector elements in the sewer network weren't installed correctly. To rework these, everything on top of the utility system, including the asphalt road, had to be removed and excavated again. In this case, when the wrong installation was evaluated immediately after placement, big rework costs could have been avoided.

[3.] Pipe damage

It was indicated that damage during the construction and installation process of the underground utilities happens regularly. For example, pipes can accidently crack or rupture when they are installed.

[4.] Design clashes with existing infrastructure

In most projects, new underground assets need to deal with existing infrastructure (like utilities, trees, and buildings). In the past, three interviewees have come across multiple clashes with the existing infrastructure. This problem is caused by the lack of data of the existing infrastructure assets during the design phase. Hence, the design/engineering team assumed that the underground was free from other assets.

[5.] Poor data from existing infrastructure

five out of six interviewees have mentioned that the lack of data from existing underground infrastructure is a current prominent cause for problems in the underground construction industry. In the case of many old utilities, the location data is not present at all. Besides, if the location data is known and registered, it usually is of poor quality. To initially collect the existing infrastructure data, a 'Klic'-notification must be requested according to the Dutch law (KLICAPP, 2021). Although this is meant to improve the information availability and exchange, this data is generally still of poor quality due to two reasons. First, the registered data from the underground, if there is any at all, are most often top views with raster-format lines. A raster image is composed of pixels that has a limited resolution. To document and read the location of utilities in much more detail, a vector format could be used in which lines are defined based on a path. This has in theory an 'infinite' resolution opposed to a raster format. Secondly, the actual utility location is often different from what is registered in the Klic-database. An interviewee indicated that he encountered differences up to a couple of meters in past projects, making the data highly inaccurate and unreliable. Improving the accuracy and reliability of the available data can help prevent defects like utility strikes and design clashes in the future.

[6.] Difficult to interpret design

Conventual QC methods use 2D documents or drawings while performing measurements and inspection. It was indicated by five interviewees that a clear representation of the design with underground assets will improve the understanding among fieldworkers. As stated by the interviewees (e.g. *quotation 9 appendix D*), 2D need interpretation by the user because depth needs to be imagined from a top view of underground utilities with annotated depth-numbers. The interviewees were experienced professionals in the field of supervision. They indicated that they generally have a feeling with what they are doing, but involving others (like fieldworkers with less experience or stakeholders such as residents) is more difficult with 2D documents or drawings.

[7.] High time-pressure

Three supervisors indicated that for almost all projects there is a high time-pressure for the contractor and associated supervisors. Tight schedules are a result of competing contactors and therefore limited budgets. The limited resources for supervisors in terms of time cause inaccurate inspections and have led them to find ways to inspect in less time, for example, by means of risk-based inspections, so that they do not have to be continuously present on-site. The implications and effects of this is further explained in next section (section 3.4).

[8.] Insufficient information exchange / lack of off-site access to latest on-site developments
All interviewees indicated that information exchange is an important issue. During the construction phase design deviations are identified by supervisors and design alterations are made by all parties (i.e. internal/external supervisors, the client, designer(s) and contractor). These deviations and subsequent alterations can cause mistakes due to parallel knowledge between project members if they are not communicated timely. To reduce the chance for those mistakes to happen, coordination meetings currently take place every week or every two weeks (depending on the project). These meetings are lengthy and therefore costly because every department need to verbally update each other on their latest decisions and/or construction progress.

Therefore, the interviewees indicated they would like to have a more efficient way of information exchange so that they have real-time off-site access to latest on-site developments and can therefore closely and timely monitor developments. In smaller projects with limited budget external supervisors are not on-site every day. When they are off-site, but do have insight into the latest developments, they still can, for example, approve or disapprove deviations from design. So, when the latest developments (i.e. deviations, design clashes and as-built progress data) are shared among all project members, off-site monitoring is made possible, ultimately reducing construction failures.

3.4 Current quality control methods

The above-mentioned issues need deeper investigation and explanation, to identify and understand their causes and/or effects. This section explores these causes and/or effects by outlining current (most-used) quality control methods. These QC practices are outlined based on three aspects. More specifically, the origin of most failures and issues (section 3.3) relates to one of the aspects as described below. Three aspects to quality control could be distinguished. Supervisors use a different technique for each aspect in different situations or projects. The three aspects are 1) information exchange, 2) measurements techniques and 3) inspection frequency. Below, for each aspect, the commonly used techniques are described based on the input from the interviews.

In addition to below in-depth analysis on the three aspects of current QC methods, a (short) literature review was done (appendix B) in order to find out if the list of issues (section 3.3) can be underlined and grounded by literature.

[1.] Information exchange: document-based vs. model-based
The construction specification was once merely physical papers but is now digitalised. However, the information exchange during the inspection process is still mainly document-based. A document-based approach is the act of producing and controlling documents by sending files back and forth (SEBoK, 2021). In the case a digital model is made during the design phase, those models are mostly used to generate relevant representations of the model in the form of drawings/documents (e.g. top views and side views) for in the construction specifications. Most of the times the supervisors have the printed documents in hand when walking around the site. None of the supervisors indicated to have used a model-based approach in which he/she directly interacts with a central digital model as platform for information exchange.

[2.] Measurement technique: manual vs. digital measurements
As for the technique used to do inspections tasks (list of inspection items in section 3.1.2), a distinction can be made between manual and digital measurements. It was indicated that, throughout the years, different digital instruments have been adopted. Manual instruments are generally labour intensive

and have therefore driven innovation and adoption of digital instruments. However, the majority of measurements are (still) performed with manual instruments. Rulers and levelling rods (i.e. for depth, dimension, and gradient checks) fall under the manual category. Also, GPS instruments are used manually to determine the right location to dig pits and construct assets (location checks). An example of a digital measurement technique is the use of an iPad (e.g. to measure excavation pits - dimension checks). Another example of a digital measurement instrument is the inspection crawler: a small remote-controlled vehicle that is mostly used for the inspection of sewers. The vehicle is able to drive inside pipes. The location (x, y, z coordinates) of the vehicle is tracked and send to the supervisor, so that checks concerning location, depth, and gradients can be performed above ground. Also, while driving, potential damages can be checked by means of live video footage from an onboard camera. None of the supervisors indicated to have used AR to perform inspection tasks.

[3.] Inspection frequency

Supervisors indicated that the inspection frequency differs a lot depending on the project. Large projects generally require daily inspections and a continual on-site presence. On the other hand, some smaller size construction projects were reported to be inspected once every week. The inspection frequency also depends on position of the supervisor. Internal supervisors (who work for the contractor), are generally continual present. External supervision (who work for the client) can have a low inspection rate. This low inspection rate resulted in some unforeseen failures in the past, because not all progress was inspected (see previous section; typical failures). The difference between external and internal supervisors is described in detail in section 3.1.

The low inspection rate is sometimes a deliberate choice, but often high time pressure or the lack of resources is the reason to inspect risk-based. Risk-based inspection means that critical construction moments and instances are identified and shared with the contractor before the construction phase is started. As a result, the quality control process can be done in a shorter period of time. However, because less work is inspected in absolute sense, the accuracy of quality control is likely to decrease. Therefore, a more efficient, low-effort QC system that can be used by all fieldworkers and can communicates across – in the case the external supervisor is not present – may prevent some time pressure issues.

3.5 Cause-and-effect analysis

To identify and select the relevant issues and associated end-user goals that will tackle these issues, the list of issues (section 3.3) and further analysis of it (section 3.4) should be structured and conveniently presented. Therefore, a cause-and-effect diagram (Van Aken, 2018) is presented (figure 5). In a cause-and-effect diagram the more symptomatic phenomena are posited on the right side, and the causes on the left side. In next section (section 3.6), a selection of the causes led to end-user goals for this research.

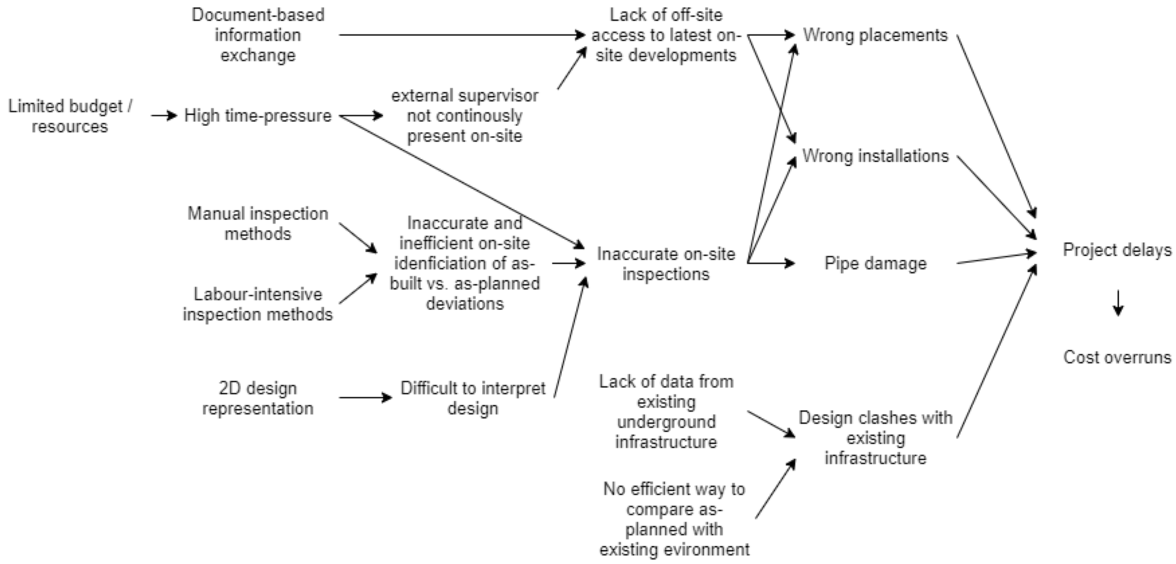

Figure 5, cause-and-effect diagram

As addressed in the introduction of this research, construction failures (and subsequent reworks) lead to project delays and cost overruns. It is therefore important to reduce the amount of failure occurrences during the construction phase. Supervisors play a vital role to identify construction and design failures timely (i.e. deviations from design like wrong placements and design clashes) and correct them, so that big rework are prevented. However, as result of the interviews, it was observed that construction failures still happen regularly and are not always timely identified. Different causes were identified throughout the investigation of current phenomena. This research aims to tackle these causes by means of a new QC method. In next section, end-user goals are developed based on these causes. These end-user goals are subsequently used to elicit specific requirements for the new QC system in next chapter of this research.

3.6 End-user goals

In total four end-user goals could be distinguished to tackle (most of) the causes as identified in figure 5. Each end-user goal is stated below. In addition, for each goal it is explained which issues it tackles, thereby underlining its importance. The end-user goals will be used to define specific functional requirements for the new system in next chapter.

The selection of which problems (i.e. the causes) sets focus to this research. The selection is a trade-off between feasibility and relevance (Van Aken, 2018). Hence, it was investigated and iteratively determined, in terms of feasibility, which problems could be tackled with a new digital quality control system using BIM and AR. This led, for example, to the exclusion of a goal that tries to solve the lack of data from existing underground. Instead, goal 3 was formulated to *identify and correct* design clashes rather than to prevent them.

End-user goal 1: Efficient and accurate on-site identification of as-built vs. as-planned deviations

Inaccurate as-built vs. as-planned inspections lead to construction failures – e.g. wrong placements - and is a result of manual and labour-intensive inspection methods. As seen in section 3.4, supervisors use conventional measurement techniques, e.g. rulers, levelling rods and GPS instruments, to perform inspections. Inaccurate and labour-intensive manual measurement techniques can potentially be replaced by digital instruments. Therefore, a new digital QC method should better assist the supervisor so that he can identify as-built vs. as-planned deviations– i.e. the inspection process - more efficiently and accurately.

As described earlier, the inspection performed by supervisor is the process of verifying whether the built environment (as-built) is in accordance with the construction specification (as-planned). There are six inspection items for supervisors which are deviation checks for *location, depth, dimensions, gradient, material use* and *damage occurrences* and are explained in detail in section 3.2. For supervisors it is important to accurately inspect these items, otherwise there is an increased chance for construction failures as seen in figure 5.

End-user goal 2: Improve design understanding among fieldworkers

One of the other causes for inaccurate on-site inspections is the difficulty of interpreting underground utility designs. In a lot of projects, 2D design are (still) only used. 2D design presentations are tricky and difficult to interpret when working with underground assets because they present two perspectives but require interpretation from three perspectives – i.e. X, Y and Z. Therefore, a new QC method should aim to improve understanding of the design among fieldworkers by providing a 3D design.

End-user goal 3: Efficiently identify design clashes

Design clashes happen regularly and are caused by the lack of data from the existing infrastructure during the design phase. To act upon design clashes, they should be spotted as early as possible. However, supervisors or designers do not have an efficient way to compare as-planned with the existing environment (also called 'as-is' in literature) nor do they have accurate as-is data. Therefore, to identify (spot) design clashes a new QC method should aim to facilitate an efficient comparison between as-planned and the existing infrastructure.

End-user goal 4: Real-time off-site access to latest on-site developments

Wrong placements and installations happen and can incur large rework costs when not discovered timely. During some of the observed accidents in which deviations were not timely discovered, supervisors were not able to timely identify the deviations because they were not on-site. They explained that in those cases if they had been present or updated by the contractor, they would have had the opportunity to disapprove a deviation from design or (at least) find a solution to which the client agrees. Should that have been the case, the contractor can then correct something while constructing, without taking the risk of expensive reworks at a later moment to rectify his errors

Therefore, to identify critical deviations from design that potentially require correction in the case the supervisor is not present on-site, the supervisors indicated they would like to have real-time insight into the latest developments. This is particularly important for external supervisor because external supervisor do not always have the resources in terms of time to be continuously present on-site to monitor the construction process. When latest developments can be efficiently shared with off-site supervisors, the off-site supervisor can monitor the progress from e.g. an office and is therefore able to approve or disapprove a deviation from design at any point in time, ultimately reducing the chance for construction failures and big reworks.

Furthermore, design clashes happen regularly as well. To be able to efficiently solve design clashes, they should be conveniently shared with designers that work from an off-site location e.g. the office.

To be able to share the latest on-site developments (i.e. deviations, design clashes, as-built progress data) with off-site supervisors and designers, a method (or methods) is needed to register this data. For instance, when a construction object is deployed on a location that differs from design, the object ID and (maybe even) the new location of the object should be registered and shared, so that other off-site supervisor can accept or decline this location deviation. Thus, the new QC method should also facilitate an efficient registration technique (or techniques) to supply off-site supervisors with the latest developments.

Next chapter, requirements engineering, presents:

- How end-user goals were translated functional requirements
- The list of formal functional requirements for a BIM AR QC system
- Contribution arguments that justify how the functional requirements contribute to the end-user goals
- How the competency questions were elicited

4. Requirements engineering

The purpose of this chapter was (1) to develop a formal list of requirements that is later used to make the technical and functional design and (2) formulate competency questions that is later used to develop the system ontology for a new QC system. First, to formulate functional requirements, the end-user goals (and to-be defined system goals and system component goals) were translated into requirements and subsequently justified by means of contribution arguments (Wieringa, 2014). Second, to define competency questions, a goal-based modelling approach was applied (Fernandes et al., 2011).

4.1 Functional requirements

The principle of end-user engagement is followed throughout the research. This assures that the system-to-be (i.e. BIM AR QC system) delivers all information and functionalities as requirement by the end-users. Therefore, to elicit functional requirements, the list of end-user goals identified in previous chapter was used to develop the initial (high level) functional requirements.

In addition, the translation from goals to requirements was also assisted by two BIM and AR experts that were consulted that could link the end-user goals to capabilities of BIM and AR to fulfil those goals. To smoothen the transition, system goals and system component goals were defined in this process. At a later moment, these system goals and system component goals were needed for the goal-modelling approach to acquire competency questions.

Furthermore, literature that described BIM and AR frameworks for a variety of construction use cases was reviewed to find the capabilities of these technologies to apply to the quality control of underground utilities. To this end, I studied five papers (Park et al, 2013; Zollmann et al, 2014; Kopsida et al, 2017; Raimbaud, 2019; Ratajczak et al, 2019). These studies are summarised in the research background in section 1 introduction. The extensive description of the capabilities and system components that were adopted from these studies is included in chapter 5, technical design. The reviewed system features shaped the formulation of system goals (and system component goals) and associated functional requirements.

As explained before in section 2.2, the list of requirements is written down using the INCOSE method. Following this method, the list of requirements was developed (and subsequently validated) by means of two criteria, being completeness (i.e. the requirement set sufficiently describes the necessary capabilities) and consistence (i.e. the set of requirements contains individual requirements that are unique and do not conflict or overlap). This method distinguishes between different domain views. The domains considered relevant for this research are (1) business operation level (end-user view), (2) system level and, (3) system component level.

The complete list of requirements can be seen in table 4. The list distinguishes between different domains as described above (depicted in the second column). The third column provides the goals view associated with those domains: end-user goals, system goals, and system component goals respectively and the fourth column provides the goals themselves. The last column depicts the formulated functional requirements.

The end-user goals, system goals, and system component goals were used as basis for the goal-modelling process to define competency questions (section 4.2). The functional requirements provided input for the technical & functional design (chapter 5). As part of development, the goals, requirements, competency questions, functional & technical design, and ontology were refined in an iterative process.

Table 4. Goals & Requirements following the INCOSE method

Req #	Domain view	Goals view	Goals	Requirements
1.1	Business operation	End-user Goals	**End-user goal 1:** Efficiently and accurately identify as-planned vs. as-built deviations on-site	Must assist the end-user to find as-planned vs. as-built deviations (i.e. inspection items) on-site
1.2			**End-user goal 2:** Efficiently identify design clashes on-site	Must assist the end-user to find design clashes on-site
1.3			**End-user goal 3:** Improve design understanding among fieldworkers	Must provide end-user clear 3D design in context to the physical environment
1.4			**End-user goal 4:** Real-time off-site access to latest on-site developments	Must be able to register latest on-site developments (i.e. design clashes, deviations, and as-built progress data) of utility objects
1.5				Must be able to share latest developments with off-site supervisors and designers
2.1	System	System Goals	**System goal 1:** Identify deviations	Must allow to identify location deviations (i.e. inspection item 1) through an AR environment (e.g. coordinates)
2.2				Must allow to identify depth deviations (i.e. inspection item 2) through an AR environment
2.3				Must allow to identify dimension deviations (i.e. inspection item 3) through an AR environment (e.g. width)
2.4				Must allow to identify gradient deviations (i.e. inspection item 4) through an AR environment
2.5				Must allow to identify damage occurrences (i.e. inspection item 5) through an AR environment (e.g. cracks, coating damage)
2.6				Must allow to identify material deviations (i.e. inspection item 6) through an AR environment (e.g. concrete, steel, PE)
2.8			**System goal 2:** Identify design clashes	Must be able to identify design clashes with existing infrastructure through an AR environment
2.9			**System goal 3:** Share latest on-site developments with off-site supervisors & designers	Must allow to transmit latest on-site developments (i.e. deviations, design clashes, as-built object attributes) to BIM
3.1	System component	System component Goals	**System component goal 1:** Establish visual comparison	AR environment must allow to superimpose as-planned BIM data (3D & meta-data) onto the physical environment
3.2			**System component goal 2:** 3D-data filtering	AR environment must allow to filter and adjust transparency of BIM objects

3.3			**System component goal 3:** Meta-data display	AR environment must allow to display attributes (i.e. meta-data) of each BIM object (e.g. dimensions, materials, function)
3.4			**System component goal 4:** Make distance measurements	AR environment must allow to make distance measurement within the user view
3.5			**System component goal 5:** Make annotations	AR environment must allow to create and show annotations attached to BIM objects
3.6			**System component goal 6:** Register object attributes of the as-built situation	AR environment must allow to change/confirm attributes of BIM objects
3.7				AR environment must allow to spatially move and rotate BIM objects
3.8			**System component goal 7:** Accurately position as-planned objects onto physical environment	AR environment must accurately (spatially) position as-planned objects onto the physical environment

4.1.1 Contribution arguments

In order to justify that the functional requirements, if implemented in the functional design, would contribute to end-user goals, a contribution argument has been given for each requirement (Wieringa, 2014). The contribution arguments are given in table 5. A contribution argument is a prediction, because it argues when the artifact (i.e. the system-to-be) would be inserted in its problem context (i.e. QC practice explored in chapter 3), it would interact with it in a way that contributes to end-user goals. At this point, the contribution argument is *fallible*, because it does not (yet) provide deductive support for its conclusion.

Table 5, contribution arguments

Req #	Goal	Contribution argument
1.1	End-user goal 1	If the supervisor is assisted with his responsibility to identify deviations, then he is more unlikely to miss critical deviations that would otherwise pose big financial consequences
1.2	End-user goal 2	If the supervisor is assisted in his responsibility to identify design clashes, then the process to solve these timely and early in the design and construction phase is smoothened.
1.3	End-user goal 3	If the supervisor can use 3D design representations that are placed in context the physical environment, then the design of the underground utility project would be clearer to him
1.4, 1,5	End-user goal 4	If the supervisor can register and share on-site developments, then the off-site supervisor & designer will have real-time access to it, giving them the possibility to monitor and approve/disapprove on-site progress which reduces the chance for big reworks at later moments.
2.1, 2.2, 2.3, 2.4, 2.5, 2.6	System goal 1	If the system through the AR environment allows the identification of the possible deviations (i.e. inspection items 1-6), then the system assists the supervisor during his inspection process.
2.8	System goal 2	If the AR environment allows the identification of design clashes with existing infrastructure, then the system assists the supervisor during his clash detection process.
2.9	System goal 3	If the latest on-site developments (deviations, design clashes, as-built progress data) can be transmitted to BIM, then the on-site progress can be monitored off-site.
3.1	System component goal 1	If the AR environment superimposes (overlays) the as-planned data (3D & meta-data) onto the physical environment, then a visual comparison is established, uplifting the identification of deviations.
3.2	System component goal 2	If the AR environment allows to filter and adjust transparency of BIM objects, then the as-planned 3D data can be effectively compared to as-built situation, uplifting the identification of deviations.
3.3	System component goal 3	If the AR environment allows to display attributes (i.e. meta-data) of each BIM object (e.g. dimensions, materials, function), then the as-planned meta-data can be effectively compared to the as-built situation, uplifting the identification of deviations.
3.4	System component goal 4	If the AR environment allows to make distance measurement within the user view, then the as-built environment can be measured and compared to as-planned spatial meta-data, uplifting the identification of deviations.
3.5	System component goal 5	If the AR environment allows to create and show annotations attached to BIM objects, then latest developments can be written down and shared with off-site members
3.6	System component goal 6	If the AR environment allows to change/confirm attributes (i.e. meta-data) of BIM objects, then the as-built meta-data is generated and can be shared with off-site members
3.7		If the AR environment allows to spatially move and rotate BIM objects, then the as-built 3D data is generated and can be shared with off-site members
3.8	System component goal 7	If the AR environment accurately (spatially) positions the as-planned objects onto the physical environment, then the supervisor can accurately compare as-planned 3D data to the as-built situation

4.2 Competency questions

The second step in requirements engineering is the definition of competency questions. As explained before, CQs can function as a set of question that the ontology should be able to answer. Therefore, they provide guidance to find concepts that should be captured by the ontology.

This research applies the goal-modelling approach to capture competency questions for ontology-based systems put forward by Fernandes et al. (2011). This approach (figure 6) uses the goal model methodology of Tropos (Bresciani, 2004) and modified it to capture and link competency questions to actor goals to help the ontology engineer reason and model competency questions.

The first activity in this process is 'early requirements activity' in which the goals of actor A1 (actor A1 is in our case the end-user) are analysed. In activity two, late requirements activity, the Goal Diagram of actor A1 is extended and linked with competency questions for the system-to-be. Furthermore, the system actor (A2) (i.e. the system-to-be) is also depicted on the side of this diagram together with the dependency of the competency questions. Activity two then continues to develop a Goal Diagram of actor A2 from the perspective of the system-to-be. Goal Diagram of system actor (A2) visualises the competency questions identified from previous diagram and links it to system goals. This poses a solution because it requires the thought process to define system goals and thus describing what the system-to-be should be capable of. Besides modelling the competency questions, the Goal Diagram of system actor (A2) can also assist the ontology engineer to find concepts (involved in the competency questions) that should be modelled by the ontology. The last activity, Ontology Modelling, is then to capture the identified concepts from previous activity in the ontology to guide its development.

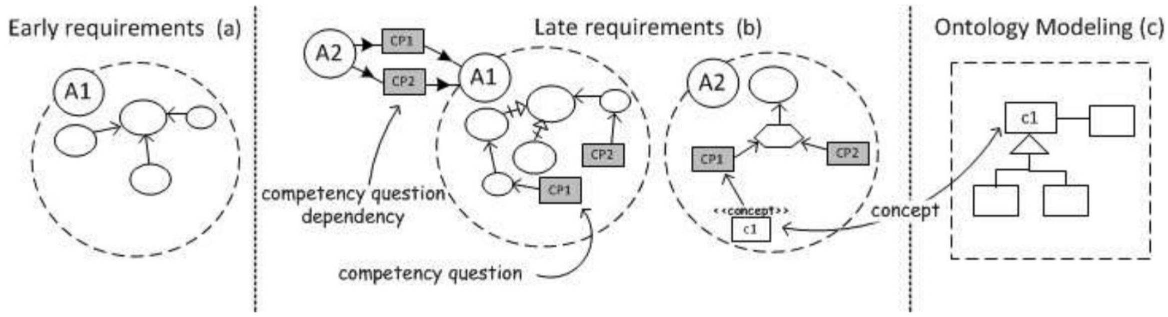

Figure 6, Goal-Modelling Approach to capture Competency Questions for Ontology-based Systems adopted from Fernandes et al. (2011)

Figure 7 presents the Tropos Constructs of this approach. The *Actor perspective* outlines (with a dotted line) the goals and resources of interest for the actor. A *resource* is defined as information/knowledge or physical entity. A special resource is the *Competency Question Resource* which represents the competency question. Competency questions pose knowledge to be covered by the ontology and is therefore considered a resource. The *Ontology Concept Resource* represents the concepts that should be modelled in the ontology (as 'classes' following UML). A *means-end* link shows the connection between a goal or resource that provide means to achieve the other goal or resource. A *decomposition* link decomposes a root goal or resource into sub-goals or sub-resources. The *dependency* link indicates that some actor depends on the other actor to acquire a resource.

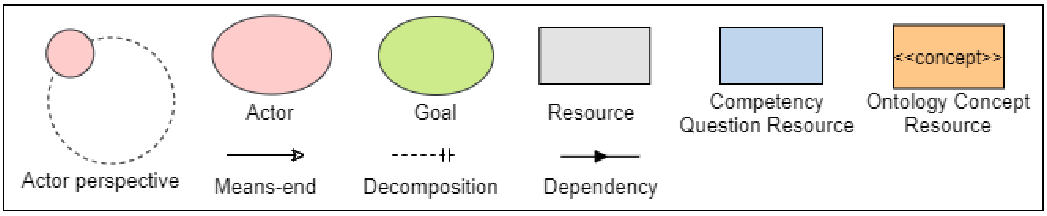

Figure 7, Tropos Construct adopted from Bresciani et al. (2004)

4.2.1 Early requirements activity

In this section and in next section, the above-mentioned approach is applied for this research. In the first activity the end-user goals should be identified. This has already been done in previous chapter and resulted in the identification of four end-user goals.

- **End-user goal 1:** Efficient and accurate on-site identification of as-built vs. as-planned deviations
- **End-user goal 2:** Improve design understanding among fieldworkers
- **End-user goal 3:** Efficient identify design clashes
- **End-user goal 4:** Real-time off-site access to latest on-site developments

The end-user goals were modelled as Goal diagram. However, this diagram is left out because in next activity the same diagram is seen, only it is there extended with competency questions.

4.2.2 Late requirement activity

The late requirement activity consists of two steps: (1) developing the Goal Diagram of the end-user and (2) developing the Goal Diagram of the BIM AR QC system.

[1.] Goal Diagram of End-user

In this step of the goal-modelling process the competency questions are capture and modelled. The competency questions determine the scope of the ontology. To this end, the Goal Diagram for End-user is made (Figure 8) that captures and delegates competency questions. Thus, such competency questions' start being captured in the perspective of the end-user. Furthermore, the system actor is called the BIM AR QC system - this is the system under consideration in this research.

Table 6 textually presents the competency questions. The diagram uses codes e.g. CQ1, CQ2 etc. to refer to the competency questions presented in the table.

Table 6, Competency Questions

CQ1.	What are the deviations (i.e. inspection items)?
CQ2.	What system component identifies (on-site) deviations?
CQ3.	What are the attributes of the as-planned utility object?
CQ3a.	What is the location (x and y coordinate) of the as-planned utility object?
CQ3b.	What is the depth (z coordinate) of the as-planned utility object?
CQ3c.	What are the dimensions of the as-planned utility object?
CQ3d.	What material does the as-planned utility object consist of?
CQ3e.	What is the gradient of the as-planned utility object?
CQ3f.	What is the surface texture of the as-planned utility object?
CQ4.	What are the attributes of the as-built utility object?
CQ4a.	What is the location (x and y coordinate) of the as-built utility object?
CQ4b.	What is the depth (z coordinate) of the as-built utility object?
CQ4c.	What are the dimensions of the as-built utility object?
CQ4d.	What material does the as-built utility object consist of?

	CQ4e. What is the gradient of the as-built utility object?
	CQ4f. Has the as-built utility object any damages?
CQ5.	What system component identifies design clashes?
CQ6.	What system component superimposes 3D design onto the physical environment?
CQ7.	What system components register and share deviations and design clashes?
CQ8.	What system components register and share as-built progress data?

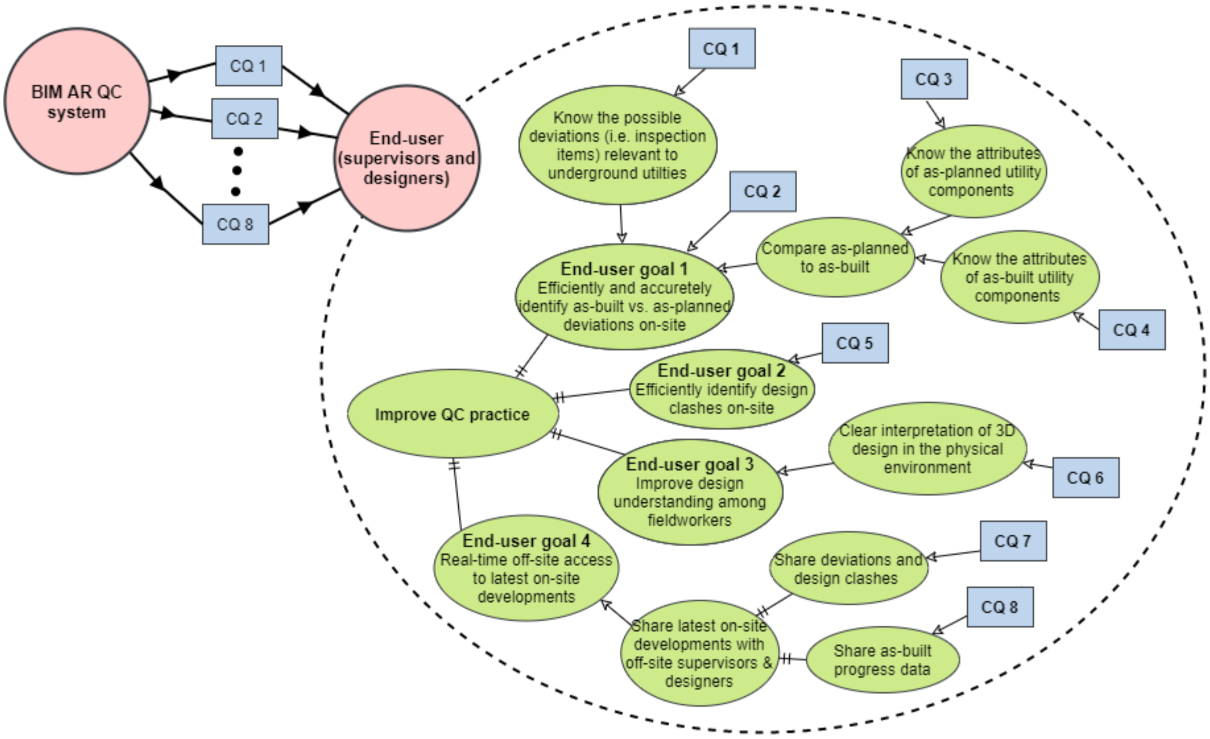

Figure 8, Goal Diagram of End-user capturing and delegating Competency Questions

The *"improve QC practice"* goal is considered the main goal and represents the remainder of the identified issues (e.g. wrong placements) from chapter 3. That goal is decomposed by the four **End-user goals.** In addition, some sub-goals are adopted from chapter 3 and linked via Means-end and Decomposition to define a finer goal structure that clarifies the origin of some of the competency questions.

In table 6 can be seen that **CQ 1**, **CQ 3** and **CQ 4** are questions that impose data to be included in the system ontology. At this point, **CQ 1** assists the **End-user** by delivering the possible deviations (i.e. inspection items) that can occur during the inspection process. It important to know these deviations otherwise the supervisor (i.e. an end-user) does not know what he is looking for. **CQ 3** and **CQ 4** assist the **End-user** by providing the necessary data (attributes of utility objects) to be included for the "*compare as-planned data with as-built data*" goal therefore being able to identify deviations. In accordance with the scope of this research, utility objects are considered cables (i.e. electricity, telecoms) and pipes (i.e. gas, water, and sewer).

The remainder of the competency questions impose components to be covered by the system ontology. The actual system components capable of the required behaviour for the BIM AR QC system are explored and described in chapter 5, technical design. At this point, the required components are only 'requested' by means of competency questions ('requested' means the ontology should answer it, thus in this case imposing components to be included). **CQ 2** assists the **End-user** by requesting a component that enables him to efficiently compare as-planned data to as-built data. **CQ 5** requests a component that is needed for the *"efficiently identify design clashes on-site"* goal. **CQ 6** requests a component that assist the **End-user** to achieve the "*Clear interpretation of 3D design in the physical environment*" goal. Last, **CQ 7** and **CQ 8** requests system components to be included in the ontology that achieve the *"share latest on-site developments with off-site supervisors & designers"* goal.

[2.] Goal Diagram of BIM AR QC System

In this step, we apply goal-modelling from the perspective of the system-to-be (i.e. BIM AR QC system). Therefore, the system goals (and system components goals) should be captured by the Goal model. As described earlier, this poses a solution, because this outlines the required behaviour of the system.

As already been stated, the (system) goals, functional requirements, and associated system components (together compromise the design solution of this research) were developed in an iterative process. The choice and development of system goals and system component goals is described and justified in previous section (section 4.1). To read this justification process, I refer to that section. The list below provides the system goals and system component goals. The system component goals are the sub-goals, so they decompose and therefore define a finer goal structure.

- **System goal 1:** Identify deviations
- **System goal 2:** Identify design clashes
- **System goal 3:** Share latest on-site developments with off-site supervisors
- **System component goal 1:** Establish visual comparison
- **System component goal 2:** 3D-data filtering
- **System component goal 3:** Meta-data display
- **System component goal 4:** Make distance measurements
- **System component goal 5:** Make annotations
- **System component goal 6:** Register attributes of as-built objects
- **System component goal 7:** Accurately position as-planned objects onto physical environment

In previous step, the Goal diagram for End-user shows the actor **BIM AR QC system** together with competency questions dependencies. In this step, Figure 9 models the goals and competency questions from the perspective of the **BIM AR QC system actor**. It is important to note that although the goals of the system are modelled, the competency questions refer to the ontology and not the system itself. Thus, the ontology is also depicted as a resource within the system actor perspective. A means-end link connects the competency questions to the ontology.

After capturing the competency questions, the ontology engineer is able to already start eliciting a few concepts which will later compose the ontology that is the basis of the BIM AR QC system. For example, I elicited the "*Localization mechanism*" and "*Visual comparison-component*" concepts that are linked to **CQ 2**. Some of the concepts compose a higher-level concept such as "*AR environment*" and "*BIM environment*" (the two technologies fundamental to the intended system). The aim here is not to be exhaustive. Capturing a few concepts that more obviously derive from the modelled competency questions provides a smooth transition to the following stage of ontology modelling (Fernandes et al., 2011). The elicited concepts are later modelled in the actual ontology in chapter 6.

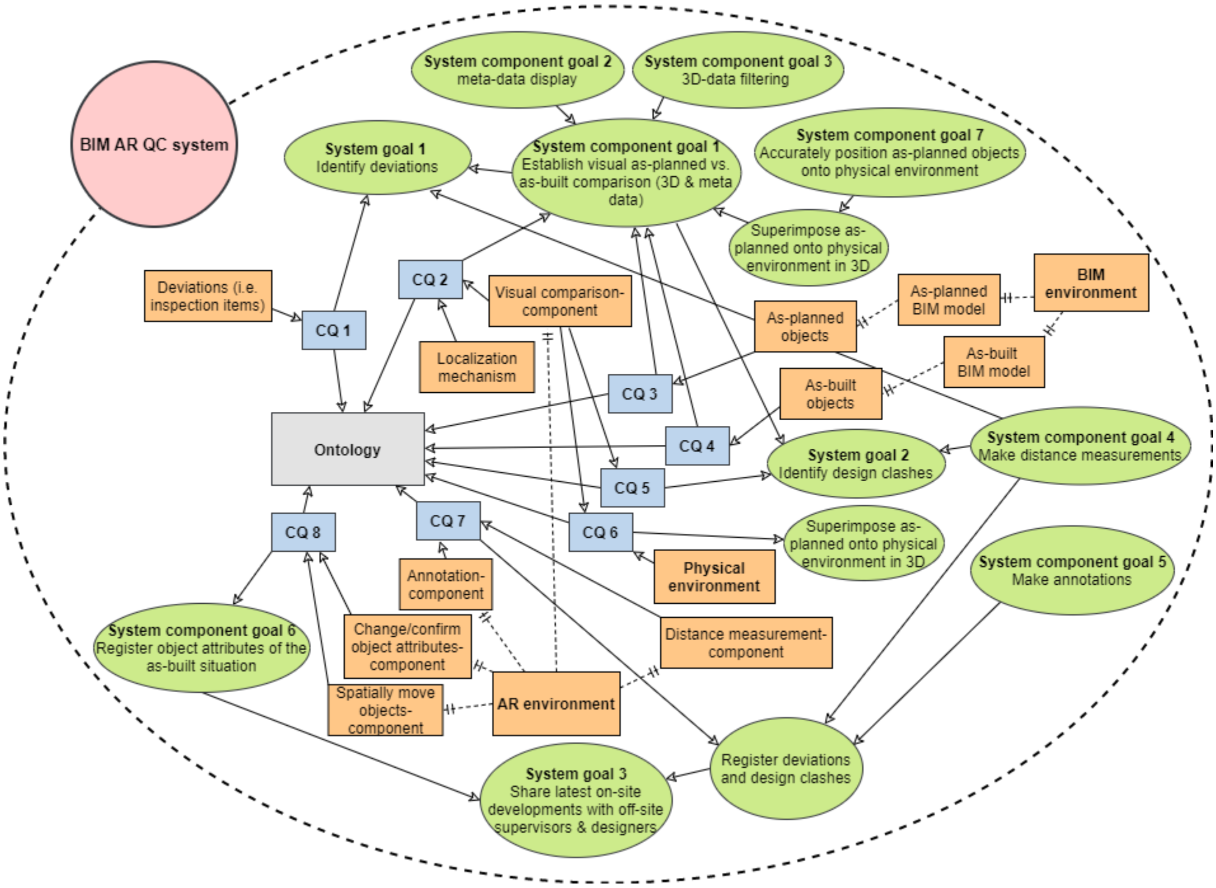

Figure 9, Goal Diagram of BIM AR QC System

5. Technical and functional design

In this chapter the technical and functional design of the envisioned BIM AR QC system is described. The requirements elicited in last chapter are used to compose the technical capabilities in the form of system components (section 5.1), and the functional design in the form of a Use Case Diagram (section 5.2) and an Activity Diagram (section 5.3).

5.1 System components

To enable the functional requirements from chapter 4, the system must have several technical capabilities. These are the hardware and software components, together called system components. As said earlier, the system components were elicited from consulting BIM and AR experts and a literature review of earlier studies investigating BIM and AR use cases for construction in other domains. The system can be divided into four main elements, being (1) AR environment, (2) the localization mechanism (3) the integration between of AR and BIM, and (4) BIM environment. Each of these four main technical elements are described in detail with their system components below. In addition, it is specifically mentioned what functional requirements (table 4, chapter 4) are satisfied with each component.

5.1.1 AR environment

The AR environment has five distinctive system components that assist the supervisor to accurately inspect the construction progress, being: (1) visual comparison component, (2) distance measurement component, (3) annotation component, and (4) change/confirm object attributes component and (5) spatially move objects component.

[1.] Visual comparison component

The unique ability of AR is superimposing the 3D design model onto the physical environment (i.e. the real world), which establishes an efficient *visual comparison* between as-planned and as-built. This is considered as the 'main feature' for the intended system. The AR environment utilizes live video feed (captured with a camera) of the physical environment and superimposes (overlays) that in real time with as-planned objects from an as-planned BIM model. Thus, the concept of 'as-built vs. as-planned', in the context of AR, is considered the comparison between the physical video as-built layer and virtual as-planned layer. The supervisors can make use of the visual comparison between as-planned virtual objects and the as-built physical objects to manually identify deviations between the two. This concept is investigated for facility construction by Park et al (2013), Zollmann et al (2014), Kopsida et al (2017), Raimbaud (2019), Ratajczak et al. (2019). Adopting this concept will satisfy req. 1.1 and 3.1. An example of how such a superimposition of virtual utility objects onto the physical environment would look like is given in figure 10.

In principle, this enables the supervisor to identify location, depth, dimension, and gradient deviations, because those inspections items essentially determine whether the constructed physical utility object has the right (i.e. in accordance with design) spatial attributes in the three-dimensional space. This satisfies req. 2.1 – 2.4. Furthermore, by superimposing as-planned virtual objects with a life-like material surface (e.g. as seen in Zollman, 2014), the supervisor can visually compare those with the as-built physical object surfaces to perform material checks and damage checks within the AR environment. This satisfies req. 2.5 – 2.6.

The identification of design clashes can be done following the same concept. The superimposition of as-planned virtual objects onto the physical existing utility network allows to visually localize spatial overlaps (clashes) between the two environments. This satisfies req. 1.2 and 2.8.

Two sub-components are needed to make *visual comparisons* work even better: (a) filter and adjust transparency of BIM objects and (b) display BIM object data.

a. BIM object filtering and transparency

The AR environment should facilitate an interactive BIM model in which the BIM objects can be filtered, and their transparency can be adjusted (as seen in Kopsida et al., 2017; Ratajczak et al, 2019). These interactive features are required for the supervisor to make visual judgements and accurately localize spatial differences and design clashes during AR-assisted inspections. This satisfies req. 3.2.

b. BIM object meta-data display

By integrating the AR environment with an as-planned BIM model, the user can interact with the 3D interactive model to display meta-data related to each BIM object (Ratajczak et al., 2019). The ability to display the meta-data of each object can help the supervisor during his inspection process, e.g. by displaying the planned material use. This satisfies req. 3.3.

[2.] Distance measurement component

This system component allows to make measurements of an object or a distance between objects in the user's view within the AR environment. AR is found to be capable to measure distances and surfaces according to Bergquist et al. (2018) and is also seen in Ratajczak et al. (2019). Likewise, ARCore (an augmented reality platform developed by Google) also enables to make measurements with most android-supported mobile device (Burduli, 2018). This feature gives the supervisor the ability to determine the exact size of the deviation or design clash by measuring the distance between a physical object and the virtual as-planned object. Moreover, certain inspection items do not require a visual superimposition of virtual objects onto physical objects. For example in case of a dimension deviation, the supervisor can also merely measure (within the AR environment) the physical object and compare it to the textual dimension data (thus not visual 3D data) of the associated as-planned virtual object.

The mobile device can perform distance measurements by placing two points in the three-dimensional space and calculating the distance between them. To accurately position virtual points onto physical objects most often a depth camera is used (vGIS, 2020), such as a time-of-flight camera (as seen by android devices and the HoloLens) or a LiDAR scanner in newer iPhone and iPad models. An example of measurements within AR is given by figure 11. This feature satisfies req. 3.4.

[3.] Annotation component

To specify with more detail and share findings (e.g. deviations or measurements) related to the inspection, the user should be able to attach annotations to each object of the interactive BIM model within the AR environment (as seen in Zollman et al., 2014; Ratajczak et al., 2019). In case textual annotations does not suffice, the user should also be able to make pictures or a screenshot of his user view and attach it as annotation to each BIM object. Figure 12 depicts how annotations could look like within the user's view of the AR environment. This feature satisfies req. 3.5.

[4.] Change/confirm object attributes component

To address the end-user goal of real-time off-site access to latest on-site developments, the AR environment should be able to register the as-built situation of newly constructed utility objects. Therefore, the supervisor can change or confirm the attributes of the as-planned BIM objects. By changing and/or confirming attributes according to how it is built, for example by changing the material attribute from copper to steel, the as-built situation is gradually being registered. The identification of deviations and the results of measurements can also be attached (as attribute) to each BIM objects. This satisfies req. 1.4, 1.5, 2.9 and 3.6.

Figure 10, Superimposition of virtual objects onto physical objects (Augview, 2014)

Figure 11, Measurements with AR (AR Ruler App, 2017)

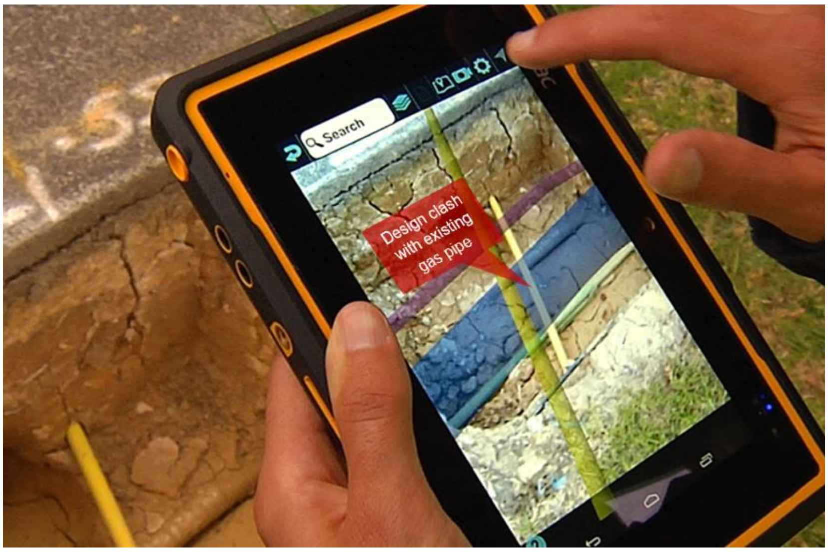

Figure 12, Annotated virtual objects within the user's view

[5.] Spatially move objects component

Aside from confirming and changing attributes, the supervisor should also have a feature that allows him to register the exact deployed location of a cable or pipe, in the case it differs from the as-planned location. The ability to manually move and rotate virtual objects within the user's view of the AR environment to match (spatial align) the physical object (as seen in Kopsida et al., 2017), allows the supervisor to spatially register the as-built situation. Subsequently, the new location can be shared with other (off-site) project members, by transmitting it to an as-built BIM model. Although the task for construction workers is to align the physical object with the superimposed as-planned virtual object, instead of the other way around, this feature gives the ability for supervisors, or other field workers, to share deviations from design with others and make collective decision to either correct the physical object or accept the deviation. Simultaneously, a spatially correct as-built BIM model is being generated without the need for as-built remodelling based on other databases (e.g. scan models). This feature satisfies req. 1.4, 1.5, 2.9 and 3.7.

5.1.2 Localization mechanism

The mobile device that supports the AR environment needs a localization mechanism to accurate position the as-planned virtual objects onto the physical environment. Strand (2008) tested multiple tracking methods on their precision level for outdoor AR. He found differential GNSS (Global Navigation Satellite System) systems, especially RTK (real-time kinematic) versions, to be capable of centimeter, or even millimeter level positioning accuracy and concluded that those systems have the required accuracy for the use of AR in the outdoor environment. According to vGIS (an AR service provider for construction), GNSS/RTK positioning systems deliver an accuracy of up to 1 centimeter (vGIS, 2021). This component satisfies req. 3.8.

5.1.3 Data integration between AR and BIM

An BIM and AR integration is required to be able to visualise an interactive BIM model within the AR environment on one hand, and to share inspection results with off-site supervisors and designers on the other hand. An example for such an interactive integration is seen in Ratajczak et al. (2019). Another example is Autodesk BIM360 in combination with third-party AR software applications (Autodesk, 2020). The inspection data for each object that should be transmitted from the AR environment back to BIM (therefore sharing it with other projects members) consists of the following things: 1) deviations, 2) design clash(es), (3) the size (distance) of spatial deviations or design clashes in case it is measured, 4) the attached annotations, and 5) the registered as-built attribute data.

5.1.4 BIM environment

The BIM environment for the system is required to have an as-planned model and as-built model. The as-planned model should (at least) consist of the following data for each object: location, dimensions (interior and exterior), material use, surface texture. The as-planned location should therefore be modelled with coordinates, so that it accurately represents the actual real-world location. The as-built model is generated gradually during the construction phase by using the system, as described above. The as-built BIM model has two purposes: (1) it gives off-site supervisors access to the latest on-site developments and can therefore monitor and accept/decline deviations and (2) the as-built BIM model can be used after the construction phase for maintenance and operation purposes. The two models within the BIM environment and the integration with AR as mentioned above, addresses almost all requirements from table 4 as this serves as the backbone of the envisioned BIM AR QC system.

5.2 Use Case Diagram

One way to depict the functional design of the BIM AR QC system is through a UML Use Case Diagram (figure 13). This diagram visualises the possible interactions that the end-user can do with the envisioned system. The use cases are depicted as ellipses and the end-users as stick figures. The internal relations in the system boundary are either *include* or *extend*. *Include* indicates that the process of doing the first use case always involves doing the other use case as well. *Extend* indicates that a use case is extended by a specific use case, that may or may not be executed depending on the situation. A *generalization* relation means that one use case generalises the other use cases.

Figure 13 shows that within the system boundary of the AR environment the three 'base' use cases for the on-site supervisor are *identify deviations*, *identify design clashes,* and *share latest on-site developments with off-site supervisors and designers*. These three always have other use cases that are required to execute within the system such as *visually compare as-planned virtual layer vs. as-built physical layer* or *register object attributes of as-built situation*, which in-turn have extended (specific) use case that may be executed such as *filter and adjust transparency of BIM objects*. *Identify deviations* is in fact a generalization of the six possible deviations, which are also referred to as inspection items in section 3.2.

The BIM environment is interacted with by the off-site supervisor to monitor the construction process and thereby to *accept/decline deviations*. The off-site designer interacts with BIM to *resolve design clashes*. Both these 'base' use cases always include to *view BIM object attributes of as-built situation* and *view annotations*. Both the object attribute data and the annotations that have been generated by the on-site supervisor and sent to the BIM environment can contain the information that hold the deviations, design clashes and measurements. Therefore, those use cases that view that specific data all extend the "*view BIM object attributes of as-built situation"* and "*view annotations"* use cases.

5.3 Activity Diagram

A UML Activity Diagram (figure 14) is used to depict the step-by-step approach while using the envisioned system. Actions are the activity undertaken by the actor that is indicated by the swim lane. The flow from one action to another is depicted by a control flow. Objects that can have input from/to actions are connected via an object flow. A decision element splits the input from one action into different possible action based on a decision or criteria. Last, the joint element combines multiple flows to one flow and the fork element splits one flow into multiple flows.

As seen in the Activity Diagram, the on-site supervisor starts using the AR environment to compare as-planned vs. as-built in order to find possible deviations or design clashes. In the case deviations are identified, the supervisor has the option to measure it with AR to gain more precise data. Thereafter, the supervisor decides whether he accepts the deviation from design. When the deviation is not accepted by the supervisor, for example a location deviation where a pipe is misaligned 30 cm, the on-site supervisor can impose construction workers to adjust the pipe so that it is adjusted accordingly. In the case the on-site supervisor does accept it, he is able to share the deviation in three ways: (1) by adjusting the attribute data of the concerned virtual utility object, or (2) in the case of a spatial deviation, spatially move the virtual object so that it aligns the real as-built situation, or (3) by making annotating the virtual object. In our example, the virtual pipe object can be spatially moved 30 cm so that it aligns his real location. This new as-built information is thereby registered and shared, via BIM, with the off-site supervisor. The off-site supervisor can, in turn, accept or decline the deviation. In the case he declines, the physical object(s) can subsequently (but timely) be corrected on-site. In the case he accepts the deviations, the data of the as-built situation is registered accordingly.

When the on-site supervisor identifies a design clash after comparing as-planned virtual objects with the existing (also called as-is) environment, the supervisor has again the option to measure the overlap between the virtual 3D surface and the physical objects that it clashes with. He then can register the design clash (and his measurements if he made any) by changing the attribute data of the concerned virtual object (this is detailed out in chapter 6), or by annotating the virtual object. This information can subsequently be shared with the off-site designer, so that he is able to resolve it.

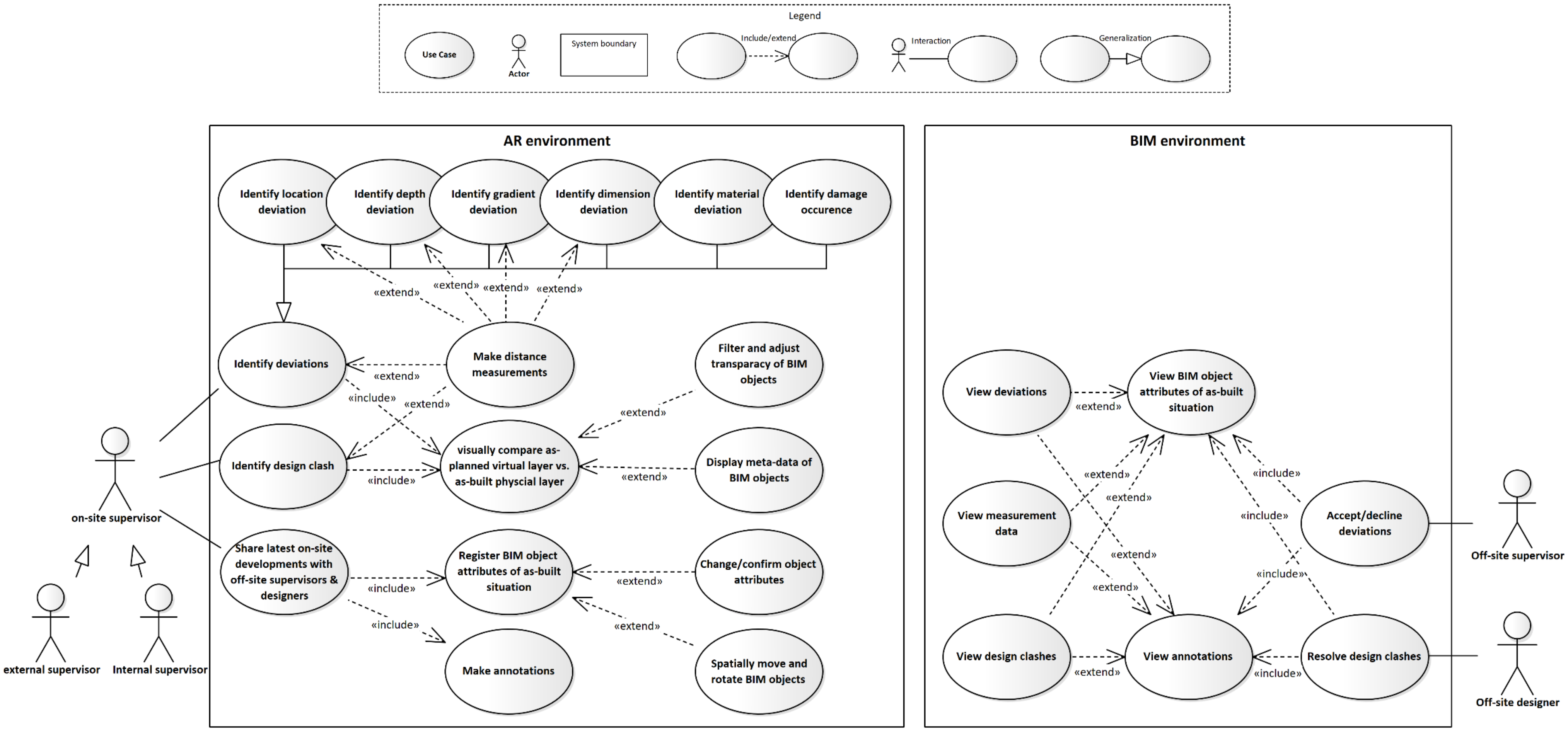

Figure 13, UML Use Case Diagram of the BIM AR QC system

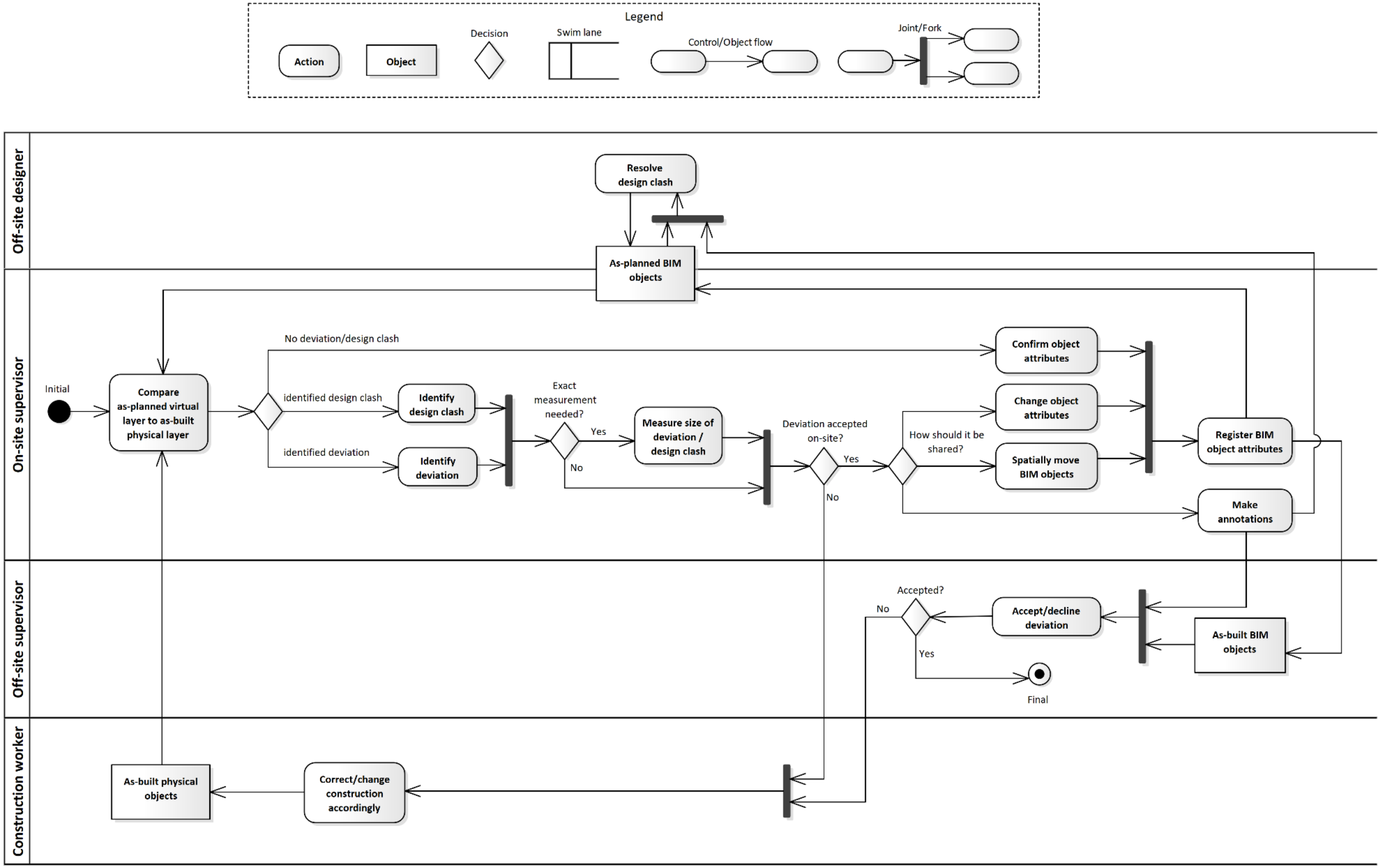

Figure 14, UML Activity Diagram of the BIM AR QC System

6. System ontology

In this chapter the previously described system components and behaviour diagrams are synthesized into one conceptual diagram called the system ontology. The competency questions were used to elicit some initial concepts, which was subsequently used as basis for the development of the full ontology. The result can be seen in figure 15. The system ontology is modelled as UML Class Diagram. In UML, classes are concepts, programming classes or types of objects. Attributes (within a class) are the properties/characteristics that an object and class can have. The relations between classes can be an association (any logical connection), generalization (indicates a child class is a type of the parent class), composition (indicates that a concept is divided into sub-concepts, which cannot exists on their own) or an aggregation (the same as composition, but the child classes can exist on their own).

The system ontology is divided into four viewpoints, namely the Physical environment, the BIM environment, the AR environment, and the Process model. Below, the system ontology and the captured concepts are explained from each viewpoint. Concepts from the ontology are *italicized*.

6.1 Physical Environment

The *PhysicalEnvironment* depicts the real world consisting of actual physical assets. The physical environment of interest for the envisioned system are the *UtilityNetwerk*, *SurroundingEnvironment* and required Hardware. The scope of this research and therefore the scope of the system focussed specifically on *Pipes* and *Cables*, which are both *ConstructionComponents* of the *UtilityNetwork*. *Cables* and *Pipes* have attributes that are derived from ter Huurne (2019). Note that these components can be modelled in much more detail with more attributes, only here the relevant attributes were adopted. The enumeration classes (i.e. a class that depicts the possible values an attribute can be given) that belong to *FunctionalValue*, *ClassValue*, *MaterialValue*, *CableTypeValue* and *PipeTypeValue* that were adopted can be seen in appendix D.

The *Hardware* of interest for the system is the *MobileDevice* and the *GNSS/RTK_LocationDevice*. These devices are connected and track each other, to position the virtual objects onto the physical environment. The *MobileDevice* should also consist of a *DepthCamera* and a regular (video) *Camera*. The regular *Camera* is used to capture a video feed of the physical environment, so that it can be overlaid with virtual content, and the *DepthCamera* is used to be able to make distance measurements with a *MobileDevice*.

6.2 BIM environment

The *BIM_Environment* depicts the concepts of a digital application that runs BIM software. Generally, it has several models. Relevant to the envisioned system is the *As-plannedModel*, which represent the design, and *As-builtModel*, which represents the as-built situation. Both these models consist of 3D objects with meta-data (i.e. attribute data), namely the *As-builtObjects* and *As-plannedObjects*. The objects have shared attribute data (depicted by the *ConstructionObjects* class), which is mostly the same as the physical class ‘*ConstructionComponents*’, only the dimensions are divided into width, height, etc. These attributes should all be modelled during the design phase by the designer. Thereafter during the construction phase, this data can be compared (visually with AR) to the as-built situation during inspections. When the supervisor identifies design clashes, it can be registered in the field by changing the (unique) attribute data of the as-planned object, that is by changing the ‘*designClash*’-attribute to ‘true’. In the case the size of the design clash is measured, it can also be added as attribute to the as-*plannedObject*. *Annotations* are also attached to objects, only it is visually present in the user view and not attached as attribute. Thus, when design clashes are identified and registered, the off-site designer can use the as-planned model to resolve those.

As said, *As-builtObjects* also contain unique attribute data that is being generated by the supervisor during inspections. The '*deviation*'-attribute can be given a value when deviations are identified (the enumeration class of *deviationTypeValue* can be seen in the top right corner of figure 15). In the case there is a material deviation, the '*deviateMaterial*'-attribute can be given a value. Furthermore, the '*spatialDeviationSize*'-attribute can be given a value if (spatial) deviations are measured and the '*damageType*'-attribute can be given a value when damage occurred on-site (the enumeration class of *damageType* is also seen in the top right corner of figure 15). Last, *Annotations* made in the user view are also attached to *As-builtObjects*. Therefore, off-site supervisors that have the responsibility to accept/decline deviations can use as-built model to monitor the construction progress. At last, a '*verified*'-attribute is there to indicate that the off-site supervisor has verified and accepted the new as-built object.

6.3 AR environment

The *AR_Environment* represents the AR application that runs on a *MobileDevice*. The AR application has a main component which is the *GUI* (Graphical User interface). The *GUI* presents the user with a view of the different layers and other system components that facilitate different features. The *SceneLayerManager* is the component that overlays the *as-builtVideoLayer* with virtual *As-plannedObjects*. The *SceneLayerManager* therefore also calculates the position of the virtual content. The *As-plannedObjects* should be directly integrated (preferably in real-time) with BIM. The *as-builtVideoLayer* represents the video of the physical environment captured by the *Camera*.

ObjectAttributesInterface is the component that makes it possible to change attributes of the virtual objects within the *GUI*. The attribute data of each object is tabular data of which the view can be turned on or off. The *MoveObjectInterface* uses the two layers described above and makes it possible to spatially move individual virtual objects inside AR so that it can be aligned with real (newly built) objects. This allows to accurately register and share the as-built situation with off-site project members in case some objects are deployed during construction that deviate spatially from design. The *AnnotationsInterface* is the system component that facilitates the creation of *annotations* and attaches it to objects within the *GUI* (for an example see figure 12, section 5.1).

Last, the *DistanceMeasureInterface* is the system component that enables distance measurements with AR. As said, it uses the *DepthCamera* of the *MobileDevice*. Furtermore, it is indicated for which *deviations* it may be useful to make measurements as supervisor in order to better judge whether a deviation is acceptable or not.

6.4 Process model

The process model is included in the system ontology to outline what processes during the *designPhase* and *ConstructionPhase* can occur and how the envisioned system can act upon those processes. To this end, *designClashes* and *Deviations* are included. As seen in section 3.2, the possible Deviations that can occur are *LocationDevation*, *DepthDeviation*, *GradientDeviation*, *DimensionDeviation*, *MaterialUseDeviation* and *DamageOccurence*. The first four of these deviations are all in fact spatial deviations, which can be measured as indicated by the ontology. Moreover, the *GUI* of the AR environment is able to support the supervisor (by overlaying as-built with as-planned) to visually identify all deviations and design clashes.

Last, some specific attributes are given to a variety of classes within the ontology. The '*location*'-attribute represents the actual location of an object and is given a '*GeoPoint*'-value that represents the X, Y, Z, coordinates. Furthermore, specific *ID's* have been given to many classes in the ontology so that the system can internally keep track of the different projects and associated models, objects, and processes.

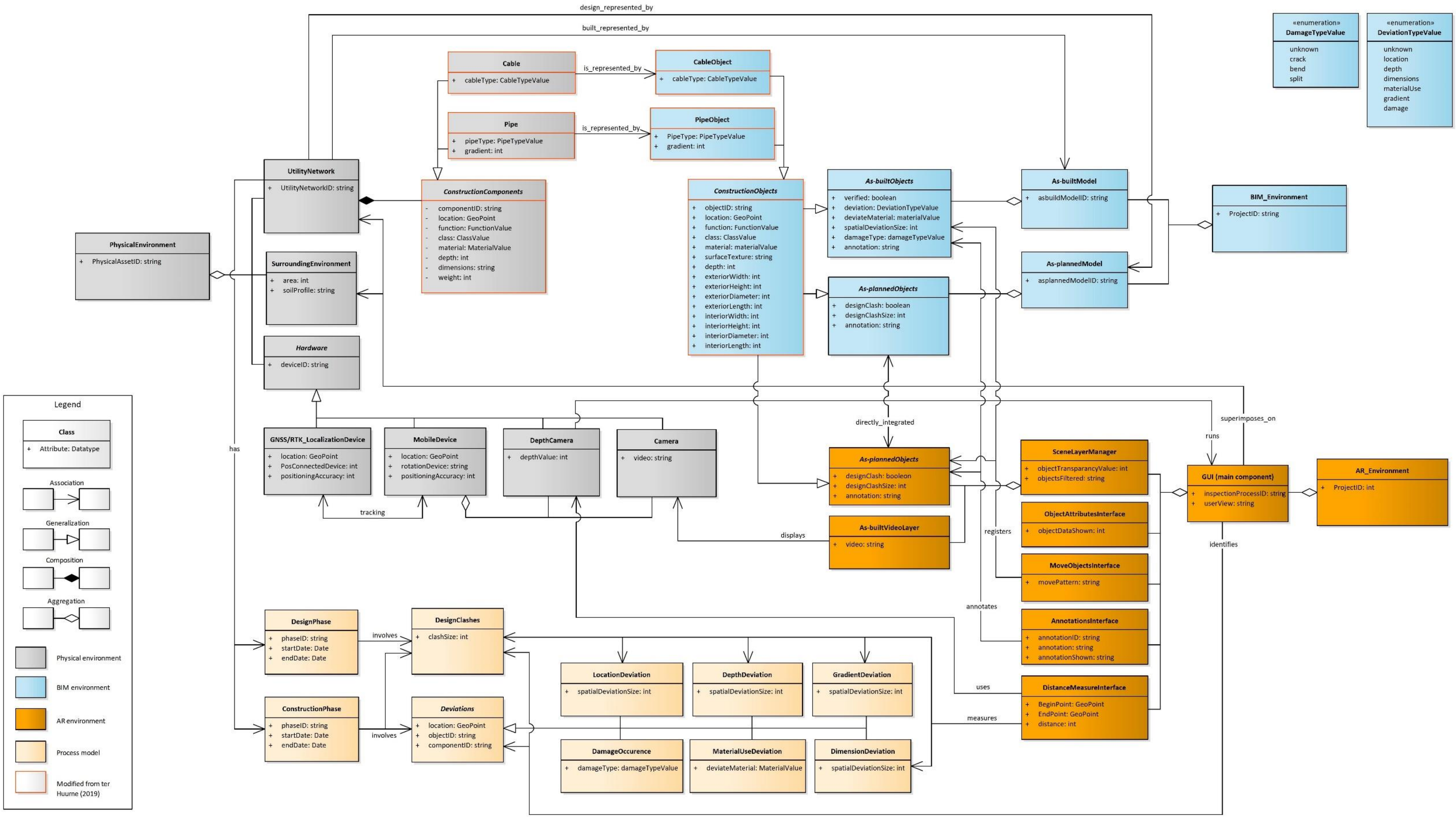

Figure 15, System Ontology (UML Class Diagram)

7. Validation

This chapter validates the system ontology by means of the competency questions. Furthermore, validations sessions with domain experts were held that could evaluate the formal list of requirements and system ontology based on several criteria.

7.1 Assessment against competency questions

Competency questions can be used to make sure the knowledge and information as required by the end-user is included in ontology. The CQs were elicited in section 4.2 through a goal-modelling approach. Afterwards, they were used to develop and simultaneously validate the defined concepts and terms as captured by the ontology. As a result, I assessed and validated the ontology against CQs multiple times during development in an iterative process. Table 7 provides an overview of the competency questions, the concepts involved in those questions, and the concepts as captured in the ontology, respectively.

7.2 Assessment against expert panel

The validation sessions were held with nine participants. The participants can be divided into three domains, namely (1) supervisors, (2) designers/BIM experts, and (3) AR experts. The first two domains are the end-users of the envisioned system. The third domain, AR experts hold the expertise to evaluate the system components as covered by the requirements and ontology. All domain experts were asked to fill in a validation questionnaire from their perspective. The structure of the validation sessions is included in appendix E. Table 8 provides the overview of the expert panel validation results. Thereafter, the outcome for each assessment criteria is described more extensively.

As explained before, the list of requirements was validated based on two criteria following the method proposed by INCOSE (2019): completeness and consistence. The ontology was evaluated based on five criteria as defined by Degbelo (2007): accuracy, clarity, completeness, conciseness, and practical usefulness. For their respective definitions I refer to section 2.4.

Table 7, validation of captured concepts involved in competency questions

Competency question	Involved concept(s)	Concept(s) as captured in system ontology
CQ1. What are the deviations (i.e. inspection items)?	*Deviations*	*Deviations, LocationDeviation, DepthDeviation, GradientDeviation, DimensionDeviation, MaterialUseDevation, DamageOccurence*
CQ2. What system component identifies (on-site) deviations?	*A system component*	*GUI (Graphical User Interface), SceneLayerManager, DistanceMeasureInterface*
CQ3. What are the attributes of the as-planned utility object?	*As-planned utility object*	*As-plannedObjects*
CQ3a. What is the location (x and y coordinate) of the as-planned utility object?	*Location*	*Attribute: location*
CQ3b. What is the depth (z coordinate) of the as-planned utility object?	*Depth*	*Attribute: depth*
CQ3c. What are the dimensions of the as-planned utility object?	*Dimensions*	*Attribute: exteriorWidth, exteriorHeight, exteriorDiameter, exteriorLength, interiorWidth, interiorHeight, interiorDiameter, interiorLength*
CQ3d. What material does the as-planned utility object consist of?	*Material*	*Attribute: material*
CQ3e. What is the gradient of the as-planned utility object?	*Gradient*	*Attribute: gradient*
CQ3f. What is the surface texture of the as-planned utility object?	*Surface texture*	*Attribute:*
CQ4. What are the attributes of the as-built utility object?	*As-built utility object*	*As-builtObjects*
CQ4a. What is the location (x and y coordinate) of the as-built utility object?	*Location*	*Attribute: location*
CQ4b. What is the depth (z coordinate) of the as-built utility object?	*Depth*	*Attribute: depth*
CQ4c. What are the dimensions of the as-built utility object?	*Dimensions*	*Attribute: exteriorWidth, exteriorHeight, exteriorDiameter, exteriorLength, interiorWidth, interiorHeight, interiorDiameter, interiorLength*
CQ4d. What material does the as-built utility object consist of?	*Material*	*Attribute: material*
CQ4e. What is the gradient of the as-built utility object?	*Gradient*	*Attribute: gradient*
CQ4f. Has the as-built utility object any damages?	*Damage*	*Attribute: surface texture*
CQ5. What system component identifies design clashes?	*A system component*	*GUI (Graphical User Interface)*
CQ6. What system component superimposes 3D design onto the physical environment?	*A system component*	*GUI (Graphical User Interface), SceneLayerManager, DistanceMeasureInterface*
CQ7. What system components register and share deviations and design clashes?	*System components*	*ObjectAttributesInterface, MoveObjectsInterface, AnnotationsInterface,*
CQ8. What system components register and share as-built progress data?	*System components*	*ObjectAttributesInterface, MoveObjectsInterface*

Table 8, overview expert panel validation results

Criterion	Average score (out of 5)			Comments/Improvements
	Superv.	BIM	AR	
frequency	Three experts	Four experts	Two experts	
List of requirements				
Completeness	3.7	4.0	4.0	• The system should be able to visualise in BIM all transmitted inspection data • The system should use an indicator in its BIM and AR environment to know if it uses the most recent version • The system could support the registration of annotations in the XYZ space • The system could incorporate and indicate whether a minimum value for positioning accuracy is reached • The system could register pictures and videos location-bound
Consistence	4.3	4.0	4.5	• Some overlap between req. 2.1 and 2.2
System ontology				
Accuracy	4.0	4.0	4.5	• The ontology should add the adjacent utilities to the 'construction components'-class
Clarity	3.3	3.8	4.0	• It is somewhat difficult to imagine the features and input options of the system based solely on the ontology
Completeness	4.0	3.8	3.5	• The ontology should address the different 'type' of design clashes • The BIM model should capture whether a cable or pipe is active or inactive • Distance measurements and as-built registration should indicate an accuracy value • As-built registration should have attribute DateTime
Conciseness	4.3	4.5	5.0	• Interior dimensions not always necessary within a BIM model.
Practical usefulness	4.3	4.3	5.0	• The system loses its functionality when new utilities are not visible, e.g. during directional boring • Hard to reach appropriate positioning accuracy of as-planned objects with the superimposition through AR • Hard to visualize (represent) the actual depth of virtual objects with the superimposition through AR

7.3.1 List of requirements assessment results

Completeness

Six experts found the set of requirements to be mostly complete, two experts assessed it as moderately complete, and one assessed it as fully complete. One participant with a design background mentioned that, in general, design experts have difficulties querying the attribute data themselves, especially in the case it is transmitted as tabular data to their BIM (like the inspection attribute data). Hence, it was proposed to make the inspection data visually present and detectable within the BIM environment. Another expert stated that there should be a way to know whether the model version you use, is the most recent version available.

Furthermore, an AR expert suggested to register annotations in the XYZ space, so that information sharing via annotations is even more precise. Besides, the system also opens up the opportunity to register and share on-site pictures and videos bounded to a location. Last, that expert recommended to incorporate an indicator that tells the user of the AR environment whether the superimposition has the minimal requirement positioning accuracy.

Overall, the completeness criterion for the list of requirements scored a 3.7 out of 5 among supervisors and 4.0 out of 5 among BIM and AR experts.

Consistence
Seven participants found the list of requirements to be largely consistent, and two participants assessed it as absolutely consistent. Two expert states that there is bit of an overlap between requirements 2.1 and 2.2, because those are checks for spatial characteristics in the three-dimensional space. More specifically, they recommended to merge those requirements as one which expresses that the AR environment should be able to do checks for the X, Y, and Z coordinate.

Overall, the consistence criterion for the list of requirements scored high with an average score of 4.3 out of 5 among supervisors, 4.0 out of 5 for BIM experts and a 4.5 among AR experts.

7.3.2 System ontology assessment results

Accuracy
Two participants found the ontology to be absolutely accurate, one expert found it to be somewhat accurate, and de rest of the participants assessed it as largely accurate. For instance, one of them stated there is an accurate coherence between the three environments – the physical, BIM, and AR environment. One of the design experts suggested to add the connecting utilities to construction components.

In general, the accuracy criterion for the system ontology scored a 4.0 out of 5 among supervisors and BIM experts and a 4.5 among AR experts.

Clarity
Three participants found the ontology to be somewhat clear and the rest found it to be largely understandable. In general, the participants had some difficulties imagining how the system works exactly based solely on the ontology. For instance, one expert stated that based on terminology in the schema, it is somewhat hard to imagine the input options within the AR environment. Hence, the participants were presented the list of requirements and ontology for the envisioned system, alongside with some system components from section 5.1 to provide more context. However, it should also be taken into account that all participants were unfamiliar with UML class diagrams.

Overall, the clarity criterion scored a 3.3 out of 5 among supervisors, a 3.8 out of 5 among BIM experts and 4.0 out of 5 among AR experts.

Completeness
Two experts found the ontology to be somewhat complete, another expert assessed it as absolutely complete, while all others assessed it as largely complete. A design expert suggested the addition of design clash 'types'. He explained that there are not only hard clashes but also clearance clashes. Clearance refers to the minimum space around a cable or pipe that sometimes must be kept free from other utilities.

Two experts from different domains suggested to include an attribute to the cable object and pipe object that indicates if it is active or not, because this determines whether there is an actual design clash, or the existing infrastructure is inactive and can simply be removed on-site.

An AR expert suggested that the distance measurement and as-built registration should also indicate the accuracy value during the registration moment, for example as attribute value attached to a BIM object. The same expert also recommended to add a 'DateTime'-attribute during the as-built registration, so that you are able to see moment of registration.

Overall, the completeness criterion for the system ontology scored a 4.0 out of 5 among supervisors, 3.8 out of 5 among BIM experts and a 3.5 out of 5 among AR experts.

Conciseness

Four the participants found that there are almost no unnecessary definitions and the others found none at all. One expert mentioned that the interior dimensions are unusual attributes to inspect. He argued that most of the times pipes have one height, width, and diameter value.

The average score of the conciseness criterion results in a 4.3 out of 5 among supervisors, 4.5 out of 5 among BIM experts and a 5.0 out of 5 among AR experts.

Practical usefulness

One participant assessed the ontology as somewhat useful, three participants found it to be mainly useful, while five participants found it to be absolutely useful. For this criterion, the supervisors and designers are especially important, because they are the end-users of the system. For instance, one supervisor found the intended system to be useful for (re)constructions of sewage treatment plants, because in those projects there are a lot of underground utilities stacked on top of each other. A few experts also mentioned that they liked the distinction between the different deviations that can occur and activities/features within AR to act upon those deviations.

As for the downsides, a supervisor mentioned that the proposed inspection system loses its functionality when underground utilities are not visible during construction, for instance during directional boring. Furthermore, AR experts had their doubts whether AR can reach the appropriate positioning accuracy of virtual objects to determine spatial deviations and to the register the as-built correctly. Another participant addressed the fact that it is hard to visualize (represent) the actual depth of virtual objects within AR. The participant who assessed it as somewhat useful, explained that he would like to test in practice in order to make a better judgement.

Overall, the practical usefulness of the ontology that represent the envisioned system scored a 4.3 out of 5 among supervisors and BIM experts, and a 5.0 out of 5 among AR experts.

Additional comments

In addition to the criteria above, some interesting comments were elicited during the discussions of the validation sessions.

Firstly, it was brought up multiple times that there is a difference between theory and practice regarding digital technologies, especially AR, in the construction sector. The system ontology is presented as conceptual schema, although the included system components are either from existing AR services or are described and evaluated by other literature. However, in practice, the system will most likely have technical limitations. For instance the required positioning accuracy of the virtual objects is unlikely to be satisfied with the current maturity levels of localization devices.

Furthermore, it was highlighted that in an ideal (future) scenario, all parties need to register all changes and deviations, preferably with the same system, so that the existing as-built data of the underground will remain up to date.

Another participant said that it would be favourable if every fieldworker is able to use the inspection system to correctly identify deviations. Otherwise, when there is a need for specialists in order to apply this method, the costs will likely rise, and the practical usefulness will likely decrease.

Furthermore, one participant with an AR background addressed that in theory, in terms of practical usefulness, the identification of certain deviations and associated system components of AR can be applied to a wide variety of above and underground objects, not only cables and pipes.

At last, with the envisioned system one supervisor saw the opportunity to store all failures in a database, so that companies can analyse and gain insight into where and which damages occur. As a result, they can determine strategy to prevent future failures, by e.g. avoiding certain high-risk areas or material uses.

8. Discussion

As described in the problem statement, current studies do not sufficiently cover the use of BIM and AR for quality control in the domain of underground utilities. Besides, end-user engagement is lacking among these studies. Earlier studies applied a technology push strategy instead of a more bottom-up approach in which a new system vision is suited towards the needs of the end-users. The envisioned BIM AR QC system is specifically tailored to the domain of underground utilities. Supervisors and designers were involved at an early stage of the research. By analysing current practices, the goals and needs of end-users could be mapped and a formal list of functional requirements could be developed, that subsequently gave input to the technical and functional design of the system. To this end, a system ontology was developed that is an attempt to cover the knowledge of technical concepts related to BIM and AR for quality control in the context of the physical environment during underground utility projects. The system ontology introduced conditions to BIM models that are required for an efficient information feedback loop between the field and the office. More specifically, BIM object attribute data is extended so that it supports the on-site collection of inspection data, efficiently resolving unaccepted deviations and design clashes. Furthermore, features for the AR environment were introduced that can help the on-site supervisor to identify, register, and share inspection items related to the construction progress. Moreover, registering the as-built situation during the quality control process, thereby generating an accurate as-built model, can also be of use for the operation and maintenance of underground utility project. As a result, the developed ontology shows a wide range of possibilities uplifting current practices. Ultimately, the ontology can help innovators and programmers in the underground utility sector understand the potential of and develop a system that uses BIM and AR. Therefore, this research offers support for the transition from conventional QC methods to innovative methods using digital technologies.

8.1 Managerial implications

The purpose of this research was to investigate the potential of BIM and AR technologies for QC in the domain of underground utilities. Besides, this research applied the principle of end-user engagement while following a structured system development approach. This resulted into a careful analysis of end-user needs and a system vision that meet those needs. Therefore, the outcome of this research which consists of a list of functional requirements and a system ontology has a high practical value that can inform practitioners on the potential of BIM and AR for QC in the underground utility domain.

The system ontology compromises of a variety of system components. When implemented, they facilitate an efficient on-site as-planned vs. as-built comparison that can help the supervisor to accurately identify deviations and spot design clashes. Furthermore, the integration between BIM and AR enables the ability to share the latest on-site development with off-site supervisors and designers. This means that off-site supervisors and designers can monitor the construction progress by accepting/declining deviations and resolve design clashes. It is anticipated that all above mentioned features are an improvement compared to conventional QC methods and can therefore prevent costly reworks and project delays.

As said, the system ontology imposes a variety of system components. Those components together comprise the requirements that should be met in order bring the envisioned system to practice. Hardware components include localization and mobile devices. The software components include a BIM environment, in which cable and pipe objects and associated attributes are modelled, and an AR environment with a GUI that supports the management of scene layers and objects attributes, and facilitates distance measurements, the movement of virtual objects and the creation of annotations. One of the novel concepts (not seen in literature) is the movement of the virtual objects to align it with the real (as-built) objects, in order to register and share spatial deviations. Using this concept, an accurate spatial as-built model is simultaneously generated, without the need for as-built remodelling at a later moment.

8.2 Academic contribution

This research investigated the potential of BIM and AR for QC and applied it to the practical domain of underground utility construction. It was found that the foremost feature of AR is the on-site presentation of as-planned information. By considering this feature, six relevant inspection items could be identified (i.e. location, depth, dimensions, gradient, material, and damage occurrence) that can be inspected more efficiently within this domain by using BIM and AR. How and by what means each of the inspection items can be inspected is described by the functional and technical design and depicted by the system ontology.

Besides, by applying the principle of end-user engagement while following a structured system development approach, this research gained the insight that end-users not only need better identification (spotting) of as-planned vs. as-built deviations on-site, but also need an efficient information feedback to off-site supervisors. By optimally using AR on-site integrated with a BIM model, off-site supervisors have access (from e.g. their office) to the latest on-site developments, therefore being able to timely accept or decline deviations that can otherwise result in costly reworks. This principle was found relevant to underground utility projects but may also be useful in other construction domains.

In terms of novelty, the system ontology is the first of its kind that describes BIM and AR concepts in UML relevant to the QC of underground utilities. This conceptualisation of reality can be used by practitioners and developers for knowledge sharing and implementation of the envisioned system.

To sum up, the main contribution of this research is the obtainment of a formal description and conceptualisation of BIM and AR technologies applied and coupled to specific user needs for QC and relevant inspection items within the underground utility domain.

8.3 Limitations and recommendations

During the interviews with supervisors and designers, a number of limitations came to light which are discussed here. Regarding the practical limitations, one of the main components within the envisioned system is the visual comparison facilitated by the AR environment. That is comparing the as-built physical layer with the as-planned virtual layer. Thus, quality control by means of AR requires the newly built utility objects to be visible in order to compare it to the virtual as-planned objects. Because underground objects during the construction phase are generally visible for a short period of time before they are covered with ground, measures are needed to timely align the new ways of inspection with the construction of each component. A way to deal with this is to have the system standby to use at any moment on-site without much preparation or time to it start up, so that new assets can be inspected during or right after deployment. For the same reason, it was discussed during the validation sessions that, ideally, all fieldworkers (thus also construction workers themselves) should be able to use the new QC method, without the need for on-site ‘specialists’ to be continuously present.

Regarding visibility, the identification of design clashes is also limited to the degree to which the existing underground infrastructure is visible. During the design phase, test pits are therefore required to reveal the real location of the existing utility network. As a result, the proposed system can identify and solve design clashes at sections that are exposed by the test pit. During the construction phase, however, the proposed BIM and AR system may identify more design clashes at sections of the network that were previously not visible.

Furthermore, this research found some barriers for the adoption of a new digital QC method. First, the system should reach a positive ROI. Project members indicated that cost trade-offs are made continuous throughout a project. During the tender submission the contractor and/or consultancy firms reduce the contract price as much as possible to gain a better chance of getting appointed. This often results in tight schedules. Hence, the supervisors indicated that it is difficult to apply new or innovative construction methods, because the upfront investment of using those methods are generally higher than conventional methods. However, a new QC method could (1) lower the risk for high rework costs during and after the execution phase of a project and (2) make the construction process itself more efficient. These advantages can reduce significant costs. Once these cost reductions outweigh the extra upfront costs, the system has a positive ROI.

A second adoption barrier is the interaction with construction workers. A supervisor during the interviews pointed out that construction workers do like to be given tasks, but generally do not like to be criticized during their progress. It is for that reason that controlling tools, much like the proposed system in this research, can be perceived as too controlling. The contractor is less likely to accept such tools, although the purpose of it is to ultimately increase construction quality. In line with the former, it was also pointed out that when supervisors are appreciative towards the construction workers, e.g. by letting them know when they are delivering good work, the supervisor provides trust. This assures that fieldworkers stay motivated to deliver good work, which subsequently leads to better quality. Therefore, the new ways to conduct QC should be carefully implemented so that it retains the social interaction between the supervisors and fieldworkers and moreover it is not perceived as too controlling.

The last practical aspect important to a supervisor is the satisfaction of his own work. One interviewee indicated that he may lose interest in his inspection work if it is too much computer aided. He stated that a lot of roles over the years have been replaced by technology and that he would like to detect deviations himself. In other words, if the detection of deviation is shifted from manual to computer aided detection, the fun of the supervising tasks can potentially be reduced. This can potentially be a barrier to adoption of the envisioned system. Still, the new QC method does retain some form of manual identification of deviation, only is made more easily through an efficient visual comparison with AR.

Besides the practical aspects, there are also some technical limitations to discuss. First, the envisioned system uses AR to overlay virtual content onto the physical environment in order to identify spatial deviations between the two layers. To do this reliably, the superimposition of virtual objects should be positioned with high accuracy. Therefore, the use of GNSS/RTK localization devices is proposed that delivers the highest precision available. According to Strand (2008) and vGIS (2021) such a system can deliver an accuracy of up to 1 centimeter. However, those results are with ideal conditions. Whenever this accuracy level decreases, the result of the visual judgements and measurements during inspections will become unreliable. Therefore, localization mechanisms used to superimpose virtual objects should be further investigated and developed with the aim to reach near-perfect precision levels so that the full potential of AR can be achieved.

Another issue related to AR is the difficulty to visualize/represent the actual depth of virtual objects as was pointed out by one of the participants during the validation sessions and is also emphasized by Scholtenhuis et al. (2017). Therefore, either the AR user should be experienced to know how to interpret the visualisation in his user view, or additional virtual features/measures (e.g. artificial colour schemes, shadows etc.) should be implemented to be able to represent the depth of virtual utility objects more accurately. The right way to deal with this limitation should be investigated further.

Regarding the (technical) limitation of the developed system ontology, the aim of the ontology was to conceptually represent the reality a BIM AR QC system is built upon. Therefore, a conceptual modelling approach is used, which means that static entities (objects) and operational entities (processes) were modelled as classes. Consequently, the system ontology is not (yet) computer interpretable. When such a system is to be implemented, developers should first create a detailed software design of the envisioned system.

8.4 Reflections on methodology

Regarding the research methodology, the principle of end-user engagement is one that is followed throughout the study that brought strong practical relevance to the research output. The concepts included in the ontology were elicited by first identifying the supervisors' responsibilities in terms of inspection items and further needs during their quality control practice and subsequently linking it to BIM and AR features to meet those needs. Competency questions were also used that structured the identification of included concepts. Thereafter, to further assure and simultaneously assess the relevance of the outcomes, domain experts validated the formal list of functional requirements and system ontology on their structural soundness and practicality. However, the number of end-users involved does have a low statistical significance, so the outcomes of the problems analysis and formulated end-user goals should be taken with caution. This also applies to the validation sessions held with nine participants from three different domains. Further research should expand that data set. Another relevance issue is the fact that the domain experts could not validate the final version of the set of requirement nor system ontology, because those two products were further developed after the sessions were held. A last remark concerning relevance is the fact that the experts involved came from two companies that operate in the Dutch construction industry. Thus, it may be that the observed issues may only be observable within those particular companies or industry.

Regarding the outcomes and their scientific contribution, this research intended to show how AR and BIM can improve quality control during underground utility construction specifically. To do so, this research followed a structured system development approach in which end-user were involved at an early stage. As a consequence, existing digital concepts of literature were (mostly) adopted and applied to underground utility construction. Although the outcomes may be viewed as rather general instead of ground-breaking, this research has highlighted the practical value of these digital concepts for the QC in underground utility construction and showed how the envisioned system meet the end-user needs. Based on this, companies may decide to implement and use the envisioned system. However, to increase the scientific contribution, this research could have zoomed in more on the domain of underground utilities rather than the link to digital technologies. If the domain of underground utilities was explored more in-depth (looking beyond the six identified inspection items) more domain-specific requirements for the BIM AR QC system may appear.

8.5 Directions for further research

As mentioned earlier, it is recommended to expand the data set concerning end-users (i.e. supervisors and designers) to further assess and collect input to improve the envisioned BIM AR QC system. Ideally, to make the vision more robust, the system ontology should not only be evaluated by experts within the Dutch construction projects but should also reach further than that.

Furthermore, the proposed system could also be implemented and field-tested to see if it holds its practical value. This, however, requires sophisticated software and other resources. During field tests, specific data on the practical usefulness for each system component can be collected, that provides input to further improve the proposed BIM AR QC system. Regarding the technical maturity as of now, the proposed positioning device does not yet deliver the required accuracy. Research to determine the best approach for localization could therefore be initiated to fill this technology gap.

Besides implementing and testing, the system components itself could also be expanded. Currently, measures and annotations generated within AR are attached to BIM objects. The use of depth sensor to conduct measurements also provides the necessary conditions to generate point that are spatially registered (with coordinates) in a 3D space. The possibility to register certain points in space, or maybe even a whole point cloud, and share in real time with BIM could potentially improve the communication and data provision from the field to the office even more. This is advanced from a technical point of view but does deliver real potential for further methodological improvements in the quality control field.

9. Conclusion

The current QC practice in the underground utility sector is characterized by manual measurement techniques, information exchange that is mainly document based and a low inspection frequency. As a consequence, a variety of issues happen such as wrong placements that can incur large rework costs. To enhance current QC practices and help the supervisor in his responsibility to accurately inspect the six inspection items that are found relevant to underground utility construction, a vision for a BIM AR QC system was developed. To do so, a formal list of functional requirements and a system ontology were systematically developed in this research. The system ontology describes the domain concepts from the viewpoint of the physical, BIM and AR environment and related processes, including the integration of as-planned and as-built BIM objects, the required hardware like the mobile and positioning device, the necessary software components such as the GUI (Graphical User Interface) and describes how those concepts treat the possible deviations and design clashes that can occur. The requirements set and system ontology were positively evaluated by domain experts and can therefore offer the necessary knowledge for the transition towards the new QC method.

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Appendix A – Structure interviews

Structured according to Kvale (1996).

Who?

- Supervisors / People with QC experience
- Designers

Purpose?

Outline and elicit:

- Current QC practices (and data/document exchange)
- Typical underground utility construction failures (e.g. wrongly constructed, misalignments, reworks)
- User goals/needs

Format?

Semi-structured, open ended

Selection based and prioritized on:

- Experience within the domain of utility quality management of relevant construction project
- People with practical knowledge are prioritized above people that pursue higher level managerial or advisory roles.

Interview guide *(Duration +/- 1 hour)*

- ➢ Personal introduction
- ➢ Purpose of interview is explained
- ➢ Start questioning

Throughout interviews the following potential additional/follow up questions are kept in mind:

Follow up questions:

- *Can you give more detail...?*
- *What did you mean...?*

Probing questions:

- *Do you have an example?*
- *Could you say more about...?*

Interpreting questions:

- *Interpreting questions: 'Do you mean that...?*

Theme 1: General

1. What and how many underground utility related construction projects have you worked on and can you describe your role in those?

Theme 2: Current practices

2. Could you describe in a nutshell a typical project from design to construction completion? (i.e. parties/roles/planning/(technical) agreements)
3. How in this process is the quality controlled?
    a. What resources&methods are used?
    b. What information is being exchanged? (design&construction)
    c. How is (design&construction) data and information being exchanged between people (i.e. designer/supervisor/worker) and parties (i.e. contractor/ consultant/client)?

Theme 3: Experiences

4. What are the most common/typical (underground utility) construction failures?
5. Can you give an example of a most recent incident/error/failure?
6. Could a different method of QC made the difference?
    i. in what way? Can you specify aspects? (technical level/organisation level/communicative level)
        1. Technical level
        2. Organisational level
        3. Communicative level
    ii. Are there more aspects that you would like to see improve?

Theme 4: (future) Needs

7. Out of your experience, what are the most important things that contribute to proper QC? *(Field)*
8. If you were to develop a new/better support system for QC, what kind of requirements would you have for that system / where would you pay extra attention? (hardware/software/organisational)

➢ [If time left]: the aim of the research and the QC system using BIM and AR are explained

9. According to you, what are the merits/disadvantages of a QC system using BIM and AR?

Analysis

Interviews were recorded (mostly via Teams) and transcribed.

Analysis of transcripts:
- two different approaches to analyse transcripts were used (Kvale, 1996):
    - Meaning condensation
    - Meaning categorisation
- Computer tool: Atlas.ti
- The aim was to have transparency and consistency throughout the analysis.

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Appendix B – Literature review of causes related to observed failures

To see if the observed phenomena in section 3.3 are underlined by literature, six literature studies were analysed that identified and ranked factors affecting schedule delay and cost overrun in large public construction projects. The factors seen in the literature were not limited to underground utility construction, however, three of these factors could be linked to five observed failures in this research. The first column in table 9 outlines the relevant and comparable factor/cause. In the second column, the studies that identified and used that cause are given. The third column links the comparable factor/cause to the observed underground utility failures elicited during the interviews in this research.

Table 9, Causes related to typical failures

		Link to observed failure in underground utility construction			
Comparable factor/cause	**Literature**	*Wrong placement*	*Wrong installation*	*Pipe damage*	*Design clashes*
1. Errors or discrepancies in design documents	Larsen (2016), Maqsoom (2018), Memon (2014), Assaf (2006), Rafieizonooz (2015)				x
2. Inadequate on-site supervision	Larsen (2016), Ahzabar (2011), Maqsoom (2018), Memon (2014), Assaf (2006), Rafieizonooz (2015)	x	x	x	
3. Optimistic expectation regarding time, cost	Larsen (2016), Memon (2014), Assaf (2006), Rafieizonooz (2015)	x	x	x	

Below, it is explained how the comparable factors/causes relate to the findings of this research.

1. Errors or discrepancies in design documents (Larsen, 2016; Maqsoom, 2018; Memon, 2014; Assaf, 2006; Rafioizonooz, 2015)

This cause is underlined by four studies and is about errors and discrepancies in design documents. This is highly related to the *lack of data from existing underground infrastructure* (identified as one of the typical issues in section 3.3). This prominent phenomenon leads to design clashes because designers nor fieldworkers did expect existing infrastructure to be at the location of interest.

2. Inadequate on-site supervision (Larsen, 2016; Ahzabar, 2011; Maqsoom, 2018; Memon, 2014; Assaf, 2006; Rafioizonooz, 2015)

As underlined by all five studies, inadequate supervision is one the prominent causes for project delays and cost overruns. It was found in this underground utility research that inadequate on-site supervision (also called *inaccurate on-site inspections* in figure 5) is caused by a combination of high-time pressure and manual/labour-intensive measurement techniques. Consequently, this causes wrong placement, wrong installations, and pipe damages, because the deployment of objects should be inspected timely and accurately by the supervisor.

3. Optimistic expectation regarding time, cost (Larsen, 2016; Memon, 2014; Assaf, 2006; Rafioizonooz, 2015)

Underlined by four studies, optimistic/inaccurate planning and schedule leads to project delays and cost overruns. This highly relates to high time-pressure which is one of the observed typical issues in this research. It was found that high time-pressure for supervisors in underground utility construction leads to (1) inaccurate on-site inspections and (2) lack of insight into latest developments because external supervisors are not continuously present on-site. This research focusses on solving both effects, not by giving the supervisors more resources in terms of time, but by developing a more efficient way to conduct QC.

Appendix C – Sample of quotations indicating typical issue, failure, or other phenomena

Quotation #	***Interviewee #***	***Quotation (Dutch)***	***Observed issue/ failure/phenomena***
Quotation 1	Interviewee 5, supervisor	**Interviewee:** *"ik heb een keertje een werk gehad in Arnhem. Daar hadden ze de putten op een gegeven moment verkeerd uitgezet. En dan ging het riool helemaal kris kras lopen. En toen wist de aannemer het zo te zeggen, ja we hebben een fout gemaakt alleen ja ja.. en toen hadden ze mij dat ook niet gemeld en ik kwam er toevallig een keertje achter en toen moesten we nog de weg er overheen gaan brengen, ik zeg ja maar wat denk je nu wat we gaan doen.. en toen zei hij, ja dat is toch niet erg dat er zo'n grote knik in zit en zo en zo, want als het allemaal maar goed gaat. Ik zeg ja.. ik weet niet of dat goed gaat, ik ga dat niet met jou discussiëren, ik geef jouw geen toestemming om te zeggen gooi de straat er nu maar overheen. Ik kom er nu toevallig achter, ik ga dat informeren, of dat wel of niet goed is. En twee dagen later, aannemer.. je moet het riool.. dat beslist dan de directievoerder of in dit geval was dat opdrachtgever, van hee aannemer het riool moet op die en die plek liggen en niet op een andere plek want daar krijgen we weer problemen met dat en dat. Dus het moet gewoon weer verlegt worden. Nou ja daar ben je natuurlijk niet blij mee.. alleen ja ze hadden een fout gemaakt. En hadden ze die fout nou gelijk doorgegeven toen ze het geconstateerd hadden, dan hadden ze ik zegmaar wat voor een paar duizend euro de schade was het goed, en nu kost het in één keer 10 keer zoveel omdat ze denken van we gaan wel gewoon door en de opdrachtgever vind het wel goed."* **Interviewer:** *"Omdat bewijs van spreken was de grond nog gewoon open? Dan kon je al gewoon gelijk verleggen."* **Interviewee:** *"Ja ze hadden op dat moment.. ze moesten weer natuurlijk opnieuw bronneringen en alles gaan zetten om het riool te gaan verleggen. Ja.. als je de zaken gewoon niet eerlijk speelt dan moet je het ook op een gegeven moment maar voelen. Daar moet je ook heel simpel in zijn."*	Issue 1: Wrong placement
Quotation 2	Interviewee 6, supervisor	**Interviewer:** *En komt het vaak voor dat het verschilt, ten op zichten van hoe het ooit ontwerpen was?* **Interviewee:** *"Ja, zeker."* **Interviewer:** *"Ook bij ondergrondse voorzieningen veel?"* **Interviewee:** *"Ja, ook wel. Maar dan is het zaak dat je aan de voorkant dus weet dat het is ontstaan en waarom het is ontstaan en dat je nog een keuze mogelijkheid hebt. Dus als je ziet dus dat een bepaalde put, even weer op rioleringen ingaande, 20 centimeter te hoog staat, dan keur je hem gewoon af. Dan zeg je tegen zo'n aannemer van jongens dit klopt niet. En dan roept zo'n aannemer van ja maar dit en dit is er het geval we kunnen niet dieper, dit is het beste. Dan moet je dus samen met de aannemer, terug naar de opdrachtgever en aan gaan geven, van jongens dit en dit is het geval, we hebben eigenlijk geen keuze. Of we hebben wel een keuze, maar daar hangt een financiële component aan vast. En dan heb je dat gesprek. Maar dan kun je in ieder geval nog met elkaar in gesprek, van jongens we kiezen ervoor om de put 5 meter verderop neer te zetten, want dan kunnen we nog 20 centimeter lager."*	Issue 1: Wrong placement

Quotation 3	Interviewee 5, supervisor	**Interviewer:** *“Komt het vaak voor dat er schade wordt geconstateerd? Dat ze goed waren en dat bij het aanleggen dat er toch schade is opgelopen?”* **Interviewee:** *“Dat gebeurt regelmatig. Eén keer heb ik het werk van een collega overgenomen en toen waren ze aan het asfalteren en toen kwam ook gelijk het inspecteren van een riool ter sprake. Ik zeg jongens is dat nog niet gebeurt dan, hoe kun je dat nou nu nog willen doen dan. Ja haast haast haast.. ik zeg nou volgens is dit de verkeerde volgorde. En toen kwamen ze.. was het asfalt erin, kwamen ze volgende dag terug om te inspecteren. En toen hadden ze alle aanslutingmoffen zogenaamde klikmoffen, hadden ze verkeerd aangebracht, alleen het riool lag wel 3 meter diep. En dan moesten ze ze allemaal weer op gaan graven. En er waren 17 plekken en overal bronneringen erbij, overal dit, overal het asfalt weer opbreken. Nou daar waren ze niet blij. Ik zeg ja.. Je moet eerst stap één doen, dan stap twee en dan stap drie. En dan soms dan doen ze gekke dingen en dan jammer dan het is niet goed.”*	Issue 2: Wrong installation, Issue 3: Pipe damage
Quotation 4	Interviewee 3, designer	**Interviewee:** *“Of leiding die je, of rioleringen die je gaat aanleggen en waar toch een leiding ligt die niet op plek ligt zoals aangegeven op de nutstekeningen. Dat kan, dat komt voor. Dat de geleverde informatie verkeerd was van de kabels en leidingen die er al lagen. Je plant een riooltracé ergens. En volgens de tekeningen die je hebt gekregen volgens de nutsbedrijven, zou het moeten kunnen. Maar het kan toch niet, want die leiding lag niet helemaal zoals op de tekening getoont”*	Issue 4: Design clash with existing infrastructure
Quotation 5	Interviewee 3, designer	**Interviewee:** *“Tijdens de werkzaamheden, voor een toezichthouder, afhankelijk van het soort project, zou het handig kunnen zijn, als hij bijvoorbeeld de toekomstige situatie kan projecten. Als er bijvoorbeeld cunet al gegraven is. Of er zijn kabels en leidingen stroken bekend, of er zijn proefsleuven gegraven, dan zie dus de echte kabels en leidingen liggen, dan zou het fijn zijn als je daarover heen het nieuwe ontwerp kan projecteren. Dan zie je dus het nieuwe ontwerp in relatie tot de kabels en leidingen die je vrij hebt gegraven met je proefsleuven. Dus dat zou meerwaarde kunnen hebben. Misschien in relatie tot bomen. Ontwerp van nutsstroken, met betrekking tot bestaande bomen. Dat is ook handig.”*	Issue 4: Design clashes with existing infrastructure
Quotation 6	Interviewee 5, supervisor	**Interviewee:** *“Wat ik wel gemist heb, of ja gevonden heb, is dat de KLIC meldingen, de liggingen van bestaande leidingen en kabels, verrotte slechte is. Je zou eigenlijk bij aanvang van een project ofzo, leidingen moeten controleren. Waar liggen ze, met apparatuur. Ik weet, we hebben vroeger bij Tauw al is een keer zo'n rare mol gehad aan een lang snoer, die konden we dan door de leiding heen drukken. En dan met een pieper bovengronds konden we volgen waar die ligt. Dus ja, ik denk in het geheel van het begin van projecten dat ondergrondse leidingen eerst in kaart gebracht moeten worden. Heb niet vertrouwen op de KLIC meldingen”*	Issue 5: Poor data from existing infrastructure
Quotation 7	Interviewee 3, designer	**Interviewee:** *“Maar, nutsbedrijven die zeggen wel altijd van, je moet wel goed controleren met behulp van proefsleuven want wij garanderen niet dat die leiding precies ligt waar die getekend staat en we gaan ook niet zeggen hoe diep die ligt. Dus die informatie heeft een hele grote bandbreedte. En dat moet je controleren van proefsleuven. Dat neem je ook op in je bestek. Dat een aannemer ook de locatie van nutsvoorzieningen voor kabels en leidingen moet controleren door het graven van proefsleuven. Tegenwoordig, daar is niet veel aan verandert eigenlijk. Niemand staat in voor de kwaliteit van de data die die levert. Die nutsbedrijven. En een gasunie gaat dan ook niet zeggen waar het ligt. Die zeggen gewoon het ligt in dit gebied ongeveer en we zeggen al helemaal niet diep. Of het is gewoon geheim.”*	Issue 5: Poor data from existing infrastructure
Quotation 8	Interviewee 6, supervisor	**Interviewee***: “Kijk wat wij in het verleden altijd deden was gewoon de platte tekening buiten erbij pakken, afschalen en in de praktijk weer nameten van jongens zitten we goed. Dan heb je het over een platte tekening, terwijl je ook driedimensionaal moet inschatten of het ook, je kan wel x en y goed liggen, maar qua hoogte de z-as is het natuurlijk weer ander verhaal. Ja, dat zou mooi zijn. Dus binnen dat*	Issue 6: Difficult to interpret design

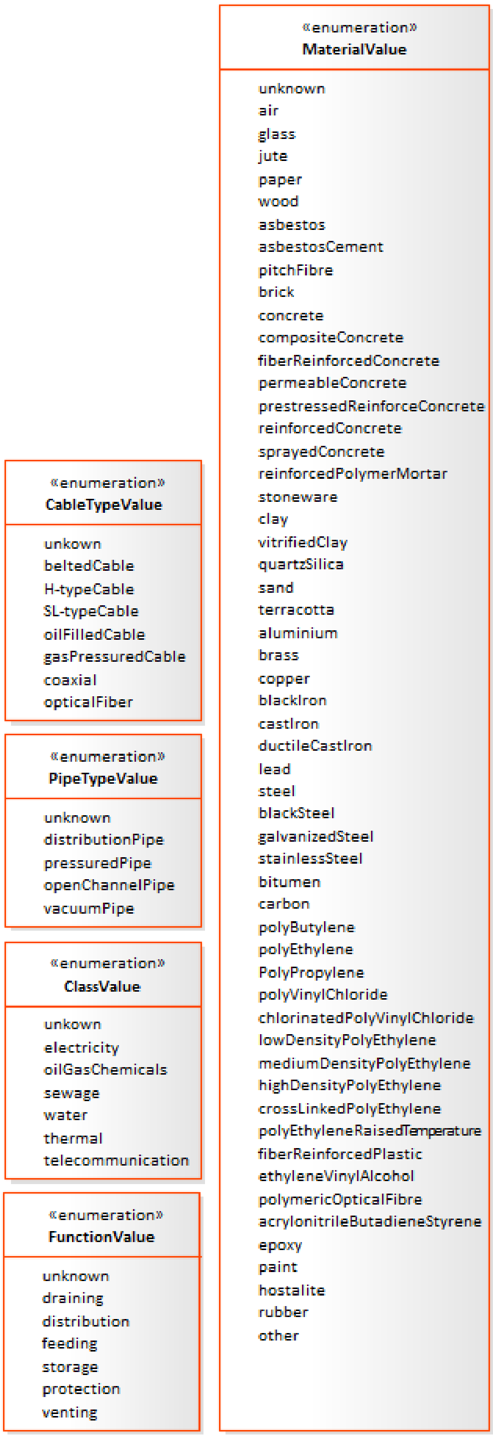
		kader denkende, ook de ligging van de kabels en leidingen, het nieuwe rioolstelsel, hoe moet dat er komen te liggen. Als je dan met zo'n blik in het veld even kan scannen van jongens nouja hij ligt helemaal conform tekening, ja perfect."	
Quotation 9	Interviewee 4, supervisor	**Interviewee:** *"Je zou uit zo'n 3D tekening ook de afmetingen moeten kunnen lezen, kijk gewoon een platte tekening staan maatvoeringen bij. En ja ik ben niet anders gewend, dus ik kan van een platte tekening wel in mijn kop een 3D model bouwen. Maar als je op je 3D tekening ook de maatvoering kan verwerken, ja, dan ben je in één keer klaar natuurlijk he. Dan heb je dus iets voor mensen die niet in staat zijn, om van een platte tekening iets te maken, mensen die niet kunnen voorstellen hoe het eruit ziet. En dat is natuurlijk ook met name met leidingwerk he, in de grond. Een kruis op een platte tekening, zie je wel eens een kruis maar je kunt geen hoogte zien, dan moet je echt in de getalletjes gaan duiken, om dan in je hoofd te gaan denken, oja dat is zo hoog, dat is zo hoog, oja dat is boven elkaar, deze loopt erboven en deze eronder. En dat kun je in een 3D tekening laten zien natuurlijk. Als je daar dan ook nog maatvoering bij laat zetten, dan is het helemaal top, of tussenmaten."*	Issue 6: Difficult to interpret design
Quotation 10	Interviewee 2 supervisor & designer	**Interviewee:** *"Maar dat is wel achteraf, ik hou ervan om, ik loop al een tijdje mee, risico gestuurd toetsing of uitvoeringsbegeleiding noemen we het, dus die dingen als er echt bijzonderheden gewoon te bespreken met de opdrachtgever en daarna met de aannemer in het veld, let op hierop, let op daarop. Zodat je niet achteraf met vervelende dingen wordt geconfronteerd. Verzakking van je sleuf of dat soort dingen. Kijk, jonge uitvoerders worden aangestuurd op tijd, maar goed als jij iets ziet, maak het bespreekbaar zoals dit gaat niet goed anders kom je vanmiddag in de problemen, ja maar mijn baas etc. nee, terug, je bent minder tijd kwijt als je het zo doet"*	Issue 7: High time-pressure, risk-based inspection
Quotation 11	Interviewee 2, supervisor	**Interviewee:** *"Je hebt elke week, of elke twee weken coördinatieoverleggen. Met alle nevenaannemers of onderaannemers, installateur etc., die installateur zegt bijvoorbeeld ja die pomp is net iets anders, die sparing moet daar. Heeft direct gevolgen. Als je direct jouw constructie erop aanpast, dan heb je bij elk overleg de juiste documenten. Dus voor de uitvoeringsperiode is het veel gemakkelijker. En je maakt minder kans op fouten."* **Interviewer:** *"Goede informatievoorzining is belangrijk dus?"* **Interviewee:** *"Ja, je kunt direct afvinken, dit wandje is de revisie al voor klaar. Anders moet na jouw werk of na de oplevering in de revisie, moet je dat nog eens een keer allemaal gaan toetsen. Dus dat is vaak te laat, heel veel dingen kun je niet zien, zit onder de grond. Moet je vervolgens aannemen dat het klopt. Kijk.. tijdens de uitvoering ben je overal bij, kun je direct zien, klopt dat?. Ja, het heeft voordelen, direct voordelen."*	Issue 8: Insufficient information exchange / lack of off-site access to latest on-site developments
Quotation 12	Interviewee 3, designer	**Interviewee:** *"Ja het is wel eens gebeurt dat een opdrachtgever het niet nodig vind om een toezichthouder op het werk te hebben. Dat hij het zelf doet. En dan kan het zijn.. het gebeurt ook wel eens dat de aannemer zegt het is een slecht bestek. En dan is het ons antwoord tegen de zijne. Ja, wij hebben geen toezichthouder op het werk dus wij kunnen niet bewijzen dat de aannemer iets verkeerd heeft gedaan"*	Issue 8: Insufficient information exchange / lack of off-site access to latest on-site developments
Quotation 13	Interviewee 5, supervisor	**Interviewee:** *"Kijk, wij hadden het net over de verkeerde ligging van het riool in Arnhem zeg maar. Ja als ik buiten met zo'n stok ga lopen en meten waar hij wel of niet ligt, ja dan had ik dat misschien ook al wel eerder ontdekt. Maar ja aan de andere kant, die aannemer gaat het na die tijd inmeten en die heeft het volgens mij al veel eerder gezien dat het fout lag. We doen tegenwoordig ook deeltijd toezicht, dus we zijn ook maar heel af en toe op het werk he"*	Issue 8: Insufficient information exchange / lack of off-site access to

			latest on-site developments
Quotation 14	Interviewee 6, supervisor	**Interviewer:** "Je wil eigenlijk bij ondergrondse werken een monitoring hebben, Eigenlijk constant?" **Interviewee:** *"Ja. Kijk eigenlijk met de aannemer vanuit zijn kwaliteitscontrole moet hij al wijzigingen aantonen aan de voorkant en bespreekbaar maken en niet achteraf, want dan hebben we geen keuze mogelijkheid meer. Dan sta voor een gedwongen feit. En ja dan kun je dus.. uiteindelijk als een nieuw project wordt opgeleverd, draag je het over aan een beheersorganisatie binnen de gemeente, binnen de provincie, zeg het maar. En die moeten het accepteren. Als die roepen, van jongens ja die put staat nu 20 centimeter te hoog waardoor er altijd water in het systeem blijft staan, dat accepteren we niet. Ja dan zitten we op dat moment met een project wat we niet overgedragen krijgen. Dan hebben we een probleem."*	Issue 8: Insufficient information exchange / lack of off-site access to latest on-site developments
Quotation 15	Interviewee 6, supervisor	**Interviewee:** *"Als alles volgens het boekje loopt hoeft er geen toezichthouder te zijn, hoeft er geen projectleider te zijn en lever je een tekening af bij de aannemer, en een contract, en aan het einde van de tijd levert hij het op, en dan heb je het perfecte plaatje liggen. Maar zo werkt het niet, dus je wilt altijd enige mate van controle hebben.* *Communiceren met de aannemers van wat gebeurt er. Lig je op planning, want stel dat je vertraging op loopt en je constateert dat wil je dat vroegtijdig melden bij je opdrachtgever, maar ook bij de omgevingspartijen. Zie je aan het begin al dat een aannemer een hele rooskleurige planning heeft opgesteld en die roept al binnen een week ligt de riolering op deze streng ligt erin, en je merkt al binnen een dag van ja dat gaat niet goed komen, dan heb je dat gesprek met de aannemers, van jongens waar mankeert dat aan, is dat een opstart probleem, of valt het gewoon tegen, wees eerlijk want dan kunnen we die planning bij gaan stellen en kunnen we onze opdrachtgever ook inlichten. En de winkelier die 100 meter verderop ligt, kunnen we dan ook melden dat de weg nog twee weken langer gestremd is. Daar heb je als toezichthouder, directievoerder, projectleider vaak gesprekken over, afwijkingen. Dus niet over dat het werk zo perfect verloopt, en dat het allemaal mooi gaat, en dat je binnen 5 minuten weer de bouwvergadering uit kunt, het gaat over afwijkingen."*	Issue 8: Insufficient information exchange / lack of off-site access to latest on-site developments
Quotation 16	Interviewee 6, supervisor	**Interviewee:** *"En dan wordt er voorzichtig gegraven rondom de kabels en leidingen, en dan moet blijken of de praktijk klopt met de theorie. En dat is altijd natuurlijk een punt. Kabels en leidingen liggen in het algemeenheid nooit exact zoals ze op papier gaan en dat gaat dus wel vaak mis. Het heeft vaak ook wel met een stukje productiewens te maken van een aannemer te maken, dat hij veel productie wil draaien en snel wilt graven, veel kuubs wil ontgraven en die neemt gewoon bewust risico's, maar dat betekent ook het risico op schade. Met name als de boel niet volgens tekening ligt. Ze mogen conform een bepaalde marge, mogen ze afwijken van theorie. Liggen ze er ver buiten die marge, ja dan ligt het risico ook weer bij de Nuts partijen. Dus dat is altijd wel een worsteling. Het liefst wil je gewoon met bewijs van spreken een theelepetje ontgraven, net zoals de archeologen doen, dan weet je zeker dat je geen schade treft. Maar praktijk is vaak weerbarstiger en staat er gewoon een rupskraan met een kuubsbak te graven en die moet de vrachtwagen weer in 5 minuten vol hebben en dan heb je een ander verhaal."*	Issue 9: Utility strike
Quotation 17	Interviewee 5, supervisor	**Interviewee:** *"Het verhang, controleer je achteraf, de ligging, de hoogte maatvoering, breken constateer je, als een inlaat bijvoorbeeld niet goed is of dat er een bocht verkeerd zit of een verkeerde aansluiting. Of het netjes is afgewerkt, dan zit ik bijvoorbeeld te denken aan inspectieputten die volgens het stroomprofiel er netjes in moet zitten."*	Inspection items
Quotation 18	Interviewee 2, supervisor & designer	**Interviewee:** *"Voor kabels en leidingen is dat een apart verhaal. Riool hebben we het net al over gehad, fysiek boven controleren en dan checken of de hoogtes goed zijn. Met de laserbaak kijken of de lasers [locatie] nog goed staan en dan heb je een [interne] camera inspectie. Dat zijn die drie elementen. Kabels en leidingen heb je te maken met andere partijen, niet met die aannemer, de opdrachtgever geeft opdracht voor het verleggen of aanleggen van kabels en leidingen. Als je het hebt over de voorbereiding, ik als coördinerende rol*	Measurement techniques, working risk-based

		als, zet dan een benchmark uit in het veld, dat het ook goed komt, dat is ook meer risico gestuurd dan, gebeurt niet altijd. Dan kom je daar achteraf achter, het is te hoog of te laag, dus daar hou ik niet van, ik heb ook een landbouwkundige achtergrond, dus dat moet gewoon goed. En eigenlijk als een kabeltje,.. wij toetsen niet of een kabeltje, zoals glasvezel of daar beschadiging in komt en dat soort dingen, daar toetsen wij niet op. Want dat is ook hun 'pakkie aan'. Je wordt ook nooit eigenaar, van een riool wordt de gemeente eigenaar. Daar ben je een verlengstuk van je opdrachtgever, maar van een kabel blijft het nutsbedrijf eigenaar, dus die hebben daar eigen toezichthouders op. Dus een energieleverancier die kijkt allemaal daarin mee, die moeten een bepaalde dekking hebben.	
Quotation 19	Interviewee 4, supervisor	**Interviewee:** *"Ja nou het is natuurlijk wel zo, als je een beetje handig bent, dan probeer je dus het peiltoestel even samen met de aannemer, met de werknemers even in te stellen, en dan ze de ligging altijd controleren of die goed op hoogte ligt. Dat kun je gewoon op afstand wil zien. Ja hij meet nu, en dan oké ja is goed. Op die manier kun je de ligging een beetje bij houden.* **Interviewer:** *"Ja dus of die diep genoeg ligt?"* **Interviewee:** *Op de juiste diepte ligt, en of die op het juiste afschot ligt.* **Interviewer:** *"Hoe werkt zo'n peilmeter? Stoppen ze dat de grond in of is dat als de grond nog open is?"* **Interviewee:** *"Wat ze vaak doen, je hebt zo'n apparaatje en als je die goed op pijl hebt begint die te piepen. Langzaam achter elkaar en op een gegeven moment krijg je een vaste toon. Dan ligt die precies op lijn. Nou die wordt dan met een klemmetje vastgezet op de goede hoogte. Als die begint te piepen dan ligt die goed, of niet en dan moet de leiding iets hoger of iets lager gelegd worden. En dat kun je gewoon vanaf de kant, kun je dat meekijken. Dat is de enigste mogelijkheid om te kijken of je pijp inderdaad op de goede plek ligt."*	Measurement techniques
Quotation 20	Interviewee 6, supervisor	**Interviewee:** *"Kijk.. zolang de rioolsleuf nog open ligt, kun je gewoon metingen doen. En dan doe je gewoon referentiemetingen van jongens put A staat goed put B staat goed, waar het {streng} tussen komt te liggen, nou dan moet de riolering opzich ook op de juiste hoogte liggen. Als de sleuf aangevuld is en je komt dan pas tot de conclusie, van jongens hij ligt niet helemaal goed. Dan heb je een probleem.* *Alleen de aannemer doet ook altijd, die moet achteraf middels een camera inspectie aantonen dat alle buizen nog gewoon goed liggen, na de aanvulling. Dat alle huisaansluitingen goed aangesloten zijn."*	Measurement technique

Appendix D – System ontology enumeration classes

Adopted from ter Huurne (2019)



Appendix E – Structure validation sessions

Who?

- Supervisors
- Designers/BIM experts
- AR experts

Purpose?

Human-based expert validation of:

- Functional requirements
- System ontology

Session guide *(Duration 30 min – 1 hour)*:

- (Personal) introduction
- Purpose of session explained
- Present:
  - Functional requirements
  - System ontology
- Ask respondents to fill in questionnaire

For every criterion, the respondent is asked to give a score between 1 (poor) and 5 (good). To do so, the respondent is asked the question associated to each criterion. Additionally, they are asked to provide comments to their score. Especially In the case of a poor score, for which they are asked if they have any suggestions for improvements.

- For the FR's the following evaluation criteria are used (INCOSE, 2019):
  - **Completeness** – Question: To what degree is does the requirement set standalone such that it sufficiently describes the necessary capabilities, characteristics, constraints, and/or quality factors to meet the needs without requiring other requirements at the appropriate level of abstraction?)
  - **Consistence** – Question: To what degree contains the requirement set individual requirements that are unique, do not conflict with or overlap with other requirements in the set?
- For the data structure ontology, the following evaluation criteria are used (Degbelo, 2007):
  - **Accuracy** – Question: To what degree is the system ontology a correct representation of aspects of the real world?
  - **Clarity** – Question: To what degree is the system ontology an effective communication of the intended meaning of defined terms?
  - **Completeness** – Question: To what degree does the system ontology have an appropriate coverage of the domain of interest
  - **Conciseness** – Question: To what degree is there an absence of unnecessary or useless definitions or axioms in the system ontology?
  - **Practical usefulness** – Question: To what degree can the system ontology solve practical problems?

References

INCOSE, R. (2019). Guide for writing requirements. Version 3. Prepared by: Requirements Working Group.

Degbelo, A. (2017, September). A snapshot of ontology evaluation criteria and strategies. In Proceedings of the 13th International Conference on Semantic Systems (pp. 1-8).