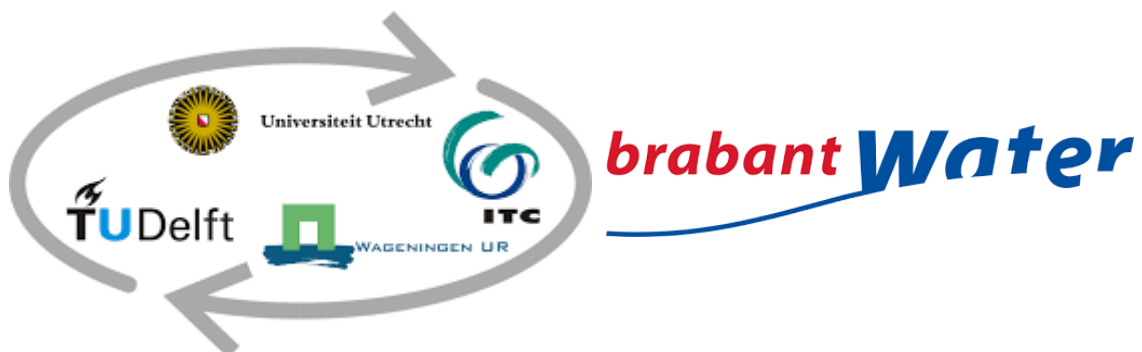# 3D GIS distribution network of Brabant Water
Possibilities for spatial decision support
Final Report

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March 2023

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Jack van Alphen – Brabant Water

3D GIS distribution network of Brabant Water
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Final Report

In Fulfilment
of the requirements for the Degree of The master
Geographical Information Management and Applications (GIMA)

Msc Thesis Final Report

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Summary

This research is focused on evaluating the potential value and benefits of transforming the Drinking Water Distribution System (DWDS) of Brabant Water from a traditional two-dimensional (2D) Geographical Information System (GIS) to a cutting-edge three-dimensional (3D) GIS in which Z coordinates are stored and maintained. The objective is to examine the possibilities of using 3D GIS with a Spatial Decision Support System (SDSS) for more effective analysis and visualization.

The study is explicitly conducted for Brabant Water and is publicly accessible, although confidential data is not disclosed. The primary research question that the study aims to address is ''*How can the drinking water distribution system of Brabant Water be transformed from a two-dimensional to a three-dimensional geographical information system, and what are the possibilities of spatial decision support system usage for Brabant Water?''*

The research delves into the various reference systems for registering underground networks in the Netherlands and introduces multiple systems, such as KLIC-Win, CityGML, INSPIRE, and IMKL standards. The text explains the accuracy of depth measurement and the regulations surrounding excavation work in the Netherlands, including the WIBON law and CROW500 publication. With excavation work on the rise, the number of damages to underground infrastructure has also increased, and therefore Brabant Water would like to minimize damage to its water networks.

The study outlines a comprehensive data governance model for Brabant Water, which outlines five crucial roles in the data flow process - data producers, owners, regulatory bodies, integrators, and users. This model is aimed at ensuring the quality, accessibility, and integrity of the data and providing clear guidelines for data management.

Despite the potential benefits of switching to a 3D GIS environment, Brabant Water faces several limitations, such as data quality, verifying depth information, possible deviations in-depth, obtaining data for new pipes, and decreased performance due to increased data usage and computing power. Nevertheless, the benefits of the transformation to a 3D GIS include more accurate analysis, improved communication and collaboration, and the ability to make more extensive geospatial analyses like the relationship between water temperature and soil temperature, which can be calculated by knowing the depth of the DWDS.

The growing volume of big geospatial data from sources like Global Positioning Systems (GPS), smartphones, and Internet of Things (IoT) creates a significant challenge in obtaining valuable insights. However, SDSS and Mixed Reality (MR) technologies like Augmented Reality (AR) and Virtual Reality (VR) in relation to 3D GIS can provide a solution to this challenge. AR and 3D GIS can be utilized by field workers to examine complex underground infrastructure, outage management, and maintain the DWDS.

Brabant Water is considering requiring contractors to report Z coordinates to enhance data quality. More measured Z coordinates also contribute to a reliable future digital twin. The analysis will consist of five Models using datasets such as the DWDS, Dutch opensource elevation data of the ground surface (AHN4), and measured Z coordinates. The output will be a comprehensive data model with a field for tracking measurement methods and storing Z coordinates for depth and surface level and the difference between the two. The Z coordinate measurement data will be merged with the AHN4 to create a comprehensive Z coordinate DWDS dataset.

The ultimate goal of the study is to create a complete dataset with Z coordinates for Brabant Water by following the five-Model process that involves clipping, validating, placing, creating, and merging datasets using FME software and ArcGIS Pro. The resulting 3D GIS system will be optimized for AR applications. It will include adding vertical reference features to emphasize the distance to the surface level from the pipe in AR and to track the Z coordinates' quality via the data model.

In conclusion, the study presents a change strategy for Brabant Water to create a 3D GIS by integrating Z coordinate datasets into the DWDS. Z coordinates from the AHN4 will be used when the DWDS lacks measured Z coordinates. The data model will track Z coordinates and using vertical reference features that also can be used to show the distance from the pipe to the ground surface in AR.

I am pleased to present my master's thesis titled "3D GIS distribution network of Brabant Water and possibilities for spatial decision support." This thesis is submitted in fulfillment of the requirements for the Master of Science (MSc) degree in Geographical Information Management and Applications (GIMA), a collaborative program between the universities of Delft, Utrecht, Wageningen, and Twente in the Netherlands, each with their own expertise in the field of Geo-Information.

Throughout my engagement from May 2022 to March 2023, I had the opportunity to work in collaboration with the Technical University (TU) Delft and Brabant Water, a Dutch drinking water utility, to explore the analysis and visualization of 3D GIS data. I chose this topic because of my interest in exploring new techniques and applications of 3D GIS data, which I had limited experience with before embarking on this research.

I learned to analyze point clouds using AHN4 data and integrate this data with underground utility networks (UUNs) to produce 3D datasets using FME and ArcGIS Pro. Additionally, I gained knowledge on how to apply 3D GIS data for Augmented Reality (AR) applications and its practical usage in the field. Brabant Water provided me with the opportunity to experiment with an AR application and discover its possibilities.

I extend my sincere appreciation to my supervisors from TU Delft, Prof.dr.ir. Peter van Oosterom and Ir. Edward Verbree, for their valuable guidance and support throughout my research. Their expertise and direction pointed me in the right direction, providing me with new ideas and opportunities to develop my research.

I am also grateful to the professionals at Brabant Water, including Jack van Alphen, Harrie van Meel, Daan van Os, Roel Diemel, Sjanny van Laar, and Ed van Leeuwen, for their support and guidance throughout the project. Furthermore, I would like to thank Hans Tan, Annerieke van Vessem and Kitty Poelgeest - Lombarts for their assistance with the AR application and various field visits to test 3D GIS data. Diemer Cohen Stuart from V-Labs provided excellent technical support in developing new features for the AR application.

Finally, I would like to thank my family, friends, and girlfriend for their unwavering support and encouragement throughout my thesis. And to my readers, I hope you enjoy reading my thesis research.

Sibe van den Beukel,
Rotterdam, March 3, 2023

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List of terms

2D	2D contains two dimensions in X and Y coordinates.
2.5D	2.5D can be used for simulation by assigning Z coordinates to points, lines, and planes. Each point, line, or plane has a single Z coordinate per vertex.
3D	3D geometry can be recorded by assigning a Z coordinate to each point, line, or plane in a 2D representation, creating a Digital Terrain Model, and integrating objects at the correct height above or below ground level, resulting in a complete 3D object with volume.
AHN(4)	Dutch opensource elevation data of the ground surface (Actueel Hoogtebestand Nederland). 4 is the fourth edition of the dataset.
AR	Augmented Reality.
ArcGIS	Geographical Information System software by Esri Inc., Redlands (USA).
BGT	The basic registration of large-scale topography (BGT).
BIM	Building Information Model (Bouw Informatie Model).
CAD	Computer-Aided Design.
Ch(s)	Chapter(s).
CityGML	CityGML is a data model for the representation of urban objects in 3D.
Datum	A datum is a reference for measuring positions on Earth and defining a geographic coordinate system.
DGNSS	Differential GNSS.
DWDS	Drinking Water Distribution System.
DWG	Drawing files used in AutoDesk Applications like AutoCAD.
EGNOS	European Geostationary Navigation Overlay Service.
FGDB	File GeoDataBase.
GIS	Geographical Information System.
GNSS	Global Navigation Satellite System.
GPR	Ground Penetrating Radar.
GPS	Global Positioning Systems.
IoT	Internet of Things
IMKL	Information Model for Cables and Pipelines (Informatie Model Kabels en Leidingen).
INSPIRE	Digital network for exchanging data about the living environment.
KLIC-WIN	KLIC-WIN is an elaboration and application of WIBON and INSPIRE.
LARA	LBS Augmented Reality Assistive System for Utilities Infrastructure Management through Galileo and EGNOS.
LADM	Land Administration Domain Model.
LOD	Level of Detail.
NAP	Amsterdam Ordnance Datum (Normaal Amsterdams Peil).
NLCS	NLCS is the Dutch CAD standard with its own color scheme and is used for internal data sharing within AutoCAD.
MAGIC	Mapping Assets and Geographic Information System.
PMKL	Presentatie Model Kabels en Leidingen.
PPP	Precise Point Positioning.
RD	RD coordinates (Rijksdriehoeksstelsel) is the coordinate system that is used in the Netherlands on a national level.
RDNAPTRANS	Rijksdriehoek, Normaal Amsterdam Peil, Transformation.
RTK	RTK is short for Real Time Kinematics. RTK is a GPS receiver that uses correction signals to achieve 1-centimeter positional accuracy.
RQ	Research Question.
SA	Situational Awareness.
SBAS	Satellite-Based Augmentation System.
SDSS	Spatial Decision Support System.
SMEs	Small to Medium Enterprises.
UID	Underground Infrastructure Data.
UNM	Utility Network Model in ArcGIS by Esri.
UUN(s)	Underground Utility Network(s).
VR	Virtual Reality.

WIBON	Law of above and below ground utility networks information exchange (Wet Information-uitwisseling Bovengrondse en Ondergrondse Netten en netwerken).
WION	Law for information exchange of underground utility networks (Wet Informatie-uitwisseling Ondergrondse netten).
XML	eXtensible Markup Language.
XSD	XML Schema Defenition: Specifies how elements in an XML should be formally described.

1. Introduction

Registering and managing Underground Utility Networks (UUNs) have always been a concern in many countries, including the Netherlands (Du, Zlatanova, & Liu, 2006). Accurate Underground Infrastructure Data (UID) about the location and depth of cables and pipelines is crucial to minimize risks and prevent problems and accidents. Utilities that manage underground infrastructure in the Netherlands register their data in a Geographical Information System (GIS). Recording GIS data often happens in a two-dimensional (2D) environment. A 2D GIS has proven to be a helpful tool for maintaining networks and managing data effectively. However, an increasing amount of underground infrastructure is being placed in the Netherlands. This trend is projected to persist, increasing the concentration of objects above and below ground. A crowded underground infrastructure especially applies to cities due to the increased need for housing and already crowded underground infrastructure (Koek, 2020). As the Dutch Cadastre notes (Bliemer, Eertink, & Staarink, 2021), the demand for data in the registries and the complexity of relationships between the various registries has been growing, thus necessitating the development of a new outlook for the future of basic registration systems. As a result, the demand for underground solutions and the need for accurate data from utilities will only increase.

This research is performed for Brabant Water, a water utility in the Netherlands, with the province of Noord-Brabant as a management area. Brabant Water can be defined as an unlisted public limited company whose shares are divided over the province of Noord-Brabant (31.6%) and 50 municipalities (68.4%) into specific distribution areas (Brabant Water, 2022a). Their water distribution network is essential for the province of Noord-Brabant and is considered critical infrastructure. Brabant Water maintains its distribution network in GIS, which is three-dimensional (3D) enabled, but the data is used in 2D. Brabant Water registers Z coordinates with revisions and newly placed pieces of the Drinking Water Distribution System (DWDS). Z coordinates are also registered for depths of the DWDS that diverge from the standard depths. Transport pipes are located at a standard depth of 1,20 meters below the ground surface, distribution pipes 1 meter, and connection pipes 0,80 meters (Penninga, & Van Oosterom, 2006; Pieterse-Quirijns, De Groot, De Rijck, Ruijg, 2011; Van Os, 2022). All of the pipes above are considered the DWDS. When the depth diverges from the standard depth, this is registered in a separate GIS point file. In theory, all the deviation depths are registered in GIS. It should be recorded when this is not the case, and another depth is detected. Otherwise, the standard depths apply, which is assumed for most of the DWDS.

Project MAGIC (Mapping Assets and Geographic Information System) went live in December 2020, which was the transfer to a new GIS network model: The Utility Network Model (UNM) of Esri. Since then, Z coordinates have been registered in the GIS DWDS. About 10.000 of 1.725.000 DWDS pipes have one or more Z coordinates attached to them, roughly 0,58% of the network when looking at feature count. Brabant Water is considering registering Z coordinates for all new measured distribution pipes, including projects from contractors (often those are not registered as contractors don't have to report the Z coordinate), laying the foundations for a 3D GIS network. However, since each vertex can only have one Z coordinate, no tilt is possible, making it a two-and-a-half dimensional (2.5D) representation. The way measurements are performed is stored in the attributes of the DWDS. However, each object representing one attribute can have multiple vertices beneath them. Some of these vertices can have Z coordinates, and others won't. Although most objects, as explained above, won't have any Z coordinates, which is a lack in the data model since one field in which the way the measurements are recorded is not enough when multiple measurements in multiple ways are performed under one object. This thesis will further elaborate on how this will look exactly. By using 3D GIS, Brabant Water would like to perform more accurate analyses of factors affecting its DWDS depending on the depth of it, such as soil pollution, subsidence, tree roots, effective maintenance, mitigation of defects, etc.

Not only analysis in 3D is promising, but also in visualization, it can be of added value for Brabant Water, especially when both the depth and diameter are taken into account in visualizing the distribution network. In fieldwork, the situation can be more easily interpreted in the case of complex underground infrastructures with many stakeholders involved (Smits & Wang, 2019). This process can improve communication with other UUNs (e.g., municipalities for sewer and district heating, grid managers, natural gas, etc.). GIS can thus potentially be used as a Spatial Decision Support System (SDSS), a system that provides decision aid in infrastructural planning (Coutinho-Rodrigues, Simão, & Henggeler Antunes, 2011), helping Brabant Water with dealing with the problems of now and of the future.

1.1. Identification of the problem

From the literature, several relevant problems were identified. Next to the literature, several problems related to Brabant Water were identified. First, the problems from the literature will be addressed. Subsequently, the problems which link to Brabant Water will be addressed.

1.1.1. Problems related to Brabant Water

Brabant Water is facing several challenges, including a retirement wave, a digitizing society, an out-of-balance water system, and increasing costs of resources. To address these challenges, Brabant Water needs to utilize the information available to make better decisions. However, a lot of information is out there, including knowledge in the heads of employees who are increasingly retiring, that needs to be incorporated into a system to make full use of it. Therefore, the problem from the perspective of Brabant Water in relation to this research is how to effectively capture and utilize the available information to make better decisions and address the challenges faced by Brabant Water. The challenges are stated below:

- Retirement wave: Brabant Water faces a retirement wave for a substantial part of its employees. A lot of knowledge, for instance, for mechanics about pipe locations, is stored in the head. This knowledge must be captured in a centralized system to use it to its full potential and pass it on to the next generation.
- Digitizing society: In relation to this, there are a lot of individual files that contain essential information. An example can be directional drilling of pipes stored in Computer-Aided Design (CAD) or PDF files which contain the respective coordinates of the pipes. In an increasingly digitizing world, this information is expected to be put in a smart system with all relevant information. Data coherence is created if this information is put in a smart system instead of individual files, and smart solutions can be made. In this case, for geographical data, this is a GIS.
- Out-of-balance water system: Currently, more water is produced than sold, which means water is lost due to leakage. Optimal data of optimal quality can help in identifying these kinds of problems and tackling them.
- Increasing costs of resources: Due to rising costs of resources, Brabant Water is looking at innovation and smart solutions where costs can be saved.

1.1.2. Problems from the literature

Pieterse-Quirijns et al. (2011) reported that the depth of a substantial portion of underground infrastructure remains unknown to many water utility companies. According to Van Os (2022), for most of the DWDS, the exact depth is unknown and the standard depths from table 1 are assumed. 3D GIS can provide significant benefits to utilities in understanding their UUN. Firstly, it can act as a supportive tool for planning processes by preventing distribution pipes from being placed too shallow or exceeding temperature limits that could pose health hazards (Pieterse-Quirijns et al., 2011). Secondly, it can provide added value through visualization for communication with customers, contractors, and stakeholders (Smits & Wang, 2019). Thirdly, it can decrease the time needed to analyze and understand the situation of underground situated assets. The limitations of 2D visualization with overlapping pipelines to provide accurate and reliable information about UUNs are highlighted by Penninga and Van Oosterom (2006). Fourthly, when the position of UUNs is better known, it can potentially reduce excavation damages resulting from land-level changes (Penninga & Van Oosterom, 2006). Therefore, a depth relative to the Amsterdam Ordnance Datum or Normaal Amsterdams Peil (NAP) is beneficial to register the DWDS for long-term accuracy. In Brabant, subsidence is minimal compared to the West of the Netherlands, mainly due to soil characteristics (Stowa, 2020). However, ground-level changes may still occur (Penninga & Van Oosterom, 2006). Research has been conducted to investigate the benefits of 3D GIS for UUNs, with findings indicating that it enables more visible relationships between other pipes, objects, and related assets, thereby reducing the chances of misunderstanding (Du et al., 2006). Guerrero, Zlatanova & Meijers (2013) highlight the need for a smooth 3D visualization experience to reduce blind cutting and fault damage to pipelines. Chong (2006) argues that registering 3D components is necessary for the Dutch cadastre as it provides efficient means to register and provide the legal status of objects with a 3D component.

Despite the benefits of 3D GIS, Brabant Water has not yet implemented a 3D GIS distribution network. Previous research done explicitly at Brabant Water regarding 3D GIS suggests future research in this field (Kennedy, 2013; Smits & Wang, 2019). In 2013 research was done concluding that, at the time, it was too soon to take the step to a 3D GIS network. There was little available elevation information on the distribution network of Brabant Water, fewer 3D GIS analysis tools available, and no Dutch open-

source elevation data of the ground surface or Actueel Hoogtebestand Nederland (AHN). Furthermore, the quality and the costs of the AHN data were also a barrier (Kennedy, 2013). At this time, the quality in terms of point density of the AHN has increased in resolution from 6-10 points per m2 on average for AHN2 and AHN3. AHN4 increased to 10-14 points per m2 on average (AHN, 2022). The AHN has become opensource now as well. Also, more 3D GIS tools have become available.

3D is a promising technique for analysis and visualization purposes. Utilities and government organizations are increasingly implementing this technology, making research in this field more relevant. In the Netherlands, Rotterdam is an excellent example of this. Rotterdam's municipality has built a 3D model of the city, including underground infrastructure, based on registration, elevation, management, and pictures, demonstrating the increasing implementation of this technology (Rotterdam, 2022). The Dutch cadastre aims to make a complete 3D overview of the Netherlands by ensuring interoperability between above-ground and underground registrations, which can provide a realistic view of the private and public law situation, as well as facilitating the development of digital twins (Bliemer et al., 2021). Brabant Water is actively working on developing digital twins using 3D modeling. As 3D becomes more relevant for the Dutch cadastre, it becomes more suitable for utilities to report their data to the cadastre in 3D, but guidelines for reporting this data are crucial (Stoter, Louwman, Ploeger, & Van Oosterom, 2011).

Therefore, this research seeks to identify the barriers and added value of a 3D GIS for the UNM of Brabant Water and aims to develop strategies to transform the network to a 3D GIS environment and data usage. Furthermore, opportunities arise for SDSS in combination with 3D GIS. Brabant Water and potentially other water utilities should also benefit from the innovations in the field of GIS and the added value that a 3D GIS network can bring them in terms of better decision-making.

Table 1: Overview of types of UUN and their size in the Netherlands.

Network	Type	Scope (km)	Depth (cm)
Electricity	High voltage (50/110/150 kV)	3.500	100
	Medium voltage (3 t/m 25 kV)	103.000	80
	Low voltage (0,4 kV)	150.000	60
Gas transport	High pressure (40-80 Bar)	11.600	120
Gas distribution	Medium and high pressure (1-8 Bar)	88.150	90
	Low pressure (<0,1 Bar)		90
District heating	N/a	3.600	80-100
Telecom (Group)	Routes (often 2 casings per route)	>15.000	30-60
Telecom (KPN)	Routes	225.000	30-60
CAI (Radio/TV)	Routes (often 2 casings per route)	>150.000	30-60
Sewer	N/a	82.406	110
Water transport	Main and transport network	109.366	120
Water distribution	Distribution pipes	Unknown.	100
Water connection	Connection pipes to properties		80
Industrial transport pipes	N/a	3.500	120
Public lightning	N/a	>150.000	Unknown
House connections	All grids	>150.000	30-90
Remaining	Unknown	Unknown	Unknown
Total	N/a	>1.279.122	N/a

Source: Penninga & Van Oosterom, 2006; Pieterse-Quirijns et al., 2011.

1.1.3. Coherence of problems
From the literature, one major problem is the unknown depth of underground infrastructure for many water utility companies. This unknown depth also applies to most of the DWDS of Brabant Water, where the exact depth remains unknown. Knowing the depth of the DWDS in a digital twin in GIS would be beneficial for planning processes, visualization for communication, analyzing assets, and maintaining long-term accuracy. Another problem is the retirement wave and digitizing society faced by Brabant

Water, which requires the effective capture and utilization of available information to make better decisions and address the challenges faced. This includes capturing knowledge stored in employees' heads, centralizing individual files, and identifying and tackling problems with the DWDS to reduce costs.

1.1.4. Scope

The scope of this research has been identified to maximize the utility of this research. The scope of this research is presented in figure 1.

Figure 1: The scope of this research.
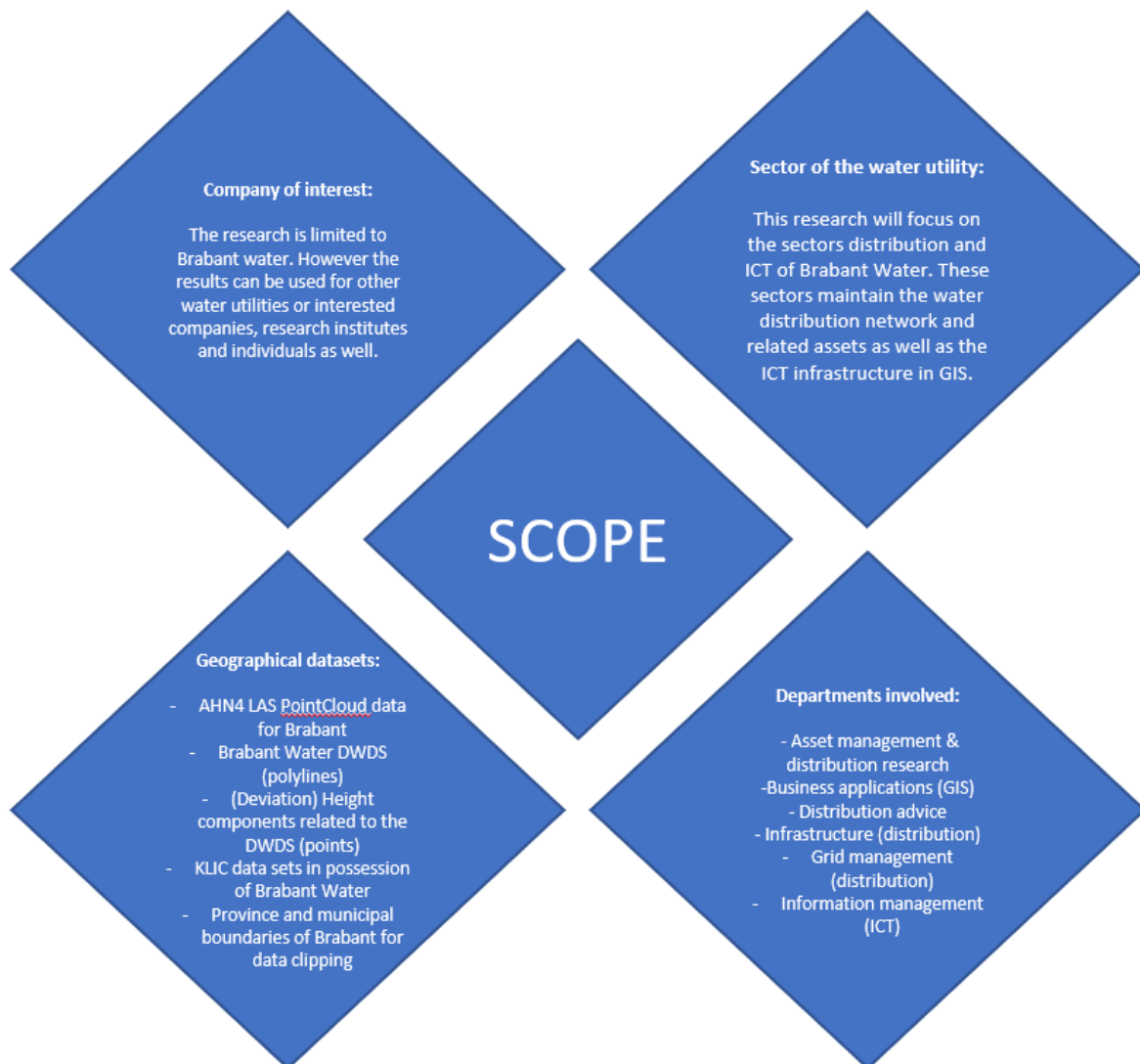
This research is limited to and written for Brabant Water but can be used as a framework for other water utilities or interested companies and individuals. The study is about the added value of a 3D DWDS in terms of spatial decision support for Brabant Water and how to get to a 3D environment. An analysis to generate Z coordinates relative to NAP for the DWDS is part of this research. The entire distribution area will be used to assign Z coordinates using the AHN4 and measured Z coordinates. However, first, a smaller test and study area will be analyzed within the municipality of 's-Hertogenbosch. The methodology for this analysis will be further elaborated upon in chapter 6 of the research report, so it will be possible for Brabant Water to reproduce this analysis.

The research will take place at the headquarters of Brabant Water in 's-Hertogenbosch. This research will be publicly accessible, but the data of Brabant Water used in this research won't be. The utility

network remains confidential and cannot be shared as it's critical infrastructure on which safety precautions apply.

1.1.5. Out of scope

Using the MoSCoW method, the boundaries of this research will be made clear (Van Vliet, 2007). The MoSCoW method prioritizes tasks, particularly in software engineering projects. Using the MoSCoW method, the requirements of the results of a project are classified. During this project, there will still be the possibility to switch must requirements to should requirements and vice versa, but the aim is to complete all must requirements. MoSCoW is an abbreviation for (Van Vliet, 2007):
- M – Must haves: these are the requirements that have to appear in the result. Without these requirements, the product is not usable;
- S – Should haves: These requirements are highly desired, but without them, the product is still usable;
- C – Could haves: These requirements will only be addressed if there is enough time;
- W – Won't haves: These requirements will not be discussed in this study but may be interesting for future research.

An overview of this project using the MoSCoW Method is provided in table 2.

Table 2: MoSCoW method: The requirements for the research for Brabant Water

MoSCoW:	Requirements for the research for Brabant Water:
M – Must haves:	- Developments and goals explained concerning 3D GIS. - Analysis of involved parties for the GIS data flow of Brabant Water concerning data acquisition and registration for the DWDS. - Limitations and added value of 3D data utilization. - Explained how a 3D GIS can help as an SDSS. - Explained how measured spatial information for the DWDS is currently handled and processed. - The method described how the depth relative to NAP for the DWDS could be determined using GIS and AHN4 point clouds. - Apply the above method and show results for Augmented Reality (AR) in the study area of the municipality of 's-Hertogenbosch. - Test deviation of measured Z coordinates to AHN4 reference level. - Explained how the DWDS will be projected with height data in GIS (e.g., start and end point, middle point, etc.). - Explained how the DWDS can be transformed from a 2D to a 3D GIS. - The research is limited to the DWDS.
S – Should haves:	- A dataset in 3D with the depth relative to the NAP of the DWDS for either the study or the entire distribution area.
C – Could haves:	- Elaborated examples can be given and explained of possible analyses performed with the generated 3D AHN4 height dataset of the DWDS.
W – Won't haves:	- Other assets of Brabant Water than the DWDS won't be considered, like valves and fire hydrants. - Other stakeholders concerning Brabant Water related to data acquisition and registration won't be considered. - There will be only 1 test, 1 study, and one distribution area, which are the boundaries for the DWDS of the Paleiskwartier, the municipality of 's-Hertogenbosch, and the distribution area. - Pipes located beneath buildings, bridges, canals, rivers, and surface water in general and don't have a deviation depth won't be considered. The AHN4 offers no river bottom data of surface water and neither of the ground surface below buildings and bridges. Moreover, the data on the depth is not standard for these kinds of pipes. Their height data is registered in individual construction drawings, making it hard to get it into a database. Therefore, these places will not be taken into account as well. Since there is limited time available, these pipes are out of the scope of this research if deviation depth is not available.

1.1.6. Research questions and objectives

This thesis aims to investigate the possibilities and the added value of a 3D DWDS for Brabant Water and the possibilities for SDSS. This is expressed as the following main research question:

How can the drinking water distribution system of Brabant Water be transformed from a two-dimensional to a three-dimensional geographical information system, and what are the possibilities of spatial decision support system usage for Brabant Water?

Table 3 presents the sub-research objectives and the related sub-research questions. The italics and underlined sub-research objectives are the chapters' headings corresponding to the research questions.

Table 3: The research objectives and the linked research questions

Nr.:	Sub-Research objective:	Sub-Research question:
1	*Identifying requirements, developments, and goals concerning excavation work, three-dimensional geographical information system for UUNs, and spatial decision support systems for Brabant Water*. Elaborate on reference systems, vertical reference systems, and Dutch reference systems, the legal framework for 3D and UID, developments regarding excavation work and UUN, and goals for Brabant Water concerning 3D GIS and SDSS.	What are the requirements, developments, and goals concerning excavation work, a three-dimensional geographical information system for underground network registration, and spatial decision support systems for Brabant Water?
2	*Identifying how spatial data is obtained for the drinking water distribution system* and if and how this data is processed in the (geo)databases of Brabant Water (also identify what's happening with the Z coordinate). Identify all the parties involved in the GIS data flow of Brabant Water.	How is measured spatial information of the drinking water distribution system of Brabant Water currently handled and processed?
3	*Identifying limitations and added value of a three-dimensional geographical information system for the drinking water distribution system of Brabant Water.* Research the pros and cons of introducing a 3D GIS system for Brabant Water's management of assets, analysis, visualization, and fieldwork related to UUNs, specifically the DWDS.	What are the limitations, and what is the added value of a three-dimensional geographical information system for the drinking water distribution system for Brabant Water?
4	*Identifying how a three-dimensional geographical information system can be used as a spatial decision support system in combination with Brabant Water goals.* Look at Virtual Reality (VR) and AR in combination with 3D GIS concerning fieldwork. Go into technical details and utility fieldwork from the literature. The field tests with AR will be displayed in the results of chapter 5.	How can a three-dimensional geographical information system be used as a spatial decision support system in combination with the goals of Brabant Water?
5	*Identifying the depth relative to the NAP of the drinking water distribution system and available KLIC datasets using current available Dutch open-source elevation data of the ground surface (Actueel Hoogtebestand Nederland).* Research how the depth relative to the NAP of the DWDS can be determined using the standard depths combined with the AHN4. Explain how depth should be displayed relative to the ground surface & in NAP. With this data, it's possible to do a test with an AR application.	How can the depth relative to the NAP of the drinking water distribution system and available KLIC datasets of Brabant Water be determined using Dutch open-source elevation data of the ground surface (Actueel Hoogtebestand Nederland)?
6	*Change strategy plan – going from a two-dimensional to a three-dimensional geographical information system of Brabant Water.* Identify how the current spatial data can be transformed and used in a change strategy plan from a 2D to a 3D GIS environment. Consider how the data should be registered regarding data interoperability and standards (average, min/max depth, begin, end, middle point, and standards like IMKL, INSPIRE gov/utility services). Also, describe regarding data quality how missing data should be handled.	How can the drinking water distribution system be transformed and used from a two-dimensional to a three-dimensional geographical information system at Brabant Water?

1.2. Methodology

The methodology is described in the text for each research question (RQ). At the end of each subchapter, an overview of the methodology steps and their corresponding research method is given in tables.

1.2.1. Identifying requirements, developments, and goals

The objectives of Brabant Water regarding 3D GIS and SDSS will be determined. This chapter will focus on current advancements in 3D GIS for underground infrastructure registration, regulations, and standards. The use of vertical reference systems and Dutch reference systems regarding the legal framework for 3D and UID will be examined. Additionally, the goals for Brabant Water concerning 3D GIS and SDSS will be discussed. Table 4 provides a summary of the methodology for research question 1.

Table 4: Required data, software, and research materials for RQ1.

Research part:	Research method:
- Research the reference systems needed for registering 3D data, including vertical and horizontal reference systems, and provide background information. - Research regulations and standards for registering 3D GIS data, specifically UUN, UID, and excavation work. - Developments in excavation work in terms of excavation notifications and damage trends. - Brabant Water goals in relation to 3D GIS and SDSS	Literature review, desk research, and interviews

1.2.2. Spatial data flow of Brabant Water

Research the process of gathering spatial and depth information for the DWDS using desk research, interviews, field visits, and GIS data examination. Also, examine current DWDS information and (deviation) depth in available datasets. Table 5 provides an overview of the methodology for RQ2.

Table 5: Required data, software, and research materials for RQ2.

Research part:	Research material:
- Research spatial data acquisition and measurement for the DWDS, including depth information and the current data model, through desk research, interviews, field visits, and examination of GIS data. - Conduct field visits to understand the land survey process and spatial data flow at Brabant Water. - Examine and describe the datasets of the distribution network and the deviation depth point file.	Desk Research and interviews, field visits, and GIS dataset examination.

1.2.3. Limitations and added value of a 3D GIS

Analyze the benefits and challenges of implementing a 3D GIS system at Brabant Water. Identify potential roadblocks and explore the benefits, such as improved asset management, analysis, visualization, and fieldwork for UUN. Investigate how 3D GIS can be used as a decision-making tool. Conduct interviews with experts. Table 6 gives an overview of the methodology for RQ3.

Table 6: Required data, software, and research materials for RQ3.

Research part:	Research material:
Investigate the limitations and benefits of implementing a 3D GIS system for Brabant Water in asset management, analysis, visualization, and fieldwork for UUN, especially the DWDS.	Literature review, desk research, and interviews

1.2.4. 3D GIS as a spatial decision support system

In this RQ, the goals of Brabant Water with GIS and SDSS were identified, such as modeling, visualization, and geo-analytics for spatial decision support. However, Brabant Water wants to integrate smart glasses into mechanics' work processes. This RQ will explore new ways of using 3D GIS in this context through a literature review and a field visit to test available AR smart glasses with geospatial data. RQ5 will focus on the testing, while RQ4 will cover the literature background for smart glasses and AR. Table 7 gives an overview of the methodology for RQ4.

Table 7: Required data, software, and research materials for RQ4.

Research part:	Research material:
• New ways of using (3D) GIS as a spatial decision support system with a focus on AR.	Literature review, desk research, interviews, and field visits.

1.2.5. Identifying depth relative to NAP for the DWDS using AHN4 data

This analysis will use various study areas (figure 2). A small test area will be used during this analysis to test tools and workflows. The next step will be explained below. The AR tests are also performed in the test area since the test sites are close to the headquarters of Brabant Water. KLIC data is nearby, and two directional drilling sites are in the area, which can be used to show the added value of AR in the case of deviation depth. The data, however, was prepared for the entire municipality of 's-Hertogenbosch and later for the whole distribution area.

Figure 2: Map of the test, study, and distribution area for the GIS analysis.

Paleiskwartier (test area), Municipality of Den Bosch (study area) and Province of Noord-Brabant (distribution area)
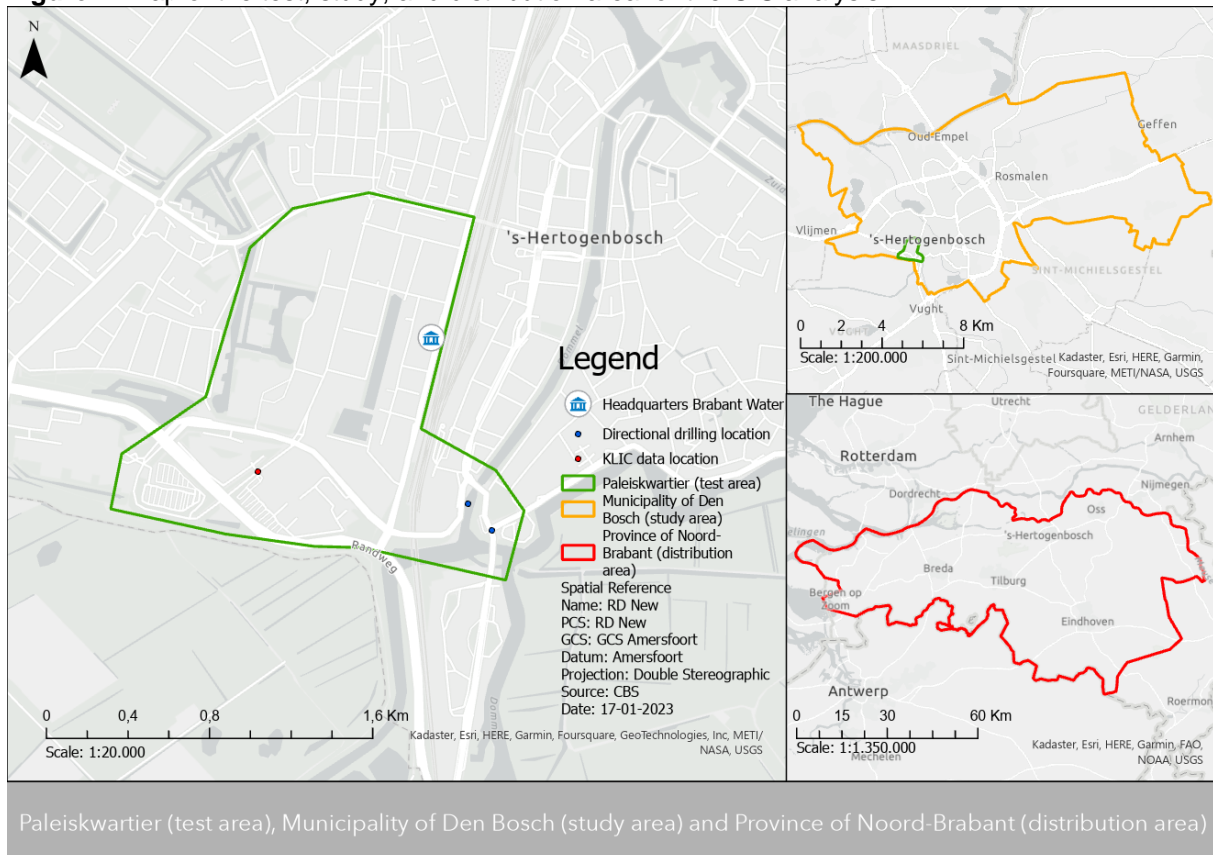
Source: own map.

Currently, most of the Z coordinates are lacking, and there is only a dataset with deviating depth for a small portion of the DWDS and Z coordinates for 0.58% of the DWDS. The AHN4, a high-quality dataset containing data about the Netherlands' ground surface, will be used to assign a depth relative to the NAP to the DWDS using the standard depths in table 1 by matching them with attributes in the database. The analysis will consist of 5 models, including the AHN4 LAS on the buffer of the DWDS (distribution area). This analysis will be performed on a personal computer with an additional 2 Terabyte SSD card for enhanced speed.

Three datasets contain Z coordinates:

1. The first dataset, which is also the biggest, is a 3D point cloud dataset of the AHN4, which contains X, Y, and Z coordinates for a collection of points in a geographic location. These points can represent buildings, trees, terrain features, or other objects. For this analysis, only the classified ground surface values are used. Each AHN4 tile, a rectangle area, contains about

$4x10^9 - 7x10^9$, depending on the amount of surface water or surface in the Netherlands, as Belgium is not part of the dataset.

2. The DWDS in GIS contains 35.246 measurements relative to NAP.
3. The deviation depth point file contains 2.645 measurements relative to NAP and the ground surface.

The five models that are produced and used in this depth analysis are the following:

1. Using three input datasets, a personal computer with 2TB SSD, ArcGIS Pro, and FME software were used to clip the AHN4 LAS on a buffer of the DWDS.
2. The analysis aims to give insight into the data quality of the measured Z coordinates of the DWDS and deviation depth point file, compared to the NAP derived from the AHN4.
3. The data is fit for an AR application by clipping the AHN4 LAS, combining it with Z coordinate datasets from measurements, erasing Z coordinates intersecting with surface water, adjusting Z coordinates, and publishing it to ArcGIS online.
4. A feature class with vertical reference features and a data model is created using the DWDS and AHN4 height points as input.
5. A polygon is created on top of the vertical reference features to highlight the surface level in the AR application.

Table 8 gives an overview of the methodology for RQ5.

Table 8: Required data, software, and research materials for RQ5.

Research part:	Research material:
• Determine the depth relative to the NAP of the DWDS using the standard installation depth. Using GIS analysis, subtract the depth relative to NAP from the AHN4 LAS ground surface values.	GIS & FME analysis • Height measurement data of deviation depth dataset. • DWDS data • AHN4 point cloud data with CLASS_CODE = 2 Ground surface (to only use the ground surface point values). • First, analyze the test area, the study area, and, subsequently, the distribution area.
• Explain how the depth should be displayed in the distribution network	Literature review, desk research, and interviews.

1.2.6. Change strategy plan – going to a 3D GIS

Develop a strategy for Brabant Water to transition from a 2D to a 3D GIS and incorporate Z coordinates in their DWDS using AHN4 or existing datasets. The strategy will consider the best approach for Brabant Water, including how depth should be displayed and registered, the most efficient way to transition to 3D GIS, data quality improvements, and combining datasets that contain measured Z coordinates. For the remaining DWDS, Z coordinates will be calculated using the AHN4.

Table 9 gives an overview of the methodology for RQ6.

Table 9: Required data, software, and research materials for RQ6.

Research part:	Research material:
• Outline the approach for adding Z coordinates to the DWDS, including a method for calculating depth relative to the ground surface or relative to NAP, and the reasoning behind this approach.	Literature review, desk research, and interviews
• Data model to keep track of the quality of the Z coordinates.	
• Explain the best approach to transform the DWDS from a 2D to a 3D GIS infrastructure for Brabant Water in a change strategy.	

1.2.7. Overview of the research questions

Figure 3 provides an overview of all the research questions concerning each other.

Figure 3: Overview of the research questions
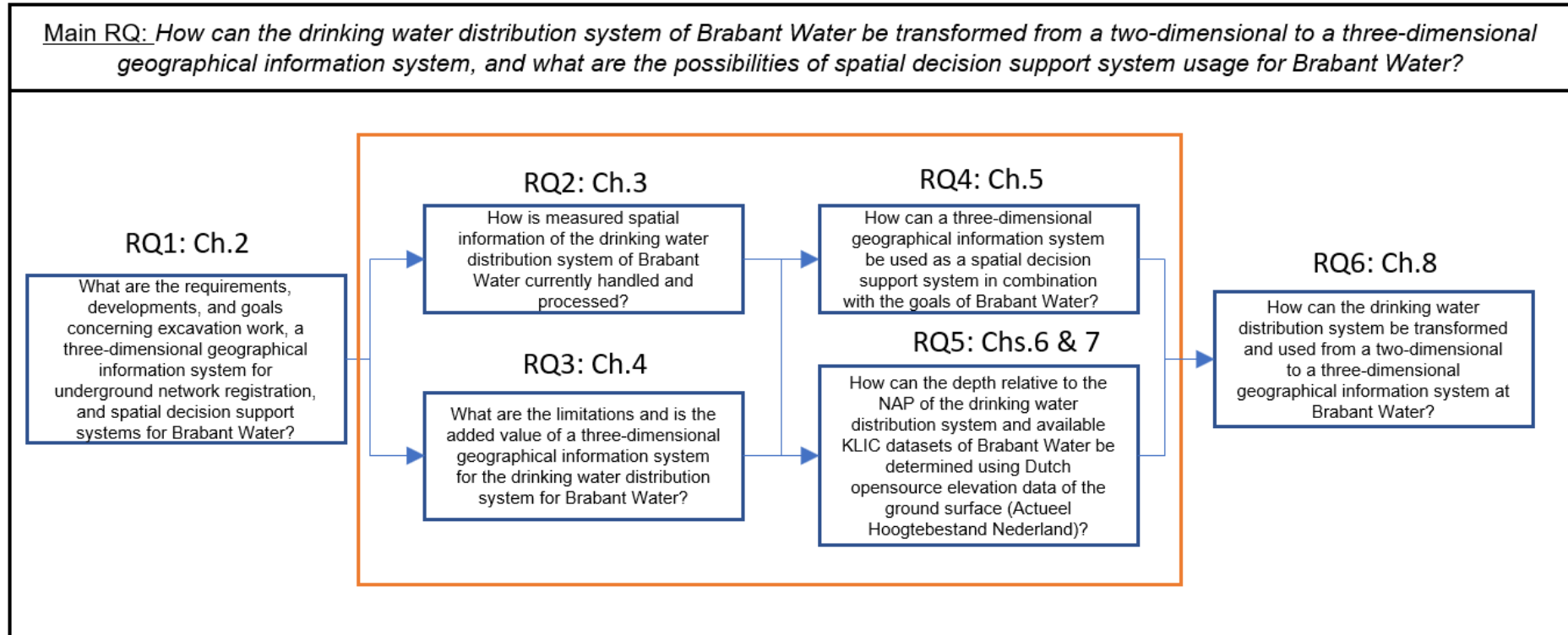
This chapter will give background information regarding requirements, developments, and goals concerning excavation work and 3D GIS for UUN registration. Several reference systems will be explored in section 2.1, including geographic coordinate systems, cartesian coordinates, Dutch national reference systems, and vertical reference systems. In section 2.2, an introduction about CityGML, INSPIRE, IMKL, 2.5D and 3D GIS data and depth information, WIBON, CROW500, KLIC-WIN, Land Administration Domain Model (LADM), UNM and the data model of Brabant Water will be introduced. In section 2.3, developments regarding excavation damages will be given, and in section 2.4, the goals of Brabant Water related to 3D GIS and SDSS will be discussed. Finally, section 2.5 will provide a sub-conclusion.

2.1. Reference systems

In geospatial positioning, various types of coordinates are employed to position objects within a 2D or 3D space. In the case of objects located on the Earth's surface or reference surface (which may be represented as an ellipsoid or sphere) in 2D space, spatial coordinates, also referred to as global coordinates, are utilized. These include geographic and geocentric coordinates in 2D or 3D space, synonymous with 3D Cartesian coordinates. On the other hand, planer coordinates are utilized for positioning objects within 2D space, such as on a flat map. Examples include 2D Cartesian and 2D polar coordinates (Knippers & Mehlbreuer, 1999).

2.1.1. Geographic coordinate systems

The most widely utilized coordinate system in geography comprises lines of geographic latitude (phi, ϕ, or φ) and longitude (lambda or λ). Lines of equal latitude are referred to as parallels and form circles on the surface of an ellipsoid. Meanwhile, lines of equal longitude are known as meridians, which are the basis for forming ellipses on an ellipsoid (figure 4). By incorporating an intrusion value (height h), a three-dimensional geographic position (ϕ, λ, h) can be obtained, which represents the height above the ellipsoid (figure 5). Geographic coordinates are always expressed in angular units, for example: ϕ = 52° 13'26.2''N, λ = 6°53'32.1''E. These coordinates are calculated based on the Amersfoort datum, and when using a different reference surface, these values will vary. A notable example of a geographic coordinate system is the one employed by Google Earth, which uses the World Geodetic System of 1984 (WGS84) datum (latitude longitude) for topographic representation. Geographic coordinates are commonly utilized to locate, store and exchange spatial data (Knippers & Mehlbreuer, 1999).

Figure 4: The two-dimensional geographic coordinate system is represented by the latitude (ϕ) and longitude (λ) angles.
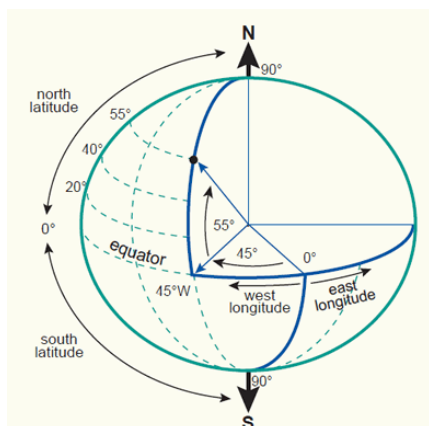
Figure 5: The latitude (ϕ) and longitude (λ) angles, as well as the ellipsoidal height (h), comprise the 3D geographic coordinate system.

Source: Knippers & Mehlbreuer, 1999
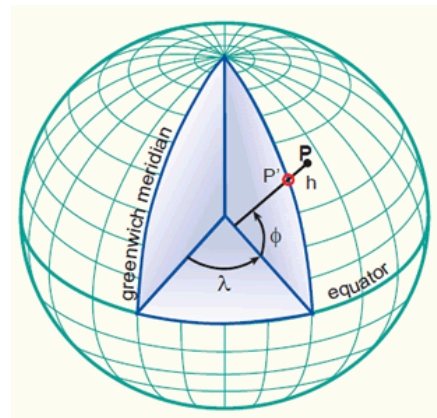
Source: Knippers & Mehlbreuer, 1999

2.1.2. Projected coordinate systems

The transformation of a three-dimensional representation of the Earth into a two-dimensional form is subject to the processes of map projections and coordinate transformations. Flat maps, by definition, possess only two dimensions: width (left to right) and length (bottom to top). To describe the location of any point on a map, projected coordinate systems, also known as Cartesian coordinates (X, Y), are employed. The two-dimensional Cartesian coordinate system is comprised of intersecting perpendicular lines, including an X-axis (referred to as Horizontal or Easting) and a Y-axis (referred to as Vertical or Northing). The intersection of the X-axis and Y-axis constitutes the point of origin. This system is characterized by evenly spaced coordinate lines, known as the map grid (Knippers & Mehlbreuer, 1999). By providing two coordinates for X and Y, any location on the map can be precisely and objectively specified, such as point p (figure 6).

The origin of a coordinate system is typically established at the point (X, Y) = (0, 0). However, in some instances, the origin may be relocated to a false origin, where negative values for X and Y are avoided if the origin falls within the region of interest. This practice is exemplified by the Rijksdriehoekstelsel (RD) coordinate system used in the Netherlands. This system employs the azimuthal stereographic projection and references the Bessel ellipsoid to approximate the shape of the Earth on a plane. The Bessel ellipsoid has mathematical properties that are useful in calculations. To avoid the use of negative coordinates within the Netherlands, the origin of the RD coordinate system was shifted from the original projection center in Amersfoort to the southwest (Knippers & Mehlbreuer, 1999) (figure 7).

Figure 6: An illustration of the 2D Cartesian coordinate system.
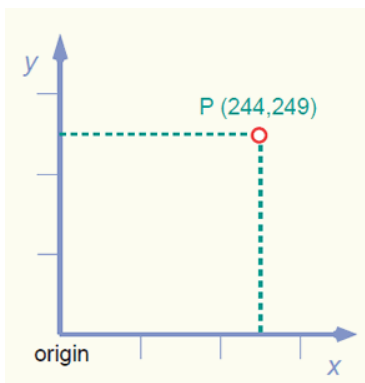
Source: Knippers & Mehlbreuer, 1999

Figure 7: The coordinate system of the Netherlands wherein the false origin is applied due to the shift of the origin from the projection centre in Amersfoort to the south-west.
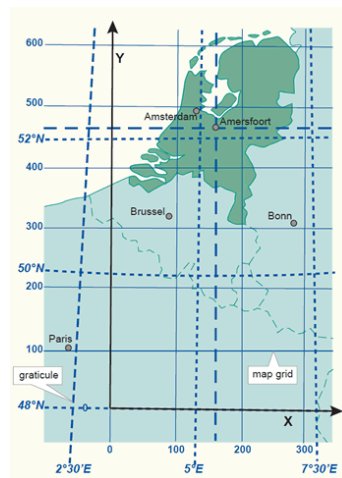
Source: Knippers & Mehlbreuer, 1999

Figure 8: An illustration showing how a three-dimensional cartesian coordinate system works.

Source: Knippers & Mehlbreuer, 1999

12
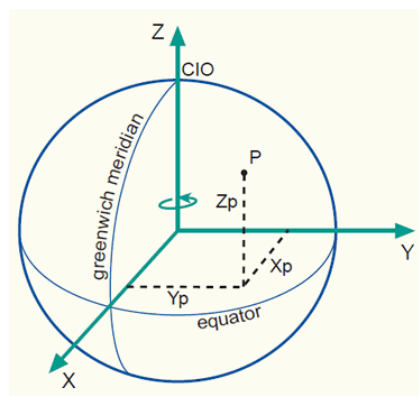
The Greenwich Meridian intersects the X-axis, while the Z-axis aligns with the Earth's rotational axis. The three axes form a right-handed orthogonal system. The 3D Cartesian coordinates specified at a given point, such as point P (figure 8), define its position on the Earth's surface (Knippers & Mehlbreuer, 1999).

2.1.3. Dutch national reference systems and vertical reference systems

A homogeneous geodetic reference system ensures precision in location and height measurements. In the Netherlands, the RD coordinates serve this purpose, while the NAP is utilized for height measurements (De Bruijne, Van Buren, Kösters, & Van der Marel, 2005). The maintenance of RD is overseen by the Dutch Cadastre and that of NAP by Rijkswaterstaat. The RD system has its roots in the 19th century and was initially based on traditional triangulation methods. With the increasing utilization of Global Positioning Systems (GPS), the GPS factors were redefined in 2000, linking RD directly to the European Terrestrial Reference System 1989 (ETRS89) via a transformation procedure referred to as RDNAPTRANS (Rijksdriehoek, Normaal Amsterdam Peil, Transformation). GPS measurements in the Netherlands are recorded in ETRS89 and then transformed to RD coordinates through RDNAPTRANS. The use of RDNAPTRANS is regulated by the Dutch Cadastre, granting access to the transformation procedure only to parties who have demonstrated their ability to effectively perform the transformation (Tiberius et al., 2021).

Figure 9: GNSS receiver Stonex S700 from Geodirect

Brabant Water utilizes the Stonex S700 - Cube A (figure 9) Global Navigation Satellite System (GNSS) receiver produced by Stonex, which incorporates the RDNAPTRANS transformation procedure (Geodirect, 2022a). The RDNAPTRANS procedure is the method by which coordinates from ETRS89 are transformed to RD coordinates and NAP height in the Netherlands. The RD system is utilized for X- and Y-coordinates, while the NAP is used for Z coordinate height measurements, referenced to NAP points. GNSS provides latitude, longitude, and altitude values. Implementing the RDNAPTRANS transformation procedure allows a land surveyor to simultaneously measure location and height with a single device through GNSS. ETRS89 is an Earth-Centered, Earth-Fixed geodetic Cartesian reference frame. The entire Eurasian plate is static, resulting in European maps and coordinates being based on ETRS89 and immune to change due to continental drift (Tiberius et al., 2021).

Source: Own photo

When utilizing GPS measurements, it became evident that distortions were present within the RD system. To address these distortions, this was modeled into the RDNAPTRANS. Despite the widespread usage of GPS technology, it has not entirely replaced traditional leveling methods in determining elevations. This is because GPS measurements do not provide the same level of accuracy as horizontal positions and because GPS measurements provide ellipsoidal heights. In contrast, orthometric heights are preferred in many applications. A vertical reference system is necessary to express the elevation of a point. While the radius to the Center of Mass of the Earth could be used as a measure, it is only practical for points in space and not on the surface of the Earth. The use of ellipsoidal height is more convenient than a more physical definition of height. However, it does have the drawback that surfaces with constant ellipsoidal height are not necessarily equipotential, which can result in undesirable water flow patterns. The RDNAPTRANS procedure provides accurate measurements of height with an accuracy of 1-2 cm, correcting and transforming from ellipsoidal height to NAP height, considering the correction for the geoid height. In the RDNAPTRANS method is also corrected for a maximum distortion of 25 centimeters in X, Y coordinates. Implementing GPS technology through RDNAPTRANS will not render the dense NAP grid obsolete soon, particularly for applications requiring millimeter accuracy (Tiberius et al., 2021).

Figure 10: Relation between ellipsoidal height *h*, orthometric height *H* and geoid height *N*.
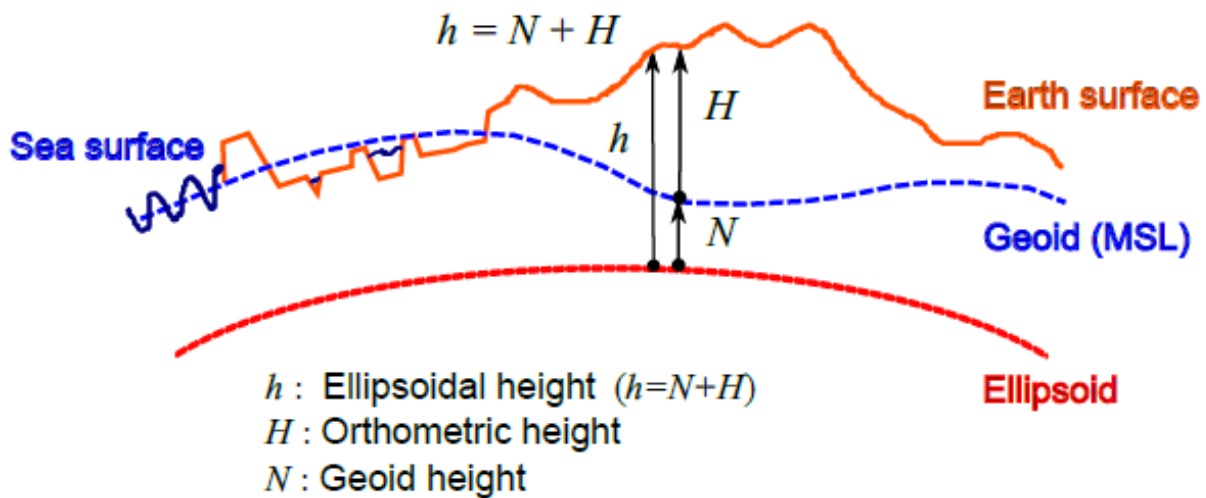
The NAP grid comprises a primary grid and a secondary grid. The primary grid shall consist of 30,000 underground points and 70 inaccessible posts, known as "nulpalen", serving as a secure foundation for the secondary grid measurements. The secondary grid comprises bronze bolts, ranging in height between 5 and 20 millimeters, affixed to objects of sufficient stability, such as buildings. The heights of these bolts are determined through leveling loops, which have an average length of 2 kilometers and exhibit precision better than 1 millimeter per kilometer. Additionally, every kilometer is marked by a bronze marker, with approximately 35,000 markers installed throughout the Netherlands. These height markers serve as geographic height reference points for various agencies and are meant to be within a radius of no more than 1 kilometer (Tiberius et al., 2021).

2.2. Excavation work, UUNs, and 3D GIS – standards & legal framework

The Netherlands implements the KLIC-Win process based on the information model for cables and pipelines (IMKL) data specification. The Law on the Information Exchange of Above and Underground Networks (WIBON) governs the exchange of information regarding cables and pipelines. The information must be made available to the Dutch cadastre (land registry). This requires a planning application to submit an excavation report during the excavation work. Network operators and utilities must also maintain digital records of cables and pipes and provide them to the land registry when requested. To comply with WIBON and INSPIRE data protocols, the KLIC (Cables & Pipes Information Centre) online tool was created for the exchange of information on cable and pipe networks, and the new KLIC-WIN system has been in use since 2017 (Dewyngaert, 2017).

2.2.1. CityGML

CityGML is a 3D data model that displays urban objects and underground infrastructure. The current version, CityGML2.0, consists of a limited number of archetypes, organized into 12 modules, most of which categorize different objects, such as buildings, bridges, and water bodies. Each class has a distinct structure and set of characteristics. CityGML geometries, represented by boundary surfaces in three dimensions, are consistent across all classes and comprise triangular and polygonal primitives. In GeoBIM, the Building Information Model (BIM), known in Dutch as the ''Bouw Informatie Model'', is the most critical component of CityGML (Noardo et al., 2022).

2.2.2. INSPIRE

The European Union's maintenance of public networks, excluding telecommunication networks, is governed by the INSPIRE directive. The INSPIRE directive mandates European member states to provide geographic information about the environment and make it accessible online. The directive aims to ensure the reliability, accessibility, compatibility, and legitimacy of geo-information in various applications and to guarantee the unambiguous coding and uniform representation of cross-border data (Mulder, 2022).

The INSPIRE Utility and Governmental Services model is the foundation for the IMKL model. Within the

INSPIRE theme, only the UNM-related models are relevant to IMKL. IMKL encompasses the entire content of the INSPIRE specification and adds the specific information necessary for IMKL processes. This allows for creating INSPIRE-compliant datasets that meet the detail requirements set forth by INSPIRE. However, it is important to highlight that IMKL, as an extension of the INSPIRE model, does not automatically make the IMKL data INSPIRE data, particularly for themes not covered by INSPIRE (Van den Berg & Janssen, 2021).

In the illustration below (figure 11), IMKL represents the INSPIRE Utility Networks. The INSPIRE Utility Networks model encompasses various network types, including electric power, gas pipelines, water and wastewater utilities, water distribution and supply, and ground-weathering initiatives. Each of these models is based on the INSPIRE network model, which incorporates a topology model and is part of the INSPIRE Generic Conceptual Model, including basic models and basic types general to all INSPIRE theme models. IMKL constitutes a separate package with its namespace and uses the packages managed by INSPIRE. The domain in which information elements are defined is referred to as a namespace, and IMKL has established standards for namespaces and abbreviations to be employed within it. The IMKL namespace is called 'IMKL' (Van den Berg & Janssen, 2021).

Figure 11: The IMKL model is depicted in relation to the INSPIRE data specifications in a diagram.
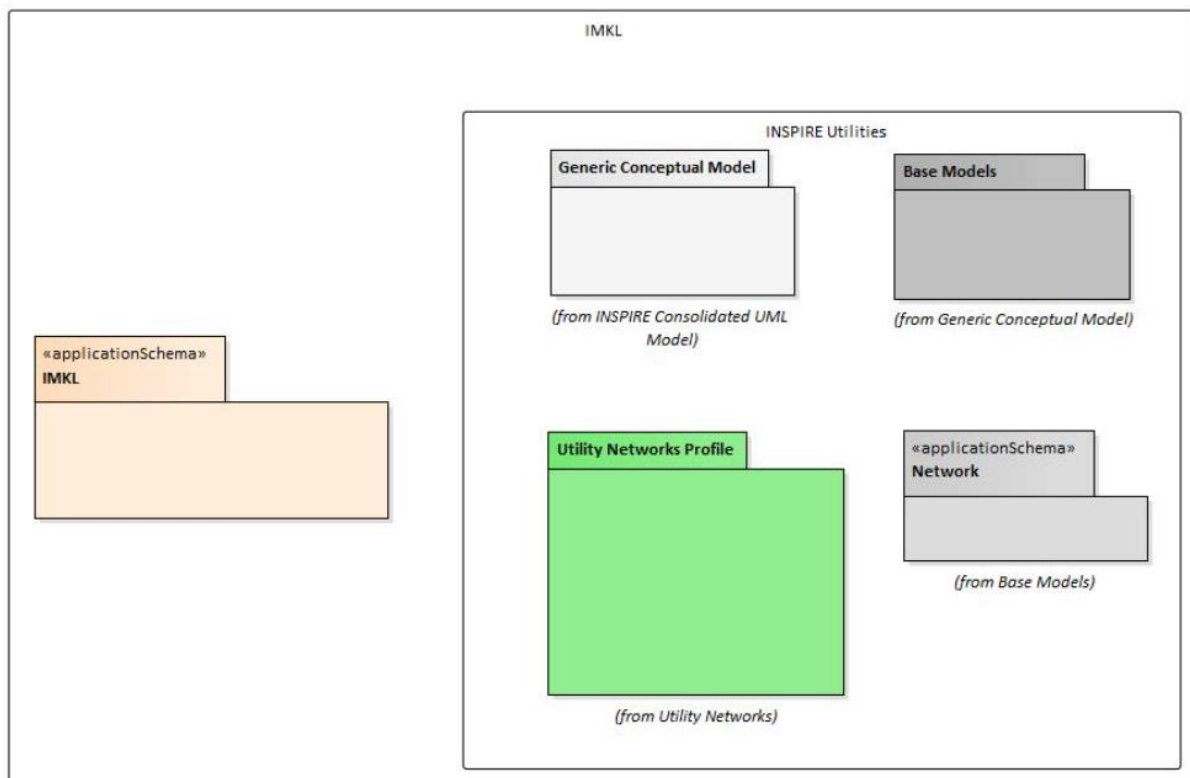
Source: Van den Berg & Janssen, 2021.

2.2.3. IMKL

The IMKL Cadastre Model is a peer-to-peer data exchange system that provides information on underground utilities for excavation purposes. The model assigns unique Network IDs to each underground network, with the operator responsible for maintaining cable and pipe information. The model considers various types of underground networks and construction materials to understand the characteristics of the networks below the ground surface. The IMKL model provides an online service that facilitates the end user's ability to locate and examine the underground infrastructure networks of utilities (Sainovic, 2009).

The IMKL model and Network IDs are centered around the proprietor's legal rights. The Theme Map serves as the central repository for the IMKL model, which contains all the cables and pipes that belong to a single network operator. The Theme Map may include topography elements that refer to each utility, such as a detailed map and relative position to other topographic objects (Sainovic, 2009).

The utility class is a crucial aspect of the IMKL model, which holds information about the location, depth, deviations, materials, and types of networks, including electricity, gas, and water (Sainovic, 2009). The IMKL model has been created with specific requirements, such as location, administrative data, and accuracy. The Presentation Model for Cabels and Pipes (PMKL) has been developed to visually represent the data using a color-coding system, where each type of network is assigned a unique color. The PMKL model deviates from the Dutch CAD standard (NLCS), which uses its color scheme for data sharing within AutoCAD environments (Anton, 2019).

Figure 12: NLCS and PMKL color codes.
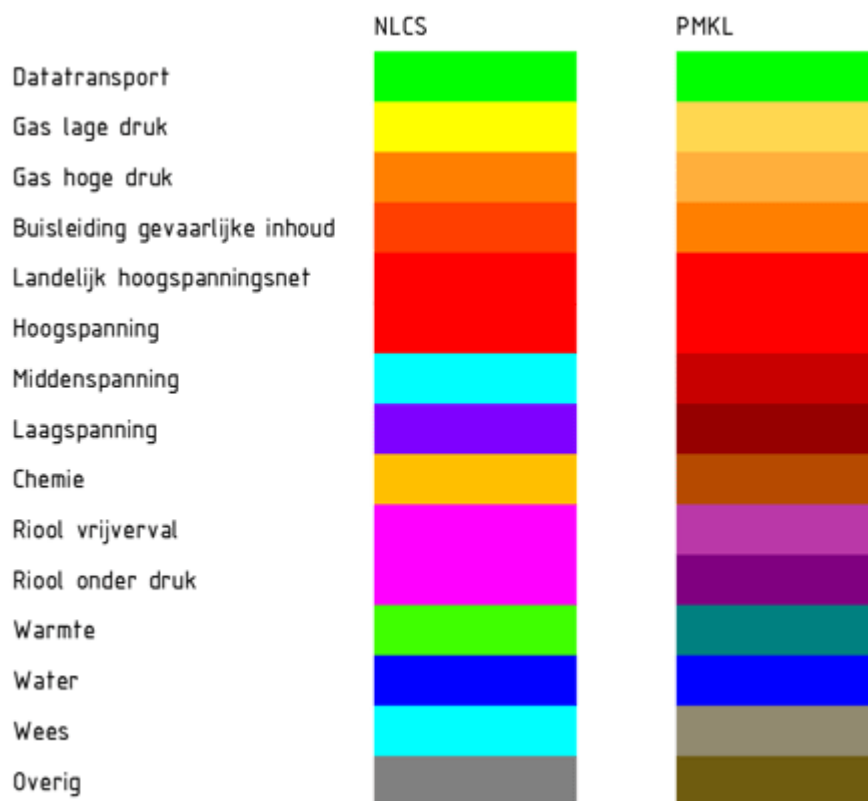
Source: Guideline for visualization rules – Anton, 2019.

IMKL also has the option to apply 3D geometry when necessary, but 2D modeling is mandatory. The 2.5D and 3D geometry are optional extensions that do not affect the 2D modeling. There may be some 3D data within the 2D dataset, and IMKL strives for coordination with the CityGML-Utility extension and the INSPIRE Utility networks (Van den Berg & Janssen, 2021).

The network components of the IMKL model are modeled after the INSPIRE Network model, with all network elements consisting of topological network components and a geometric network formed by nodes or links. The geometry of the network elements is represented by required lines or points, composed of several segments and reference lines in the center that define the centers of the network elements. Optionally, the network may contain geometry as a plane, with reference to an object using the extraGeometry relation. Only one network element uses each link in the IMKL exchange, and different geometries are not permitted to be used simultaneously (Van den Berg & Janssen, 2021).

Figure 13: Network elements can have additional 2D, 2.5D, or 3D geometry besides mandatory points and center lines.
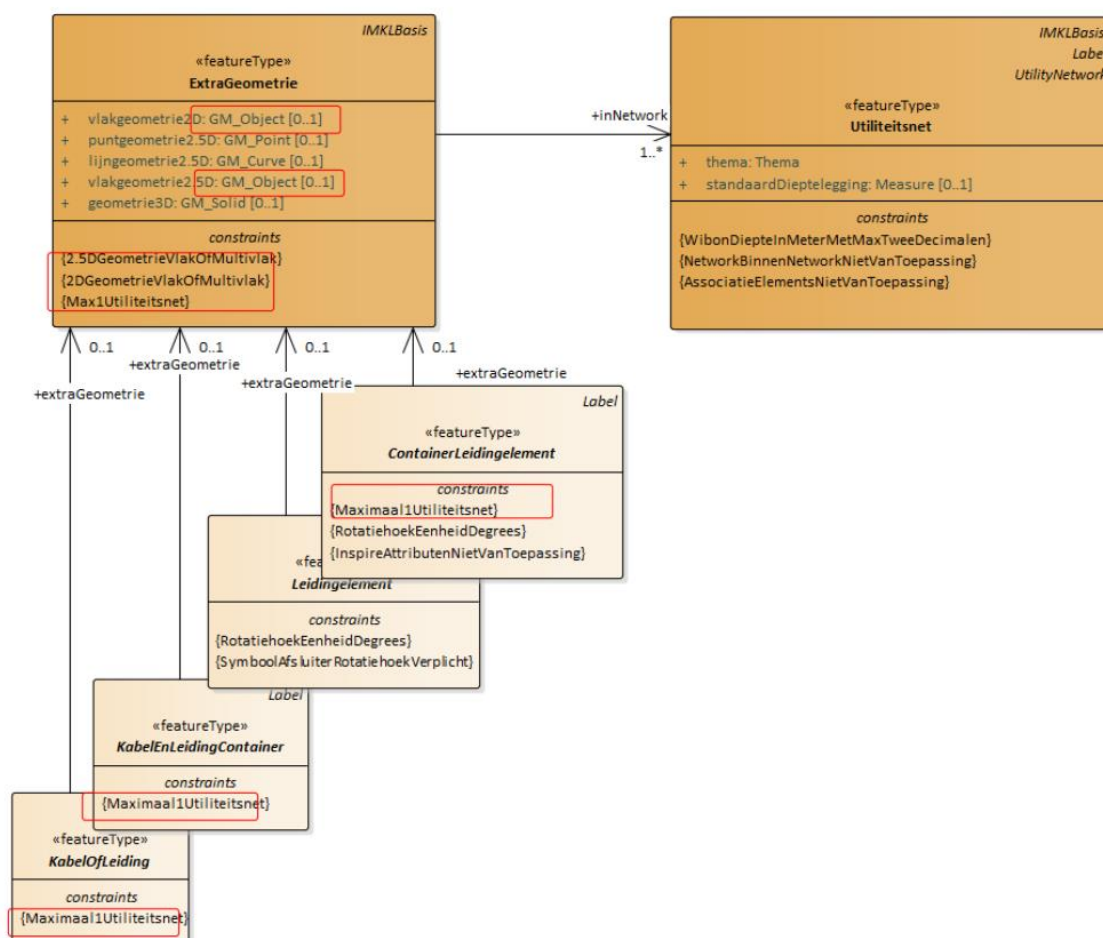
Source: Van den Berg & Janssen, 2021

In the KabelOfLeiding, KabelEnLeidingContainer, Leidingelement, and ContainerLeidingelement, there is the option to include 3D geometry in two different levels of detail (LOD). The 2.5D point, line, and plane can be used for simulation purposes at LOD0, adding a Z coordinate to each point, line, and plane. The Z coordinates are assigned to each pair of coordinate values in the IMKL model. The 3D geometry, referred to as LOD1, allows the IMKL object's full representation as a complete 3D volume (figure 14). The spatial reference system EPSG 7415, with RD coordinates for the XY dimension (EPSG 28992) and NAP for the Z dimension (EPSG 5709), is utilized in the IMKL model (Van den Berg & Janssen, 2021).

Figure 14: Pipe object in 2.5D and 3D.

maaiveld
Leiding in LOD0

Detail van een
leidingobject in LOD1

maaiveld
Leiding in LOD1
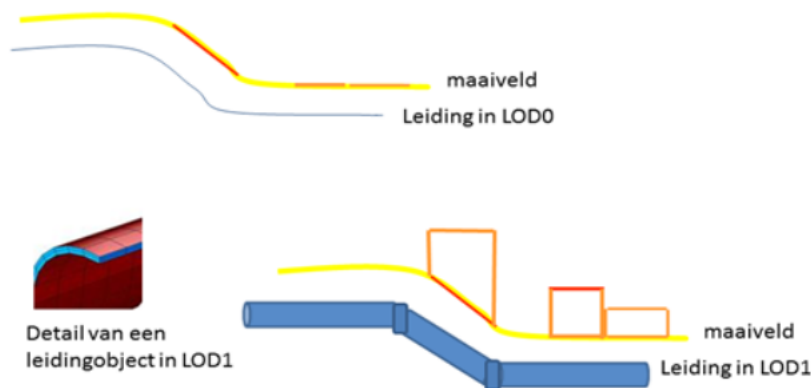
Source: Van den Berg & Janssen, 2021

The depth attribute provides information on the depth of network elements, expressed relative to local ground level or the NAP. Each object type, including KabelOfleiding, KabelEnLeidingContainer, Leidingelement, and ContainerLeidingelement, has two attributes, "DiepteTovMaaiveld" and "DiepteNAP," to describe the depth of the object. The attribute "DiepteAangrijpingspunt" represents the point of measurement, usually the top of the object by default but can also include the inner bottom of a pipeline in sewerage systems. The unit of measure for the depth is in meters, with a maximum of two decimal places for WIBON (figure 15) (Van den Berg & Janssen, 2021).

The precision of the recorded depth is indicated, reflecting the degree of accuracy at the time of recording or updating. The accuracy is classified into four categories, with a minimum of +-1. The standard depth recording attribute in the utility grid is explicit, and depth information can have multiple levels along the course of a pipeline. When depth information cannot be linked directly to a grid element, it is connected to the utility grid (Van den Berg & Janssen, 2021).

2.2.1. WIBON

The WION (Law for Information Exchange of Underground Networks) was established in 2008 to reduce excavation-related damages. After a review in 2013, the law was improved to include information on house connections, which accounted for 48% of excavation damages (CUMELA Nederland, 2016). Utilities must provide house connection information to the Dutch Cadastre, which then informs the excavation party via KLIC notification.

Extra precautions are also required for underground networks with hazardous materials and valuable networks. The utility must provide additional precautionary measures to the excavation party, with agreements on how to proceed with excavation work. This information must be provided within three working days.

In the event of deviations in underground infrastructure depth, the excavation party must notify the Dutch Cadastre, which then informs the relevant utility. For projects on behalf of Brabant Water, the information is sent directly to Brabant Water. The utility must update the deviation depth data within 30 working days (art. 19 section 3 Law of WIBON, 2019).

Figure 15: Depth data is modeled as objects with values relative to the surface or NAP. Standard depth data is added to the Utility grid, with deviations from this in the grid elements.
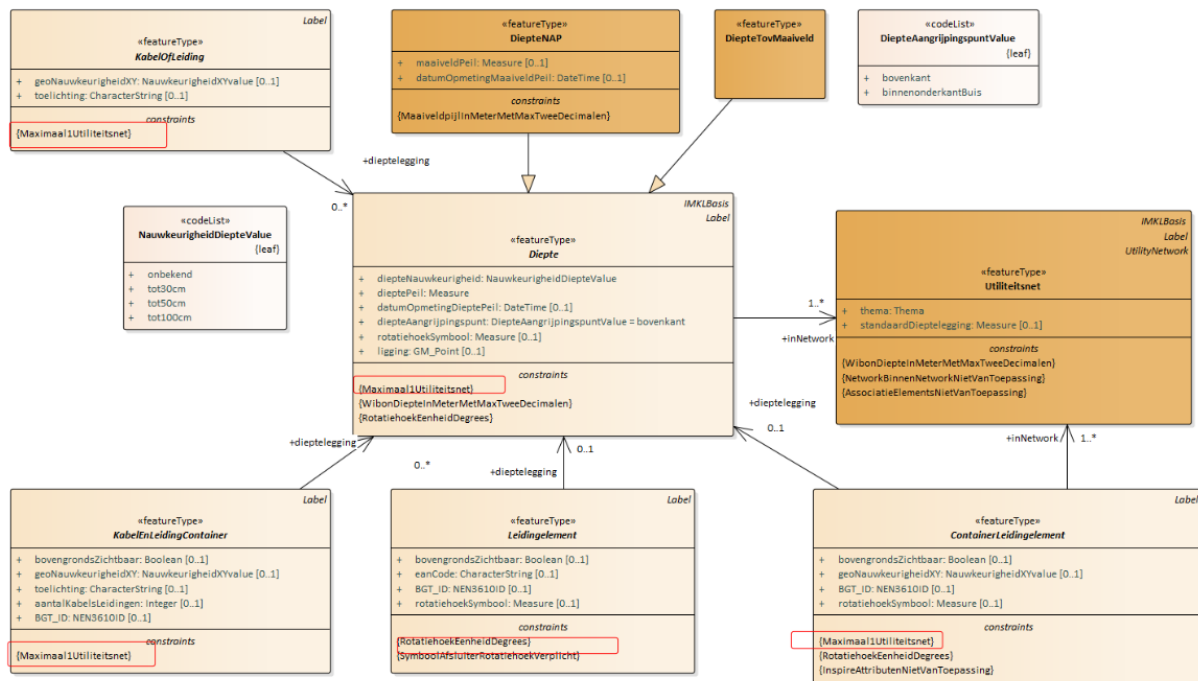
Source: Van den Berg & Janssen, 2021

2.2.2. CROW500

As of January 2022, Agentschap Telecom enforces the guidelines established in the CROW500 publication. The "Preventing damage to cables and pipelines" publication serves as a comprehensive guide covering all aspects of a project, bridging the gap between legislation and practical application. It was created by collaborating with major organizations involved in excavating underground infrastructure. The CROW 500 mandates that contractors and clients adhere to provisions to prevent cable and pipeline damage during excavation (Agentschap Telecom, 2022c).

During inspections, Agentschap Telecom assesses the following obligations (Agentschap Telecom, 2022c):
- Adequate funding has been reserved for preparing and launching the excavation project.
- The excavator has sufficient time to complete the activity on the construction site.
- A comprehensive inventory has been created to ensure that the proposed excavation does not conflict with local underground infrastructure based on location data from the land registry.
- Measures have been implemented to address any conflicts identified from the risk inventory.

Agentschap Telecom also evaluates the excavation process, including (Agentschap Telecom, 2022c):
- The contractor has provided work instructions to the excavation team and made necessary updates.
- The excavation team has correctly executed the work instruction.

If the result obligations are not adequately fulfilled, Agentschap Telecom may enforce administrative law, which may include a warning, fine, or penalty.

2.2.3. KLIC-WIN

The digging industry has established the KLIC-WIN program to meet the requirements of the WIBON law of 2018 and the EU INSPIRE regulations. KLIC-WIN is a combination of the Dutch Information Exchange Act for above-ground and underground networks (WION) and the European directive Infrastructure for Spatial Information in the European Community (INSPIRE) and was launched on January 2, 2019, by the cadastre. The KLIC-WIN program will enhance the exchange of information about cables and pipelines and ensure (Mulder, 2022):

- Accurate representation of utility information using a new information model;
- The option to centrally store utility information at the cadastre;
- A gradual transition from raster to vector data formats for delivering utility data to end users.

2.2.4. LADM

The standard encompasses essential elements of land administration, including information about the land, below ground, above ground, and at water levels. It is an abstract conceptual model comprised of three main packages: parties, which cover people and institutions; basic administrative units, rights, responsibilities, and restrictions, which pertain to ownership rights; and spatial units, which encompass parcels, buildings, and utility networks, with a sub-package for surveying, geometry, and topology (Lemmen, Van Oosterom, & Bennett, 2015).

The LADM standard enables the recording of pipeline ownership geometrically, as it includes a class for legal space utilities with attached rights. For instance, this can take the form of a right of superficies through a buffer. This right should be established for utility networks in both public and private spaces to ensure that no changes are made to another person's property or assets without their consent and that these boundaries are more effectively monitored through the right of superficies.

2.2.5. Esri UNM and Brabant Water data model

The Utility Network is characterized by its simplicity, employing only two types of networks, the Structure Network and one or multiple Domain Networks. The Structure Network serves as the model for supporting infrastructure and consists of only three feature classes: Junction (point), Line (line), and Boundary (polygon). On the other hand, each Domain Network comprises five feature classes: Device, Junction, Assembly, Line, and SubnetLine. The limited number of feature classes (figure 16) and the absence of relationship classes simplify the network model using associations (Madrid & Korchakov, 2017).

Figure 16: Esri utility Network data model overview
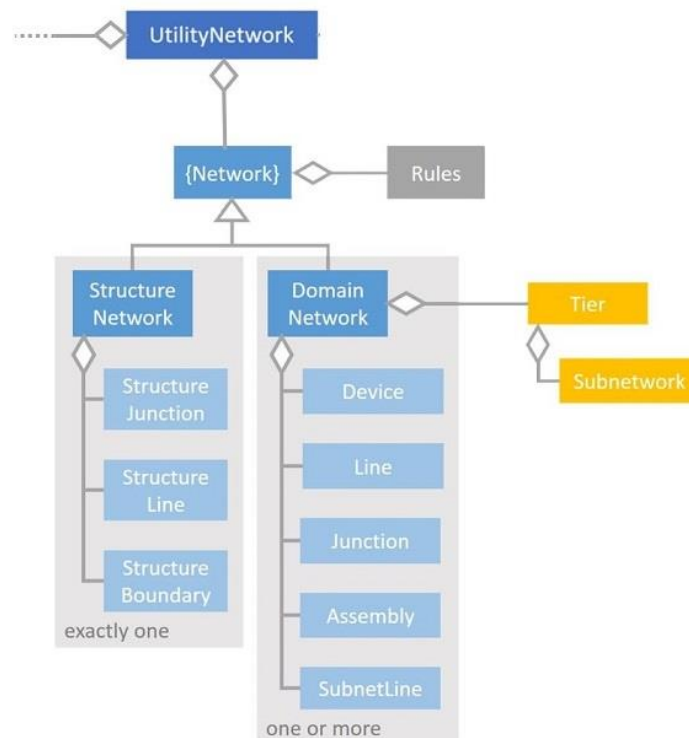
Source: Madrid & Korchakov, 2017.   20

The UNM has several Domain Feature Classes, each serving a specific purpose (ArcGIS, 2023).
- The Assembly feature class is utilized to model complex point features that contain other devices and lines, allowing them to be represented by a single symbol on the map while still showcasing their internal components and connections.
- The Device feature class models the features through which the utility resource flows and can have terminals for distinct entry points.
- The Junction feature class represents locations where lines connect to other lines or devices.
- The Line feature class models linear features such as the delivery lines of the utility resource.
- The SubnetLine feature class is an internal system-maintained set of subnetworks that plays no role in network data modeling.

Brabant Water's utility network shares similar feature classes as the standard utility network, with a few exceptions. The Structure Network does not employ the StructureJunction and StructureBoundary classes, while the StructureLine class includes a feature class for casing pipes. Similarly, the Assembly and SubnetLine classes in the Domain Network are empty. The Device class includes various devices such as valves, hydrants, taps, meters, monitoring equipment, and cleaning cabinets, while the Lines class includes pipes and house connection pipes. The Junction class comprises delivery points, links, delivery objects, and bends.

This research focuses on the Line feature class, which is the DWDS, in the UNM data model Brabant Water uses. Brabant Water has added additional classes to the data model concerning this feature class. Only the relationship between the attributes of the line feature class and those respective attributes of Brabant Water is presented in figure 17, while other feature classes have been excluded as those are not part of this research.

Figure 17: Esri UNM in relation to the addition of the data model of Brabant Water.

Esri Utility Network data model

FeatureClass
- OBJECTID: int
- SHAPE: geometry
- GLOBALID: string
- ASSETGROUP: assetGroup
- ASSETTYPE: assetType
- CREATIONDATE: date
- CREATIONUSER: string
- LASTUPDATE: date
- UPDATEDBY: string
- CONTAINMENTSTATUS: containmentStatus

StructureNetworkFC
- SUBNETWORKNAME: string
- custAttributeSN_0: type
- custAttributeSN_1: type
- ...
- custAttributeSN_N: type

DomainNetworkFC
- SUBNETWORKNAME: string
- custAttributeDN_0: type
- custAttributeDN_1: type
- ...
- custAttributeDN_N: type

If Domain has Hierarchical Tier structure, there is one SUBNETWORKNAME attribute per Tier.

StructureJunction

StructureLine

StructureBoundary

Assembly

ConnectingFC
- ISCONNECTED: bool

Junction

Line
- FROMDEVICETERMINAL: object
- TODEVICETERMINAL: object

Device
- TERMINALCONFIGURATION: terminalConfiguration
- TIERNAME: string
- TIERRANK: int
- SUBNETWORKCONTROLLERCATEGORY: controllerCategory
- SUBNETWORKCONTROLLERNAME: string

Brabant Water addition to data model Line

- Datum van aanleg: Date
- Aanleg geschat: Short int
- Bescherming inwendig: Short int
- Bescherming uitwendig: Short int
- Crucialiteit: Short int
- Diameter: Double
- Diameter geschat: Short int
- Inwendige diameter: Short int
- Dossiernummer EEL: Text
- GIS ID: Relationship
- KB nummer: Text
- Materiaal: Short int
- Materiaal geschat: Short int
- Medium: Short int
- Projectnummer initieel: Text
- Projectnummer statuswijziging: Text
- Risicovol: Short int
- Is gesaneerd: Short int
- Datum van sanering: Date
- Status: Short int
- Trace nummer: Text
- Type leiding: Short int
- Wanddikte: Double
- Wanddikte geschat: Short int
- Wijze van inmeting: Short int

2.3. Developments regarding excavation work for UUNs

The number of excavation notifications submitted to the Dutch Cadastre has increased annually. This growth in excavation work has resulted in a corresponding increase in damage to the crowded underground infrastructure, particularly in densely populated cities (Koek, 2020). Underground assets owned by Brabant Water and those of other parties can be damaged during excavation work. It is, therefore, imperative to provide high-quality data to ensure the excavation work is performed most efficiently.

Figure 18: Excavation damage percentage in 2021.

Source: Agentschap Telecom, 2021.

In 2021, 771,824 excavation notifications were reported, leading to 45,682 excavation damages, which accounted for 5.62% of the total excavation notifications (figure 18). The province of Limburg had the highest percentage of excavation damages, at 8.03%, while Flevoland experienced the lowest, at 2.89%. The number of excavation damages has increased over the years, from 34,000 in 2017 to nearly 46,000 in 2021, despite the likelihood of damages remaining constant at a ratio of 1:18 (figure 19).

The national average for excavation damage in 2021 was 5.62%, totaling 45,682 damages. The province of Noord-Brabant reported slightly more significant damages, with 6.86%. The cost of repairs has also increased, rising from €25.2 million in 2017 to €41.2 million in 2021. The damages to different networks also vary, with data transport being the most affected, accounting for 56.7% of the total damages, followed by low voltage (25.0%), low-pressure gas (9.33%), water networks (7.07%), and medium voltage (1.08%) (table 10-12).

Combining the data from table 12 with the map from figure 18 makes it possible to estimate the damage to the water network in the province of Noord-Brabant. According to Agentschap Telecom (2022a), there were 8,886 excavation damage reports in Noord-Brabant in 2021, accounting for 6.86% of the total excavation damages in the country. The nationwide water network was responsible for 7.07% of the total excavation damages, translating to 628 damages to the water network in Noord-Brabant in 2021. In 2020, the nationwide water network accounted for 4.32% of the total excavation damages, translating to 396 damages in Noord-Brabant. Despite a lower nationwide percentage for the water network, there were more excavation damages in 2020 to other networks in the province of Noord-Brabant (9,160 in total with a share of 7.82%). In 2019, the nationwide water network accounted for 7.55% of the total excavation damages, translating to 580 damages in Noord-Brabant. However, there were fewer excavation damages in the province of Noord-Brabant in 2019 (7,678).

Figure 19: Excavation movements and damage from 2017 to 2021.
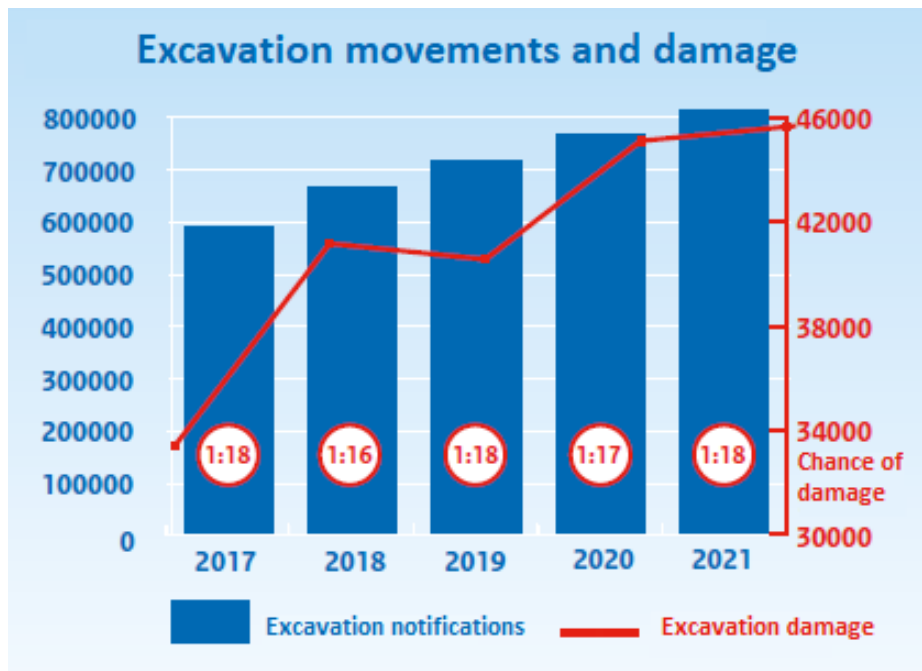
Source: Agentschap Telecom, 2022a.

Table 10: Excavation damages per network in 2019.

Excavation damages per network in 2019	Number of damages	Average direct repair costs in €	Total costs in €	Noord-Brabant total costs with a share of 6,95% in €
Data transport	20,440	438	8,952,720	622,214
Low voltage	11,848	655	7,760,440	539,351
Gas low pressure	4,321	722	3,119,762	216,823
Water	3,063	699	2,141,037	148,802
Medium voltage	550	4,591	2,525,050	175,491
Other networks	339	45,259	15,342,632	1,066,313
Total	40,561	N/a	39,841,641	2,768,994

Source: Agentschap Telecom, 2020.

Table 11: Excavation damages per network in 2020.

Excavation damages per network in 2020	Number of damages	Average direct repair costs in €	Total costs in €	Noord-Brabant total costs with a share of 7,57% in €
Data transport	24,670	801	19,760,670	1,495,883
Low voltage	12,540	678	8,502,120	643,610
Gas low pressure	4,935	785	3,873,975	293,260
Water	1,949	678	1,321,422	100,032
Medium voltage	530	4,537	2,404,610	182,029
Other networks	478	28,759	13,746,590	1,040,617
Total	45,102	N/a	49,609,387	3,755,431

Source: Agentschap Telecom, 2021.

Table 12: Excavation damages per network in 2021.

Excavation damages per network in 2021	Number of damages	Average direct repair costs in €	Total costs in €	Noord-Brabant total costs with a share of 6,86% in €
Data transport	25,906	915	23,703,990	1,626,094
Low voltage	11,419	722	8,244,518	565,574
Gas low pressure	4,260	837	3,565,620	244,602
Water	3,230	712	2,299,760	157,764
Medium voltage	492	4,492	2,210,064	151,610
Other networks	375	4,511	1,691,786	116,057
Total	45,682	N/a	41,715,738	2,861,700

Source: Agentschap Telecom, 2022a.

The type of work related to excavation damages is of utmost importance as it provides insight into the relationship between the work and the damages caused. For instance, while road construction projects can damage water and gas pipelines, the available data does not allow us to make such conclusions. Figure 20 illustrates that the top five causes of excavation damages are reconstruction work (22.25%), laying of gas pipelines (16.96%), laying of medium voltage (14.88%), road construction (14.06%), and laying of water pipes (13.42%).

Despite the increasing trend in excavation damages, the data reveals no indication of a reversal in this trend. To address this issue, Agentschap Telecom plans to adopt a strict supervisory and enforcement policy to ensure compliance with the regulations of the WIBON. This marks the end of a period during which the excavation chain could address the issue independently (Agentschap Telecom, 2022b).

Figure 20: Nature of work and excavation damages per network in 2021 on underground infrastructure.
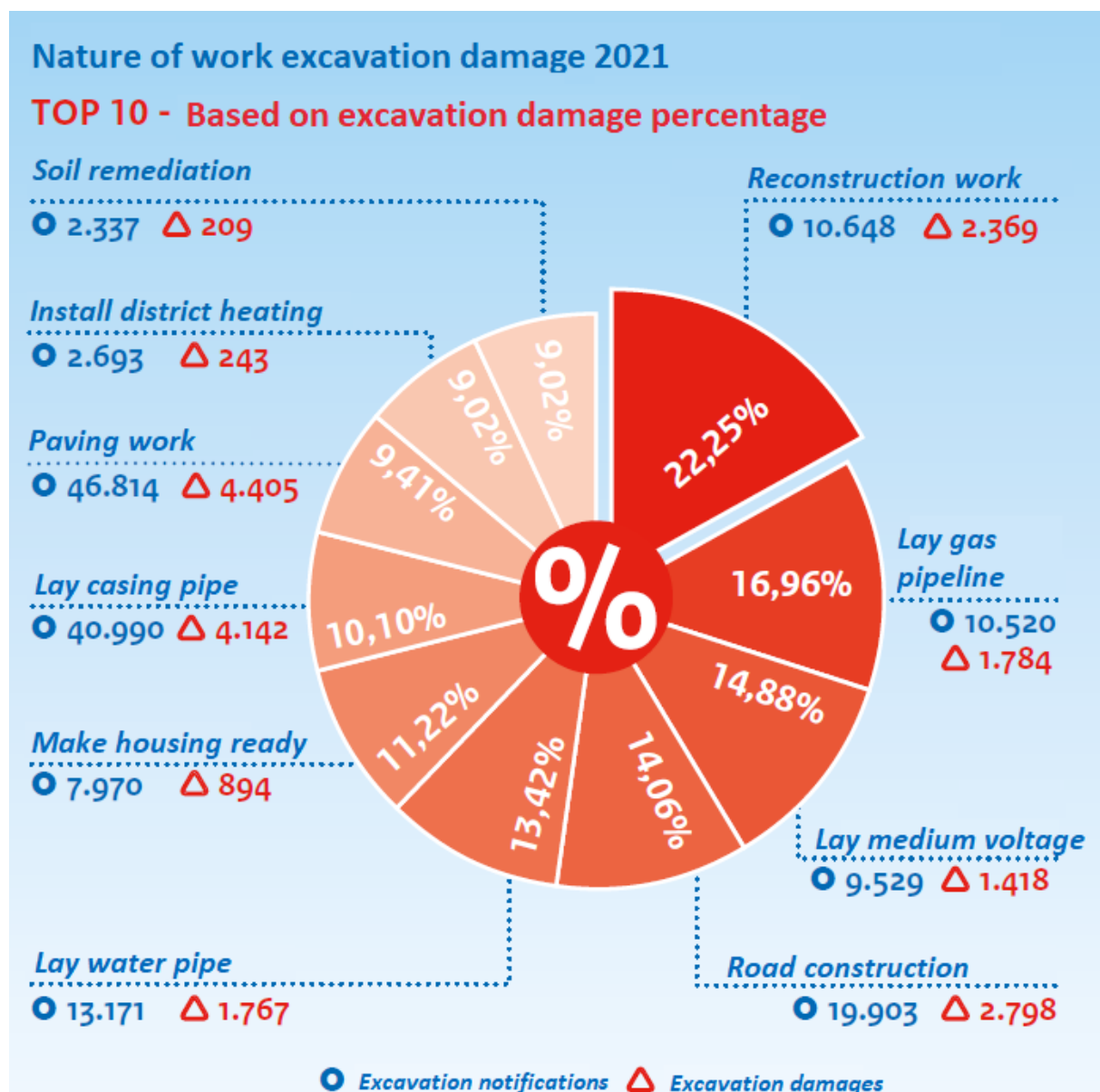
Source: Agentschap Telecom, 2022a.

2.4. Brabant Water goals in relation to 3D GIS and SDSS

The implementation of Project MAGIC at Brabant Water aimed to realize the GIS vision of providing geographical data of optimal quality that is easily accessible at all times. The aim was to modernize the registration system and enhance it into a self-sufficient, spatially-enabled decision support system (Van Meel, 2022). MAGIC employed the ArcGIS UNM of Esri at Brabant Water. Since its activation in December 2020, the decision was taken to record Z coordinates relative to the Dutch height map, which records height in NAP, and the Z coordinates are now registered in the GIS DWDS. Approximately 0.58% of the DWDS pipes, which amounts to 10,000 out of 1.725 million, have Z coordinates attached. Brabant Water is considering registering Z coordinates for all newly measured DWDS pipes, including contractors' ones, laying the foundation for a three-dimensional GIS network. By utilizing 3D GIS, Brabant Water seeks to perform more accurate analyses of factors affecting its DWDS based on the pipe's depth, such as soil pollution, subsidence in certain areas, tree roots, efficient maintenance, and mitigating defects.

However, the application of 3D has not yet been extended to the entire DWDS network, including its attachments. At the time, it was argued that registering Z coordinates for the whole network would give a false sense of certainty regarding the depth of the pipes, which could increase excavation damages. A new column was recommended to be added to the database to indicate the accuracy of the depth information, with information derived from the AHN4 and the standard depth of the water pipe being labeled as inaccurate while actual measurements being labeled as accurate.

Presently, depth information is recorded for both existing and newly installed DWDS pipes, but the information is not utilized. This is not in line with the GIS vision of providing data of an optimal quality to support processes with a geographical component. The new director of Brabant Water has set a target goal for the distribution department to provide mechanics with smart glasses such as VR or AR, which will likely be integrated into the work processes in the near future. GIS and 3D can play a crucial role in such applications linked to Brabant Water's databases. A data governance workflow for utilities is presented in figure 21, which displays the relationship between smart glasses and the workflow. It is important to note that data is not captured through Ground Penetrating Radar (GPR) but through GNSS receivers. The data user can be supported in various forms, such as a web application via a tablet or smart glasses (Yan et al., 2019). More information on this can be found in Chapter 5, Spatial Decision Support.

Figure 21: Workflow of underground utility mapping
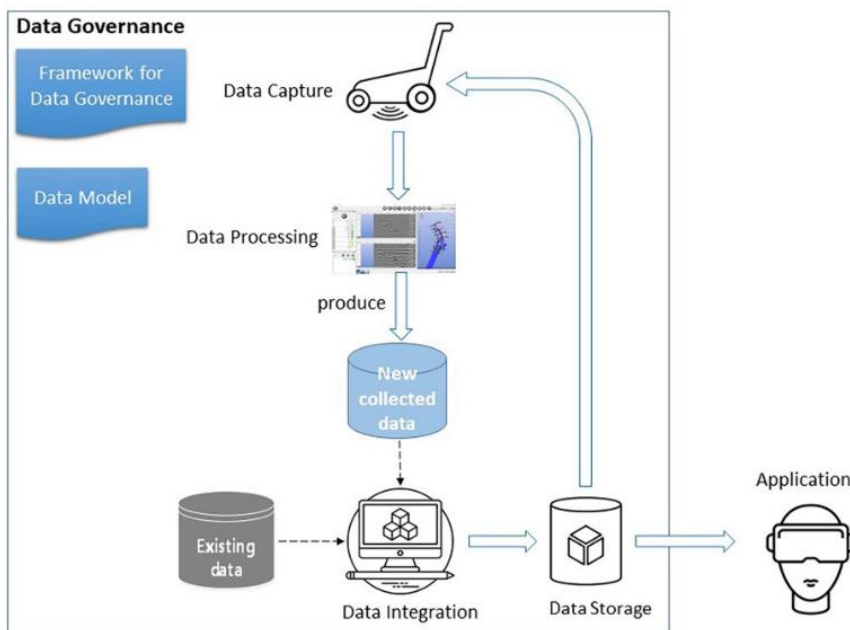
Source: Yan et al., 2019.

2.5. Sub-conclusion

In conclusion, the accurate registration of X, Y, and Z coordinates and the use of coordinate systems and vertical reference systems are essential for registering height information. In the Netherlands, measurements are taken in the European Terrestrial Reference System 1989 (ETRS89) and then transformed to RD coordinates using the RDNAPTRANS procedure. Brabant Water uses the Stonex S700 – Cube A GNSS receiver from Geodirect to record and store these coordinates in their GIS databases. The Dutch cadastre uses the KLIC-Win process, based on the INSPIRE Utility and Governmental Services data specification, to provide data about excavation work to and from stakeholders. Excavation work must be performed using the KLIC-WIN process to limit excavation damages and comply with regulations set by Agentschap Telecom.

Brabant Water is currently working to transform its GIS registration system and develop it further into an SDSS. With the project MAGIC, they transformed their GIS into the UNM of Esri. While the decision was made to register depth information with Z coordinates for new DWDS pipes and existing DWDS pipes, this depth information is currently not being used for excavation work. However, according to the GIS vision, all the processes with a geographical component should be supported with optimal quality data. Therefore, not using this information is not in line with this vision and could be better used to support processes and decision-making. Overall, it is essential for organizations like Brabant Water to effectively and efficiently manage the flow of data to ensure the safety and reliability of their utility networks and services.

LADM standard enables geometric recording of future pipeline ownership, including using a buffer as the right of superficies in both public and private spaces for utility networks, to ensure no changes are made without owner consent and better boundary monitoring.

The UNM used by Brabant Water includes similar feature classes as the standard utility network, such as Device, Line, and Junction. However, Brabant Water has added extra attributes to its data model. This research focuses on the Line feature class, which is the DWDS. Other feature classes have been disregarded in this study.

3.   Spatial data flow of Brabant Water

Understanding a data governance model is crucial for comprehending the data flow within organizations such as Brabant Water, where multiple stakeholders are involved. Figure 22 provides an insightful overview of the various aspects of data governance, including data collection through surveying, storage, and integration at the cadastre and the applications developed based on the data. Yan et al. (2019) present a framework for utility data governance that consists of five key roles:

- The data producer, typically the surveying constructor or surveyor in the data regulatory bodies organization, is responsible for conducting field surveys and submitting the collected data to the UNM database.
- The data owner, a company, data authority, utility, or other entity, keeps track of their gathered data.
- Data regulatory bodies, including local, state, or federal agencies, oversee the utility data, provide clearance for its use, and identify and provide a set of permitted utility data.
- The data integrator integrates all types of utility network data and manages the utility cadastre information for a city or country. This role provides information for applications and excavation work, linking data regulators with users.
- The data users can utilize the utility data for utility cadastre management purposes.

In this context, the surveyor serves as the data producer and submits the data they collect to the data owner or government agencies responsible for regulating the utility network data. The data owner then determines which utility data they want to submit following government requirements. The data can be submitted to data regulatory agencies using either a general utility network data model or the UNM, if available. The utility data integrator is responsible for integrating data from various utilities, with the proposed model connecting the UUN to the land management of above ground through the LADM (Yan et al., 2019). In the Netherlands, the IMKL is used to establish a connection between the UNM of the utility and the UNM of the cadastre.

To understand how data flows within Brabant Water, the stakeholders that are involved will be examined. In this chapter, Brabant Water's role in data surveying and storage will be discussed (section 3.1), contractors' use of data for excavation work (section 3.2), the People Group's integration of data with the cadastre (section 3.3), and the relation of the cadastre to Brabant Water's data flows (section 3.4). Finally, a sub-conclusion will be provided to summarize the key points discussed in this chapter (section 3.5).

Figure 22: The structure of utility network data governance.
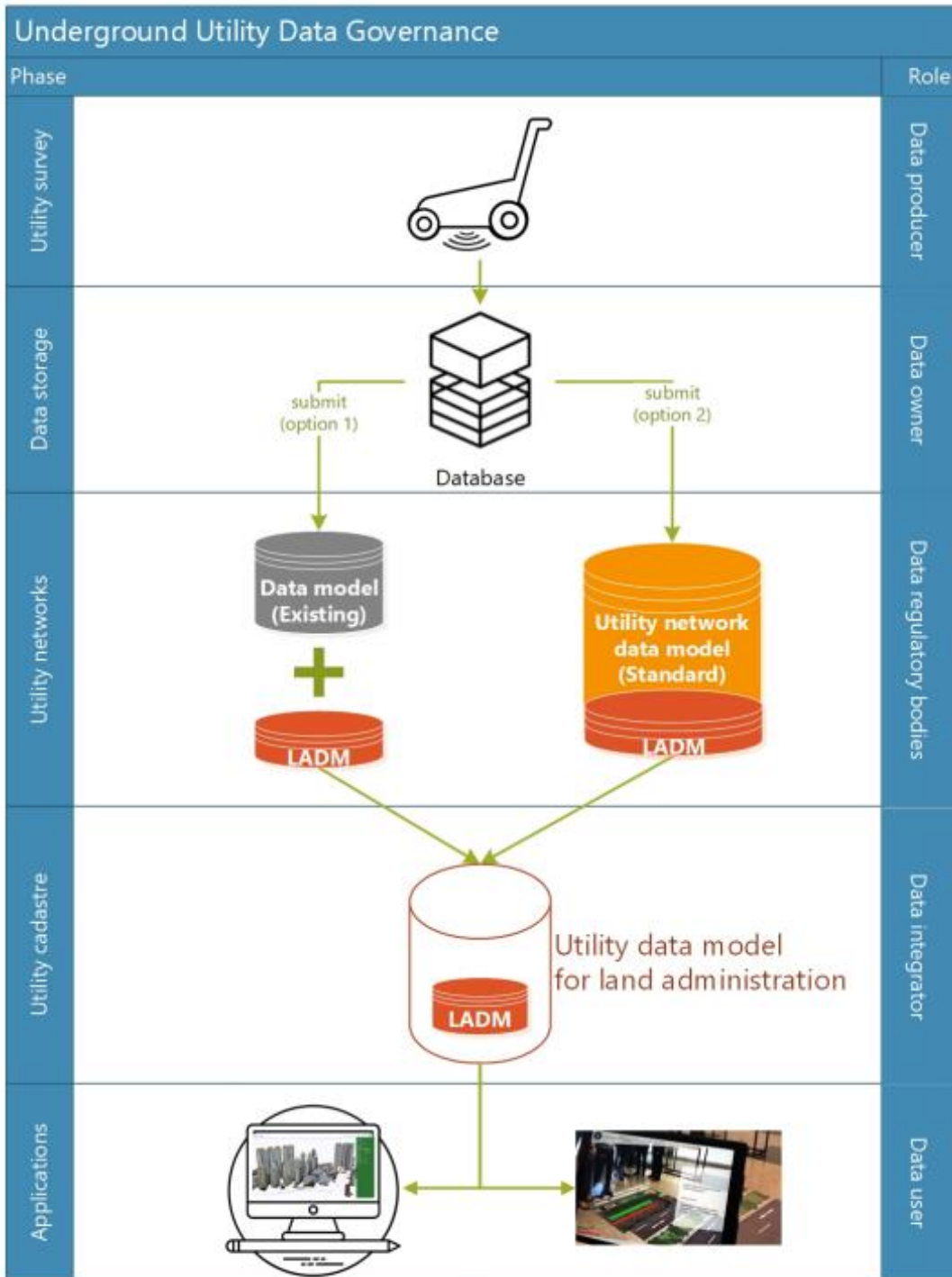

Source: Yan et al., 2019.

3.1. Brabant Water

The primary focus of Brabant Water is to deliver water that is sourced from groundwater. Brabant Water manages a comprehensive network of groundwater extraction areas, water pump stations, pump wells, clean water cellars, and a DWDS. The DWDS comprises transport pipes, distribution pipes, and house connection pipes, with a total length exceeding 18,000 kilometers (Brabant Water, 2022b). A substantial portion of the network was built in the 1950s, and as the pipes are reaching the end of their lifespan, Brabant Water has scaled up its efforts to replace 250 kilometers of pipes annually (Brabant Water, 2022c). Brabant Water has its in-house mechanics and a dedicated department but hires contractors to carry out excavation work when necessary.

Whenever excavation work is carried out, for instance, to replace a pipe, a KLIC-WIN notice via the cadastre is required when the excavation work exceeds the limit of 40 centimeters below the ground surface or is performed with an excavator. However, a KLIC notice is not necessary when the excavation work is within the limit of 40 centimeters and performed with a shovel. KLIC notices are important for personnel safety and prevent excavation damages to the UUNs (KLICAPP, 2022). During the maintenance work of Brabant Water's UUN, there is an opportunity to collect geographical data on the network. The height data of the network is updated and added through measurements.

The first measurement method uses the Geodirect Stonex S700 – Cube A measuring equipment, which is a GNSS receiver (Geodirect, 2022b). This system can accurately determine the height of objects in NAP (Z coordinate) and the X and Y coordinates in the Dutch RD coordinate system. The spatial data is surveyed with the help of the Cube-Connector software, which ensures sufficient satellite coverage and will not allow measurements in case of a non-fixed connection. Mechanics are required to carry out measurements in an open trench and provide a notification in the record if this is not possible. The measurements should be taken logically, from top to bottom and in one direction, as shown in figure 23.

Figure 23: Manual of the Stonex S700 – Cube A. Method route for measuring and curves.
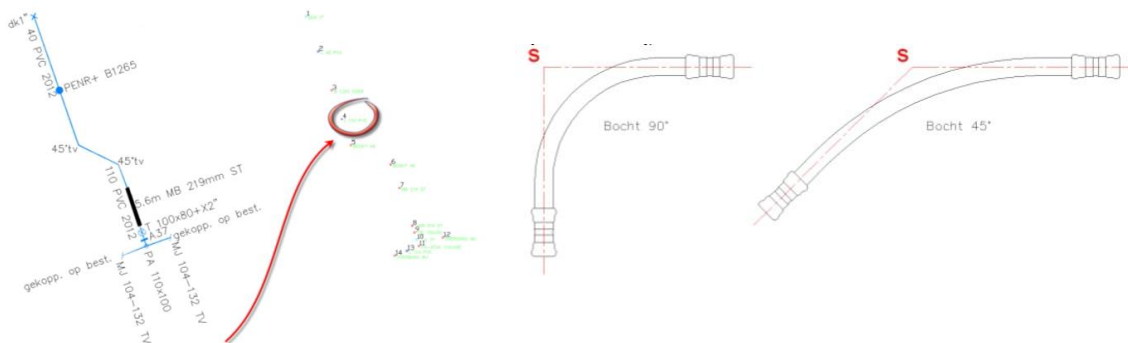
Source: Geo-Direct, 2021

The Esri Field Map app can also be utilized in the collection process, allowing viewing of network information and locations from the database. In attachments, a measurement point should be taken between them. For longer pipes, a measurement should be taken every 50 meters. Any deviation in depth is recorded in a separate GIS point file if it exceeds 20 centimeters from the standard depth. If there is an inadequate GPS signal, such as due to trees, a sketch will be made on a GIS screenshot, and the data will be entered accordingly.

In addition, the measurement information can be submitted to Brabant Water by contractors through the use of the Goconnect application. This method is utilized for smaller, shorter connection pipes. The measurement data for pipes up to 45 meters is captured in the form of an XML Schema Definition (XSD), an eXtensible Markup Language (XML) file, filled in by the contractor, and then added to the GIS when submitted. Currently, this format does not accommodate the Z coordinate. However, this may change in the future, potentially allowing for the inclusion of the coordinate for these types of pipes.

Brabant Water holds multiple roles in the underground utility data governance model put forth by Yan

et al. (2019). As data producers who conduct surveys and store the resulting data, they are considered data owners and play a role in data regulatory bodies. The data is stored in their data model and later converted to the IMKL 2015 format by The People Group, a separate company (see 3.3). Brabant Water also acts as a data user, as they retrieve data from the cadastre for excavation work through the KLIC-WIN system.

3.2. Contractors for excavation work

Brabant Water may hire contractors for larger projects, while smaller ones may be handled by their in-house mechanics. Contractors commonly use GNSS systems similar to Brabant Water's mechanics, although they are not yet required to provide the Z coordinate of their measurements. Brabant Water mechanics and contractors use GNSS systems, such as the Stonex system and XDS - an XML format, to perform their work.

As per Yan et al.'s underground utility data governance model (2019), contractors can be considered data producers as they provide the data to Brabant Water. Contractors are also data users as they require information from the KLIC-WIN system from the cadastre regarding the locations of underground infrastructure before performing excavation work.

3.3. The People Group

The conversion from the GIS UNM model utilized by Brabant Water to the IMKL 2015 format is carried out by The People Group. The data is supplied to them as a File Geodatabase (FGDB).

Following the underground utility data governance model proposed by Yan et al. (2019), The People Group plays a crucial role as a connector between Brabant Water and the cadastre. As a result of their conversion activities, The People Group has positioned itself within the domain of utility networks and data regulatory bodies. They serve as a mediator between Brabant Water and the cadastre, transforming the data model of Brabant Water into the data model required by the cadastre, which is the IMKL 2015 (Van Alphen, 2022).

3.4. The Dutch cadastre

According to the regulations established as of January 1, 2017, utilities are obligated to deliver their data to the cadastre in the IMKL 2015 format. Currently, there are no mandates for providing 3D data to the cadastre. However, this may change in the future as the cadastre aims to implement more 3D data utilization in its operations (Bliemer, Eertink, & Staarink, 2021). The IMKL specification allows for the optional use of 3D geometry where necessary. However, it does not affect underground infrastructure's traditional 2D modeling. Efforts to coordinate 3D modeling will be made in conjunction with the CityGML-utility extension, with the INSPIRE Utility networks leading these efforts (Van den Berg & Janssen, 2021). The Dutch cadastre aims to increase the consistency between the data in its basic geo-registers and unlock this information in 3D (Bliemer et al., 2021). Currently, there is no uniform implementation of 3D UUNs in the cable and pipeline sector. The question of their usefulness and necessity is under investigation at the request of representatives from the excavation sector (Kadaster, 2021). The IMKL specification allows for the optional use of 2.5D and 3D geometry, which does not affect the 2D modeling. The cadastre provides data regarding the location of cables and pipes through the KLIC-WIN, a mandatory notification system when mechanical digging activities are performed (Ministerie van Binnenlandse Zaken en Koninkrijkrelaties, 2022). The excavation party is then provided with geospatial UID regarding a predefined area of interest from the cadastre.

3.5. Sub-conclusion

The conceptual model provides an overview of the data flow in figure 24. During excavation work, the contractor receives an excavation notification request for existing underground infrastructure from the cadastre through the KLIC-WIN system or from a Brabant Water mechanic performing the excavation work. The design for the new asset is also sent from Brabant Water's database to the excavation party if the work is being performed for Brabant Water. Height measurements are taken in an open trench to record the height of the water distribution pipe relative to NAP. If the depth deviates more than 20 centimeters from the standard depth, it is registered in a separate GIS point file. This means the current database may have inaccuracies in the Z coordinates with a maximum of 20 centimeters. The measurement height data is sent to Brabant Water, the data owner responsible for maintaining the database. The cadastre also sends an excavation notice to the utility before the work begins. Afterward, the data is transformed from Brabant Water's data model to the data model required by the cadastre, which is the IMKL 2015 format. Figure 24 provides an overview of this data flow.

Various parties, such as surveyors, data owners, regulatory agencies, data integrators, and data users, are involved in the data flow. Brabant Water is responsible for maintaining its network and performing excavation work to replace aging pipes, with KLIC notices performed for safety and to prevent damage to the utility network. Geographical data is collected during maintenance work using GNSS technology to determine the height and coordinates of objects accurately. This ensures safe and efficient data flow throughout the organization and its stakeholders.

Figure 24: Overview of geographical data flow through Brabant Water
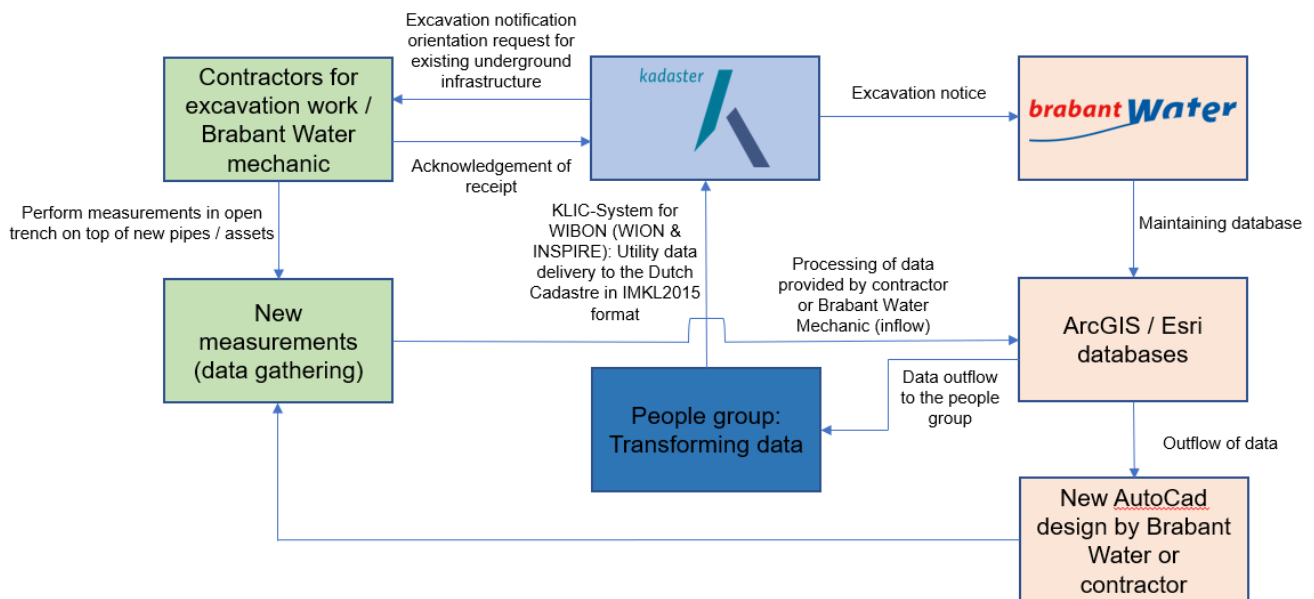
4. Limitations and added value of a 3D GIS

The adoption of a 3D GIS environment for managing the underground networks of Brabant Water has both limitations and added value. Although Brabant Water has been registering Z coordinates, they are not currently using this data due to concerns over the quality of the depth information. Currently, only a small fraction (0.58%) of their network has one or more Z coordinates, and there is a significant lack of depth information for the rest of the network. This information can be obtained by subtracting the standard depth from the ground surface points obtained from the AHN. Additionally, the pipes will continue to be updated with measurements from land surveying over time. Despite these limitations, a 3D GIS environment can offer significant added value for Brabant Water, including improved situational awareness (SA) and a better understanding of the complete construction of underground objects.

This chapter will explore the advantages and drawbacks of using 3D data. Section 4.1 will discuss the benefits of 3D data utilization, while section 4.2 will cover its limitations. To conclude this chapter, section 4.3 will provide a sub-conclusion of the key points discussed.

4.1. The added value of 3D data utilization
- Improved analysis: The exact depth of the DWDS is crucial for performing more accurate analysis, which can be done using 3D data. This is because the depth of the DWDS affects several important factors, such as the load on the DWDS from the ground surface and the resilience of the DWDS to temperature fluctuations.

  Two improved forms of analysis were identified:
  1. Drinking water temperature analysis: The 2001 Dutch Drinking Water Directive limits the maximum drinking water temperature to 25°C, but global warming often leads to violations (Blokker & Pieterse-Quirijns, 2015). Soil temperature affects drinking water temperature (Blokker & Pieterse-Quirijns, 2015), and factors such as atmospheric temperature, radiation, soil thermal conductivity, and heat capacity all have an impact (Van den Bos, 2020). Placing the DWDS pipes in deeper soil layers reduces temperature fluctuations (Van den Bos, 2020). Z coordinates of pipes and the surface level can therefore be used to determine which pipes are vulnerable to outside temperature rises and estimate the top load of pipes indicating potential weak spots to avoid damages or collapses.
  2. Chances of failure and DWDS condition analysis: The depth of DWDS burial is influenced by various factors such as load-bearing, protection from excavation damage, cost of construction and maintenance, and temperature resilience (Meerkerk & Beuken, 2017). However, standards are often applied rather than individual location assessments. Most of the DWDS in the Netherlands are buried around 1 meter beneath the ground surface. In contrast, transport pipes are deeper, approximately 1.2 meters, and home connection pipes are covered by a standard soil depth of 0.8 meters (Agudelo-Vera & Fujita, 2017; Blokker & Pieterse-Quirijns, 2010). Construction inconsistencies, subsidence, and interference from other parties may hinder exact depth estimation. Nevertheless, studies often assume the DWDS is at a depth of 1 meter and therefore use the related soil temperature for measurements (Agudelo-Vera & Fujita, 2017; Blokker & Pieterse-Quirijns, 2010; Van Summeren et al., 2017). However, the chances of failure and the condition of the DWDS can be better estimated if you know how much soil is on top of the DWDS. Depth information is crucial to calculate this and to be able to distinguish between various locations. If the same depth is used everywhere (e.g., 1 meter), all the models look like each other (Van Laarhoven, 2022). Depth is thus an essential variable in this calculation.

  Therefore, the Z coordinates of pipes and the surface level can be used in analysis to determine which pipes are vulnerable to outside temperature rises and estimate the top load of pipes indicating potential weak spots to avoid damages or collapses.

- Improved visualization, understanding, and communication: Having accurate Z coordinate information of the DWDS and storing it in a database lead to improved organization and understanding. Utilizing 3D technology offers a solution to the issue of deviations in height at bends and sewer crossings, as objects can be stored directly in 3D and improve SA for workers

and mechanics. Mallo (2022) found that 3D visualization improved SA between fieldworkers and back-office personnel and is considered a necessary addition for the utility sector, especially in crowded underground infrastructure where depth information improves SA. Du and Zlatanova (2006) also noted that 2D data in the utility sector relies on the expertise of the fieldworker and that 3D representation leads to improved communication and understanding. Although depth information from the AHN is an estimate, it provides a better understanding of the underground situation, particularly in crowded underground infrastructure, where accurate depth information can improve SA and communication. Olde Scholtenhuis et al. (2022) identified eight use cases to support design, engineering, and work preparation using 3D data visualization:

1. Orienting on project location:
   - Helps in exploring a project situation for experts and non-experts.
   - Bringing to life the layering of the underground composition.
   - Provides a first impression of necessary work in an area.
2. Exploring complexity:
   - Makes spatial complexity visually evident.
   - Adds depth and geometry to a schematic 2D drawing.
   - Offers better insight for designers and construction workers.
3. Creating a design plan:
   - Helps estimate necessary adjustments in an existing situation.
   - Becomes clearer which cables and pipes need to be relocated by presenting heights and diameters.
4. Designing a route:
   - Helps map locations that can cause spatial bottlenecks with other types of infrastructure.
   - Particularly relevant in which pipes conflict with heat networks which are difficult to relocate.
5. Preparing and executing directional drilling:
   - Makes bottlenecks, route choices, and possible entry and exit points more visible.
   - Limits excavation damages and movements by better-estimating excavation risks.
6. Determining test loop locations:
   - Helps to make a more targeted choice of loop locations based on the existing complexity and uncertainty of network information
7. Supporting execution activities:
   - Limits excavation damages and movements
   - Better estimates of excavation risks and productivity
   - Helps identify spatial bottlenecks in advance
8. Integrating the underground into spatial issues:
   - Makes dependencies between issues clear by visualizing the design of underground waste containers, trees, stormwater solutions, and groundwater levels in 3D.

Moreover, the 3D location of other cables and pipes being installed today is also increasingly being known, which is useful for understanding their relationship with other underground utility installations (Van den Berg & Janssen, 2021). According to Olde Scholtenhuis et al. (2022), 3D data can provide a more comprehensive risk assessment prior to excavation work compared to 2D data, leading to improved safety in the utility sector. This quality improvement can ultimately reduce the number of excavation damages, as potential problem areas are identified before hazardous excavation work begins. It is, therefore, essential to incorporate this 3D information in the underground infrastructure management system to avoid discarding important data (Van den Berg & Janssen, 2021).

- According to Penninga & Van Oosterom (2006), the proper method of registering underground networks in the long term is to record the depths relative to a coordinate system, such as the NAP. This is because the ground surface is subject to changes over time. Therefore, one Z coordinate per attribute will not suffice as an object can be very long, which may result in various pipe depths. Multiple Z coordinates are needed to accurately register UUNs which must be registered in the coordinates (vertices) of the feature. Brabant Water is doing this already, but as mentioned earlier, few measurements are present compared to the size of the DWDS. According to Penninga & Van Oosterom (2006), measurements of the pipes' depths and

ground surface must be registered, which may not always be available. In such cases, the AHN can be used as a solution. To address potential inaccuracies in the depth information, a label should be added in the respective data model indicating the level of accuracy, with a warning for those labeled as "not accurate." Brabant Water's databases currently have a 20-centimeter deviation threshold for registering deviation depths, already leading to some inaccuracies in the recorded data.

4.2. Limitations of 3D data utilization

- Data quality is crucial in data-driven decision-making and adaptive management (McCord et al., 2022). Inaccurate data can fail information systems to deliver value (Saberi & Ghadiri, 2014). According to Olde Scholtenhuis et al. (2022), this applies to 2D data, but this concern remains for 3D data as well. When attributes are used of UUN to register depth relative to NAP using the AHN, data quality is something to carefully consider, as these attributes will determine the depth of the pipes. The definitions of transport, distribution and house connection pipes are not waterproof within the GIS of Brabant Water, resulting in potential inaccuracies in the standard depth information and incorrect labeling (Brabant Water, 2018). This issue can only be resolved by performing data quality checks and improvements or verifying the actual status in the field (Brabant Water, 2018).
- The registration of depth information derived from measurements at specific points does not provide a complete picture of the depth of the entire pipe, leaving it unclear where the standard depth is applicable again (Brabant Water, 2018).
- Pipes are subject to changes in depth due to subsidence or changes in the ground surface level (Brabant Water, 2018). Some areas in the North-West of Brabant are subject to subsidence, which does not apply to most of the province (Nederlands Centrum voor Geodesie en Geo-Informatica, 2022). The subsidence rate can vary depending on the soil type, with sand being less susceptible to subsidence than clay (Assinck, 2010; Stowa, 2020).
- Supply of new DWDS pipes with measured Z coordinates presents a challenge, as it may be difficult to force contractors to deliver this information (Brabant Water, 2018).
- The use of 3D data can lead to increased data consumption, affecting the performance and speed of visualization and analysis (Abdul-Rahman & Pilouk, 2007; Whitaker, 1998). Additionally, using 3D data may pose difficulties regarding symbol distinction and realistic representation (Smallman, John, & Cowen, 2004).
- According to Olde Scholtenhuis et al. (2022), the actuality of registered data as part of a 3D data model is crucial, as outdated data poses an increased risk given the potential shift in the positioning of cables or pipelines over time. Additionally, the current data model of UNM does not facilitate the individual recording of data relevant to each Z coordinate (see chapters 2.2.8 and 7.5). Therefore, a supplementary data model, in relation to the UNM, is required to accommodate this additional data for Z coordinates.
- According to Olde Scholtenhuis et al. (2022) and Laarhoven (2022), there is a risk of a false sense of certainty as a result of 3D data. Recording the Z coordinate requires a combination of a usable column in a dedicated data model, accurate information source, and distinction between estimated and reliable values to avoid the danger of recorded ignorance becoming accepted as truth.

4.3. Sub-conclusion

In conclusion, the utilization of 3D data in the analysis of the DWDS in the province of Brabant has added value but also some limitations. The depth information captured from specific points may not provide a comprehensive view of the entire pipeline, and it's unclear when standard depth is applicable again in the case of deviation depth. Moreover, the quality of attribute data in relation to depth information may pose difficulties. Due to inaccuracies in the data, it may not accurately reflect the standard depth of the pipes. The increased data consumption in 3D analysis may also slow down visualization and analysis performance.

Additionally, the current data model of UNM does not support individual recording of Z coordinate-related data, requiring the implementation of an additional data model. There is a risk of a false sense of certainty from 3D data. Recording the Z coordinate must be done with a usable column in a dedicated data model, accurate information source, and distinction between estimated and reliable values to prevent recorded ignorance from becoming accepted as truth.

Despite these limitations, the use of 3D data offers several crucial benefits. Improved analysis of important factors such as water temperature, failure probability, and resilience to temperature fluctuations can be achieved through 3D data analysis. Accurate depth information is critical in performing more precise analysis and determining the top load of pipes, thereby identifying potential weak spots and enhancing SA and communication in crowded underground infrastructure. 3D data visualization has been proven to be a valuable addition for several use cases in the utility sector, as it supports project location exploration, design planning, directional drilling preparation, and execution activities. 3D data can offer a more thorough risk assessment than 2D data prior to excavation, improving safety in the utility sector and reducing the likelihood of excavation damages by identifying potential hazards before excavation begins. The benefits of accurate depth information and 3D visualization can significantly enhance the overall management and maintenance of the DWDS.

5. 3D GIS as a spatial decision support system

The utilization of innovative data sources such as GPS signals, smartphones, Internet of Things (IoT), and satellite data from the European Union Copernicus Program, which contain significant spatial and temporal components, has led to the generation of large amounts of data that also exhibit semantic interrelations among them (Grimaldi, Sebillo, Vitiello, & Pellecchia, 2020). The challenge of translating the volume of data into meaningful insights is a contemporary issue that extends to the (geospatial) big data domain, which consists of numerous tools and techniques that can be used for various data processing needs (Grimaldi et al., 2020). Advanced Analytics, such as predictive analysis and machine learning, are suited for comprehending trends and extracting insights from large data sets to support decision-making processes, thus enabling the wise utilization of geographical knowledge (Grimaldi et al., 2020). An SDSS can aid in the transformation of large amounts of data into meaningful insights. By combining conventional data, spatially referenced information, and decision logic, SDSS supports decision-makers in analyzing data and presenting the processed information in an accessible form (Italian Authority of Electricity, Gas, and Water, 2018).

Combining collaborative technologies such as GNSS, sensors, GIS, and geodatabases, a form of Mixed Reality (MR), like AR, VR, or Augmented Virtuality (AV) can aid in the creation of services and products for monitoring, documenting and managing utility-based geospatial data (Stylianidis, Valeri, Carillo, Kounoudes, & Michail, 2020). These terms are depicted in figure 25 and are further explained as follows. The physical surroundings in which the user is situated constitute the real environment. VR consists of computer-generated objects with laser lights and enables users to immerse themselves in a completely virtual and artificial environment with no physical objects (Burdea & Coiffet, 2003; Zyda, 2005). MR allows users to simultaneously experience virtual and actual objects in the real world (Milgram & Kishino, 1994a; Ohta & Tamura, 2014; Speicher, Hall & Nebeling, 2019). AR enhances the real setting by enabling digital objects to interact with the real world (Milgram & Kishino, 1994b; Carmigniani et al., 2011). AV involves projecting and controlling real objects in a virtual world (Terniet, Klemke, Kalz, Van Ulzen, & Specht, 2012; Nahon, Subileau, & Capel, 2015).

Figure 25: Reality-virtuality continuum.
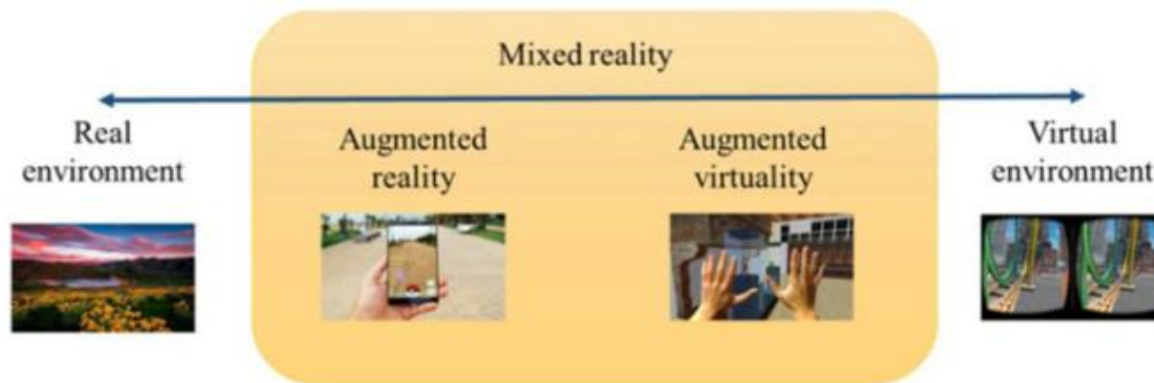
Source: Milgram & Kishino, 1994a

According to Xu & Moreu (2021), AR enhances real-world environments by overlaying interactive virtual objects and images. AR is more suitable for engineering than VR due to its interaction and see-through characteristics. AR is used in civil engineering to prevent problems in construction, increase efficiency, and reduce costs. Thus, presenting information in a friendly form is something that these technologies could help with, which is also a goal of Brabant Water to implement such technology in the form of smart glasses for mechanics work processes, as mentioned in 2.4. Safety is an important aspect of Brabant Water so this chapter will focus on AR and GIS. This is because with AV and VR technology, taking into account the environment in combination with work is more complicated.

This chapter will explore the application of AR and 3D GIS for utility fieldwork. Section 5.1 will discuss their use in this context, while section 5.2 will provide technical details and examples of AR systems. Section 5.3 discusses a field test conducted at Brabant Water involving AR and GIS data before creating a 3D dataset. Finally, section 5.4 will conclude this chapter.

5.1. AR and 3D GIS for utility fieldwork

Integrating AR with 3D GIS geodatabases presents a unique opportunity for users to visualize and comprehend the complexities of UID. By merging mixed reality with 3D GIS-based registration systems, AR offers real-time visualization of the underground utilities and the surrounding environment (Stylianidis et al., 2020). This can provide a valuable tool for various applications in the underground utility sector, including contractor training, outage management, and network planning (Schall et al., 2009).

Traditional methods of analyzing field situations, such as using mental mapping to navigate between a map and reality, can prove challenging, even for expert map readers (Schall et al., 2009). AR, on the other hand, can display interactive 3D models that can substitute for 2D plans and provide users with a form of "X-ray vision" into the underground infrastructure. This can lead to improved accuracy in underground asset detection, reducing the potential risk of damaging these structures during excavation (Schall et al., 2009). Additionally, AR can also aid in navigating trenches to investigate leaks and damages in pipes and serve as a valuable tool for resource planning for utility networks. It allows planners to overlay a proposed trench on location and make necessary adjustments on the spot without further processing (Schall et al., 2009).

Multiple studies have been conducted on applying AR systems in the utility sector for UID and have reported positive outcomes. For example, a mobile AR app tested by 20 industry experts was found to be user-friendly, effective in visualization, and easier to navigate than engineering drawings (Fenais, Ariaratnam, Ayer, & Smilovsky, 2019). Another pilot study conducted in Birmingham under six utility companies showed that the majority of participants agreed on the added value of AR and 3D GIS in communication and increased SA (Stylianidis et al., 2020).

While AR presents many advantages, there are also limitations, including hardware, software, and data-related constraints. Inaccurate registration of visualized data, limitations of GPS accuracy, and dependence on hardware are some of the challenges associated with AR (Azuma, 1997; Radu, 2014). While recent advancements in hardware and software have greatly improved these constraints, data accuracy remains a concern (Mallo, 2022).

Despite its limitations, AR can potentially enhance communication procedures when working with UID. However, no studies have been conducted to determine the productivity growth resulting from using AR in combination with UID (Fenais, Smilovsky, Ariaratnam, & Ayer, 2018). As such, the real value of AR in this context remains to be determined. Overall, AR can empower the visualization of 3D objects, both above and below ground, making it a useful option for viewing and working with UID.

## 5.2. Technical details and examples of AR systems

The measurement of underground infrastructure requires high levels of accuracy to assess its condition and determine its precise location. Various technologies exist that utilize GNSS and can achieve this level of accuracy. The European Geostationary Navigation Overlay Service (EGNOS) and Europe's regional Satellite-Based Augmentation System (SBAS) offer enhanced GNSS accuracy through differential positioning systems, which can decrease the error to a few centimeters (Gerhard et al., 1996). The use of cutting-edge technologies such as Real-Time Kinematic (RTK) (Petevello, 2011) and precise point positioning (PPP) (Chassagne, 2012; Lachapelle et al., 2006) enable high-end GNSS receivers to attain an accuracy of approximately one centimeter. Additionally, manually operated GNSS receivers with low output power can reach a similar level of accuracy through the utilization of RTK technology.

The Galileo system, developed for scientific and technological advancement, has improved the accuracy and quality of satellite data services through the increase of Galileo satellites. To further improve accuracy, differential correction processing methods such as EGNOS, Differential GNSS (DGNSS), and RTK are utilized to minimize geo-location error to at least one centimeter (Stylianidis et al., 2020).

Regarding geometric data formats, two options exist, which are KML and XML. KML, due to its versatility and widespread use, is the preferred choice for many applications (Fenais et al., 2019). Figure 26 depicts a workflow for the development of AR in combination with GIS data.

The LARA (LBS Augmented Reality Assistive System for Utilities Infrastructure Management through Galileo and EGNOS) project, which the European Commission funded from 2015 to 2017, is a prime example of a large-scale AR initiative encompassing the efforts of utilities, companies, and research institutes. The interdisciplinary program was developed to address the needs of utilities, construction companies, Small to Medium Enterprises (SMEs), university researchers, and end users (Stylianidis et al., 2020). The consortium partners of the LARA project created a new mobile (tablet) device to aid transportation management personnel and field workers in high-risk working environments by implementing AR, location-based tracking, and 3D geodatabases (Stylianidis et al., 2020).

LARA presents several innovative concepts, including integrating GNSS technology, primarily targeting Galileo and EGNOS, with AR technology to position geolocated assets precisely (Stylianidis et al., 2020). Additionally, GIS technology transfers GIS information into a specialized computing unit and converts GIS data into 3D models using rendering techniques (Stylianidis et al., 2020). The project also employed novel AR visualization techniques to handle hidden object counts (Stylianidis et al., 2020).

Figure 26: AR workflow development
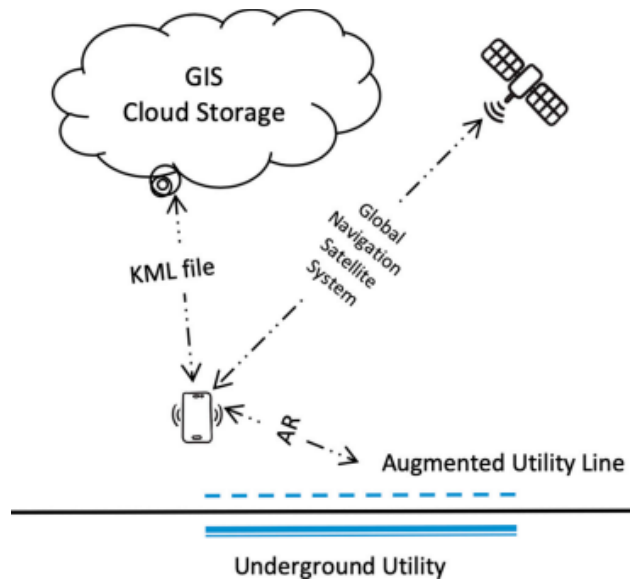
Source: Fenais et al., 2019.

The LARA project developed a specialized tool that utilizes GNSS technologies, such as AR, navigation and geography, spatial databases, and GIS, and is practical for utility field workers (Stylianidis et al., 2020). The system comprises two sensing components (a camera and a receiver for positioning), a 3D GIS tablet, and a visualization and AR module. The tablet's camera takes an image, which is then augmented with utilities using the AR module. The positioning subsystem consists of an external hardware module consisting of a microcontroller, location, and orientation sensor, as depicted in Figure 27 (Stylianidis et al., 2020).

Figure 27: The LARA-system architecture and positioning receiver block diagram.
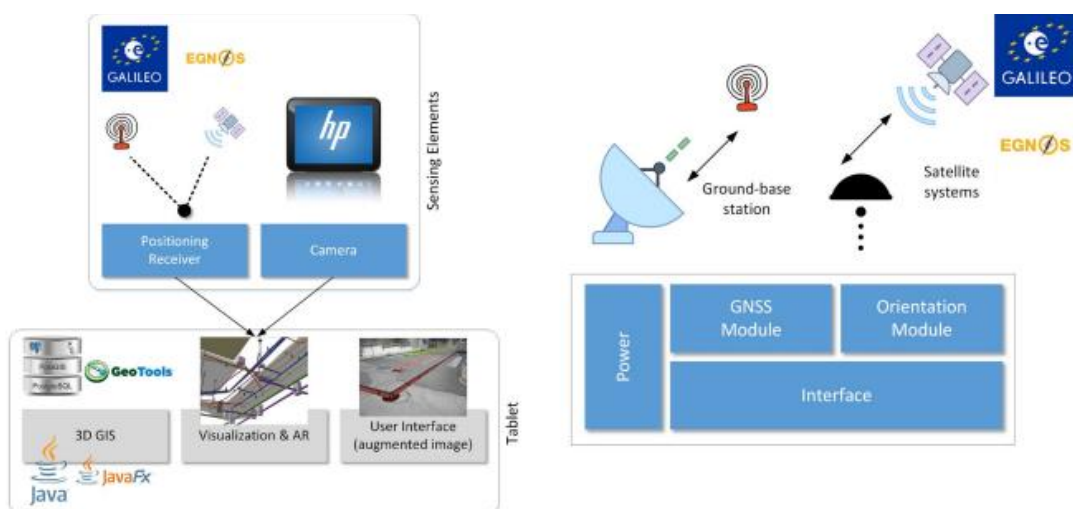
Source: Stylianidis et al., 2020.

5.3. Field test with AR and GIS data prior to creating a 3D dataset at Brabant Water

Brabant Water is exploring using AR in combination with GIS to view UID for inspections and projects related to the DWDS. In order to assess the effectiveness of the technology, a field test was conducted in collaboration with V-labs, during which two mechanics of varying technical proficiency were sent to various locations to evaluate the system's performance. The system consisted of a GNSS RTK receiver paired with AR displayed on smart glasses, similar to the LARA system, and was designed to retrieve data from Brabant Water's geodatabases. The mechanics successfully conducted inspections, took pictures, and viewed data projected in front of them, with both mechanics appreciating the system's ability to display multiple UID networks. However, the data was not displayed in 3D as it lacked Z coordinate information, which V-Labs indicated could be technically feasible and would provide additional benefits in determining the depth of each network. The accuracy of the data was high, with information displayed directly above the underground infrastructure. On rare occasions, elements such as trees would temporarily interfere with the GPS signal, but the connection was promptly re-established upon moving the device. All figures in the field test were taken in Tilburg (figures 28-32).

Figure 28: A mechanic of Brabant Water testing the AR system of V-Labs.

Source: Own photo.

Figure 29: V-Labs measuring UUN and recording UID.

Source: Own photo.

Figure 30: Viewing physical assets related to UUNs in combination with UID (1)

Source: V-Labs, 2022.

Figure 31: Viewing UID in combination with markings on the road.

Source: V-Labs, 2022.

Figure 32: Viewing physical assets related to UUNs in combination with UID (2)

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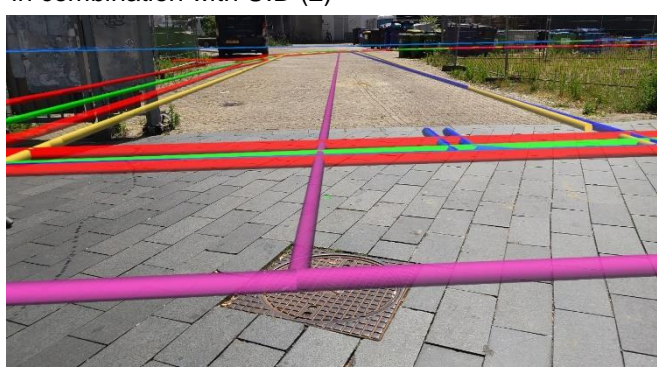
Source: V-Labs, 2022.

5.4. Sub-conclusion

Advanced data sources such as GPS signals, smartphones, the Internet of Things, and satellite data have created the challenge of translating large volumes of data into insights. An SDSS can help make large amounts of data insightful by combining conventional data, spatially referenced information, and decision logic to support decision-makers in analyzing data and presenting processed information in a friendly form. Combining collaborative technologies such as GNSS, sensors, GIS, and geodatabases, a form of MR like AR, VR, or AV can aid in creating services and products for monitoring, documenting, and managing utility-based geospatial data. Of these MR technologies, AR is the safest for fieldwork due to its see-through characteristics making manual labor possible in the meantime. In combination with 3D GIS geodatabases, AR can display a graphical overlay showing which parts of the trench workers should follow, highlighting relevant underground assets in civil engineering, contractor training, outage management, and network planning. AR and GIS technology have the potential to make the work processes more efficient and safer for workers in the field.

6. Creation of models: Identifying depth relative to NAP for the DWDS using AHN4 data

Currently, a fully 3D GIS environment for Brabant Water is not possible because of a lack of data regarding Z coordinates. This will likely increasingly change from 2025 onwards because Brabant Water is considering requiring contractors to report Z coordinates. This is because the data is now being measured by contractors but not always delivered, which means that it is a loss of data. Brabant Water would like to make its data as accurate and complete as possible, contributing to better data quality and a future digital twin. This applies only to new measurements, which means the remainder of the DWDS still lacks Z coordinates. However, when maintenance is performed on existing network pipes, measurements can be performed as well. Currently, the majority of the Z coordinates are lacking in the DWDS. There is only a dataset with deviating depth for a small portion of the DWDS and Z coordinates for 0,58% (when looking at feature count) of the DWDS. Currently, in the case Z coordinates are lacking, the standard depth is assumed for the remainder of the DWDS. The part of the DWDS for which only the standard depth is known should be transferred to a depth relative to the NAP, to make a first step towards a 3D GIS.

It is possible to assign a depth relative to the NAP to the DWDS using the standard depths in table 1 by matching them with attributes in the database and using the AHN4. The standard depths from table 1 are then subtracted from the AHN4 surface points for each vertex, resulting in a depth relative to the NAP. The AHN is a high-quality dataset containing data about the Netherlands' ground surface. The most recent version is AHN4, measured between 2020-2022. For the province of Noord-Brabant, which is the surface area for Brabant Water, the AHN4 is ready and fit for purpose. The AHN4 contains 10-14 height measurement points per square meter (AHN, 2022). By making use of the following formula, the depth relative to the NAP can be calculated for the DWDS:

The depth relative to the NAP for the distribution network = Ground surface level (AHN4) – standard depth of the water distribution network*

*Depending on the type of network and asset type as each pipe has its standard depth (table 13).

Table 13: The convergence table for the standard depths of table 1 and for the GIS DWDS data of Brabant Water.

Asset type code	Asset type text (Dutch)	Name (English)	Standard depth
102	Primair	Transport pipes	-1,2
103	Secundair	Distribution pipes	-1,0
104	Tertiar		
105	Ruw	Raw unpurified	-1,2
106	Rest	Remainder for industrial usage	-1,0
201	Drinkwater	House connection pipes	-0,8
202	Rest		

Source: (Van Os, 2022).

The AHN4 will be used to assign a depth relative to the NAP to the distribution network where measured Z coordinates are lacking. This is a point cloud dataset, a set of data points in space representing the ground surface relative to NAP. The elevation of a point can only be expressed concerning another point or reference surface (Tiberius, Van der Marel, Reudink, & Van Leijen, 2021). In the Netherlands, NAP is used as a vertical reference system for height.

This analysis will use various study areas (figure 2). A small test area will be used to test tools and workflows during this analysis. The next step is taken when the results are satisfactory, which will be explained below. The AR tests are also performed in the test area since the chosen test sites are close

to the headquarters of Brabant Water. The data, however, is prepared for the entire municipality of 's-Hertogenbosch.

The analysis will consist of 5 models. The models have a dependency on each other, whereas model 1 is the beginning of the entire analysis. There are various datasets required for the analysis. Each dataset and its relation to the analysis model is described in table 14. Model 1 in chapter 6.1 will be used to clip the AHN4 LAS on the buffer of the DWDS. Model 2 in chapter 6.2 will look at the measured Z coordinates' quality and validate them relative to the AHN4. Model 3 in chapter 6.3 will put the UUNs on their standard depth relative to NAP using the AHN4 if there are no measured Z coordinates. Otherwise, measured Z coordinates will be used from the measured Z coordinate datasets of the deviation depth point file and the measured Z coordinates from the DWDS. In model 4 in chapter 6.4, vertical reference features will be created on top of the DWDS to emphasize the distance in AR from the DWDS to the ground surface. The features will be used as a data model to accommodate data that cannot be stored in the UNM as it cannot capture data per Z coordinate. Model 5 in chapter 6.5 created polygons on top of the vertical reference features to emphasize the ground surface. Chapter 6.6 will provide a sub-conclusion.

Table 14: The following input datasets are required for the models used in the GIS analysis. The names of the required datasets are described, and related information to the dataset is provided. The standard depths are based on table 1*.

Required datasets	Source	Data type	Asset types and theme of the KLIC data	Standard depth in meters	Analysis area	Used in model
DWDS of Brabant Water (contains a few Z coordinates: 0,58% of the DWDS).	Brabant Water	Polylines	Transport, distribution, and house connection pipes	-1,20 -1,00 -0,80	Test, study, and distribution	1-5
Electricity cables (Elektriciteits kabels)	Brabant Water KLIC data		Low voltage (Laagspanning), High voltage (landelijkHoog-Spanningsnet), Medium voltage (middenspanning)	-0,60 -1,00 -0,80	Study	3
Trench (Geul)			Data transport, Gas high pressure (GasHogeDruk), Gas low pressure (GasLageDruk), Low voltage (Laagspanning), Medium voltage (Middenspanning)	-0,45 -0,90 -0,90 -0,60 -0,80		
Cable bed (Kabelbed)			Data transport, Low voltage (Laagspanning), Medium voltage (Middenspanning), ProRail	-0,45 -0,60 -0,80 -0,75		
Casing pipes (Mantelbuis)			Data transport, Gas high pressure (GasHogeDruk), Gas low pressure (GasLageDruk), Low voltage (Laagspanning), Medium voltage (Middenspanning),	-0,45 -0,90 -0,90 -0,60 -0,80		

			ProRail	-0,75		
Oil, gas, chemicals, pipeline (Olie, gas chemicalien pijpleiding).			Pipeline dangerous contents (Buisleiding Gevaarlijke Inhoud), Gas high pressure (gasHogeDruk), Gas low pressure (GasLageDruk)	-1,20 -0,90 -0,90		
Other (Overig). Only Prorail selected			ProRail = -0,75	-0,75		
Sewer (Riool)			RioolOnder OverOf Onderdruk, rioolVrijverval	-1,10 -1,10		
Telecom cable (tele communicatie kabel)			Data transport	-0,45		
's-Hertogenbosch municipal boundaries	Esri ArcGIS Online CBS district and neighborhood maps	Polygon	-	-	Test and study	
Province of Noord-Brabant			-	-	Distri-bution	
Deviation Depth (contains Z coordinates)	Brabant Water	Points	Elevation relative to NAP and ground surface	Variable		
Dutch elevation point cloud dataset AHN4 (Actueel Hoogtebestand Nederland) either in LAZ/LAS or point feature class	Esri ArcGIS Online AHN4	Polygon AHN4 tiles grid, LAZ/LAS, and Points	Filtered by only ground surface points	Variable	Test, study, and distri-bution	1-4

*The depth for the remaining category is based on an average from Prorail, as the majority of assets in this category had Prorail as administrator (Prorail, 2020).

6.1. Model 1: Clipping AHN4 LAS on the buffer of the DWDS (distribution area)

For this analysis, a personal computer was used. For this analysis, an additional 2 Terabyte SSD was purchased and installed on the motherboard. Subsequently, the needed software (ArcGIS Pro and FME) was also moved to the SSD drive to profit from the enhanced speed of the SSD. The computer specs are Intel Core i5-4690 CPU @ 3.50GHz, 24,0 GB RAM, GPU NVIDIA GeForce GTX 760, and 2TB SSD.

This analysis requires five input datasets: The DWDS, KLIC datasets, the AHN4 grid tile, the AHN4 LAZ, and the deviation depth dataset. The DWDS is needed to determine the locations in which area of the LAZ needs to be clipped. The AHN4 tiles are a feature class that contains grid tiles in which the Netherlands is divided. Each grid tile represents an area where the point cloud is cut into to manage the point cloud data due to the size of the data (ArcGIS, 2022a). As described above, the cut operation is called a clipping operation: a tool that slices a portion of one dataset using one or more features in another dataset as a cutter (Esri, 2022a). The entire province of Brabant covers 215 AHN4 tiles. This includes two small areas for which Brabant Water is also responsible, located in the province of Zeeland

and the enclave of Baarle-Hertog, located in Belgium. The area of interest in the province of Zeeland is between the town of Sint Philipsland and Anna Jacobapolder.

Each AHN4 tile contains about $4 \times 10^9 - 7 \times 10^9$ points, depending on the location. In the case of a lot of surface water, the tile will contain fewer points since surface water is not included in the dataset. The AHN4 points are classified with various classifications. This research is only focussing on ground surface points with classification = 2. Other points will not be used since they are not of interest to determine the standard depth of UUNs; only the ground surface points are needed to determine this.

The Field Manipulator Engine (FME) performs this translation since it integrates well into ArcGIS and can handle point cloud (LAZ) processing. The first step of the model is to overlay a buffer over the DWDS and the KLIC data. A buffer distance of 0,10 meters was chosen. This small buffer size was chosen for two reasons: (1) The AHN4 has a high resolution of 10-14 points per square meter. Only 1 Z coordinate per vertex needs to be joined to the DWDS, which will always be the closest point of the AHN4. Therefore, a large buffer area wouldn't make a difference. (2) The processing time for the entire province of Noord-Brabant would increase if the buffer was increased. 0,10 meters already resulted in a processing time of 7 days. An attempt was also made with a larger buffer size, resulting in errors due to memory issues. The buffer tool is used to create polygon buffers around input features to a specified distance (Esri, 2022b).

Model 1 for this analysis is performed for the entire distribution area of Brabant Water because, in the model 2 analysis throughout the entire distribution area, Z coordinates are compared to the AHN4. This is done to test their validity (see model 2).

Using FME, the LAZ is converted to LAS. Subsequently, the AHN4 data can be clipped on the created buffers of the DWDS and the KLIC data using the clipper tool in FME. Then, the PointCloudFilter tool filters out the classified ground surface values, since those are the values needed for this analysis. Subsequently, the PointCloudCombiner tool merges the 215 points clouds (Safe, 2020). The LAS is then saved on the SSD drive, converted to points, and then stored in a geodatabase. Now there are point cloud data and feature class points of the ground surface only situated on the buffers representing the DWDS pipes and KLIC UUN data.

See figure 33 for a complete overview of this model.

Figure 33: Clip AHN4 on the DWDS of Brabant Water as well as on other UUNs from the KLIC dataset with a buffer of 0,1 meter.
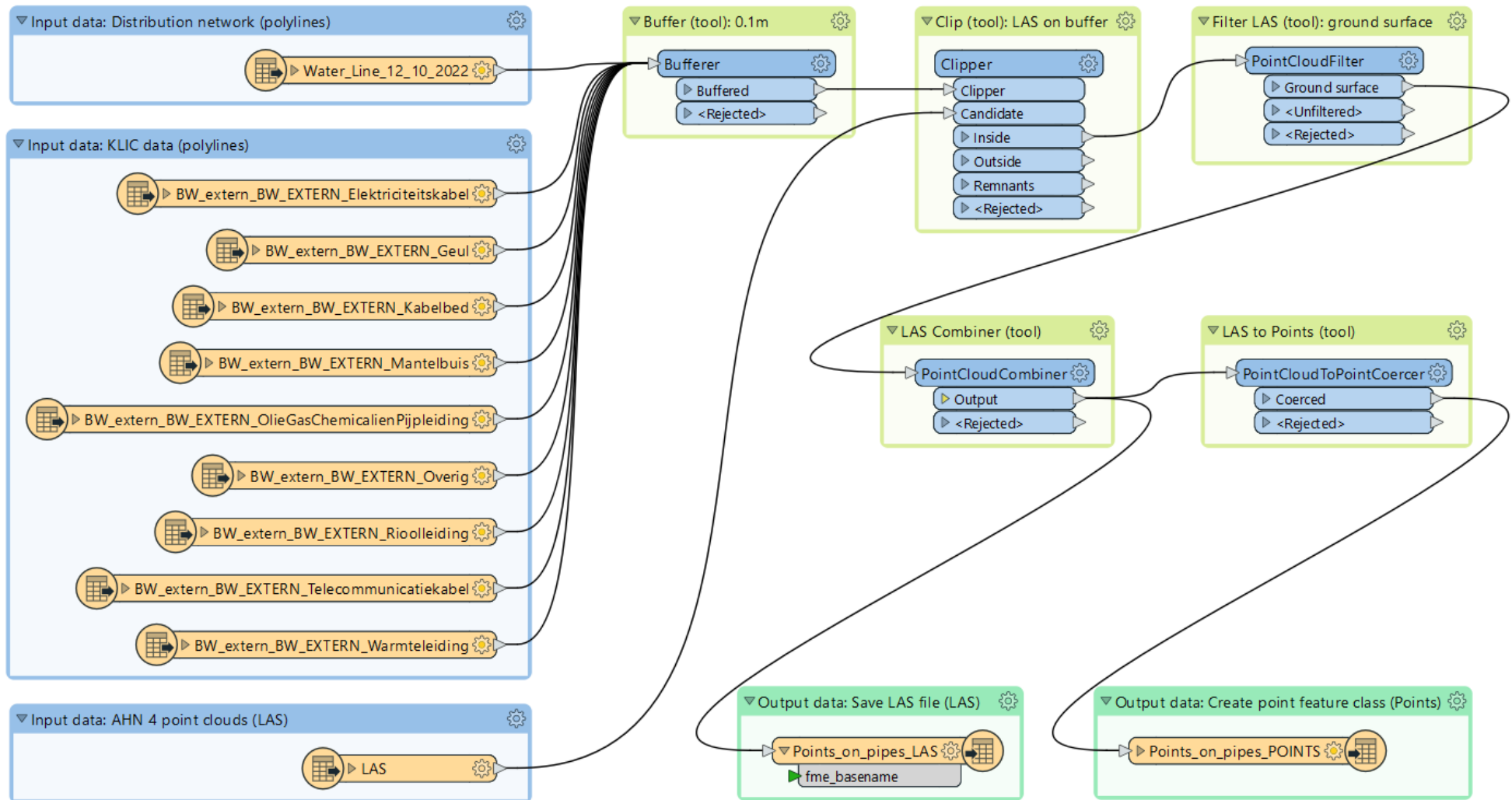
6.2. Model 2: Validation of the measured Z coordinates

Since UNM was launched, some Z coordinates have been registered for the DWDS. About 10.000 of the 1.725.020 pipes have one or more Z coordinates that can validate the derived AHN4 depth for the DWDS. This is 0,58% of the DWDS which has depth information assigned to it. Some Z coordinates are not measured correctly since they are unrealistically high or are located too deep. This analysis aims to give an insight into the data quality of those measured Z coordinates. Next to the Z coordinates of the DWDS, there is another dataset with measured Z coordinates. This is the deviation depth point file which contains Z coordinates relative to the ground surface and Z coordinates relative to NAP. However, this dataset was not included in the analysis. In table 15, the datasets are displayed.

Table 15: Z coordinate distribution of the available measurement datasets

Dataset:	The total number of measurements:	Relative to the ground surface or a depth relative to the NAP:
DWDS Z coordinates	35.246	NAP depth
Deviation depth point file	2.646	Either relative to the ground surface or depth relative to the NAP

The depth relative to NAP will be used to compare the measured Z coordinates of the DWDS and the deviation depth point file at the same location. This can be achieved by performing the analysis in figure 34.

There are two input datasets required (figure 34). The first is the distribution network, and the second is the AHN4 point dataset, both generated in the analysis of model 1 (figure 33). First, Z information is added to the DWDS in the attributes on the object level. Subsequently, a copy of the DWDS is made with a new feature class, and the tool vertices to points is used. This tool generates vertices which are points located on every X, Y, and Z location of the DWDS. The tool add Z information is used and is then run again because there are also pipes applicable that only have Z coordinates on some vertices, not all of them. Therefore, selecting layer by attributes is used as the next tool with the selection Z = 0 to delete the rows of the vertices that don't have Z coordinates. The result is a dataset with all the measured Z coordinates from the DWDS. Next, a spatial join is performed to join the AHN4 points to the vertices. The join distance of the AHN4 points to the vertices is also written to the attributes. The AHN4 points in the attributes have points instead of commas as a separator. This is fixed by adding a new field, replacing the points with commas, and rounding off to 3 decimals. The field with the original AHN4 with points as a separator is then deleted.

Figure 34: Validation of measured Z coordinates from the distribution network (polylines) with AHN4. The Python script of this model can be found in Appendix 11.2.1.
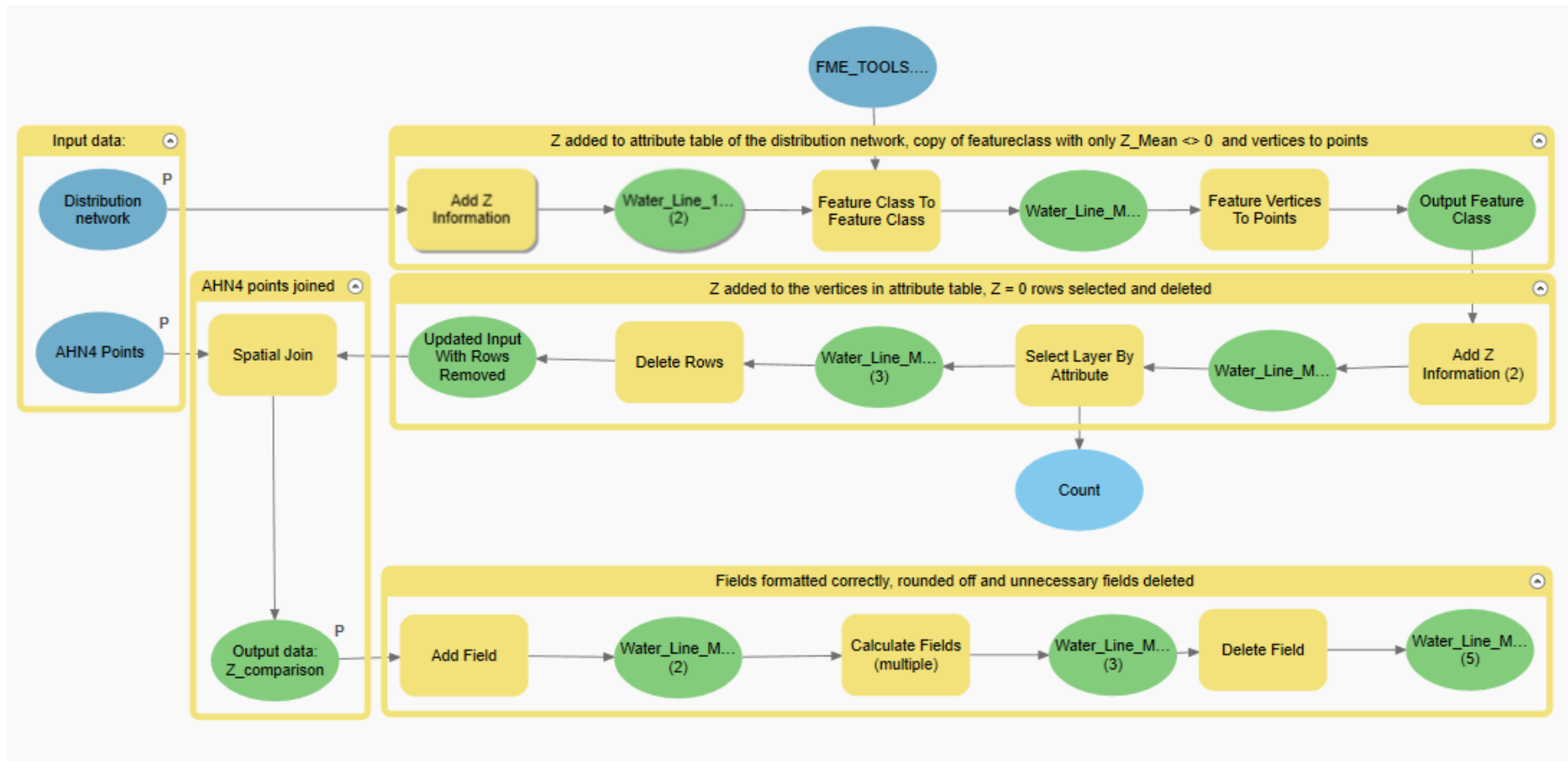
6.3. Model 3: Placing each UUN on its depth relative to NAP

In this analysis, the data is made fit for the purpose for the AR application using the AHN4 en Z coordinate datasets. Each network needs to be placed on its standard depth in correspondence to table 14 relative to NAP. To assign Z coordinates to the DWDS, various models are required.

First, the LAS file generated in model 1 (figure 33) was clipped on the distribution area. This LAS file was stored separately on the local computer, which will be used in this model.

Before the model can be used in figure 38, two datasets need to be prepared. In figure 36, the Z coordinates from the DWDS are extracted and stored in a separate point feature class. This is done because the AHN4 will overwrite all the Z coordinates in the DWDS in model 1 (figure 38). Using this point feature class, they can be joined again once the AHN4 join has been joined.

Figure 37 demonstrates the joining of the AHN4 with the deviation depth dataset, which comprises measurements relative to the surface level and NAP. To transform the surface level relative measurements to NAP relative depths, the ground surface values are necessary and stored in a single field that contains all the deviation depths' Z coordinates relative to NAP. This field is then utilized to force all points to 3D. The deviation depth dataset is then made 3D and can be joined with the AHN4 and DWDS Z coordinates.

However, a value of zero must be assigned for Z coordinates that intersect with surface water, as AHN4 data does not include ground surface information beneath surface water. Therefore, when 2.5D Delauney triangulation is used, the Z coordinates intersecting surface water won't be correct. Using the basic registration of large-scale topography (BGT), vertices of the DWDS that intersect with surface water are identified and set to zero (ArcGIS, 2022b). The vertices of the DWDS that intersect with surface water are set to zero because NaN (Not a Number) does not exist in the Z coordinates of ArcGIS, and assigning an unrealistic high number, such as 99999, would result in an unrealistic visualization of the pipe. As a result, the Z coordinate is set to 0, which is the default for Null Z coordinates (Pro.ArcGIS, 2023). Although this could lead to confusion when visualizing, assigning an unrealistic high value is inappropriate. Moreover, measurements are recorded with several decimal points, distinguishing them from null values registered as Z=0.

First, the AHN4 will be joined to the DWDS. This is done using the surface draper tool, which builds a Delaunay triangulation using input point clouds. The tool drapes input features onto the surface model and outputs them as draped features. The input features for Points/Lines can be 2D or 3D, including raster, point cloud, and aggregate geometries. 2D features will be converted to 3D by adding a Z coordinate of 0. Points extracted from this port will typically be found in the vertex pool of the underlying surface model, and a minimum of 3 unique points are required to construct a surface model. Duplicate X and Y coordinates will be removed. DrapeFeatures input can be 2D or 3D; if they are 3D, their Z coordinates will be overwritten. These features will be output as DrapedFeatures with their Z coordinates set to interpolated values on the underlying surface model (figure 35) (Safe, 2023).

The Drape Method parameter determines how to input DrapeFeatures and how they will be modified to match the underlying surface model. If set to VERTEX, the input features retain their vertex count but have their Z coordinates interpolated from the surface model. If set to MODEL, additional vertices may be added to the features to match the surface model better, but this will take more processing time (Safe, 2023).

The interpolation method used was the constant interpolation method. This method ensures the Z coordinate of each output point is set to the Z value of the closest vertex in the underlying model (Safe, 2023).

The Existing Elevation parameter determines whether input DrapeFeatures will have their Z coordinates replaced or offset: If set to ''Replace Z'', the input feature will have its Z coordinates set to the interpolated values from the underlying surface model (Safe, 2023).

Figure 35: Surface Draper tool of FME.

2d features + 3d surface map → draped features
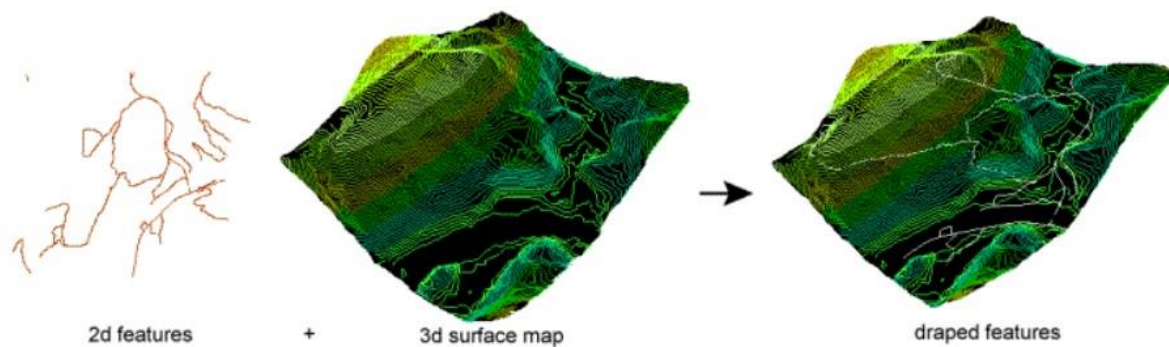
Source: Safe, 2023.

The AHN4 point cloud was used as input for the surface draper analysis. The DWDS was used as input for the DrapeFeatures. The draping method was set to VERTEX to assign Z coordinates from the AHN4 to existing vertices in the DWDS. Although the drape method MODEL would result in more accurate results, especially on varying terrain, the VERTEX method was chosen due to its faster processing time but also because the model method would result in erratic running UUNs in the case of varying terrain. The downside of not choosing this option is that certain elements could now fall outside the underlying surface model. The existing elevation parameter was set to "Replace Z" to use the interpolated Z coordinates from the underlying surface model (Safe, 2023).

In the next step, based on each attribute, the networks can be placed on their standard depth using the attribute filter. The convergence from table 13 applies to the standard depth and the asset types of the DWDS of Brabant Water. Table 1 displays the standard depths, and an overview of those two tables is given in table 14, where each network's asset type related to its standard depth is displayed. After all the attribute filters are performed, the Z coordinate will be adjusted. This is done using the Offsetter tool. The standard depth subtracts the AHN4 values to place the features at their correct depth relative to the NAP.

After the AHN4 is joined to the DWDS and other UUNs, vertices are created from the DWDS. Spatial filters are used to join the Z coordinates from the DWDS measurements, the deviation depth dataset, and the intersecting surface water Z coordinates (set to Z=0) to the DWDS and the other UUNs. First, the vertices that do not intersect with the surface water vertices are filtered out. This is followed by filtering out the vertices that do not intersect with the DWDS Z coordinate measurements and then with the deviation depth dataset. The measured Z coordinates of the DWDS, the deviation depth dataset, and the Z coordinates that intersect with surface water are now appended back to the remaining vertices again. This is done to filter out AHN4 vertices that intersect with the measured Z coordinates of the three datasets. The purpose of this method is to join the vertices from all the measured Z coordinate datasets to the DWDS with their actual measurements. The Z coordinates of the three datasets plus the AHN4 are now appended in a vertex dataset. The surface draper is used again to join all the Z coordinates on the DWDS and the UUNs.

Finally, each network is filtered and subsequently written to its output destination folder in a geodatabase.

An overview of this analysis can be seen in figure 38, with more detail in figures 39A-39D.

The datasets are now fit for the AR application. The data can now be published to ArcGIS Online, which the AR application can retrieve and read. This is done by storing the data in a local geodatabase, which is then hosted in the ArcGIS Online production environment of Brabant Water in a specified folder.

Figure 36: Extract Z coordinates from the DWDS. The Python script of this model can be found in Appendix 11.2.2.
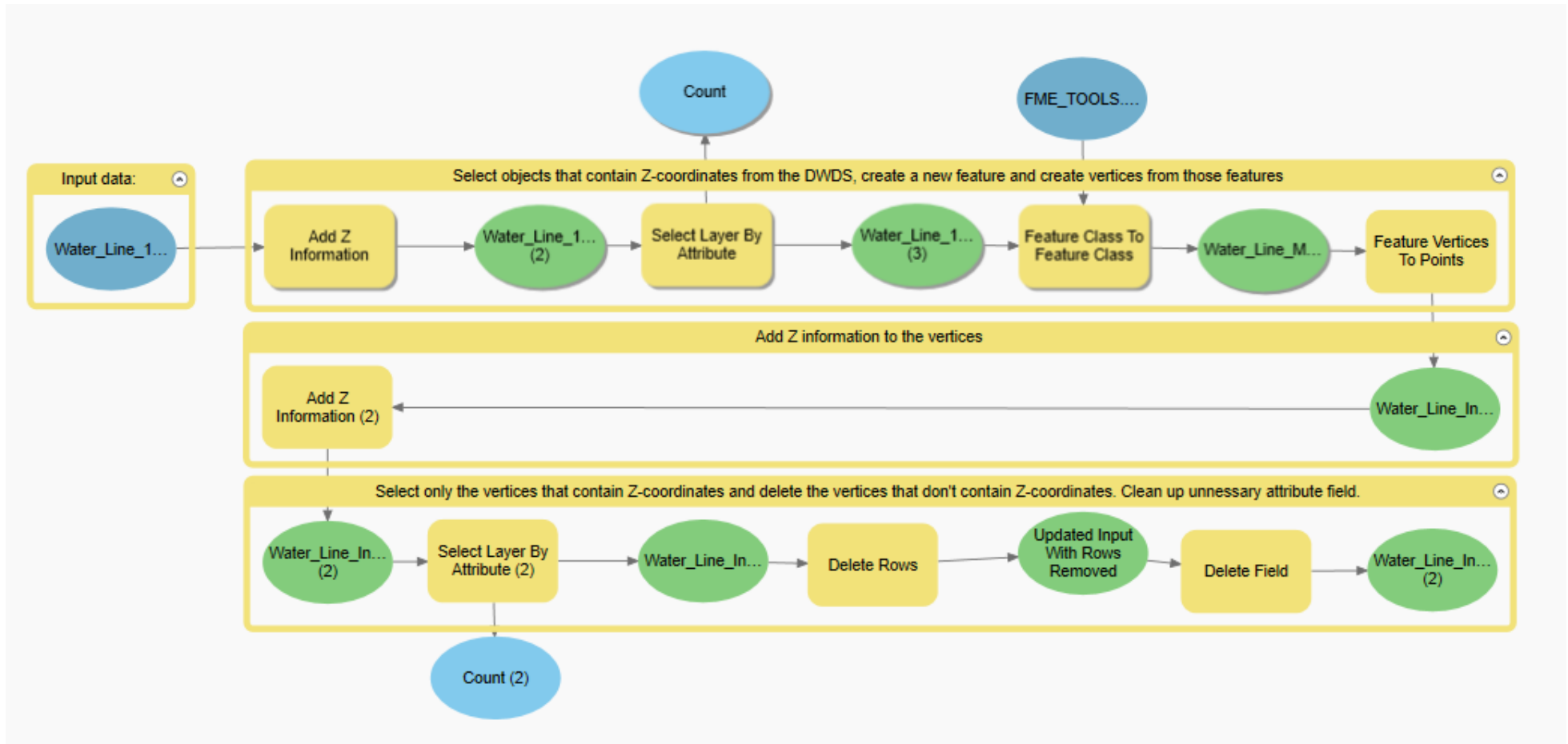
Figure 37: Join AHN4 to deviation depth dataset (Meetpunt_Hoogte_AHN) using 2.5D Delaunay triangulation. The Python script of this model can be found in Appendix 11.2.3.

Figure 38: Overview of the entire model: Placing each UUN on depth relative to NAP using Z coordinates from the DWDS, the deviation depth dataset and the AHN. Surface water is set to Z=0 using the BGT.

Figure 39A: Input datasets: The DWDS and the KLIC datasets of Brabant Water.
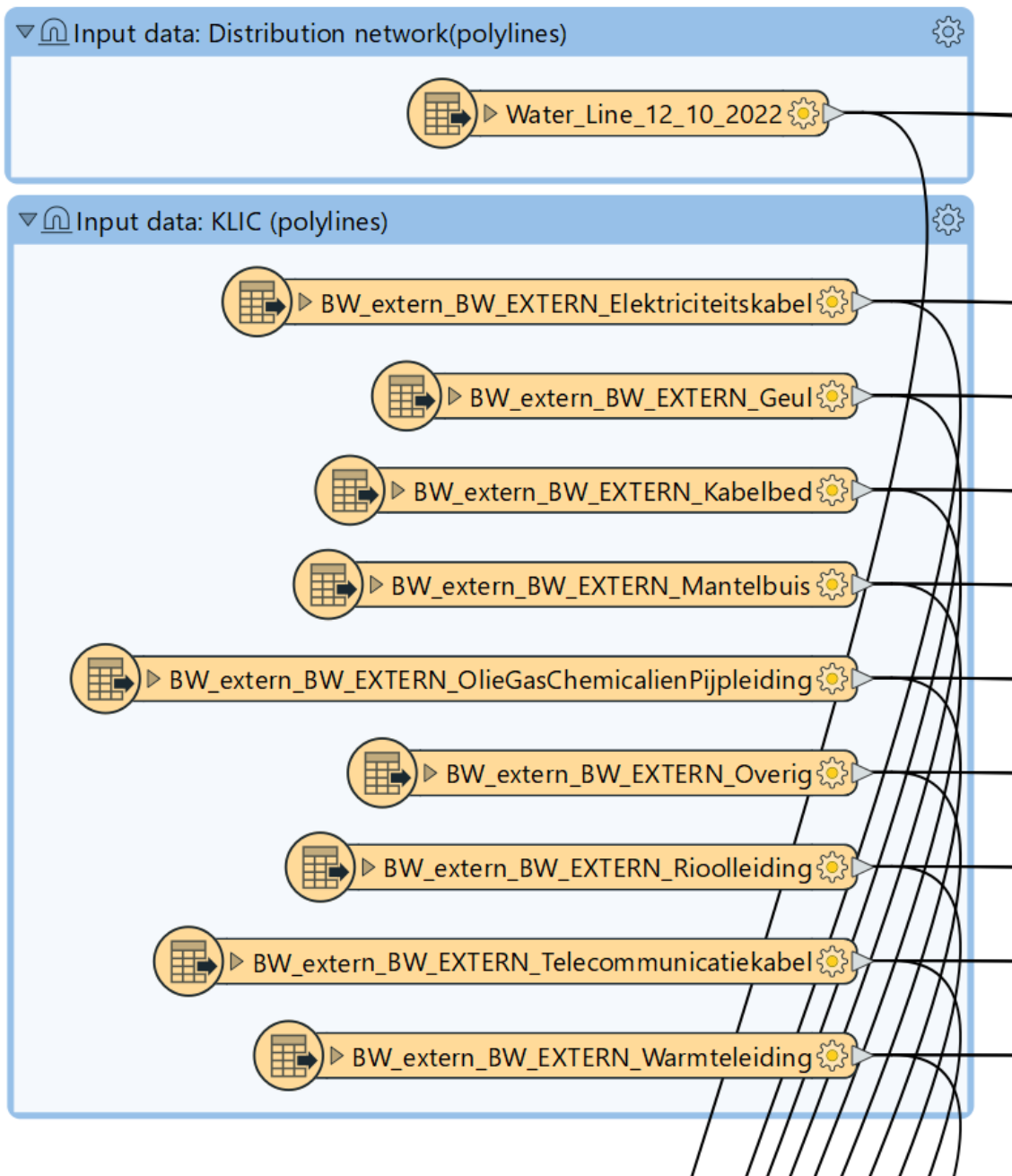
Figure 39B: Placing the DWDS and the KLIC datasets on standard depth using the AHN4.

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Figure 39C: Placing the DWDS and the KLIC datasets on standard depth using the AHN4 and Z coordinate measurement datasets.

Figure 39D: Filter each UUN and create new datasets.
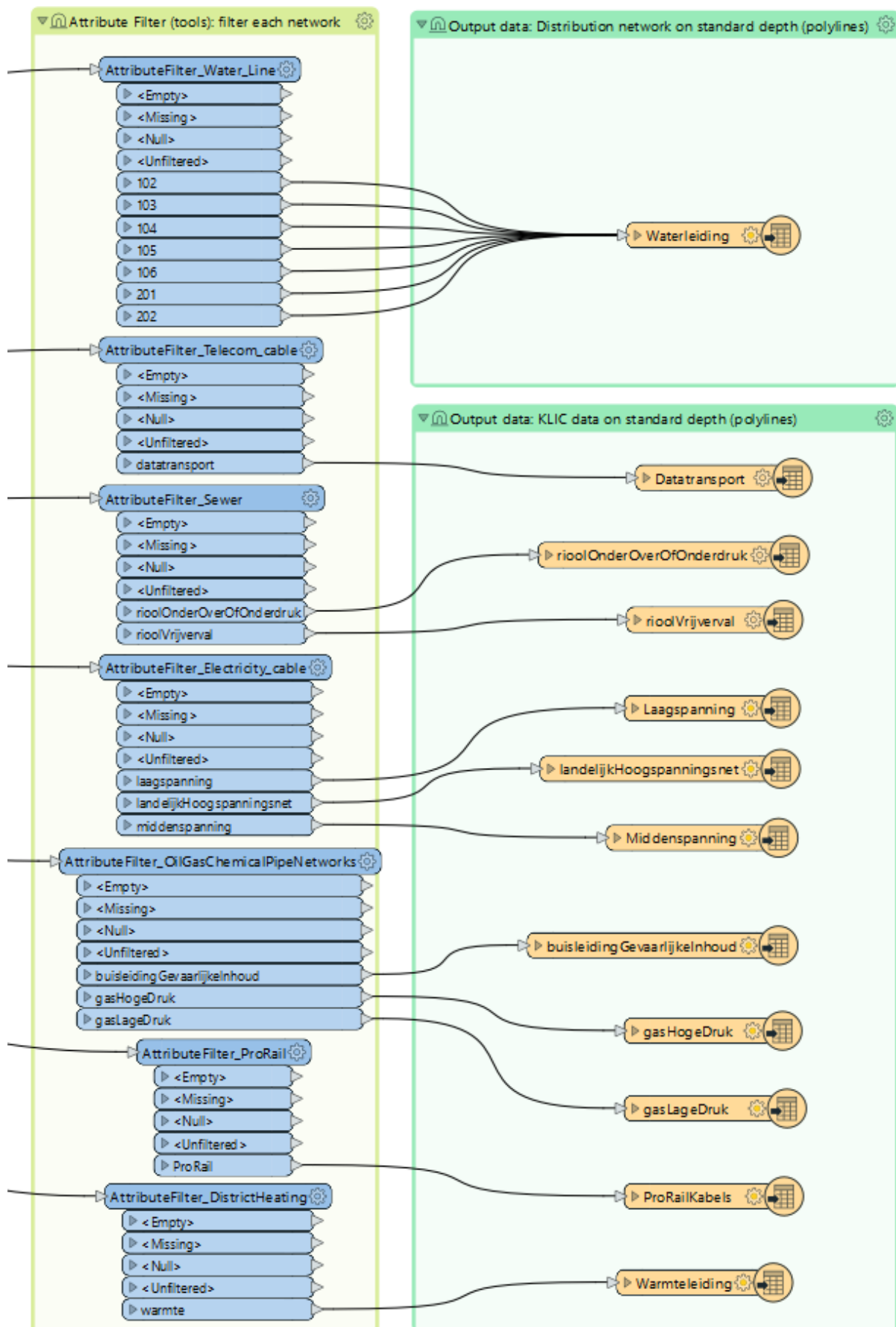
6.4. Model 4: Vertical reference features and data model to track Z coordinates

This analysis aims to generate vertical reference features meant to create perspective in the AR images of where the UUN is located relative to the surface level. This is because it's difficult to see the depth relative to other UUNs and the surface level without tools that give more perspective.

As input features for this analysis, the DWDS and the AHN4 height points are used. The individual vertices of the DWDS and the AHN4 height points are needed to create vertical reference features. The tool vertices to points is used to create vertices from the DWDS. Subsequently, a spatial join is performed to join the closest AHN4 values to the attributes of the vertices, which means one AHN4 point per vertex. The add field tool is used to create new fields:

- Z_Maaiveld (surface)
- Z_Leiding (pipe)
- Z_Verschil (difference)
- XY_ID

Then the calculate field tool is used:

- Z_Maaiveld Expression: !Z_Surface!.replace(".", ",")
- Z_Maaiveld Expression: round(!Z_Maaiveld!, 3)

Subsequently, the select layer by attribute tool is used to select asset types 102 and 105 in correspondence with table 13 to display the depth at -1,2 meters below the ground surface. This is done by calculating the field Z_Leiding (pipe) by subtracting 1,2 from the value Z_Maaiveld (surface). The calculate field tool is running to force the selected features -1,2 meters below the ground surface.

This process is repeated for asset types 103, 104, and 106, which are distribution pipes located -1,0 meters below the ground surface. Also, for the house connections this applies with asset type codes 201 and 202 with a depth of -0,80 meters below the ground surface.

Subsequently, the difference between the Z coordinates is calculated by selecting all features and subtracting Z_Leiding (pipe) from Z_Maaiveld (surface). Later, two separate features are made: Z_Maaiveld and Z_Leiding, by running the feature class to feature class tool. After that, their Z coordinates are adjusted from their respective attributes Z_Maaiveld and Z_Leiding. This is done using the adjust 3D Z tool, which can modify the Z coordinates of 3D features (Esri, 2022c). Then both features are merged back together again.

The next step is to add XY coordinates to be able to make a unique identifier. The earlier created field XY_ID is now calculated by adding up the X and Y coordinates. The tool points-to-line is then run with line field XY_ID. Lines can be generated because there are two points with the same XY_ID.

Subsequently, the spatial join tool is run again to join the attributes from the point feature class to the line feature class, as the points-to-line tool doesn't take into account attributes. Finally, fields that are not needed are deleted.

The final output and data model is displayed below in figure 41. The quality of each Z coordinate can be tracked in this data model as a vertical reference feature is now equal to each vertex. The way the Z coordinate was measured can be stored under ''Wijze_van_inmeting'' which is a field also present in the data model of the DWDS.

In figures 40A and B, the workflow for this analysis is described.

Figure 40A: Creating vertical reference features for AR reference and simultaneously using the features for quality tracking (data model) of the Z coordinates. The Python script of this model can be found in Appendix 11.2.4.
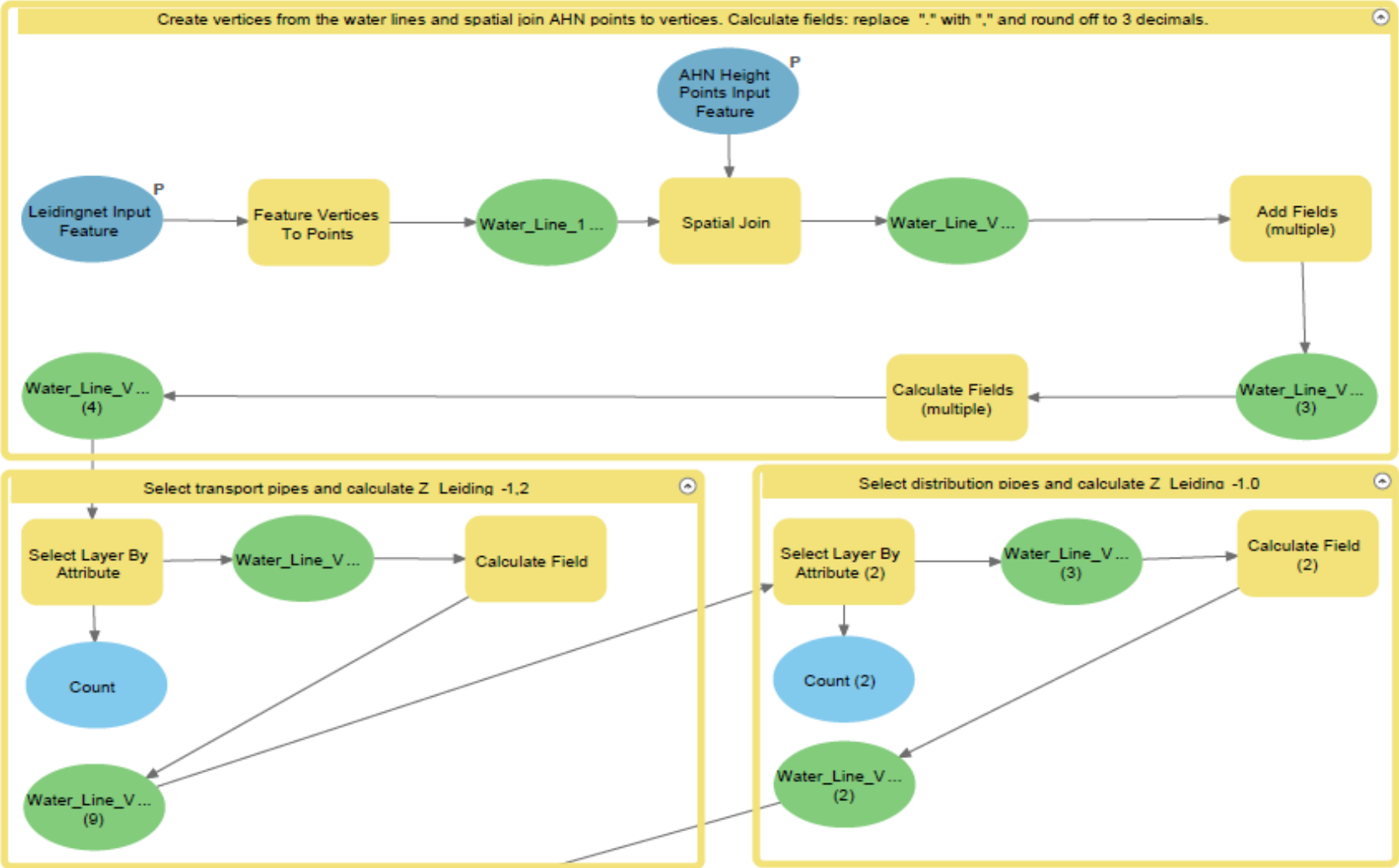
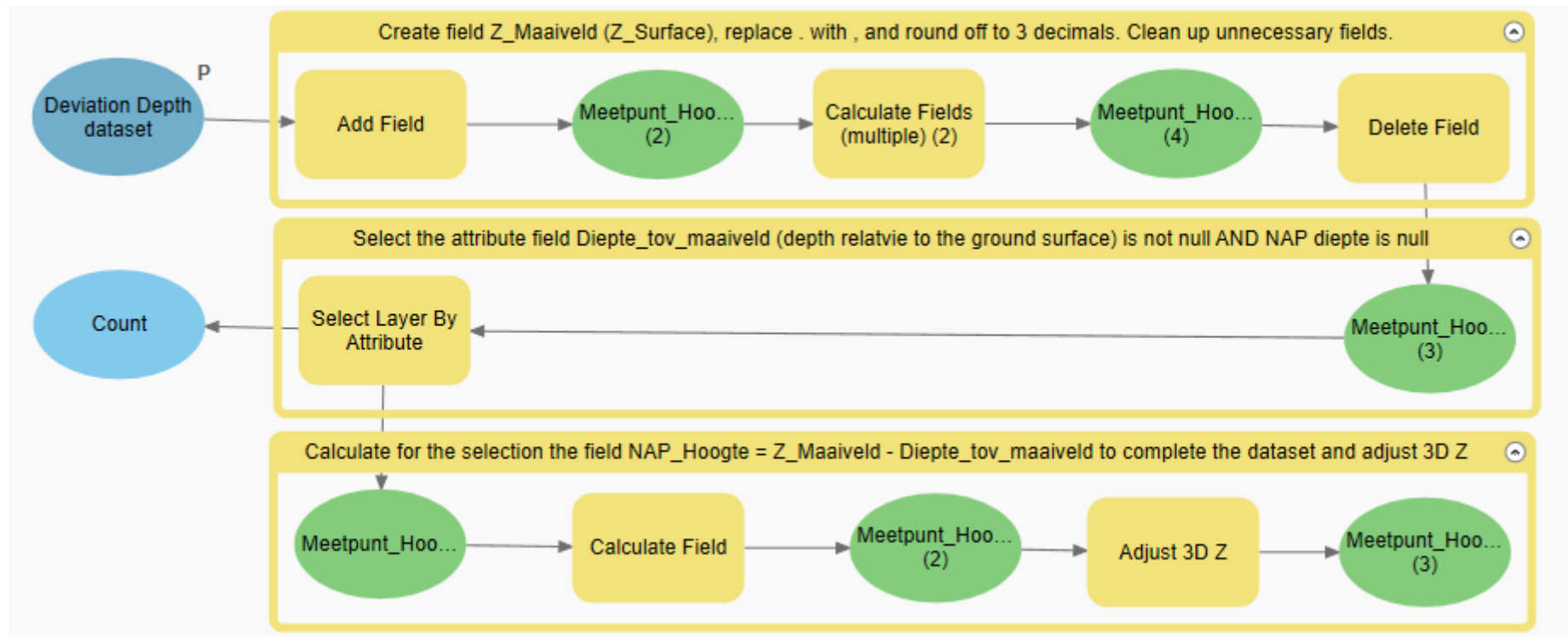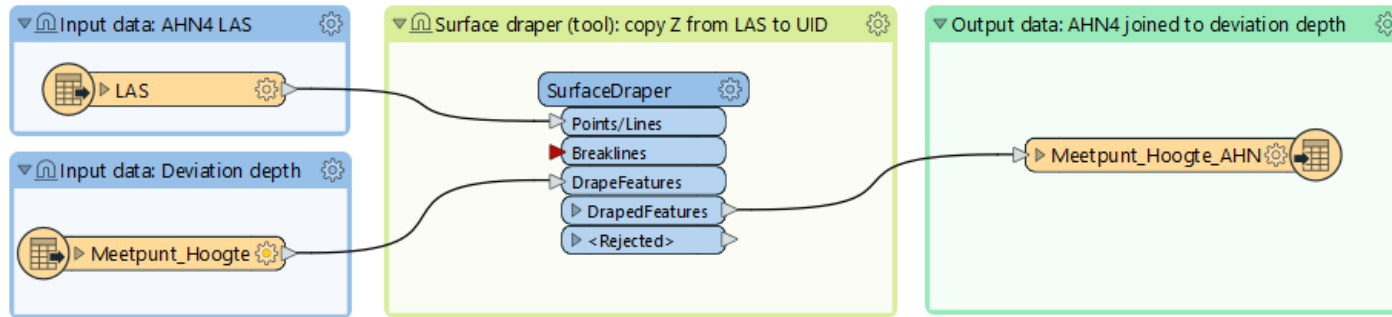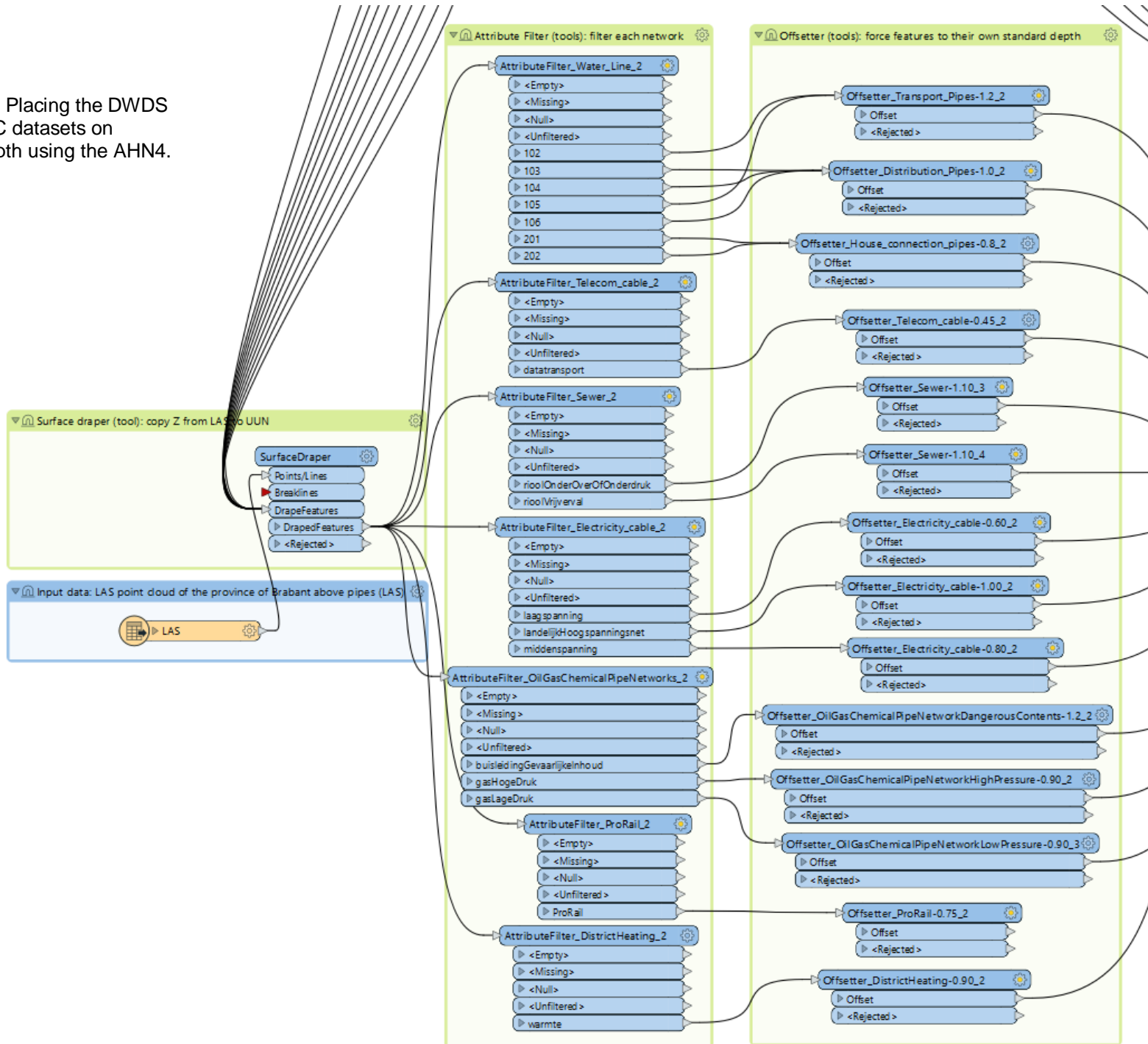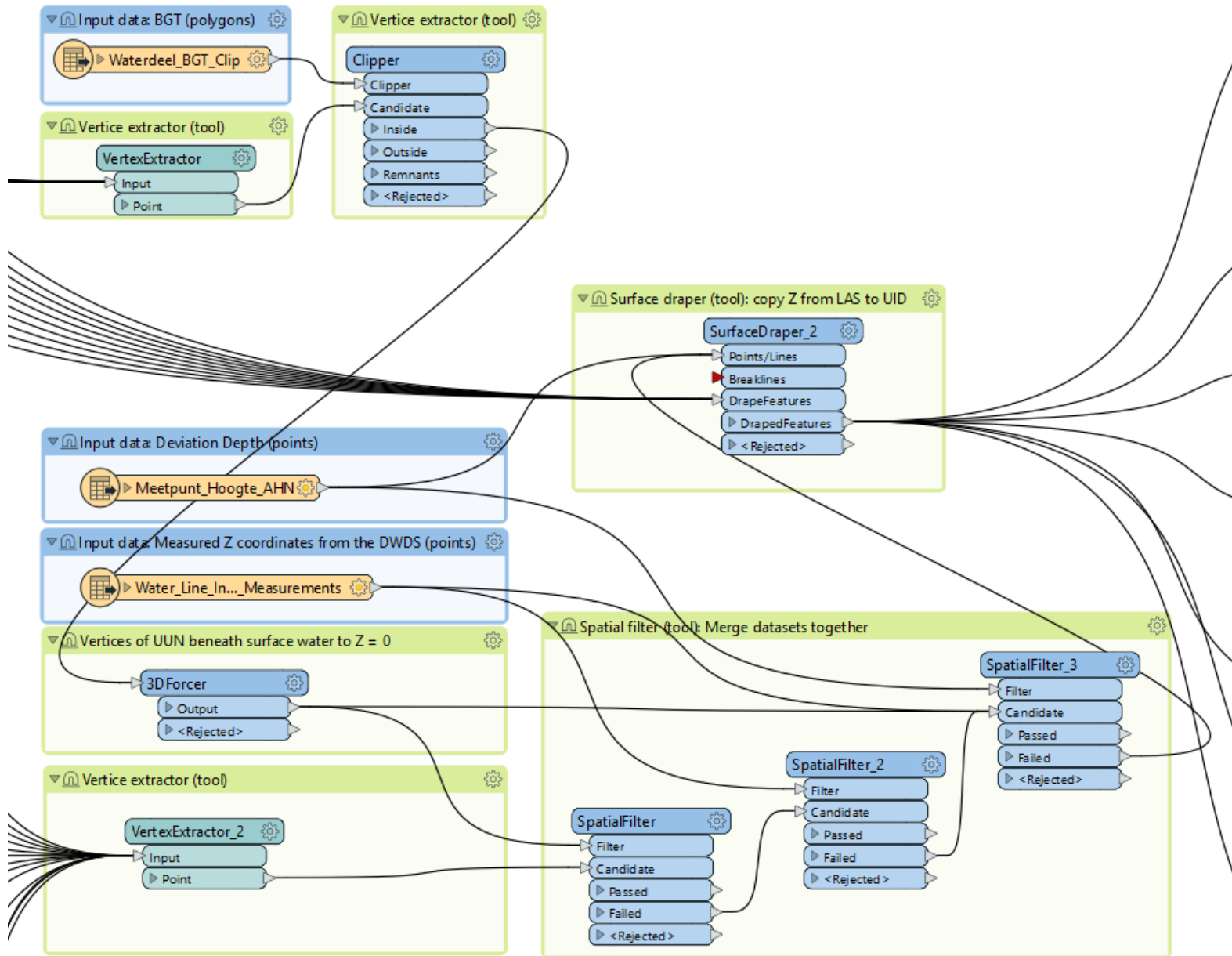**Figure 40B:** Creating vertical reference features for AR reference and simultaneously using the features for quality tracking (data model) of the Z coordinate.
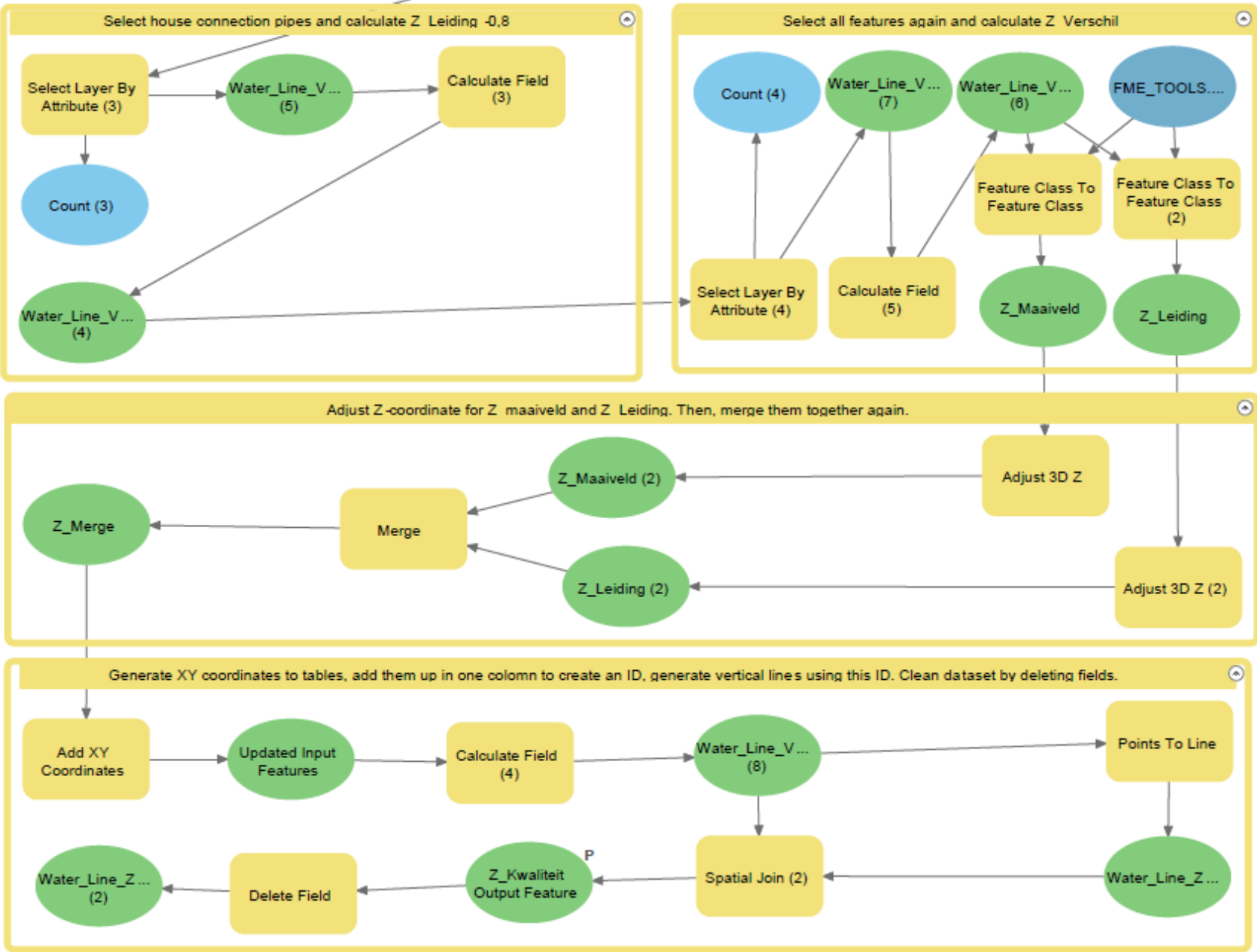
The current data model in the DWDS database has a field for recording the measurement method, but it falls short of accommodating multiple vertices below each object. Each object, represented as one record in the attribute table, may have multiple vertices with X, Y, and Z coordinates. Still, there is only one place to register the method of measurement. This limitation becomes problematic when multiple measurements are performed in different ways under one object, as it is impossible to see the various methods used. In such cases, there may be multiple Z coordinates, but the origin of each coordinate is not retrievable since there is no place to register it. This limitation can be addressed by using vertical reference features to track and register the Z coordinates' origin due to the one-to-many relationship. In the future, missing Z coordinates can be calculated based on the AHN, but it is important to have the origin of the Z coordinate readily accessible (figure 41).

Figure 41: Data model with depth information for Z coordinates stored in vertical reference features.
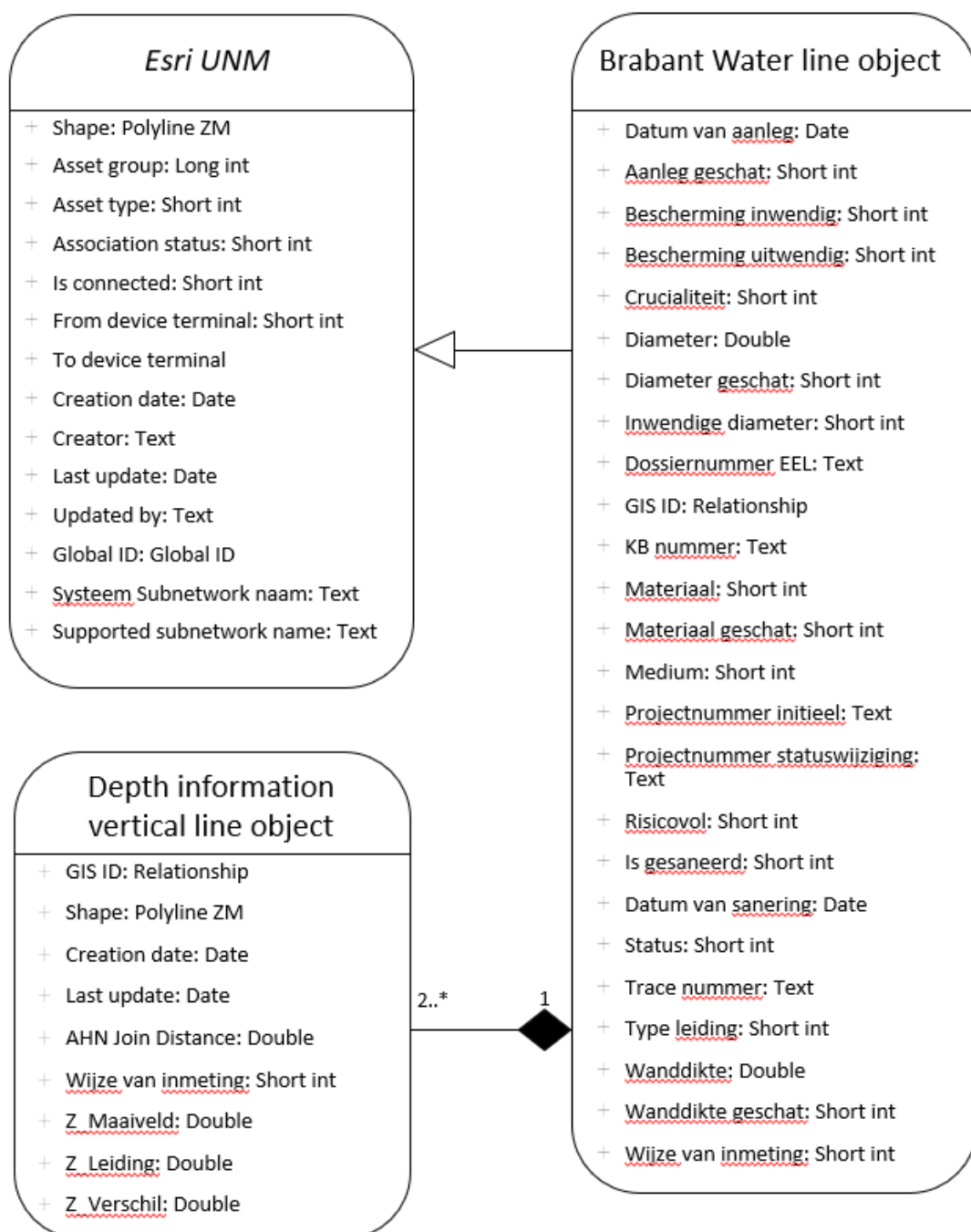
6.5. Model 5: Creating polygons to highlight the ground surface

On top of the vertical reference features, polygons can be created to highlight the surface level in the AR application. To generate polygons, the vertical reference features are needed that were generated in model 4. Also, the DWDS is needed as an input feature.

The first step is to run the buffer tool to generate the length of the polygon. This is done by a buffer, which asks for the desired length. In this analysis, a length of 0.4 is used. The buffer tool works in such a way that the input length is equal on both sides of the input features. If we want a length of 0.4, an input of 0.20 is required as the buffer tool will create equal sides of 0.20 on both sides of the input feature. So, 0.20 is the input for the first buffer, and the output is a feature with a total length of 0.40.

In the next step, an intersect tool is performed on the previously generated buffer and on the DWDS, which will run with the output as a line. This tool calculates a geometric intersection of the input features. Features or portions of features that intersect in all layers or feature classes will be written to the output feature class (Esri, 2022d). In this case, a line is generated in the buffer area equal to the DWDS. Then a new buffer is generated on the lines from the intersect. The width of the buffer is again a parameter; 0.05 is used to generate a total width of 0.10. The generated polygons on the vertical reference lines are thus 0.4 x 0.10.

The last step is to adjust the Z coordinate to place the polygon on top of the vertical reference features. The Z coordinate is adjusted with the maximum Z coordinate, which is equal to the ground surface.

In figure 42, the workflow for this analysis is described.

Figure 42: Create ground surface polygons on the vertical reference features. The Python script of this model can be found in Appendix 11.2.5.
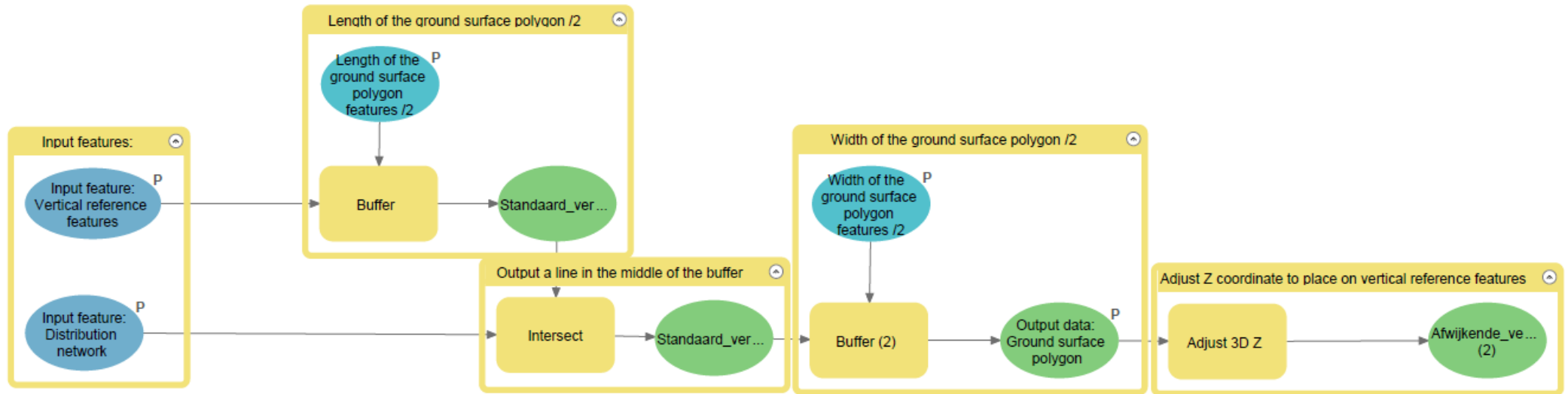
6.6. Sub-conclusion

In conclusion, Brabant Water is considering requiring contractors to report Z coordinates for new measurements from 2025 onwards to create a more accurate and complete dataset for the future digital twin. This is because a fully 3D GIS environment for Brabant Water is currently impossible due to a lack of data regarding Z coordinates. A solution to this problem is to use the AHN4 dataset, which assigns a depth relative to NAP for the DWDS by matching standard depths in table 1 with database attributes and subtracting the standard depths from the AHN4 surface points for each vertex. This analysis consists of 5 models, beginning with clipping the AHN4 LAS on a buffer of the DWDS (distribution area), and will be performed on various study areas and test sites. The analysis required various datasets and was performed on a personal computer with enhanced specifications to handle a large amount of data. This analysis also generated vertical reference features for an AR application using the DWDS and AHN4 height points as input features. This analysis aimed to create perspective in the AR images by showing the depth of the UUN relative to the surface level. In this analysis, the Z coordinates that intersect surface water were set to 0 since the AHN4 lacks data on the bottom of surface water. The final datasets were made fit for the AR application. They were published to ArcGIS Online to read and retrieve by the AR application, thus providing a more accurate and complete dataset and data model, which can also be eventually used for the digital twin of Brabant Water.

7. Results of models: Identifying depth relative to NAP for the DWDS using AHN4 data

This analysis consists of multiple models. Each model is dependent on the model above it. This means model 1 is essential for executing the rest of the models. Model 1 in chapter 7.1 is about clipping the AHN4 on the buffers equal to the DWDS and other KLIC datasets in possession of Brabant Water. The produced point cloud and feature class point dataset are then stored on the SSD to later use in the following models. Model 2 in chapter 7.2 is about validating the measured Z coordinates from Brabant Water. There are two datasets containing these measured Z coordinates. The first is the DWDS, in which ~0.58% of the features have one or more Z coordinates, in total 35.246 Z coordinates. The second is the deviation depth point dataset which contains 2.645 Z coordinates. However, this second dataset was not validated due to time constraints. In model 2, these points will be validated against the AHN4 to say something about the data quality of the datasets. Model 3 in chapter 7.3 is about placing the DWDS and the KLIC data on standard depth to use within the AR application. Model 4 in chapter 7.4 is about creating vertical reference features, which help the AR application determine the depth of the features. Also, the data model will be discussed here concerning how to keep track of the quality of the Z coordinates. Model 5 in chapter 7.5 is about creating polygons on top of the vertical reference features. This is done to emphasize where the ground surface begins with the goal of giving a clear reference in the AR application. The result of each model will now be discussed in chronological order. Chapter 7.6 will provide a sub-conclusion.

7.1. Model 1: Clipping AHN4 LAS on the buffer of the DWDS (distribution area)

The methodology for this model is described in chapter 6.1. In model 1, the AHN4 is clipped on the DWDS and the KLIC data buffers. This is done to produce a dataset in the following models, which can be used in the AR application. The dataset was created using FME. 215 AHN4 point clouds were processed during seven days of calculation in which the point clouds were clipped on the buffers of the UUNs that Brabant Water has data of. It's important to mention that those seven days of calculation are one-offs, as it's only necessary when a new AHN4 dataset is released.

This resulted in a point cloud of 3,2 GB with a buffer size of 0,10 meters, whereas the 215 input point clouds are 1,03 TB. An overview of the clipped AHN4 on the DWDS and the KLIC data can be seen in figure 43. This is the entire distribution area of Brabant Water and is viewed in a point cloud viewer called Quick Terrain Reader.

Figure 43: Overview of AHN4 point cloud of the ground surface clipped on the DWDS and KLIC data for the distribution area of Brabant Water (surface level).
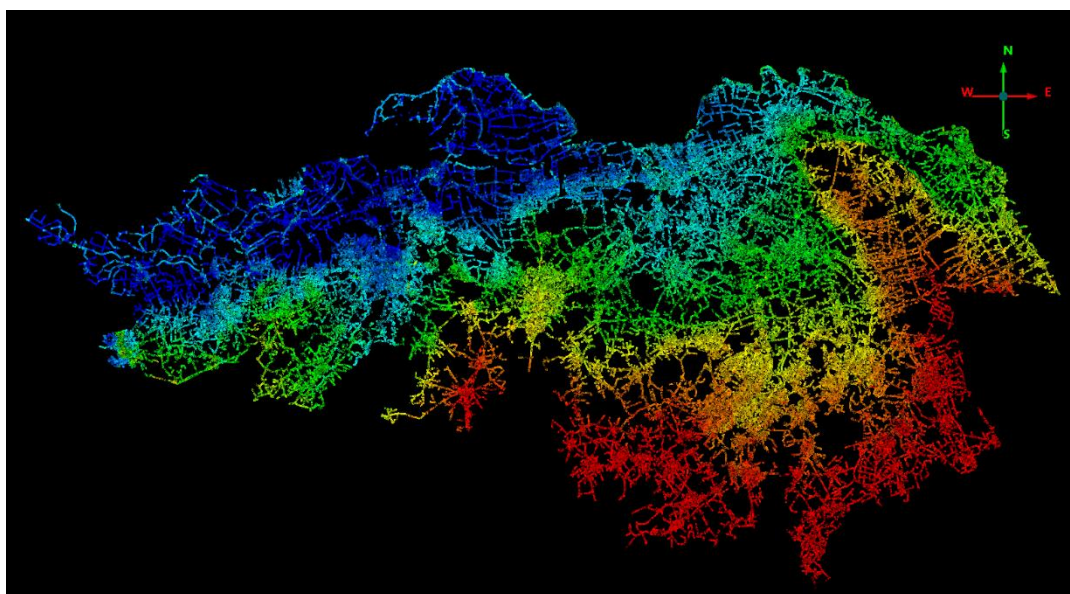
The model information can be viewed in this program as well which gives us information about the model statistics. Figure 44 shows that the model's deepest point is located at -2,69 meters NAP, which is the lowest point of the ground surface above the DWDS and other UUNs. The maximum Z coordinate has a value of 44,38 meters NAP, which is the highest point of the ground surface above the DWDS and other UUNs. Figure 43 shows this distribution well throughout Brabant, and figure 44 shows the model statistics. As shown in figure 44, the point cloud consists of 122,8 million points. Each AHN4 tile contains about $4x10^9 – 7x10^9$ points in the point cloud, with a total of 215 AHN4 tiles. The point cloud filter tool filtered out only the ground surface classified points. The other points with other classifications were discarded.

Figure 44: Model statistics of AHN4 point cloud of the ground surface clipped on the DWDS and KLIC data for the distribution area of Brabant Water.
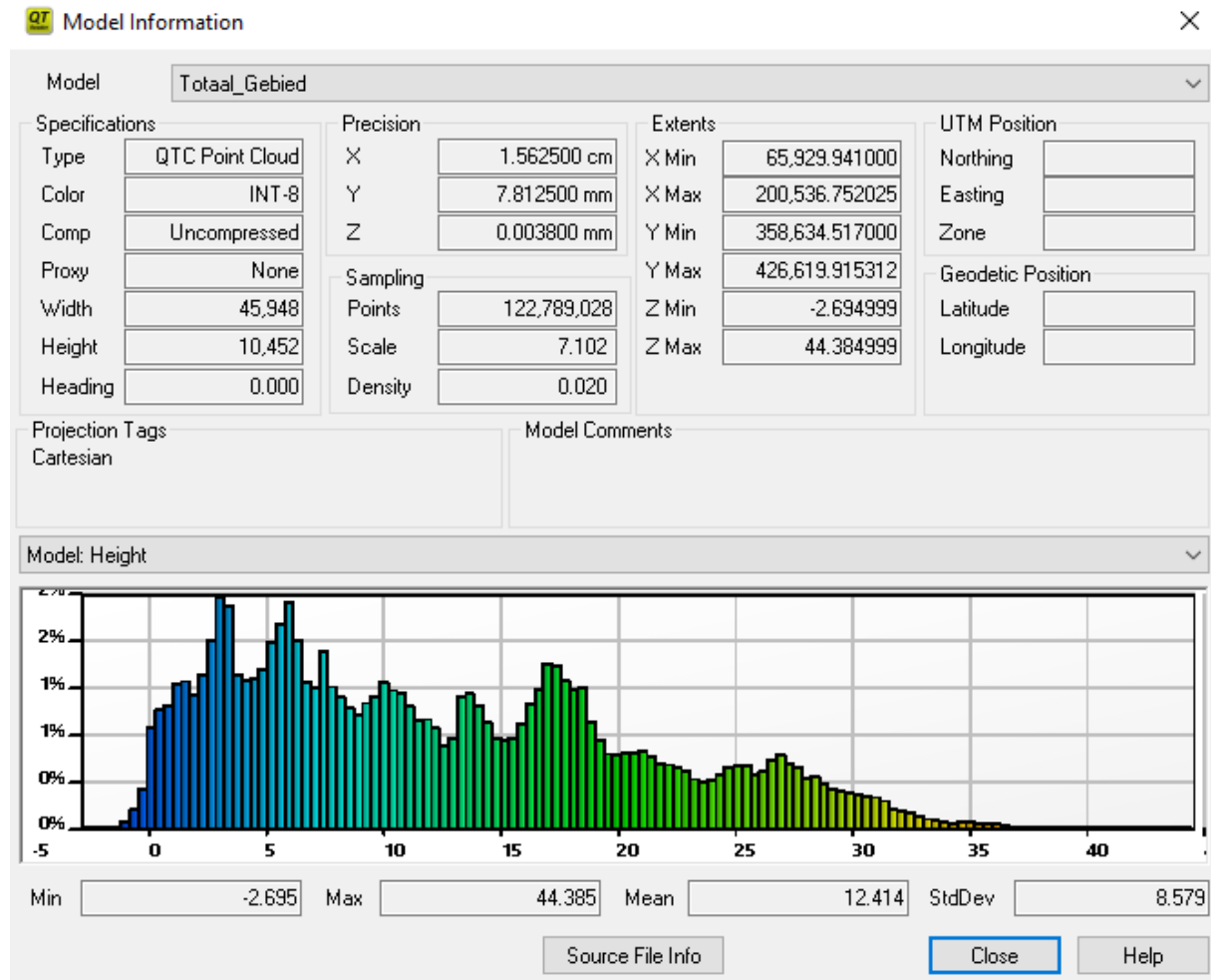
7.2. Model 2: Validation of the measured Z coordinates

The methodology for this model is described in chapter 6.2. In this analysis, the measured Z coordinates are compared to the AHN4. The measured Z coordinates are spatially joined with the closest AHN4 point. This resulted in a dataset in which both the measured Z coordinate and the AHN4 Z coordinate can be compared. In figure 45, the distribution is shown of the Z coordinate measurements relative to the AHN4 ground surface.

Figure 45: Number of Z coordinate measurements categorized on depth relative to the ground surface of AHN4. Data from October 2022.

Number of Z coordinate measurements categorised on depth relative to the ground surface for house connection, distribution and transport pipes

	≤0	0-0,2	0,2-0,4	0,4-0,6	0,6-0,8	0,8-1,00	1,00-1,2	1,2-1,4	1,4-1,6	1,6-1,8	1,8-2	>2
House connections pipes	3090	2816	928	870	1624	3218	2565	1091	288	126	63	600
Distribution pipes	2460	2312	951	1002	1763	2855	3015	1564	567	246	119	684
Transport pipes	21	37	20	15	18	67	50	77	29	15	13	32

Depth relative to the ground surface in meters

Figure 45 shows that 18% of the measured house connection pipes are on the level of the ground surface or even above. The same applies to 14% of the distribution pipes and 5% of the transport pipes. Most likely, those are measurements in which the measurement was performed in a closed trench. This occasionally happens in the fieldwork, as explained by Van de Wiel (2022) (see appendix 12.1). House connection pipes should be located at a standard depth of -0,80 meters below the ground surface, distribution pipes at -1,00 meters, and transport pipes at -1,20 meters below the ground surface (table 1). Brabant Water maintains an error margin here of 0.20 meters. In the case the depth of the pipe differs more than 0,20 meters, it's considered a deviation depth (Van de Wiel, 2022). Therefore, according to this data, 28% of the house connection pipes, 33% of the distribution pipes, and 33% of the transport pipes are located at standard depths.

Measurement of Z coordinates can also be compared to the way they were measured. However, how the measurements are performed is registered on the object level, not per X, Y, and Z coordinates (vertex). Below an object, which is one record in the attribute table, can be multiple vertices, which can be measured in different ways. Therefore, the way this data can be interpreted is uncertain due to a lack of the current data model. Figure 46 displays how the Z coordinates were measured in 3 categories for house connections, distribution, and transport pipes.

According to the data from figure 46, measuring digitally is dominant. There are more ways of measuring registered for house connection pipes than distribution and transport pipes. Regarding transport pipes, the percentage of the unknown is the highest. However, due to the distribution of measuring compared to the depth of the measurements, it can't be stated that, specifically, one way of measuring is underperforming. As can be seen in figure 47, the distribution is relatively even, except for transport pipes. Especially the unknown category is larger for measurements performed on the ground surface level. However, as shown in figure 45, the transport measurements are based on fewer measurements than the other categories. That's also because of the distribution of the values. There are fewer transport pipes compared to distribution and house connection pipes. Therefore there are also fewer measurements performed in this category. A conclusion when looking at this data is that it can't be stated which measurement way is underperforming due to too few measurement methods. Overall improvements in measurements can reduce the percentage of measurements located at or above the ground surface. It's possible to track the measurements back to certain contractors if they are not performed well.

The AHN is a great way to check contractors' performed measurements of Z coordinates periodically. When there is a new AHN available, the whole dataset can be checked again to see the data quality regarding performed measurements for Z coordinates. When a new AHN becomes available, this check should be performed with each new version in order to work with the most up-to-date ground surface data. This research aims to provide a framework for water utilities to do so in the future.

Figure 46: Way of measuring for the house connection, distribution and transport pipes. Data from October 2022. For amount of measurements per category see figure 45.

Way of measuring for house connection pipes

1%; 208   6%; 1116
14%; 2389
79%; 13566

- Unknown
- Hottap
- Measured analogously
- Measured digitally (GPS)

Way of measuring for distribution pipes

17%; 2976
83,0%; 14557

- Unknown
- Measured digitally (GPS)

Way of measuring for transport pipes

27%; 108
73%; 285

- Unknown
- Measured digitally (GPS)

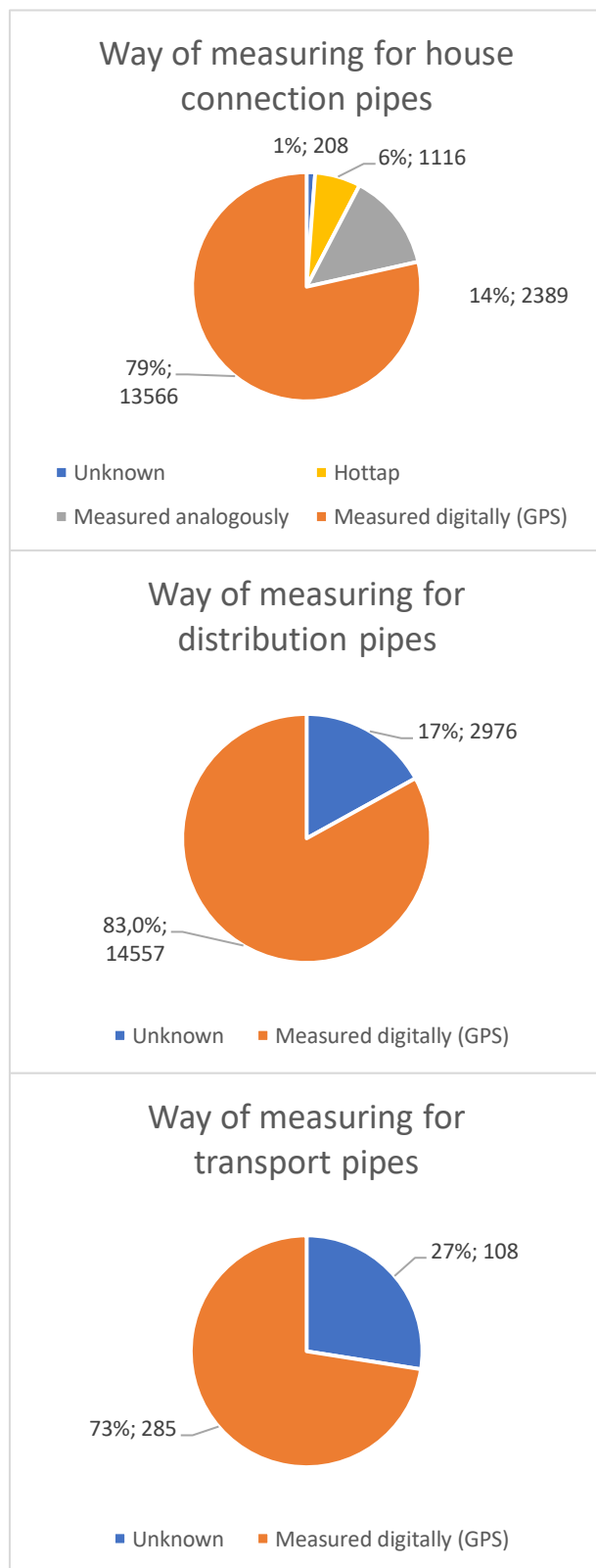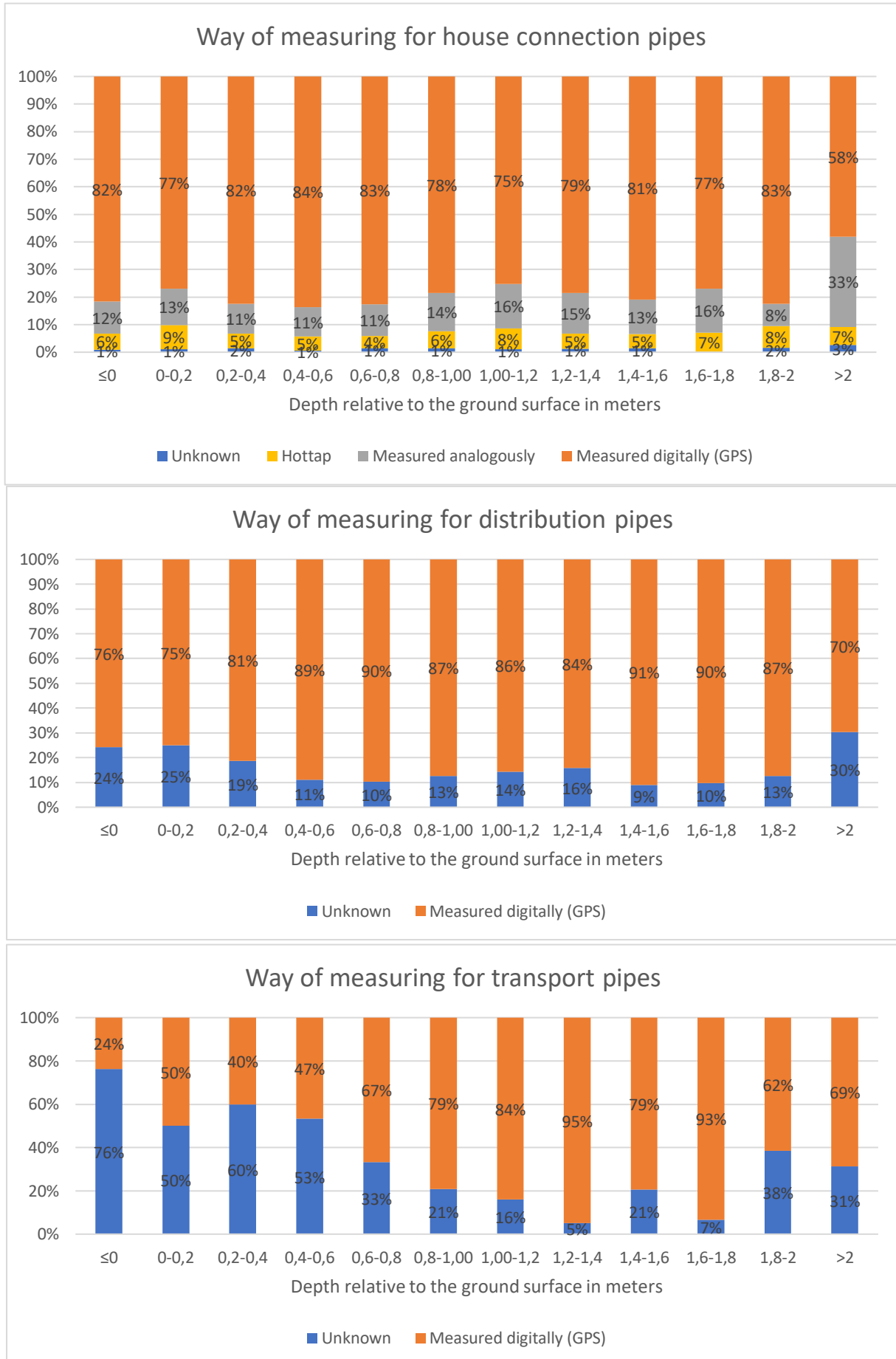**Figure 47:** Way of measuring for house connection, distribution and transport pipes categorised on depth relative to the ground surface. Data from October 2022. For amount of measurements per category see figure 45.

7.3. Model 3: Placing each UUN on its depth relative to NAP

The methodology for this model is described in chapter 6.3. To make an AR GIS dataset in which all the KLIC and DWDS data are shown on their respective standard and measurement depths, the UUNs have to be assigned the AHN4 and measurement heights to them. The closest point of the AHN4 is joined to the networks. Each network is then assigned a standard depth based on attributes by subtracting their depth from the AHN4 height. The depth that is subtracted is displayed in table 14.

Subsequently, a GIS feature layer is created and hosted in the Brabant Water GIS portal production environment. The AR Hololens can connect to the portal and read and project the dataset in AR.

If no depth is assigned to each UUN and no diameter is given, all the data will be projected the same way. Figure 48 shows what this looks like. All the UUNs are crossing each other, and it's unclear which network is above the other. The colors are equal to the IMKL colors which are shown in figure 12.

Figure 48: UUNs without an assigned diameter
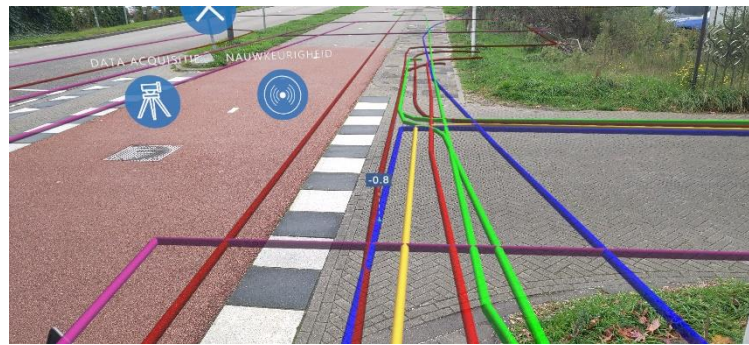
The diameters of KLIC data have to be calculated to the same units and displayed in a field with the same name as the DWDS diameter field for the AR Hololens to read the data.

In this model, the networks were put on their standard and measurement depth, and the diameter field was prepared as well for the AR application to read and interpret the data. Figure 49 shows what this looks like in AR.

As shown in figure 49, the data now has volume, which is correctly shown for each network on their standard depth. As we can see, however, due to the volume of the sewer system (pink), the networks are still crossing each other. This is because each network has its standard depth, but they can still cross each other due to the volume of the UUN. Also, some networks are quite close to each other when looking at standard depth. Table 1 shows that medium voltage and water connection pipes are located at the same standard depth of 0,80 meters below the ground surface.

In figure 49, the red circle shows that the water network is going below the other water pipe. This was manually edited to show that certain rules can be applied, which UUN goes below and which above the other. This will make the AR image clear, but those rules will have to match reality to prevent a false sense of certainty in the case it's not correct.

We can also see vertical reference features in this image. This will be explained in model 4.

Figure 49: UUNs with volume and on standard depth.

7.4. Model 4: Vertical reference features and data model to track Z coordinates

The methodology for this model is described in chapter 6.4. Vertical reference features can be created in AR to help the viewer better understand the AR view. As shown in figure 50, the distance between the ground surface and the UUN becomes clearer. It gives a better perspective of the AR image (figure 51), especially in the case of deviation depth.

Figure 50: Better perspective in AR with vertical reference features.

The value of the vertical reference feature becomes clearer in the case of deviation depth (figure 51). The vertical reference features also point out the exact location of the pipe since the location in AR is not correct as the pipe goes deeper. When looking from the side the true location is thus pointed out by the vertical reference features.

Figure 51: Deviation depth with DWDS at a directional drilling location.
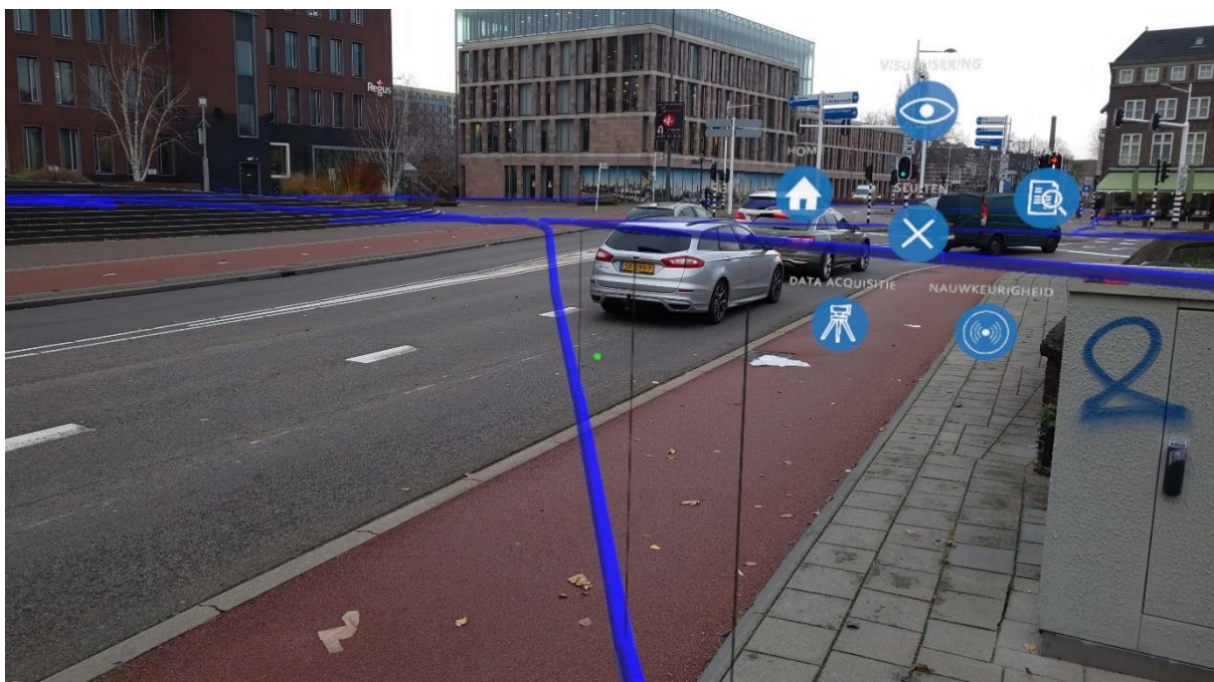
This is something that becomes clearer with the colors below. However, the diameter of the pipe is not correct there. The vertical reference features make the slope well visible and clearer (figure 52). When the UUN is located shallower below the road, the vertical reference features can also emphasize this (figure 53).

Figure 52: Vertical reference features with slope and surface water.
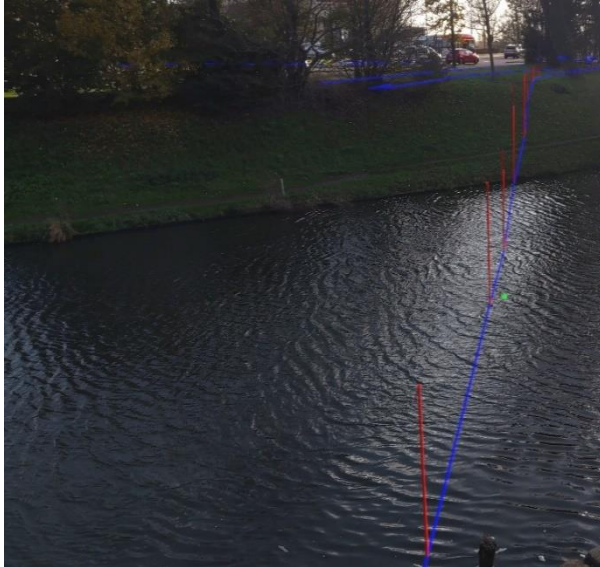
Figure 53: Vertical reference features located below a road and pavement.
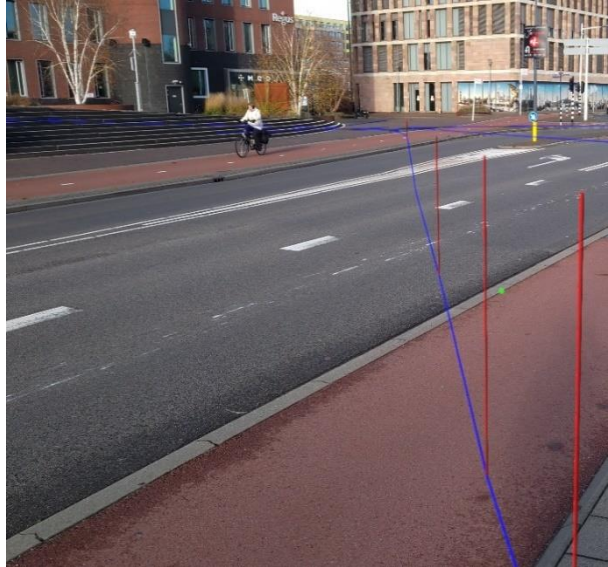
Figures 51-53 show a DWDS from directional drilling. The Z coordinates, in this case, were manually adjusted in the dataset derived from a construction drawing.

Figure 54 shows a transport pipe with a house connection pipe attached. The house connection pipe is located at -0,80 meters below the ground surface, and the transport pipe is at -1,20 meters. The difference is visible, also with a smaller vertical reference feature to again emphasize this difference between the distance to the ground surface.

Figure 54: Transport and house connection pipe which are connected to each other.

The connection in figure 54 was made by manually adjusting the Z coordinate of the last vertex of the house connection pipe. The vertex was adjusted to the same Z coordinate of the transport pipe next to it to make this connection. According to Van Os (2022), in reality, this is about the same. The connection between distribution and house connection pipes are connected in a way where the pipe difference in height gradually increases. However, in figure 54, it happens quite suddenly. In reality, this transition will be more gradual. Also, many house connection pipes only have two vertices with a few meters of distance in between. Therefore, this will be more gradual if the last vertex is matched with the adjacent network.

Regarding the data model, the current field that offers a place for registering the way of measuring is called "Wijze van inmeting" in Dutch. Table 16 shows the current options that are in the database. Option 4 is currently not present, but when Z coordinates derived from the AHN4 are used as a source, it could be registered as option 4.

Table 16: Existing options for the way of measuring, except for option 4, for the way of measuring at Brabant Water in the DWDS data model. Option 4 would be an addition to the current data model.

Number (Short int):	The text associated with the number in Dutch	The text associated with the number in English
-1	Onbekend	Unknown
1	Aanboring	Hot tap
2	Analoog ingemeten	Measured analogously
3	Digitaal (GPS) ingemeten	Measured digitally (GPS)
4	AHN4 berekend	AHN4 calculated
7	NVT (Niet van toepassing)	NVT (Not applicable)

7.5. Model 5: Creating polygons to highlight the ground surface

The methodology for this model is described in chapter 6.5. Small polygon features were created on top of the vertical reference features to emphasize the ground surface better and make the vertical reference features clearer (figure 55). This was done using the buffer tool, and the measurements were 0,40 * 0,10 meters. The polygon features run parallel to the pipe, even if it makes a bend or splits in the case of a junction, to indicate the ground level properly at all times (56). The flow direction of the water pipe can also be visualized using the polygons (Figures 57 and 58). Due to the sunlight, it can be hard to distinguish the vertical reference feature from the polygon (figure 57). A solution to this can be to visualize the polygon with another color. In the shadow, it is easier to distinguish the vertical reference feature from the polygon (figure 58).

The flow direction of the water pipe can be visualized in the polygons; however, this flow direction is subject to change in the event of a malfunction. For example, in the case of a leakage, valves can change the flow direction. However, it's likely the flow direction will return to its original flow when the malfunction is resolved.

Figure 55: Polygon on a vertical reference feature.

Figure 56: Junction polygon on a vertical reference feature.

Figure 57: Polygon on a vertical reference feature with flow direction.

Figure 58: Junction polygon on a vertical reference feature with flow direction.

7.6. Sub-conclusion

This analysis consisted of multiple models to process and validate data from Brabant Water. The first model involved clipping the AHN4 dataset on the DWDS and KLIC datasets' buffers to produce a dataset for use in an AR application. The resulting point cloud had 122.8 million points and provided information about the ground surface of the distribution area. The second model involved comparing the measured Z coordinates from Brabant Water to the AHN4 dataset to assess the data quality. Results showed that 18% of house connection pipes, 14% of distribution pipes, and 5% of transport pipes were on the level of the ground surface or even above. 28% of house connection pipes, 33% of the distribution pipes, and 33% of the transport pipes were located on standard depth with a deviation of 20 centimeters. The third model involved placing the DWDS and KLIC data on standard and measurement depth for use in the AR application. In the fourth model, vertical reference features were created to aid in determining the depth of features in the AR application and also discussed the data model concerning tracking the quality of Z coordinates. The fifth model involved creating polygons on top of the vertical reference features to give a clear reference in the AR application, with a final result of a polygon with also a flow direction. Overall, the analysis provided insights into the quality of the data from Brabant Water and suggested ways to improve the data in a 3D GIS and visualization for usage in an AR application.

To transform the GIS of Brabant Water to a 3D GIS, all datasets containing Z coordinate measurements must be combined and joined to the DWDS. The remainder where no actual measured Z coordinates are present in the DWDS will have to be filled with AHN calculated Z coordinates. However, only 1 Z coordinate per vertex is possible within the data model of Brabant Water and the UNM of Esri. The created vertical reference features in the previous models in chapters 6.4 and 7.4 can be a solution. The features are vertical polyline features and therefore don't impact the geometry as they can't be seen in a 2D map, which is often used for editing but can be selected. In an ArcScene, which is a 3D environment in ArcGIS Pro, it is possible to visualize the vertical reference features.

This chapter focuses on improving the data model to include information about Z coordinates at the individual vertex level. Section 8.1 will discuss the current UNM data model and its enhancements to track this data. Section 8.2 will discuss how all available Z coordinate datasets, including AHN4 data, can be integrated into the DWDS. Section 8.3 will discuss how to maintain data quality using AHN4. Finally, section 8.4 will provide a sub-conclusion.

8.1. Addition to the current data model

The current data model has a field to record the measurement method, but it cannot track multiple Z coordinates for one object due to the many-to-one relationship of vertices. One object in the DWDS database can have multiple vertices with X, Y, and Z coordinates, but only one place is available to record the measurement method. In the future, missing Z coordinates can be calculated using the AHN, but the origin and quality of these coordinates need to be retrievable and recorded. The vertical reference features can be used to track and register the origin of Z coordinates, addressing the lack in the current data model where one field for measurement recording is insufficient for multiple measurements under one object.

The vertical reference features won't affect the 2D map displays and won't cause discomfort for administrators and editors. Recording and being able to retrieve the Z coordinate's origin is vital. To ensure this, the data model must provide adequate storage space for the vertical reference feature (Z_quality). This feature can also enhance AR applications and 3D ArcScene displays by accurately showing the ground surface-UUN distance.

The relationship between the DWDS and the Z_quality feature is displayed as one-to-many in figure 41. Each DWDS record can have multiple vertices, with a minimum of 2 required to form a line (start and end point). The Z_quality data model needs several attribute fields to be present.

The "AHN_join_distance" is the first required attribute field in the Z_quality feature data model to assess the reliability of AHN Z coordinates. If the AHN_join_distance is large, the editor may disregard the respective Z coordinate. This can occur near houses due to fly shadow from the AHN measurement taken by an airplane. In areas lacking AHN points, the DWDS may fall in a small buffer size, resulting in an increased AHN join distance of a few meters, as shown in figure 59, which can occur near houses.

Figure 59: Point cloud seen from above with a lack of AHN4 points next to buildings most likely due to fly shadow.
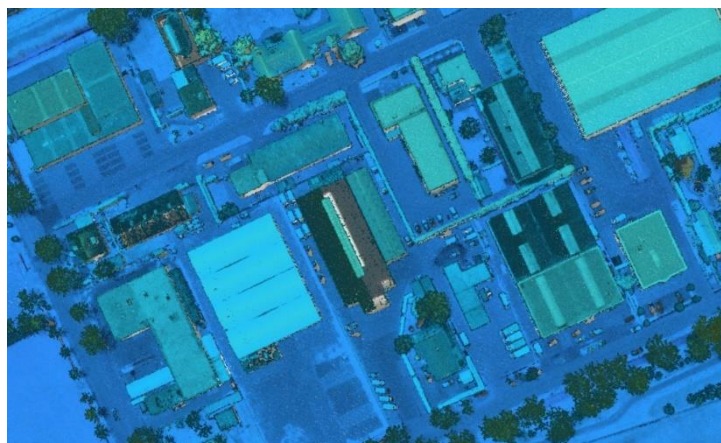
Another solution is to take measurements of a pipe with accurate GPS equipment to obtain reliable Z coordinates in the DWDS.

The following two attribute fields, "Asset_group" and "Asset_type," are needed to calculate the vertex's standard depth and Z coordinate. The "Creation_date" field provides information on when the measurement was taken. The "Last update" field records the date of the last edit made to the vertex in the GIS database. The GIS_ID is a unique identifier for each DWDS object, and each vertex can be identified based on the X-Y location. Regarding the GIS_ID, a one-to-many relationship applies from the DWDS to the vertical reference features. Relevant related attributes which apply to the vertical reference features can be identified in the DWDS using the GIS_ID.

Subsequently, the field "Wijze_van_inmeting" will track how the Z coordinate was measured in correspondence to table 16. The field ''Z_Maaiveld'' or Z ground surface will display the Z coordinate above the UUN which is equal to the ground surface. Z_Leiding will display the Z coordinate equal to the Z coordinate of the pipe. The field Z_Verschil will display the difference between the Z coordinate of the ground surface and the Z coordinate of the UUN, which is the distance from the UUN to the ground surface.

With this data model, which can be seen in chapter 6.4, figure 41, tracking all the relevant information regarding the Z coordinate will be possible. The most important attributes are the way of measuring, the Z coordinate of the pipe, the ground surface, and the difference between the two.

8.2. Integrate all available datasets that contain Z coordinates into the DWDS

To merge the Deviation Depth Point File and Z coordinates from the DWDS with the AHN4 into the DWDS, the following steps can be followed, corresponding with models 1 and 3 in 6.1 and 6.3.:

- First, the ground surface values of the AHN4 will be joined to the DWDS, and vertices intersecting surface water will be set to a Z coordinate of 0.
- Second, a copy will be made of the Z coordinates, which are present in the DWDS, as they will be overwritten in the next step. This is done by creating vertices from the DWDS.
- Third, the Z coordinates of the DWDS, which were stored in a separate point file, will be joined to the DWDS again.
- Fourth, the deviation depth point file will be joined to the DWDS.

In figure 60 below, the steps are visually shown.

Figure 60: Merge AHN4, Z coordinates of the DWDS and the deviation depth point file together in the DWDS.
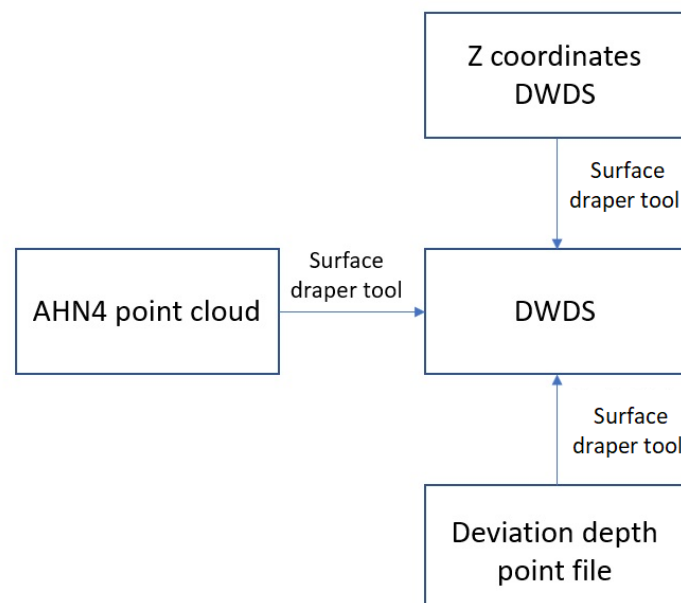
8.3. Maintain data quality

The data quality of the DWDS regarding the Z coordinates needs to be maintained. The current data model, as explained earlier, currently doesn't facilitate the need to record the quality of individual Z coordinates, including their way of measuring, the depth of the pipe, ground surface level, and the difference between those two values. Therefore, the data model needs to be adjusted, as was explained in chapters 6.4 and 7.4. This is done using vertical reference features with a one-to-many relationship to the DWDS. This means the vertical reference features have to be produced throughout the entire distribution area and have to be equal to each vertex of the DWDS. The steps below are explained to maintain the future data quality of the Z coordinates.

- The AHN gets updated every few years. The AHN3 was measured between 2014-2019. The AHN4 was measured in 2020-2022. The new measurements for AHN5 will likely start in 2023 or 2024. When a new version of the AHN arrives, the vertical reference features should be updated for the class Z_Maaiveld. The DWDS Z coordinates should not be updated, as the AHN4 should function as a base. By updating the Z_Maaiveld (Z_SurfaceLevel), changes can be detected, and the difference between the Z_Leiding (Z_Pipe) and Z_Maaiveld (Z_SurfaceLevel) can be calculated. Using this method, change detection of the ground surface can be identified. Locations, where the DWDS will be situated more shallow and deeper can be identified and acted upon.
- Current Z coordinates can also be checked by comparing them to the AHN4 surface level. As identified in chapter 7.2, figure 45 shows that 18% of the current measured house connection pipes are on the ground surface level or even above. The same applies to 14% of the distribution pipes and 5% of the transport pipes. These measurement errors can be prevented in the future when a check will be performed (automatically) in which delivered measurements by contractors are checked relative to the AHN. If the values the contractors reported are close, equal, or above the surface level, a contractor can be addressed using this information and ask for a new measurement.
- The dataset can be extended with actual Z coordinates by forcing contractors to deliver Z coordinates in newly made specifications. This enhances the trust in the data. The ultimate goal will be to create a dataset based on actual measurements, not derived from calculated AHN Z coordinates. However, this will take many years, if not decades.

8.4. Sub-conclusion

If the GIS of Brabant Water is being transformed into a 3D GIS, the current data model must be improved to track multiple Z coordinates in the DWDS database. This will be achieved by adding the Z_quality feature to the data model, which will have attribute fields to assess the reliability of Z coordinates and record measurement information. To integrate all available datasets with Z coordinates into the DWDS, a copy of the current Z coordinates in the DWDS will be made, and the ground surface values from the AHN4 will be joined together with the deviation depth point file to the DWDS. The Z_quality feature will make it possible to track the origin of Z coordinates and provide adequate storage space for the vertical reference feature. To maintain data quality in the future of the Z coordinates, the AHN can be used, which is updated every few years, with the latest version being AHN4, measured between 2020 and 2022. The vertical reference features (Z_Maaiveld) should be updated with each new version of the AHN to detect changes in the ground surface. The measured current Z coordinates can also be checked for accuracy by comparing them to the AHN surface level. 18% of the current house connection pipes, 14% of the distribution pipes, and 5% of the transport pipes have measurement errors. Contractors can be addressed if their reported values are above the surface level. By requiring contractors to deliver Z coordinates in new specifications, the dataset can be extended with actual measurements, enhancing the trust in the data. The ultimate goal is to create a dataset based on exact measurements, which will take many years or decades to achieve. The AHN4 can suffice as a base reference until those Z coordinates are updated with exact measurements.

9. Discussion, conclusion, and recommendations

In this chapter, there will first be a discussion about the results of this research. Subsequently, there will be a conclusion of this research followed by recommendations for Brabant Water which are ready for use and future work.

9.1. Discussion

Limitations also emerge from the framework of this study. They are discussed below.

This discussion will explore the relationship between old pipes in a DWDS and newly acquired data from the AHN4 (the most recent digital elevation model of the Netherlands). One of the key challenges when dealing with old pipes is updating the information in existing GIS databases. This is especially true for the Z coordinate, which provides the height information and can significantly impact decision-making in the management of the DWDS. AHN4 data can provide a more accurate and up-to-date representation of the ground surface. This information can be used to improve the accuracy of the Z coordinates of the old pipes, which may have been measured using less accurate methods in the past or have not been measured at all. Integrating the AHN4 data into the DWDS could also help identify any potential issues with the old pipes, such as misalignments or conflicts with other underground infrastructure.

However, it is important to highlight the limitations of using the AHN4 data for older pipes. This is because the AHN4 data only provides information about the ground surface and not the exact location of the old pipes. Therefore, the accuracy of the Z coordinates of the old pipes can still be limited, even with the use of the most recent AHN4 data. To address this challenge, Brabant Water could consider using advanced data sources such as GNSS, sensors, and GIS to accurately measure the old pipes and update the information in their GIS databases. This could involve using AR and VR technologies to visualize the pipes and the surrounding environment in real-time, providing more accurate and reliable data for decision-making. Recording Z coordinates for pipes based on the AHN4 involves balancing the ambiguity of their exact location with registering the DWDS against a vertical reference system for long-term precision. The stability of the ground surface changes over time, making Z coordinates relative to NAP the only solution that provides accuracy over the long term. In conclusion, using AHN4 data can help improve the accuracy of the Z coordinates of old pipes in the DWDS. However, more advanced data sources and technologies may be required to fully realize the potential of the AHN4 data and overcome the limitations of using it for older pipes.

Also, the choice in this study to use point clouds of the AHN4 instead of the rasters was a consideration. Point clouds are a set of 3D points that represent the geometry of the ground surface and contain X, Y, and Z coordinate points. They provide a highly accurate representation of the ground surface and can be used for various applications such as 3D modeling, terrain analysis, and visualization. Point clouds are typically used for applications that require high accuracy and detailed information about the ground surface. On the other hand, AHN4 raster datasets are a grid of elevation values representing the ground surface. They are less detailed than point clouds and are typically used for applications requiring a broader terrain view, such as land use planning, water management, and environmental studies. AHN4 raster datasets are less detailed than point clouds, but they are easier to process and use in GIS software. They are also more suitable for applications requiring a quick and straightforward representation of the terrain without the need for high accuracy or very detailed information for precise locations.

In terms of AHN4 datasets, both point clouds and rasters have their strengths and limitations, and the choice between the two depends on the application's specific needs. Pointclouds offer high accuracy and detailed information, making them ideal for applications requiring high precision. On the other hand, AHN4 raster datasets are better suited for applications that need a broad overview of the terrain and are easier to use in GIS software. For determining pipe depths, raster datasets perform better in large areas due to their smaller size, which results in better processing times. Still, when it comes to accuracy and finding the closest elevation point relative to the DWDS vertex, point clouds are the preferred option.

Merging the existing measurement datasets of Z coordinates of Brabant Water with the AHN4 resulted in a dataset in which inaccurate measurements apply as well, with measurements located at or above the ground surface. The decision was made not to leave those measurements out because it is not clear yet what should happen with wrong measurements. A case is also known in which a new pipe was put in the ground, and a few weeks later, the municipality made a wadi on top of the pipe, resulting in

lowering the ground surface. In the data, this looks like a wrong measurement since the distance from the pipe to the ground level is small here. However, there are also situations like this where this is the reality. What looks like a wrong measurement could thus be an actual measurement. Therefore, when performing data quality checks based on the AHN for Z coordinates, the values should be interpreted with caution due to exceptional situations that can apply.

The use of a small buffer size of 0.10 meters in clipping the AHN4 to the buffer of the DWDS of Brabant Water has been found to sometimes result in large join distances between the point cloud and the DWDS vertices, particularly in areas with buildings where flight shadow creates a challenge. This is because the buffer size affects the accuracy of the join process and the proximity of the points to the vertices of the DWDS.

In areas with relatively flat terrain, the longer join distance may not matter as much. However, a larger buffer size would be more beneficial in other areas where more accurate mapping is necessary. Increasing the buffer size would increase the chances of finding closer points and improve the accuracy of the mapping process.

A pipe was excluded due to large join distances caused by the pipe's location between two borders of the Netherlands in Belgium. The AHN4 does not provide data for Belgium, hence excluding this particular pipe from the dataset.

Unfortunately, due to hardware limitations and processing times, it has been challenging to increase the buffer size to address the issue of large join distances. This challenge highlights the importance of balancing the need for accuracy with the limitations of technology and resources. In conclusion, it is important to consider the application's specific needs when choosing a buffer size and carefully weigh the trade-offs between accuracy, technology, and resources.

This trade-off between accuracy and performance also applies to the choice between the vertex and the model option in the Surface Draper tool in FME. The model option produces better results by keeping pipes below the ground surface. Still, it creates many vertices that can negatively impact the server and the amount of data being stored. Additionally, the pipe may appear erratic when the ground level varies. On the other hand, the vertex option may result in a less accurate representation of pipes, but it is less resource-intensive. It may produce a more stable result in areas with varying ground levels. Ultimately, the decision of which option to use depends on the specific needs and resources of the application.

9.2. Conclusion

This research addressed the following research question: *How can the drinking water distribution system of Brabant Water be transformed from a two-dimensional to a three-dimensional geographical information system, and what are the possibilities of spatial decision support system usage for Brabant Water?*

This research investigates the usefulness of a 3D GIS and spatial decision support using an AR application for Brabant Water. The research examines the benefits and use cases of a 3D GIS as an SDSS and concludes that it can be created by developing a data model that complements the UNM and stores Z coordinate data. The study also found that all measured Z coordinates, in combination with the AHN4, can be integrated into the DWDS to create a 3D GIS for Brabant Water. Furthermore, it is essential to maintain data quality. The research concludes that a 3D GIS provides significant added value for Brabant Water.

The research question will be divided into two parts. The first part will explore possibilities for spatial decision support, discussing the added value, use cases, and preconditions for 3D GIS and AR. The second part will focus on transforming a 2D GIS into a 3D GIS.

9.2.1. Added value, use cases, and preconditions of a 3D GIS & AR utilization

Added value and use cases of a 3D GIS & AR utilization:

- 3D data improves the analysis of key DWDS factors such as water temperature, failure probability, resilience to temperature fluctuations, and determination of the top load of pipes.
- 3D GIS data and AR enhance SA and communication in crowded underground infrastructure. Vertical reference features give a better perspective in AR of the distance from the pipe to the

ground surface. Flow direction can also be modeled into the polygons on the features to emphasize the ground surface.

- Eight use cases were identified by research performed for the Dutch cadastre regarding 3D GIS data in the utility sector: They include orienting on project location, exploring UUN complexity, creating design plans, designing new pipe routes, preparing for directional drilling, determining test loop locations, supporting execution activities, and integrating underground into spatial issues. AR benefits are orienting and exploring complex UUNs, while other use case benefits relate to desktop 3D data.
- 3D data allows for more comprehensive risk assessment and improved safety in the utility sector, reducing excavation damage likelihood.
- Long-term accuracy requires using a vertical reference system to register multiple third-dimension values, including surface levels relative to NAP, Z coordinates relative to NAP, and pipe depth relative to the ground surface. This improves knowledge of UUN locations, specifically Brabant Water's DWDS.

Preconditions:
- Currently, the standard depths are assumed for the remainder of the pipe if no measurement is known. For long-term accuracy, registering Z coordinates when measurements are lacking relative to NAP is needed as the surface level changes over time. The AHN4 can be used to calculate the standard depth relative to NAP.
- To compute an accurate standard depth using the AHN, ensuring high data quality of attributes is imperative as these attributes determine the depth of pipes. Data quality checks enhance data reliability, and supplementary measurements are necessary in regions with subsidence risk to keep the quality of the Z coordinate in those areas up to date.
- There is a trade-off between accuracy and performance regarding increased data consumption. Vertical reference features should be rendered only on a large scale to prevent performance degradation when zoomed out, as those features are not needed then.
- A data model that complements the UNM is imperative to utilize 3D data effectively. It should include the actuality of registered data and the method used to measure the UUN, Z coordinates of the pipe and the surface level relative to NAP, and the depth of the pipe relative to the surface level. Vertical reference features can be used to store the additional data of the Z coordinates as a complementary data model, highlighting the distance between the pipe and the ground surface, which is also beneficial for AR applications to give perspective.
- Using 3D data may create a false sense of security, making it crucial to establish communication and raise awareness about the new data model before implementing and using it to avoid excavation damages.

9.2.2. Transformation to a 3D GIS
An additional data model is required to create a 3D GIS for Brabant Water. Existing datasets containing Z coordinates and the AHN4 have to be combined into the DWDS, and the data quality needs to be maintained.

Additional data model:
The current data model for the Brabant Water GIS cannot track multiple Z coordinates for one object due to the many-to-one relationship of vertices. Still, vertical reference features can track and register the origin of Z coordinates without affecting 2D map displays, as they are not visible but can be selected. The solution requires adequate storage space for the Z_quality feature and several attribute fields. With this data model, registering and tracking the Z coordinate's origin, the pipe's Z coordinate, the Z coordinate of the ground surface, and the difference between the two will be possible.

Integrate all available datasets:
- To integrate all available datasets that contain Z coordinates into the DWDS, a copy needs to be made of the existing Z coordinates in the DWDS using the vertices to point tool in ArcGIS Pro. This will ensure that the original data of Z coordinate measurements are preserved and can later be used for joining.
- The ground surface values of the AHN4 should be joined to the DWDS using a 2.5D Delaunay triangulation method using the surface draper tool in FME, and the vertices intersecting surface

water should be set to a Z coordinate of 0 since the AHN4 offers no data here.

- The Z coordinates of the DWDS and the deviation depth dataset will be joined back again to the DWDS. This step will ensure that all available Z coordinates datasets are integrated into the DWDS.

Maintaining data quality:
Maintaining the data quality of the Z coordinates in the DWDS is crucial. The data model needs to be adjusted to facilitate recording the quality of individual Z coordinates, including their measuring method, pipe depth, ground surface level, and the difference between these values. The following steps can be taken to ensure data quality in the future.

- Firstly, the vertical reference features should be updated for the class Z_Maaiveld when a new version of the AHN arrives. This will enable change detection of the ground surface, and the locations where the DWDS will be shallower or deep can be identified and acted upon.
- Secondly, current Z coordinates can be checked by comparing them to the AHN4 surface level. These measurement errors can be prevented in the future when a check is performed automatically to compare the (contractor's) reported measurement values to the AHN.
- Finally, all contractors should be forced to deliver Z coordinates in newly made specifications to extend the dataset with actual Z coordinates and enhance trust in the data. While the ultimate goal is to create a dataset based on exact measurements, this may take many years or even decades.

All of the must-have requirements of the MoSCoW method were met during this research. Also, the should-have criteria were met as a dataset with Z coordinates per vertex was produced for the entire distribution area, which will be tested for the AR application together with the mechanics of Brabant Water in the field. Examples were also given regarding the possibilities in analysis using 3D GIS together with the AHN, which was a could-have criterion.

In conclusion, using a 3D GIS combined with AR and registering depth information can bring significant value to Brabant Water's management processes in maintaining the DWDS, as it can lead to more efficient and effective decision-making through improved analysis and visualization.

9.2. Recommendations

Below, multiple recommendations are displayed. They are subdivided into two categories: (1) Ready for use for Brabant Water and (2) Future research.

9.2.1. Ready for use for Brabant Water:

- The LADM standard enables the geometric recording of pipeline ownership in the future, as it has a class to legal space utilities with rights attached. For instance, this can look like a buffer as a right of superficies. This right should be specified in public spaces and private property for utility networks. This aims to ensure that no changes are made to another person's property or assets without the owner's consent and that these boundaries are more effective and monitored through the right of superficies. This ultimately leads to less excavation damage because the underground situation is better recorded concerning rights. Brabant Water should consider adding a 3D buffer around the DWDS as a right of superficies to record the underground situation better.
- Implement checks for data quality to ensure accuracy in Z coordinates. This can be done using the AHN. Also, checks for data of Z coordinates delivered by contractors are possible using the AHN. This can potentially be automated as well.
- Conduct additional measurements for Z coordinates in high-risk areas for improved accuracy. Risk areas can be areas with a high likelihood of subsidence or areas where the surface level has changed.
- Consider making it mandatory for contractors to report Z coordinates starting from the next specifications period in 2025. Doing this will deliver more Z coordinates to the GIS, contributing to a more accurate and complete dataset.
- Leverage GPS measurements more frequently to speed up measurement processes for the entire distribution area.
- Consider increasingly using MR technologies such as AR and VR to help manage, view, and maintain utility-based geospatial data.

- Enhance the accuracy of registering UUNs by implementing vertical reference features. Keep comprehensive records of Z coordinates, including origin, measurement method, ground surface level, pipe depth, and the difference between the two. These records can be stored in the vertical reference feature data model as described in this thesis which, regarding the features themselves, also provides a clearer view of the pipe's ground surface distance in AR. It's a must-have to register this information about the Z coordinates and keep it up to date because otherwise, the origin and reliability of the Z coordinates cannot be traced. The danger is that without such an additional data model, potentially unreliable data of Z coordinates is perceived as the truth.
- Develop a strategy for registering other related assets to the DWDS in a 3D GIS, such as devices, junctions, etc. This research can be a base reference for future work in that field.
- Brabant Water should investigate ways to automate the retrieval of Z coordinates from construction drawings into a geodatabase feature class. The current Z coordinates intersecting with surface water are assigned a zero (a way to emphasize that no data is present here) in this research due to a lack of data from the AHN4. Construction drawings are the most reliable way to obtain Z coordinates for pipes under surface water. Integrating these values (automatically) into a geodatabase when directional drillings are performed could improve the accuracy and reliability of Z coordinate data of pipes located beneath surface water and simplify access.
- A decision should be made if Z coordinates get registered in the DWDS based on the AHN. Furthermore, measured Z coordinates located near, at, or above the ground surface should be erased and overwritten with AHN values since the likelihood of wrong measurements. However, exceptional situations can occur, as well as highlighted in the discussion, which may be a reason not to overwrite the measured Z coordinates which are located near, at, or above the ground surface.
- Maximize the potential of 3D GIS in combination with AR to improve the DWDS maintenance and decision-making. AR is particularly advantageous for fieldwork because it provides a transparent view and allows hands-free operation. AR/VR can also be utilized in the office with 3D GIS data, and Arc Scenes can showcase the data in a desktop setup. These technologies can serve as SDSS.

9.2.2. Future research
- Investigate the possibility of correlating Z coordinates in the deviation depth GIS file with Z coordinates from the DWDS. Some deviating Z coordinates from the DWDS can probably be explained by the deviation depth dataset reported to the cadastre and the utility.
- Assess the implementation of the "model" option in the FME surface draper tool to maintain the DWDS below ground level and eliminate an inconsistent image resulting from excessive vertices. Determine if the high number of vertices may overload the GIS server. Identify ways to mitigate this to ensure the DWDS remains below ground level and does not display an erratic image caused by too many vertices and variations in terrain elevation.
- Further research is needed on connecting equal networks from different asset types (located on two different depths) to eliminate gaps in the connection. One solution could be to modify the last vertex of the adjacent network to match the perpendicular network's depth, as shown as a test in figure 54.
- An automation tool should be developed to update this data from the data model of the vertical reference features when new Z coordinates get registered in the GIS database. More research will be necessary on how to develop such a tool.
- In this study, the vertical reference features were produced on each vertex of the DWDS. All the AR tests with the vertical reference features were performed in an urban area where many vertices are located, meaning no additional vertical reference features were needed. However, rural areas have limited intersections with long, straight pipelines. Adding a vertical reference point every 10 meters can also be interesting to see the distance from the pipe to the ground surface level in these areas. Also, recording Z coordinates is desirable with not too much distance in between. Therefore, more research for an optimal interval is desired to record Z coordinates in the DWDS.
- Costs can be minimized by measuring with alternative methods, such as GPR. This is recommended when only measurements are required, and no trench is open for maintenance work. GPR can be a cost-effective solution. However, further studies are needed on whether this method can effectively detect UUN. Also, research is needed regarding the correct frequencies for different soil types to detect UUN.

- Polygons on top of the vertical reference features can be made with a flow direction. However, due to sun light, the polygon is easier to distinguish with the vertical reference feature when it has a different color. This needs to be tested in the field to see the best characteristics for the vertical reference features in combination with the polygons on top of them.

10. References

Abdul-Rahman, A., & Pilouk, M. (2007). *Spatial data modelling for 3D GIS.* Springer Science & Business Media.

Agentschap Telecom. (2020, April 21). *WIBON en schade door graven 2019*. Retrieved from agentschaptelecom.nl: https://www.agentschaptelecom.nl/binaries/agentschap-telecom/documenten/publicaties/2020/04/21/infographic-wibon-en-schade-door-graven/EZK-Infographic_WIBON_2019_.pdf

Agentschap Telecom. (2021, May 31). *WIBON en schade door graven 2020*. Retrieved from agentschaptelecom.nl: https://www.agentschaptelecom.nl/binaries/agentschap-telecom/documenten/publicaties/2021/05/31/infographic-schade-door-graafwerkzaamheden-2020/Infographic+WIBON+schade+door+graven+2020.pdf

Agentschap Telecom. (2022a, May 31). *WIBON en schade door graven 2021*. Retrieved from agentschaptelecom.nl: https://www.agentschaptelecom.nl/binaries/agentschap-telecom/documenten/publicaties/2022/05/31/feiten-en-cijfers-over-schade-door-graafwerkzaamheden-2021/Infographic+WIBON+en+schade+door+graven+2021.pdf

Agentschap Telecom. (2022b). *Excavation damage facts and figures 2021*. Retrieved from Agentschaptelecom.nl: https://www.agentschaptelecom.nl/documenten/publicaties/2022/05/31/feiten-en-cijfers-over-schade-door-graafwerkzaamheden-2021

Agentschap Telecom. (2022c, August 28). *Agentschap Telecom en de CROW 500*. Retrieved from Agentschaptelecom.nl: https://www.agentschaptelecom.nl/onderwerpen/kabels-en-leidingen/crow-publicatie-500

Agudelo-Vera, C., & Fujita, Y. (2017). Hotspots in het leidingnet. *KWR*(023).

AHN. (2022). *Kwaliteitsbeschrijving*. Retrieved from AHN: https://www.ahn.nl/kwaliteitsbeschrijving

Anton. (2019, July 04). *Presentatiemodel Kabels en Leidingen in InfraCAD Map*. Retrieved from infracad.nl: http://www.infracad.nl/forum/viewtopic.php?t=978

ArcGIS. (2022a, June 19). *AHN4 - Download kaartbladen*. Retrieved from Arcgis.com: https://www.arcgis.com/home/item.html?id=77da2e9eeea8427aab2ac83b79097b1a

ArcGIS. (2022b). *BGT-Waterdeel*. Retrieved from Arcgis.com: https://www.arcgis.com/home/item.html?id=948c5d436a894acc863c8d6efef9a843

ArcGIS. (2023). *Water Distribution Utility Network Foundation Data Dictionary*. Retrieved from solutions.arcgis.com: https://solutions.arcgis.com/water/help/water-distribution-utility-network-foundation/DataDictionary/DataDictionary/#StructureLine

Assinck, F. (2010, May 25). *Grondsoortenkaart*. Retrieved from Wageningen University & Research: https://www.wur.nl/nl/show/Grondsoortenkaart.htm

Azuma, R. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*(4), pp. 355-385.

Bliemer, S., Eertink, D., & Staarink, H. (2021). *Meerjarenbeleidsplan 2022-2026.* Apeldoorn: Kadaster. Retrieved from https://www.kadaster.nl/documents/1953498/4796371/Meerjarenbeleidsplan+2022-2026.pdf/00285d9a-7601-6c22-4ebc-7bd4c1e4c946?t=1640616992140

Blokker, E., & Pieterse-Quirijns, I. (2010). Model voor de berekening van de watertemperatuur in het leidingnet. *H2O*(23), p. 46.

Blokker, E., & Pieterse-Quirijns, I. (2015, May 04). Modeling temperature in the drinking water distribution system. *American Water Works Association*, pp. 19-28.

Brabant Water . (2022a, August 16). *Historie Brabant Water*. Retrieved from Brabant Water : https://www.brabantwater.nl/over-brabant-water/brabant-water/historie-brabant-water

Brabant Water . (2022b, August 16). *Hoe kraanwater wordt gemaakt*. Retrieved from Brabant Water: https://www.brabantwater.nl/drinkwater/waterkwaliteit-en-hardheid/hoe-kraanwater-wordt-gemaakt

Brabant Water. (2018, November 09). *Project implementatie GIS-visie: invoeren 3D.* Retrieved from teams.brabantwater.nl.

Brabant Water. (2022c, August 16). *Vernieuwing waterleidingnet Brabant*. Retrieved from Brabant Water: https://www.brabantwater.nl/over-brabant-water/projecten/vernieuwing-waterleidingnet-brabant

Burdea, G. C., & Coiffet, P. (2003). *Virtual reality technology.* New York: John Wiley & Sons.

Carmigniani, J., Furht, B., Anisetti, M., Cervalo, P., Damiani, E., & Ivkovic, M. (2011). Augmented reality technologies, systems and applications. *Multimed Tools Appl.*(1), pp. 341-377.

Chassagne, O. (2012). *One-centimeter accuracy with PPP.* Red Bank: InsideGNSS.

Chong, S. (2006). Registration of Wayleave (cable and pipeline) into Dutch cadastre. *Internship Report for GIMA Module 7*, 56.

Coutinho-Rodrigues, J., Simão, A., & Henggeler Antunes, C. (2011, June). A GIS-based multicriteria spatial decision support system for planning urban infrastructures. *Decision Support Systems*(3), pp. 720-726.

CUMELA Nederland. (2016). *Reactie Wijzigingswet WION.* Nijkerk: CUMELA. Retrieved from https://www.internetconsultatie.nl/wijzigingwion/reactie/54439/bestand

De Bruijne, A., Van Buren, J., Kösters, A., & Van der Marel, H. (2005). *Geodetic reference frames in the Netherlands.* Delft: Netherlands Geodetic Commission.

Dewyngaert, N. (2017, October 04). *INSPIRE-based data model in the KLIP Digital platform.* Retrieved from https://joinup.ec.europa.eu/: https://joinup.ec.europa.eu/collection/are3na/news/inspire-based-data-model-t

Du, Y., Zlatanova, S., & Liu, X. (2006). Management and 3D visualization of pipeline networks using DBMS and AEC software. *ISPRS Archives*(Volume XXXVI-4), 395-400.

Esri. (2022a, June 19). *Clip (analysis).* Retrieved from pro.arcgis.com: https://pro.arcgis.com/en/pro-app/2.8/tool-reference/analysis/clip.htm

Esri. (2022b, June 19). *Buffer (analysis).* Retrieved from pro.arcgis.com: https://pro.arcgis.com/en/pro-app/2.8/tool-reference/analysis/buffer.htm

Esri. (2022c, June 19). *Adjust 3D Z (Data Management).* Retrieved from pro.arcgis.com: https://pro.arcgis.com/en/pro-app/2.8/tool-reference/data-management/adjust-3d-z.htm

Esri. (2022d, June 19). *Intersect (analysis).* Retrieved from pro.arcgis.com: https://pro.arcgis.com/en/pro-app/latest/tool-reference/analysis/intersect.htm

Fenais, A., Ariaratnam, S., Ayer, S., & Smilovsky, N. (2019). Inegrating Geographical Information Systems and Augmented Reality for Mapping Underground Utilities. *Infrastructures*(60), pp. 1-27.

Fenais, A., Smilovsky, N., Ariaratnam, S., & Ayer, S. (2018). *A meta-analysis of augmented reality challanges in the underground utility construction industry.* Infrastructure and Facility Managegement, CRC 2018.

Geodirect. (2021, July 21). *Handleiding Stonex S700 - Cube A.* Retrieved from teams.brabantwater.nl.

Geodirect. (2022a, August 14). *INVOERING RDNAPTRANS2018.* Retrieved from Geodirect: https://www.geodirect.nl/nieuws/invoering-rdnaptrans2018/

Geodirect. (2022b, August 16). *Stonex S700A.* Retrieved from Geodirect: https://www.geodirect.nl/product/gnss-systemen/gnss-ontvangers/stonex-s700a/

Gerhard, W., Andreas, B., Gimter, S., Volker, B., & Hankemeier, P. (1996). Reducing distance dependent errors for real-time precise DGPS applications by establishing reference station network. *Conference proceedings of ion GPS, Institute of Navigation*, pp. 845-852.

Grimaldi, M., Sebillo, M., Vitiello, G., & Pellecchia, V. (2020, August 10). Planning and Managing the Integrated Water System: A Spatial Decision Support System to Analyze the Infrastructure Performances. *Sustainability*(16), pp. 1-23.

Guerrero, J., Zlatanova, S., & Meijers, M. (2013). 3D Visualisation of Underground Pipelines: Best Strategy for 3D Scene Creation. *ISPRS Annals*(Volume II-2/W1), 139-145.

Italian Authority of Electricity, Gas and Water. (2018). *Directive.*

Kadaster . (2021, Juli). *Productplan KLIC.* Retrieved from Kadaster.nl: https://www.kadaster.nl/documents/1953498/2762156/KLIC+Productplan+2021-2024.pdf/1fe380a1-f32e-c221-8011-c525e56bb287?t=1626697523608

Kennedy, E. (2013). Ondergrondse Infrastructuur in 3D. *GI Minor*, 47.

KLICAPP. (2022, August 16). *Graven in de grond: Kent u de regels? .* Retrieved from KLICAPP: https://klic-app.nl/nieuws/graven-in-de-grond-kent-u-de-regels/

Knippers, R., & Mehlbreuer, A. (1999). *Geometric Aspects and fundamentals of Mapping.* Retrieved from Kartoweb: https://kartoweb.itc.nl/geometrics/Coordinate%20systems/body.htm

Koek, A. (2020). Crowded Urban Underground - An exploratory research into space demand of transitioning urban underground infrastructures. *Msc Thesis Urban System Engineering*, 63.

Lachapelle, G., Petovello, M., Gao, Y., & Garin, L. (2006). Precise point positioning and its challanges, aided-GNSS and signal tracking. *InsideGNSS*, pp. 12-16.

Lemmen, C., Van Oosterom, P., & Bennett, R. (2015, December). The Land Administration Domain Model. *Land Use Policy*, pp. 535-545.

Madrid, J., & Korchakov, K. (2017). *Esri Utility Network - Simple and Scalable Network Data Model.* Retrieved from SSP Innovations: https://sspinnovations.com/blog/esri-utility-network-simple-and-scalable-network-data-model/

Mallo, P. (2022, February 23). The effects of 3D visualisation on communication applied to the utility

sector. *Vrije Universiteit Amsterdam, UNIGIS MSc Thesis*.

Mccord, E. S. (2022, February). Ten practical questions to improve data quality. *Rangelands*(1), pp. 17-28.

Meerkerk, M., & Beuken, R. (2017). *Richtlijn drinkwaterleidingen buiten gebouwen.* Nieuwegein: KWR.

Milgram, P., & Kishino, F. (1994a). A taxonomy of mixed reality visual displays. *IEICE Transact. Inform. Sys.*, pp. 1-15.

Milgram, P., & Kishino, F. (1994b). A taxonomy of mixed reality visual displays. *IEICE Transact. Inform. Sys.*(12), pp. 1321-1329.

Ministerie van Binnenlandse Zaken en Koninkrijkrelaties . (2022, June 29). *Wat is de BRO?* Retrieved from basisregistratieondergrond.nl: https://basisregistratieondergrond.nl/inhoud-bro/bro/

Mulder, R. (2022, August 28). *KLIC-WIN.* Retrieved from GOCONNECTIT: https://www.goconnectit.nl/expertises/klic-win/

Nahon, D., Subileau, G., & Capel, B. (2015, March). "Never Blind VR" enhancing the virtual reality headset experience with augmented virtuality. *IEEE Virtual RealityVR*(27), pp. 347-348.

Nederlands Centrum voor Geodesie en Geo-Informatica. (2022, August 31). *Bodemdalingskaart 2.0.* Retrieved from bodemdalingskaart.portal.skygeo.com: https://bodemdalingskaart.portal.skygeo.com/portal/bodemdalingskaart/u2/viewers/basic/

Noardo, F. e. (2022, August 28). *CityGML.* Retrieved from GeoBIM Benchmark: https://3d.bk.tudelft.nl/projects/geobim-benchmark/citygml.html

Ohta, Y., & Tamura, H. (2014). *Mixed reality: merging real and virtual worlds.* Berlin: Germany: Springer Publishing Company.

Olde Scholtenhuis, L., Stoter, J., Pauwels, P., Borst, R., Schutten, W., & Van Nijen, N. (2022). *Eindrapport Wi3D: Onderzoek naar de waarde van 3D voor de graafsector in de context van KLIC-WIBON.* Enschede: KGO 3D Onderzoek.

Penninga, F., & Van Oosterom, P. (2006). Kabel- en leidingnetwerken in de kadastrale registratie. *GISt Rapport*(42), 1-31.

Petevello, M. (2011). *What is a virtual reference station and how does it work.* Red Bank: Inside GNSS.

Pieterse-Quirijns, I., De Groot, R., De Rijck, Y., & Ruijg, K. (2011). *Diepteligging van leidingen.* Nieuwegein: Watercycle Research Institute.

Pro.ArcGIS. (2023). *Output has Z Values (Environment setting).* Retrieved from pro.arcgis.com: https://pro.arcgis.com/en/pro-app/latest/tool-reference/environment-settings/output-has-z-values.htm

Prorail. (2020). *In de spotlights: bekabeling .* Retrieved from Prorail.nl: https://www.prorail.nl/nieuws/in-de-spotlights-bekabeling#:~:text=Het%20aantal%20kabels%20kan%20per,Die%20ligt%2090%20centimeter%20diep.

Radu, I. (2014). Augmented reality in education: a meta-review and cross-media analysis. *Personal and Ubiquitous Computing*(6), pp. 1533-1543.

Rotterdam. (2022, June 05). *Rotterdam in 3D.* Retrieved from Rotterdam: https://www.rotterdam.nl/werken-leren/3d/

Saberi, B., & Ghadiri, N. (2014, July). A sample-based approach to Data Quality Assessment in Spatial Databases with Application to Mobile Trajectory Nearest-Neighbour Search. *Journal of Computing and Security*(1), pp. 239-249.

Safe. (2020, July 29). *Clipping and Tiling Point Cloud Data.* Retrieved from FME Community: https://community.safe.com/s/article/tiling-point-cloud-data

Safe. (2023). *SurfaceDraper.* Retrieved from Safe Software: http://docs.safe.com/fme/html/FME_Desktop_Documentation/FME_Transformers/Transformers/surfacedraper.htm

Sainovic, I. (2009, December 01). STSM Scientific Report. *COST STSM*(TU0801-5171), pp. 1-6. Retrieved from https://orbi.uliege.be/bitstream/2268/249735/1/Sainovic-STSM-report-Delft.pdf

Schall, G., Mendez, E., Kruijff, E., Veas, E., Junghanns, S., Reitinger, B., & Schmalstieg, D. (2009). Handheld Augmented Reality for Underground Infrastructure Visualization. *Personal and Ubliquitous Computing*(4), pp. 281-291.

Smallman, H., John, M., & Cowen, M. (2004). Limits of display realism: Human factors issues in visualizing the common operational picture. *Visualisation and the Common Operational Picture*, pp. 16-1 - 16-18.

Smits, T., & Wang, Z. (2019). 2D-3D GIS conversion for underground utilities registration. *GI minor*, 11.

Speicher, M., Hall, B. D., & Nebeling, M. (2019, May). What is mixed reality? *In Proceedings of the*

2019 CHI conference on human factors in computing systems, Ann Arbor, MI., pp. 1-15.

Stoter, J., Louwman, W., Ploeger, H., & Van Oosterom, P. (2011). 3D-Kadaster in Nederland. *Geo-Info*(3).

Stowa. (2020). *Bodemdaling.* Stowa. Retrieved from https://www.stowa.nl/sites/default/files/assets/DELTAFACTS/Deltafacts%20NL%20PDF%20nieuw%20format/Bodemdaling%20versie%203.1%20%28feb%202020%29.pdf

Stylianidis, E., Valeri, E., Carillo, I., Kounoudes, A., & Michail, K. S. (2020). Augmented Reality Geovisualisation for Underground Utilities. *Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, pp. 173-185.

Terniet, S., Klemke, R., Kalz, M., Van Ulzen, P., & Specht, M. (2012). ARLearn: augmented reality meets augmented virtuality. *Journal of Universal Computer Science - Technology for learning across physical and virtual space*(15), pp. 2143-2164.

Tiberius, C., Van der Marel, H., Reudink, R., & Van Leijen, F. (2021). *Surveying and Mapping.* Delft: Delft University of Technology.

Van Alphen, J. (2022). Interview. (S. Van den Beukel, Interviewer)

Van de Wiel, R. (2022). Interview. (S. Van den Beukel, Interviewer)

Van den Berg, H., & Janssen, P. (2021). *Informatiemodel Kabels en Leidingen (IMKL) - versie 2.0.* Amersfoort: Geonovum. Retrieved from https://docs.geostandaarden.nl/kl/imkl/#:~:text=IMKL%20past%20waar%20nodig%2C%20optioneel,naar%20aanpassingen%20aan%20CityGML%2DUtility.

Van den Bos, L. (2020). *Quatifying the effects of anthropogenic heat sources on the water tememprature in the drinking water system.* Delft: TU Delft.

Van Laarhoven, K. (2022, 09 07). Interview. (S. Van den Beukel, Interviewer)

Van Meel, Harrie. (2022, August 30). *Brabant Water loopt voorop met het ArcGIS Utility Network.* Retrieved from Magazine.esri.nl: MAGIC incorporated the ArcGIS Utility Network Model (UNM) of Esri at Brabant Water.

Van Os, D. (2022, May 18). Interview. (S. Van den Beukel, Interviewer)

Van Summeren, J., Vires, D., Albert, M., & Verbree, J. (2017, December). Analyse van 'slimme meter' -data voor het in kaart brengen van hotspots in het distributienet. *KWR Watercycle Research Institute* , pp. 1-50.

Van Vliet, H. (2007). *Software Engineering: Principles and Practice.* Wiley.

V-Labs. (2022, August 30). *Accurate augmented reality for geospatial data.* Retrieved from v-labs.ch: https://v-labs.ch/

Wet WIBON. (2019). Retrieved from https://wetten.overheid.nl/BWBR0040728/2019-01-01

Whitaker, R. (1998). A level-set approach to 3D reconstruction from range data. *International journal of computer vision*(3), pp. 203-231.

Xu, J., & Moreu, F. (2021, June 02). A review of Augmented Reality Applications in Civil Infrastructure During the 4th Industrial Revolution. *Frontiers in Built Environment*(640732), pp. 1-16.

Yan, J., Jaw, S. W., Soon, K. H., Wieser, A., & Schrotter, G. (2019, August 21). Towards an Underground Utilities 3D Data Model for Land Administration. *Remote Sensing*(11), pp. 1-21.

Zyda, M. (2005). From visual simulation to virtual reality to games. *Computer*(9), pp. 25-32.

11.1. Appendix A – Summary of interviewed experts and main points

Interviews conducted with Brabant Water employees:
1. Jack van Alpen – Business architect ICT – multiple conversations about data structures of Brabant Water
   - The People Group arranges the conversion for Brabant Water from their data model to the data model required by the cadastre (IMKL 2015).
   - BIM and GIS will be increasingly integrated in the future.
2. Daan van Os – Advisor Asset management & asset data management
   - About 20 people are mutating GIS information at Brabant Water
   - The depth of the DWDS is important for drinking water temperature
   - There is an increasing demand from the DWDS due to extra houses being built due to housing shortages
   - Depth information brings the data closer to reality, resulting in better excavation work. Every centimeter of extra excavation work results in more costs.
   - Added value in visualizing underground infrastructure to bring the relationship forward with other assets below the ground surface.
   - You can determine the depth of fire hydrants if you know the depth of the ground surface and the DWDS.
   - Theoretically, all the deviating depth is registered in a separate GIS point file.
   - The standard depth of the DWDS according to the literature is correct: transport pipes -1,2m (In GIS label primary), distribution pipes -1,0m (In GIS label secondary and tertiary), house connection pipes -0,80m (In GIS label drinkwater and rest). Other categories are raw and unpurified water and industrial water (not drinkable).
3. Harrie van Meel – Project leader ICT
   - Project MAGIC was there to implement UNM of Esri in ArcGIS
   - From registering to operate independently
   - All the processes with a geographical component should be supported with data that is of optimal quality anywhere, anytime.
   - The previous GIS system couldn't support the future vision as it lacked several functionalities
4. Rob van de Wiel – Coordinating employee GIS-AutoCAD
   - Deviation depth is registered in GIS point files "Meetpunt_Hoogte" and "Rioolkruising." Deviation depth is considered more than 0,20 meters.
   - New agreements with contractors from 2025, including Z coordinates
   - Since 2007 measurements have been performed with GPS
   - Contractors sometimes deliver Z coordinates but often leave this data out. Often measurements are performed in the closed trench. Therefore if a Z—coordinate is delivered, Brabant Water can check their data which is not in their interest.
   - There are 34 Stonex GNSS systems and 100 mechanics at Brabant Water. Most of the time measurements are performed in open trenches.
   - Measurements are taken each 50 meters or at bends/curves in the DWDS.
5. Claudia Quintiliani - Water supply consultant
   - Depth information for the DWDS relative to NAP is very important since the designed burial depth of a pipe rarely matches the real one because soil and the ground surface are subject to change due to various causes, one of which is subsidence (due to soil characteristics).
6. Lisette Verkerk – Project leader ICT
   - XSD – XML is a format used by contractors for connecting pipes to get measurement data in the GIS. The XML format contributes to the standardization of data exchange between grid operators and contractors in the Netherlands. Each contractor has a software solution that supports creating this XML format for each connection. E.g., GoMapForms is used for smaller distances up to 45m, where the technician uses measuring tape to determine the distances. The larger distances are performed with GPS measurements (e.g., Stonex GNSS equipment).
   - The XSD form is subject to change, and the Z coordinate may be incorporated into the new template in the future.

7. Sjanny van de Laar – Senior applications specialist
   - Depth information for the DWDS has a lot of added value in combining it with other UID.
   - For excavation work performed by Brabant, Water depth information could be of added value. However, for contractors, it's a risk of a false sense of certainty regarding the depth of information.
   - Below pavements, the DWDS is subject to more temperature increases.
   - Depth information has added value for analysis; for example, which three roots affect the DWDS, or near dikes and rivers, more subsidence is applicable. Depth information could be used to analyze whether polluted soil affects the DWDS.

8. Annerieke van Vessem - Procesdevelopment & Change development
   - The Director of Brabant Water stated that it aims to implement smart glasses in the mechanic's work processes.
   - With AR glasses, a significant benefit is that your hands are free to work with, and you can observe the surroundings. That's a big difference with VR, where this is not possible.

9. Two Senior Mechanics were present with the AR test from V-labs at Brabant Water:
   - Both were able to carry out inspections using the glasses and read the data.
   - One mentioned that 3D could be of added value, especially for new mechanics to realize the depth of each network. More experienced mechanics know the different depths of each type of network.

Other interviews:

- Dimitry Dekker – NET4S & Brabant Water (external) – 14-06-2022
  - The AHN is limited for surface water and viaducts.
  - Sometimes contractors deliver Z coordinates in AutoCAD files in drawing file (.DWG) format.
  - V GIS application which works on a tablet, enables mechanics to directly view KLIC notifications and see where the DWDS is located.
- Theo Kolman – NET4S & Brabant Water (external) – 07-02-2023
  - Measuring pipes and excavating can be costly. Thus, to avoid these expenses, GPR is advisable if only measurements are needed and no trench is open for maintenance work. GPR is a budget-friendly option. Further research on the appropriate frequencies for various soil types is necessary to locate UUNs accurately.
- Diemer Cohen tuart – V-Labs – 28-06-2022
  - V-Labs GNSS/RTK integrated AR Glasses visualize and measure geospatial data with cm accuracy in the field while having hands free for manual labor.
  - Can display drinking water distribution data, related assets, and other underground infrastructure GIS data in 2D and 3D from Brabant Water Databases.
  - Can measure data in RD coordinates using RDNAPTRANS and make pictures for inspections.
  - Diemer mentioned that 3D GIS data of the DWDS would be of added value for the mechanics in terms of visualization and viewing complex UUNs in the field.
  - The solution can guide people in the field through step-by-step work instructions to optimize operational work and improve data quality.
- Mirjam Blokker – KWR Water Research Institute & TU Delft - Team Water infrastructure – 09-08-2022 (via e-mail).
  - The deeper the DWDS is located below the ground surface, the less it's subject to fluctuations in outside temperature in the summer.
  - It is important to know the depth to estimate the top load of pipes. The deeper, the greater the load, and possibly the sooner the pipe breaks.
  - Others who will work on underground infrastructure and have access to the depth information can also consider the existing pipes better if the position is better known (less chance of fractures).
- Karel van Laarhoven – KWR Water Research Institute – Team Water Infrastructure – 07-09-2022

- Chances of failure and the condition of the DWDS can be better estimated if you know how much soil is on top of the DWDS. Depth information is crucial to calculate this and to be able to distinguish between various locations. If the same depth is used everywhere (e.g., 1 meter), all the models look like each other. Depth is thus an essential variable in this calculation.
- Recording the Z coordinate has a software-technical component (having a usable column in the system to store the Z coordinate) and an information source aspect (is the value entered correct, and how is this known?). When implemented, care must be taken to distinguish current values based on estimates and guesswork from reliable and traceable measurements. Perhaps multiple columns will be necessary for this purpose.
- It's a danger that the ignorance of today will become the truth of tomorrow because it's recorded in the system as such.

- Esri – 15-06-2022
  - In the Esri Field Map app, the mechanic can see all the coordinates of the DWDS, including Z coordinates.
  - The mechanics work with Esri field maps to read and view data.
  - NaN values in Z coordinates are impossible because NaN cannot be visualized in an ArcGIS Scene since no location would be correct as the Z is unknown. Currently, no data is visualized as Z = 0. As a workaround, a Z of 99999 could be possible. However, this significantly impacts how the data is visualized with, for example, a polyline.

11.2. ArcGIS Model builder – Python documentation

11.2.1. Validation of measured Z coordinates with AHN

1. `# -*- coding: utf-8 -*-`
2. `"""`
3. `Generated by ArcGIS ModelBuilder on : 2023-03-02 12:31:30`
4. `"""`
5. `import arcpy`
6. `from sys import argv`
7. ```
def
ComparisonOfZCoordinates(Output_data_Z_comparison="Q:\\ArcGIS\\Projects\\FME_TOOLS
\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_Mea_F_SpatialJoin",
Distribution_network="Water_Line_12_10_2022",
AHN4_Points="Q:\\ArcGIS\\Projects\\Study_Area\\Study_Area\\FME_Tool\\Data\\Stap_3.gdb\\
Punten_op_leidingen"): # Comparison of measured Z coordinates with AHN
```
8. `# To allow overwriting outputs change overwriteOutput option to True.`
9. `arcpy.env.overwriteOutput = False`
10. `FME_TOOLS_gdb = "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb"`
11. `# Process: Add Z Information (Add Z Information) (3d)`
12. ```
Water_Line_12_10_2022_2_ =
arcpy.ddd.AddZInformation(in_feature_class=Distribution_network, out_property=["Z_MEAN"],
noise_filtering="")[0]
```
13. `# Process: Feature Class To Feature Class (Feature Class To Feature Class) (conversion)`
14. ```
Water_Line_Measured_Z_coordinates =
arcpy.conversion.FeatureClassToFeatureClass(in_features=Water_Line_12_10_2022_2_,
out_path=FME_TOOLS_gdb, out_name="Water_Line_Measured_Z_coordinates",
where_clause="Z_Mean <> 0", field_mapping="ASSETGROUP \"Asset group\" true true false
4 Long 0 0,First,#,Water_Line_12_10_2022,ASSETGROUP,-1,-1;ASSETTYPE \"Asset type\"
true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,ASSETTYPE,-1,-
1;ASSOCIATIONSTATUS \"Association status\" true true false 2 Short 0
0,First,#,Water_Line_12_10_2022,ASSOCIATIONSTATUS,-1,-1;ISCONNECTED \"Is
connected\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,ISCONNECTED,-1,-
1;FROMDEVICETERMINAL \"From device terminal\" true true false 2 Short 0
0,First,#,Water_Line_12_10_2022,FROMDEVICETERMINAL,-1,-1;TODEVICETERMINAL
\"To device terminal\" true true false 2 Short 0
0,First,#,Water_Line_12_10_2022,TODEVICETERMINAL,-1,-1;CREATIONDATE \"Creation
date\" true true false 8 Date 0 0,First,#,Water_Line_12_10_2022,CREATIONDATE,-1,-
1;CREATOR \"Creator\" true true false 255 Text 0
0,First,#,Water_Line_12_10_2022,CREATOR,0,255;LASTUPDATE \"Last update\" true true
false 8 Date 0 0,First,#,Water_Line_12_10_2022,LASTUPDATE,-1,-1;UPDATEDBY
\"Updated by\" true true false 255 Text 0
0,First,#,Water_Line_12_10_2022,UPDATEDBY,0,255;GLOBALID \"Global ID\" false false
true 38 GlobalID 0 0,First,#,Water_Line_12_10_2022,GLOBALID,-1,-
1;SysteemSubnetworkNaam \"SysteemSubnetworkNaam\" true true false 2000 Text 0
0,First,#,Water_Line_12_10_2022,SysteemSubnetworkNaam,0,2000;SUPPORTEDSUBNET
WORKNAME \"Supported subnetwork name\" true true false 2000 Text 0
0,First,#,Water_Line_12_10_2022,SUPPORTEDSUBNETWORKNAME,0,2000;aanleg_datum
\"Datum van aanleg\" true true false 8 Date 0
0,First,#,Water_Line_12_10_2022,aanleg_datum,-1,-1;aanleg_geschat \"Aanleg geschat\"
true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,aanleg_geschat,-1,-
1;bescherming_inwendig \"Bescherming inwendig\" true true false 2 Short 0
0,First,#,Water_Line_12_10_2022,bescherming_inwendig,-1,-1;bescherming_uitwendig
\"Bescherming uitwendig\" true true false 2 Short 0
0,First,#,Water_Line_12_10_2022,bescherming_uitwendig,-1,-1;crucialiteit \"Crucialiteit\" true
true false 2 Short 0 0,First,#,Water_Line_12_10_2022,crucialiteit,-1,-1;diameter \"Diameter\"
true true false 8 Double 0 0,First,#,Water_Line_12_10_2022,diameter,-1,-1;diameter_geschat
\"Diameter geschat\" true true false 2 Short 0
0,First,#,Water_Line_12_10_2022,diameter_geschat,-1,-1;diameter_inwendig \"Inwendige
diameter\" true true false 8 Double 0 0,First,#,Water_Line_12_10_2022,diameter_inwendig,-
```

1,-1;dossier_eel \"Dossiernummer EEL\" true true false 50 Text 0 0,First,#,Water_Line_12_10_2022,dossier_eel,0,50;gis_id \"GIS ID\" true true false 23 Text 0 0,First,#,Water_Line_12_10_2022,gis_id,0,23;kb_nummer \"KB nummer\" true true false 20 Text 0 0,First,#,Water_Line_12_10_2022,kb_nummer,0,20;materiaal \"Materiaal\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,materiaal,-1,-1;materiaal_geschat \"Materiaal geschat\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,materiaal_geschat,-1,-1;medium \"Medium\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,medium,-1,-1;projectnummer \"Projectnummer initieel\" true true false 50 Text 0 0,First,#,Water_Line_12_10_2022,projectnummer,0,50;projectnummer_status \"Projectnummer statuswijziging\" true true false 50 Text 0 0,First,#,Water_Line_12_10_2022,projectnummer_status,0,50;risicovol \"Risicovol\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,risicovol,-1,-1;sanering \"Is gesaneerd\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,sanering,-1,-1;sanerings_datum \"Datum van sanering\" true true false 8 Date 0 0,First,#,Water_Line_12_10_2022,sanerings_datum,-1,-1;status \"Status\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,status,-1,-1;trace_nr \"Trace nummer\" true true false 20 Text 0 0,First,#,Water_Line_12_10_2022,trace_nr,0,20;type \"Type leiding\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,type,-1,-1;wanddikte \"Wanddikte\" true true false 8 Double 0 0,First,#,Water_Line_12_10_2022,wanddikte,-1,-1;wanddikte_geschat \"Wanddikte geschat\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,wanddikte_geschat,-1,-1;wijze_inmeting \"Wijze van inmeting\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,wijze_inmeting,-1,-1;Shape_Length \"Shape_Length\" false true true 8 Double 0 0,First,#,Water_Line_12_10_2022,Shape_Length,-1,-1;Z_Mean \"Z_Mean\" true true false 0 Double 0 0,First,#,Water_Line_12_10_2022,Z_Mean,-1,-1", config_keyword="")[0]

15. # Process: Feature Vertices To Points (Feature Vertices To Points) (management)
16. Output_Feature_Class = "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_Mea_Fea tureVertic"
17. arcpy.management.FeatureVerticesToPoints(in_features=Water_Line_Measured_Z_coordinat es, out_feature_class=Output_Feature_Class, point_location="ALL")
18. # Process: Add Z Information (2) (Add Z Information) (3d)
19. Water_Line_Mea_FeatureVertic = arcpy.ddd.AddZInformation(in_feature_class=Output_Feature_Class, out_property=["Z"], noise_filtering="")[0]
20. # Process: Select Layer By Attribute (Select Layer By Attribute) (management)
21. Water_Line_Mea_FeatureVertic_3_, Count = arcpy.management.SelectLayerByAttribute(in_layer_or_view=Water_Line_Mea_FeatureVertic , selection_type="NEW_SELECTION", where_clause="Z = 0", invert_where_clause="")
22. # Process: Delete Rows (Delete Rows) (management)
23. Updated_Input_With_Rows_Removed = arcpy.management.DeleteRows(in_rows=Water_Line_Mea_FeatureVertic_3_)[0]
24. # Process: Spatial Join (Spatial Join) (analysis)
25. arcpy.analysis.SpatialJoin(target_features=Updated_Input_With_Rows_Removed, join_features=AHN4_Points, out_feature_class=Output_data_Z_comparison, join_operation="JOIN_ONE_TO_ONE", join_type="KEEP_ALL", field_mapping="ASSETGROUP \"Asset group\" true true false 4 Long 0 0,First,#,Water_Line_Mea_FeatureVertic2,ASSETGROUP,-1,-1;ASSETTYPE \"Asset type\" true true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,ASSETTYPE,-1,-1;ASSOCIATIONSTATUS \"Association status\" true true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,ASSOCIATIONSTATUS,-1,-1;ISCONNECTED \"Is connected\" true true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,ISCONNECTED,-1,-1;FROMDEVICETERMINAL \"From device terminal\" true true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,FROMDEVICETERMINAL,-1,-1;TODEVICETERMINAL \"To device terminal\" true true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,TODEVICETERMINAL,-1,-1;CREATIONDATE \"Creation date\" true true false 8 Date 0 0,First,#,Water_Line_Mea_FeatureVertic2,CREATIONDATE,-1,-1;CREATOR \"Creator\" true

true false 255 Text 0
0,First,#,Water_Line_Mea_FeatureVertic2,CREATOR,0,255;LASTUPDATE \"Last update\"
true true false 8 Date 0 0,First,#,Water_Line_Mea_FeatureVertic2,LASTUPDATE,-1,-
1;UPDATEDBY \"Updated by\" true true false 255 Text 0
0,First,#,Water_Line_Mea_FeatureVertic2,UPDATEDBY,0,255;GLOBALID \"Global ID\" false
false true 38 GlobalID 0 0,First,#,Water_Line_Mea_FeatureVertic2,GLOBALID,-1,-
1;SysteemSubnetworkNaam \"SysteemSubnetworkNaam\" true true false 2000 Text 0
0,First,#,Water_Line_Mea_FeatureVertic2,SysteemSubnetworkNaam,0,2000;SUPPORTEDS
UBNETWORKNAME \"Supported subnetwork name\" true true false 2000 Text 0
0,First,#,Water_Line_Mea_FeatureVertic2,SUPPORTEDSUBNETWORKNAME,0,2000;aanle
g_datum \"Datum van aanleg\" true true false 8 Date 0
0,First,#,Water_Line_Mea_FeatureVertic2,aanleg_datum,-1,-1;aanleg_geschat \"Aanleg
geschat\" true true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,aanleg_geschat,-
1,-1;bescherming_inwendig \"Bescherming inwendig\" true true false 2 Short 0
0,First,#,Water_Line_Mea_FeatureVertic2,bescherming_inwendig,-1,-
1;bescherming_uitwendig \"Bescherming uitwendig\" true true false 2 Short 0
0,First,#,Water_Line_Mea_FeatureVertic2,bescherming_uitwendig,-1,-1;crucialiteit
\"Crucialiteit\" true true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,crucialiteit,-
1,-1;diameter \"Diameter\" true true false 8 Double 0
0,First,#,Water_Line_Mea_FeatureVertic2,diameter,-1,-1;diameter_geschat \"Diameter
geschat\" true true false 2 Short 0
0,First,#,Water_Line_Mea_FeatureVertic2,diameter_geschat,-1,-1;diameter_inwendig
\"Inwendige diameter\" true true false 8 Double 0
0,First,#,Water_Line_Mea_FeatureVertic2,diameter_inwendig,-1,-1;dossier_eel
\"Dossiernummer EEL\" true true false 50 Text 0
0,First,#,Water_Line_Mea_FeatureVertic2,dossier_eel,0,50;gis_id \"GIS ID\" true true false 23
Text 0 0,First,#,Water_Line_Mea_FeatureVertic2,gis_id,0,23;kb_nummer \"KB nummer\" true
true false 20 Text 0 0,First,#,Water_Line_Mea_FeatureVertic2,kb_nummer,0,20;materiaal
\"Materiaal\" true true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,materiaal,-1,-
1;materiaal_geschat \"Materiaal geschat\" true true false 2 Short 0
0,First,#,Water_Line_Mea_FeatureVertic2,materiaal_geschat,-1,-1;medium \"Medium\" true
true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,medium,-1,-1;projectnummer
\"Projectnummer initieel\" true true false 50 Text 0
0,First,#,Water_Line_Mea_FeatureVertic2,projectnummer,0,50;projectnummer_status
\"Projectnummer statuswijziging\" true true false 50 Text 0
0,First,#,Water_Line_Mea_FeatureVertic2,projectnummer_status,0,50;risicovol \"Risicovol\"
true true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,risicovol,-1,-1;sanering \"Is
gesaneerd\" true true false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,sanering,-1,-
1;sanerings_datum \"Datum van sanering\" true true false 8 Date 0
0,First,#,Water_Line_Mea_FeatureVertic2,sanerings_datum,-1,-1;status \"Status\" true true
false 2 Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,status,-1,-1;trace_nr \"Trace
nummer\" true true false 20 Text 0
0,First,#,Water_Line_Mea_FeatureVertic2,trace_nr,0,20;type \"Type leiding\" true true false 2
Short 0 0,First,#,Water_Line_Mea_FeatureVertic2,type,-1,-1;wanddikte \"Wanddikte\" true true
false 8 Double 0 0,First,#,Water_Line_Mea_FeatureVertic2,wanddikte,-1,-
1;wanddikte_geschat \"Wanddikte geschat\" true true false 2 Short 0
0,First,#,Water_Line_Mea_FeatureVertic2,wanddikte_geschat,-1,-1;wijze_inmeting \"Wijze
van inmeting\" true true false 2 Short 0
0,First,#,Water_Line_Mea_FeatureVertic2,wijze_inmeting,-1,-1;Shape_Length
\"Shape_Length\" true true true 8 Double 0
0,First,#,Water_Line_Mea_FeatureVertic2,Shape_Length,-1,-1;Z_Mean \"Z_Mean\" true true
false 0 Double 0 0,First,#,Water_Line_Mea_FeatureVertic2,Z_Mean,-1,-1;ORIG_FID
\"ORIG_FID\" true true false 0 Long 0 0,First,#,Water_Line_Mea_FeatureVertic2,ORIG_FID,-
1,-1;Z \"Z\" true true false 0 Double 0 0,First,#,Water_Line_Mea_FeatureVertic2,Z,-1,-
1;_clipped \"_clipped\" true true false 3 Text 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\..\\..\\..\\Study_Area\\Study_Area\\F
ME_Tool\\Data\\Stap_3.gdb\\Punten_op_leidingen,_clipped,0,3;Z_Surface \"z\" true true false
2048 Text 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\..\\..\\..\\Study_Area\\Study_Area\\F
ME_Tool\\Data\\Stap_3.gdb\\Punten_op_leidingen,Z_Surface,0,2048;_part_number

```
    \"_part_number\" true true false 20 Text 0
    0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\..\\..\\Study_Area\\Study_Area\\F
    ME_Tool\\Data\\Stap_3.gdb\\Punten_op_leidingen,_part_number,0,20",
    match_option="CLOSEST", search_radius="", distance_field_name="AHN_Join_Distance")
```

26. # Process: Add Field (Add Field) (management)
27. Water_Line_Mea_F_SpatialJoin_2_ =
    arcpy.management.AddField(in_table=Output_data_Z_comparison,
    field_name="Z_Maaiveld", field_type="DOUBLE", field_precision=None, field_scale=None,
    field_length=None, field_alias="Z_Maaiveld", field_is_nullable="NULLABLE",
    field_is_required="NON_REQUIRED", field_domain="")[0]
28. # Process: Calculate Fields (multiple) (Calculate Fields (multiple)) (management)
29. Water_Line_Mea_F_SpatialJoin_3_ =
    arcpy.management.CalculateFields(in_table=Water_Line_Mea_F_SpatialJoin_2_,
    expression_type="PYTHON3", fields=[["Z_Maaiveld", "!Z_Surface!.replace(\".\", \",\")"],
    ["Z_Maaiveld", "round(!Z_Maaiveld!, 3)"], ["Z_Meting", "round(!Z_Meting!, 3)"]], code_block="",
    enforce_domains="NO_ENFORCE_DOMAINS")[0]
30. # Process: Delete Field (Delete Field) (management)
31. Water_Line_Mea_F_SpatialJoin_5_ =
    arcpy.management.DeleteField(in_table=Water_Line_Mea_F_SpatialJoin_3_,
    drop_field=["AHN_Join_Distance", "ASSETGROUP", "ASSETTYPE", "LASTUPDATE",
    "UPDATEDBY", "aanleg_datum", "Z_Meting", "Z_Maaiveld"], method="KEEP_FIELDS")[0]
32. if __name__ == '__main__':
33. # Global Environment settings
34. with
    arcpy.EnvManager(scratchWorkspace=r"Q:\ArcGIS\Projects\FME_TOOLS\FME_TOOLS\FME
    _TOOLS.gdb",
    workspace=r"Q:\ArcGIS\Projects\FME_TOOLS\FME_TOOLS\FME_TOOLS.gdb"):
35. ComparisonOfZCoordinates(*argv[1:])

11.2.2. Extract Z coordinates from the DWDS

1. # -*- coding: utf-8 -*-
2. """
3. Generated by ArcGIS ModelBuilder on : 2023-03-01 22:36:07
4. """
5. import arcpy
6. def CreateZmeasurementDatasetofDWDS(): # Create Z Measurement Dataset of DWDS
7. # To allow overwriting outputs change overwriteOutput option to True.
8. arcpy.env.overwriteOutput = False
9. Water_Line_12_10_2022 = "Water_Line_12_10_2022"
10. FME_TOOLS_gdb = "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb"
11. # Process: Add Z Information (Add Z Information) (3d)
12. Water_Line_12_10_2022_2_ = arcpy.ddd.AddZInformation(in_feature_class=Water_Line_12_10_2022, out_property=["Z_MEAN"], noise_filtering="")[0]
13. # Process: Select Layer By Attribute (Select Layer By Attribute) (management)
14. Water_Line_12_10_2022_3_, Count = arcpy.management.SelectLayerByAttribute(in_layer_or_view=Water_Line_12_10_2022_2_, selection_type="NEW_SELECTION", where_clause="Z_Mean <> 0", invert_where_clause="")
15. # Process: Feature Class To Feature Class (Feature Class To Feature Class) (conversion)
16. Water_Line_Measurements = arcpy.conversion.FeatureClassToFeatureClass(in_features=Water_Line_12_10_2022_3_, out_path=FME_TOOLS_gdb, out_name="Water_Line_Measurements", where_clause="", field_mapping="ASSETGROUP \"Asset group\" true true false 4 Long 0 0,First,#,Water_Line_12_10_2022,ASSETGROUP,-1,-1;ASSETTYPE \"Asset type\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,ASSETTYPE,-1,-1;ASSOCIATIONSTATUS \"Association status\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,ASSOCIATIONSTATUS,-1,-1;ISCONNECTED \"Is connected\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,ISCONNECTED,-1,-1;FROMDEVICETERMINAL \"From device terminal\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,FROMDEVICETERMINAL,-1,-1;TODEVICETERMINAL \"To device terminal\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,TODEVICETERMINAL,-1,-1;CREATIONDATE \"Creation date\" true true false 8 Date 0 0,First,#,Water_Line_12_10_2022,CREATIONDATE,-1,-1;CREATOR \"Creator\" true true false 255 Text 0 0,First,#,Water_Line_12_10_2022,CREATOR,0,255;LASTUPDATE \"Last update\" true true false 8 Date 0 0,First,#,Water_Line_12_10_2022,LASTUPDATE,-1,-1;UPDATEDBY \"Updated by\" true true false 255 Text 0 0,First,#,Water_Line_12_10_2022,UPDATEDBY,0,255;GLOBALID \"Global ID\" false false true 38 GlobalID 0 0,First,#,Water_Line_12_10_2022,GLOBALID,-1,-1;SysteemSubnetworkNaam \"SysteemSubnetworkNaam\" true true false 2000 Text 0 0,First,#,Water_Line_12_10_2022,SysteemSubnetworkNaam,0,2000;SUPPORTEDSUBNETWORKNAME \"Supported subnetwork name\" true true false 2000 Text 0 0,First,#,Water_Line_12_10_2022,SUPPORTEDSUBNETWORKNAME,0,2000;aanleg_datum \"Datum van aanleg\" true true false 8 Date 0 0,First,#,Water_Line_12_10_2022,aanleg_datum,-1,-1;aanleg_geschat \"Aanleg geschat\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,aanleg_geschat,-1,-1;bescherming_inwendig \"Bescherming inwendig\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,bescherming_inwendig,-1,-1;bescherming_uitwendig \"Bescherming uitwendig\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,bescherming_uitwendig,-1,-1;crucialiteit \"Crucialiteit\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,crucialiteit,-1,-1;diameter \"Diameter\" true true false 8 Double 0 0,First,#,Water_Line_12_10_2022,diameter,-1,-1;diameter_geschat \"Diameter geschat\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,diameter_geschat,-1,-1;diameter_inwendig \"Inwendige

diameter\" true true false 8 Double 0 0,First,#,Water_Line_12_10_2022,diameter_inwendig,-1,-1;dossier_eel \"Dossiernummer EEL\" true true false 50 Text 0 0,First,#,Water_Line_12_10_2022,dossier_eel,0,50;gis_id \"GIS ID\" true true false 23 Text 0 0,First,#,Water_Line_12_10_2022,gis_id,0,23;kb_nummer \"KB nummer\" true true false 20 Text 0 0,First,#,Water_Line_12_10_2022,kb_nummer,0,20;materiaal \"Materiaal\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,materiaal,-1,-1;materiaal_geschat \"Materiaal geschat\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,materiaal_geschat,-1,-1;medium \"Medium\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,medium,-1,-1;projectnummer \"Projectnummer initieel\" true true false 50 Text 0 0,First,#,Water_Line_12_10_2022,projectnummer,0,50;projectnummer_status \"Projectnummer statuswijziging\" true true false 50 Text 0 0,First,#,Water_Line_12_10_2022,projectnummer_status,0,50;risicovol \"Risicovol\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,risicovol,-1,-1;sanering \"Is gesaneerd\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,sanering,-1,-1;sanerings_datum \"Datum van sanering\" true true false 8 Date 0 0,First,#,Water_Line_12_10_2022,sanerings_datum,-1,-1;status \"Status\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,status,-1,-1;trace_nr \"Trace nummer\" true true false 20 Text 0 0,First,#,Water_Line_12_10_2022,trace_nr,0,20;type \"Type leiding\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,type,-1,-1;wanddikte \"Wanddikte\" true true false 8 Double 0 0,First,#,Water_Line_12_10_2022,wanddikte,-1,-1;wanddikte_geschat \"Wanddikte geschat\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,wanddikte_geschat,-1,-1;wijze_inmeting \"Wijze van inmeting\" true true false 2 Short 0 0,First,#,Water_Line_12_10_2022,wijze_inmeting,-1,-1;Z_Mean \"Z_Mean\" true true false 8 Double 0 0,First,#,Water_Line_12_10_2022,Z_Mean,-1,-1;Shape_Length \"Shape_Length\" false true true 8 Double 0 0,First,#,Water_Line_12_10_2022,Shape_Length,-1,-1", config_keyword="")[0]

17. # Process: Feature Vertices To Points (Feature Vertices To Points) (management)
18. Water_Line_Individual_Measurements = "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\Measured_Z_coordinates\\Measured_Z_Coordinates_DWDS.gdb\\Water_Line_Individual_Measurements"
19. arcpy.management.FeatureVerticesToPoints(in_features=Water_Line_Measurements, out_feature_class=Water_Line_Individual_Measurements, point_location="ALL")
20. # Process: Add Z Information (2) (Add Z Information) (3d)
21. Water_Line_Individual_Measurements1_2_ = arcpy.ddd.AddZInformation(in_feature_class=Water_Line_Individual_Measurements, out_property=["Z"], noise_filtering="")[0]
22. # Process: Select Layer By Attribute (2) (Select Layer By Attribute) (management)
23. Water_Line_Individual_Measur, Count_2_ = arcpy.management.SelectLayerByAttribute(in_layer_or_view=Water_Line_Individual_Measurements1_2_, selection_type="NEW_SELECTION", where_clause="Z = 0", invert_where_clause="")
24. # Process: Delete Rows (Delete Rows) (management)
25. Updated_Input_With_Rows_Removed = arcpy.management.DeleteRows(in_rows=Water_Line_Individual_Measur)[0]
26. # Process: Delete Field (Delete Field) (management)
27. Water_Line_Individual_Measur_2_ = arcpy.management.DeleteField(in_table=Updated_Input_With_Rows_Removed, drop_field=["Z_Mean"], method="DELETE_FIELDS")[0]
28. if __name__ == '__main__':
29. # Global Environment settings
30. with arcpy.EnvManager(scratchWorkspace=r"Q:\ArcGIS\Projects\FME_TOOLS\FME_TOOLS\FME_TOOLS.gdb", workspace=r"Q:\ArcGIS\Projects\FME_TOOLS\FME_TOOLS\FME_TOOLS.gdb"):
31. CreateZmeasurementDatasetofDWDS()

11.2.3. Join AHN4 to deviation depth dataset (Meetpunt_Hoogte_AHN)

```
1.  # -*- coding: utf-8 -*-
2.  """
3.  Generated by ArcGIS ModelBuilder on : 2023-03-01 22:50:56
4.  """
5.  import arcpy
6.  from sys import argv
7.  def CreateZmeasurementDatasetOfDeviationDepth1(Deviation_Depth_dataset="Q:\\ArcGIS\\Proj
    ects\\FME_TOOLS\\FME_TOOLS\\Meetpunt_Hoogte\\Meetpunt_Hoogte.gdb\\Meetpunt_Hoog
    te"):  # Create Z Measurement Dataset of Deviation Depth 1
8.  # To allow overwriting outputs change overwriteOutput option to True.
9.  arcpy.env.overwriteOutput = False
10. # Process: Add Field (Add Field) (management)
11. Meetpunt_Hoogte_AHN_2_ =
    arcpy.management.AddField(in_table=Deviation_Depth_dataset, field_name="Z_Maaiveld",
    field_type="DOUBLE", field_precision=None, field_scale=None, field_length=None,
    field_alias="Z_Maaiveld", field_is_nullable="NULLABLE",
    field_is_required="NON_REQUIRED", field_domain="")[0]
12. # Process: Calculate Fields (multiple) (2) (Calculate Fields (multiple)) (management)
13. Meetpunt_Hoogte_AHN_4_ =
    arcpy.management.CalculateFields(in_table=Meetpunt_Hoogte_AHN_2_,
    expression_type="PYTHON3", fields=[["Z_Maaiveld", "!z!.replace(\".\", \",\")"], ["Z_Maaiveld",
    "round(!Z_Maaiveld!, 3)"]], code_block="", enforce_domains="NO_ENFORCE_DOMAINS")[0]
14. # Process: Delete Field (Delete Field) (management)
15. Meetpunt_Hoogte_AHN_3_ =
    arcpy.management.DeleteField(in_table=Meetpunt_Hoogte_AHN_4_, drop_field=["z"],
    method="DELETE_FIELDS")[0]
16. # Process: Select Layer By Attribute (Select Layer By Attribute) (management)
17. Meetpunt_Hoogte_AHN_Layer, Count =
    arcpy.management.SelectLayerByAttribute(in_layer_or_view=Meetpunt_Hoogte_AHN_3_,
    selection_type="NEW_SELECTION", where_clause="DIEPTE_TOV_MAAIVELD IS NOT
    NULL And NAP_HOOGTE IS NULL", invert_where_clause="")
18. # Process: Calculate Field (Calculate Field) (management)
19. Meetpunt_Hoogte_AHN_Layer_2_ =
    arcpy.management.CalculateField(in_table=Meetpunt_Hoogte_AHN_Layer,
    field="NAP_HOOGTE", expression="!Z_Maaiveld! - !DIEPTE_TOV_MAAIVELD!",
    expression_type="PYTHON3", code_block="", field_type="TEXT",
    enforce_domains="NO_ENFORCE_DOMAINS")[0]
20. # Process: Adjust 3D Z (Adjust 3D Z) (management)
21. Meetpunt_Hoogte_AHN_Layer_3_ =
    arcpy.management.Adjust3DZ(in_features=Meetpunt_Hoogte_AHN_Layer_2_,
    reverse_sign="NO_REVERSE", adjust_value="NAP_HOOGTE", from_units="", to_units="")[0]
22. if __name__ == '__main__':
23. # Global Environment settings
24. with
    arcpy.EnvManager(scratchWorkspace=r"Q:\ArcGIS\Projects\FME_TOOLS\FME_TOOLS\FME
    _TOOLS.gdb",
    workspace=r"Q:\ArcGIS\Projects\FME_TOOLS\FME_TOOLS\FME_TOOLS.gdb"):
25. CreateZmeasurementDatasetOfDeviationDepth1(*argv[1:])
```

11.2.4. Z_Kwaliteit – Vertical Reference Features (Polylines)

1. `# -*- coding: utf-8 -*-`
2. `"""`
3. `Generated by ArcGIS ModelBuilder on : 2023-03-02 10:34:57`
4. `"""`
5. `import arcpy`
6. `from sys import argv`
7. `def VerticalReferenceFeaturesLine(Leidingnet_Input_Feature="Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_12_10_2022_Clip", AHN_Height_Points_Input_Feature="Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Punten_op_leidingen_Clip", Z_Kwaliteit_Output_Feature="Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Kwaliteit"): # Vertical Reference Features Line`
8. `# To allow overwriting outputs change overwriteOutput option to True.`
9. `arcpy.env.overwriteOutput = False`
10. `arcpy.ImportToolbox(r"q:\program files\arcgis\Resources\ArcToolbox\toolboxes\Data Management Tools.tbx")`
11. `FME_TOOLS_gdb = "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb"`
12. `# Process: Feature Vertices To Points (Feature Vertices To Points) (management)`
13. `Water_Line_12_Vertices = "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_12__Vertices"`
14. `arcpy.management.FeatureVerticesToPoints(in_features=Leidingnet_Input_Feature, out_feature_class=Water_Line_12_Vertices, point_location="ALL")`
15. `# Process: Spatial Join (Spatial Join) (analysis)`
16. `Water_Line_Vertices_AHN = "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_Vertices_AHN"`
17. `arcpy.analysis.SpatialJoin(target_features=Water_Line_12_Vertices, join_features=AHN_Height_Points_Input_Feature, out_feature_class=Water_Line_Vertices_AHN, join_operation="JOIN_ONE_TO_ONE", join_type="KEEP_COMMON", field_mapping="ASSETGROUP \"Asset group\" true true false 4 Long 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_12__Vertices,ASSETGROUP,-1,-1;ASSETTYPE \"Asset type\" true true false 2 Short 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_12__Vertices,ASSETTYPE,-1,-1;CREATIONDATE \"Creation date\" true true false 8 Date 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_12__Vertices,CREATIONDATE,-1,-1;LASTUPDATE \"Last update\" true true false 8 Date 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_12__Vertices,LASTUPDATE,-1,-1;aanleg_datum \"Datum van aanleg\" true true false 8 Date 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_12__Vertices,aanleg_datum,-1,-1;aanleg_geschat \"Aanleg geschat\" true true false 2 Short 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_12__Vertices,aanleg_geschat,-1,-1;gis_id \"GIS ID\" true true false 23 Text 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_12__Vertices,gis_id,0,23;wijze_inmeting \"Wijze van inmeting\" true true false 2 Short 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_12__Vertices,wijze_inmeting,-1,-1;Z_Surface \"z\" true true false 2048 Text 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Punten_op_leidingen_Clip,Z_Surface,0,2048", match_option="CLOSEST", search_radius="", distance_field_name="AHN_Join_Distance")`

18. # Process: Add Fields (multiple) (Add Fields (multiple)) (management)
19. Water_Line_Vertices_AHN_3_ =
    arcpy.management.AddFields(in_table=Water_Line_Vertices_AHN,
    field_description=[["Z_Maaiveld", "DOUBLE", "Z_Maaiveld", "", "", ""], ["Z_Leiding", "DOUBLE",
    "Z_Leiding", "", "", ""], ["Z_Verschil", "DOUBLE", "Z_Verschil", "", "", ""], ["XY_ID", "DOUBLE",
    "XY_ID", "", "", ""]], template=[])[0]
20. # Process: Calculate Fields (multiple) (Calculate Fields (multiple)) (management)
21. Water_Line_Vertices_AHN_4_ =
    arcpy.management.CalculateFields(in_table=Water_Line_Vertices_AHN_3_,
    expression_type="PYTHON3", fields=[["Z_Maaiveld", "!Z_Surface!.replace(\".\", \",\")"],
    ["Z_Maaiveld", "round(!Z_Maaiveld!, 3)"]], code_block="",
    enforce_domains="NO_ENFORCE_DOMAINS")[0]
22. # Process: Select Layer By Attribute (Select Layer By Attribute) (management)
23. Water_Line_Vertices_AHN_Laye, Count =
    arcpy.management.SelectLayerByAttribute(in_layer_or_view=Water_Line_Vertices_AHN_4_,
    selection_type="NEW_SELECTION", where_clause="ASSETTYPE = 102 Or ASSETTYPE =
    105", invert_where_clause="NON_INVERT")
24. # Process: Calculate Field (Calculate Field) (management)
25. Water_Line_Vertices_AHN_Laye_9_ =
    arcpy.management.CalculateField(in_table=Water_Line_Vertices_AHN_Laye,
    field="Z_Leiding", expression="!Z_Maaiveld! - 1.2", expression_type="PYTHON3",
    code_block="", field_type="TEXT", enforce_domains="NO_ENFORCE_DOMAINS")[0]
26. # Process: Select Layer By Attribute (2) (Select Layer By Attribute) (management)
27. Water_Line_Vertices_AHN_Laye_3_, Count_2_ =
    arcpy.management.SelectLayerByAttribute(in_layer_or_view=Water_Line_Vertices_AHN_Lay
    e_9_, selection_type="NEW_SELECTION", where_clause="ASSETTYPE = 103 Or
    ASSETTYPE = 104 Or ASSETTYPE = 106", invert_where_clause="")
28. # Process: Calculate Field (2) (Calculate Field) (management)
29. Water_Line_Vertices_AHN_Laye_2_ =
    arcpy.management.CalculateField(in_table=Water_Line_Vertices_AHN_Laye_3_,
    field="Z_Leiding", expression="!Z_Maaiveld! - 1.0", expression_type="PYTHON3",
    code_block="", field_type="TEXT", enforce_domains="NO_ENFORCE_DOMAINS")[0]
30. # Process: Select Layer By Attribute (3) (Select Layer By Attribute) (management)
31. Water_Line_Vertices_AHN_Laye_5_, Count_3_ =
    arcpy.management.SelectLayerByAttribute(in_layer_or_view=Water_Line_Vertices_AHN_Lay
    e_2_, selection_type="NEW_SELECTION", where_clause="ASSETTYPE = 201 Or
    ASSETTYPE = 202", invert_where_clause="")
32. # Process: Calculate Field (3) (Calculate Field) (management)
33. Water_Line_Vertices_AHN_Laye_4_ =
    arcpy.management.CalculateField(in_table=Water_Line_Vertices_AHN_Laye_5_,
    field="Z_Leiding", expression="!Z_Maaiveld! - 0.80", expression_type="PYTHON3",
    code_block="", field_type="TEXT", enforce_domains="NO_ENFORCE_DOMAINS")[0]
34. # Process: Select Layer By Attribute (4) (Select Layer By Attribute) (management)
35. Water_Line_Vertices_AHN_Laye_7_, Count_4_ =
    arcpy.management.SelectLayerByAttribute(in_layer_or_view=Water_Line_Vertices_AHN_Lay
    e_4_, selection_type="NEW_SELECTION", where_clause="ASSETGROUP = 100 Or
    ASSETGROUP = 200", invert_where_clause="")
36. # Process: Calculate Field (5) (Calculate Field) (management)
37. Water_Line_Vertices_AHN_Laye_6_ =
    arcpy.management.CalculateField(in_table=Water_Line_Vertices_AHN_Laye_7_,
    field="Z_Verschil", expression="!Z_Maaiveld! - !Z_Leiding!", expression_type="PYTHON3",
    code_block="", field_type="TEXT", enforce_domains="NO_ENFORCE_DOMAINS")[0]
38. # Process: Feature Class To Feature Class (Feature Class To Feature Class) (conversion)
39. Z_Maaiveld =
    arcpy.conversion.FeatureClassToFeatureClass(in_features=Water_Line_Vertices_AHN_Laye
    _6_, out_path=FME_TOOLS_gdb, out_name="Z_Maaiveld", where_clause="",

field_mapping="Join_Count \"Join_Count\" true true false 0 Long 0
0,First,#,Water_Line_Vertices_AHN_Laye,Join_Count,-1,-1;AHN_Join_Distance
\"AHN_Join_Distance\" true true false 0 Double 0
0,First,#,Water_Line_Vertices_AHN_Laye,AHN_Join_Distance,-1,-1;TARGET_FID
\"TARGET_FID\" true true false 0 Long 0
0,First,#,Water_Line_Vertices_AHN_Laye,TARGET_FID,-1,-1;ASSETGROUP \"Asset group\"
true true false 4 Long 0 0,First,#,Water_Line_Vertices_AHN_Laye,ASSETGROUP,-1,-
1;ASSETTYPE \"Asset type\" true true false 2 Short 0
0,First,#,Water_Line_Vertices_AHN_Laye,ASSETTYPE,-1,-1;CREATIONDATE \"Creation
date\" true true false 8 Date 0 0,First,#,Water_Line_Vertices_AHN_Laye,CREATIONDATE,-
1,-1;LASTUPDATE \"Last update\" true true false 8 Date 0
0,First,#,Water_Line_Vertices_AHN_Laye,LASTUPDATE,-1,-1;aanleg_datum \"Datum van
aanleg\" true true false 8 Date 0 0,First,#,Water_Line_Vertices_AHN_Laye,aanleg_datum,-1,-
1;aanleg_geschat \"Aanleg geschat\" true true false 2 Short 0
0,First,#,Water_Line_Vertices_AHN_Laye,aanleg_geschat,-1,-1;gis_id \"GIS ID\" true true
false 23 Text 0 0,First,#,Water_Line_Vertices_AHN_Laye,gis_id,0,23;wijze_inmeting \"Wijze
van inmeting\" true true false 2 Short 0
0,First,#,Water_Line_Vertices_AHN_Laye,wijze_inmeting,-1,-1;Z_Surface \"z\" true true false
2048 Text 0 0,First,#,Water_Line_Vertices_AHN_Laye,Z_Surface,0,2048;Z_Maaiveld
\"Z_Maaiveld\" true true false 0 Double 0
0,First,#,Water_Line_Vertices_AHN_Laye,Z_Maaiveld,-1,-1;Z_Leiding \"Z_Leiding\" true true
false 0 Double 0 0,First,#,Water_Line_Vertices_AHN_Laye,Z_Leiding,-1,-1;Z_Verschil
\"Z_Verschil\" true true false 0 Double 0
0,First,#,Water_Line_Vertices_AHN_Laye,Z_Verschil,-1,-1;XY_ID \"XY_ID\" true true false 0
Double 0 0,First,#,Water_Line_Vertices_AHN_Laye,XY_ID,-1,-1", config_keyword="")[0]
40. # Process: Adjust 3D Z (Adjust 3D Z) (management)
41. Z_Maaiveld_2_ = arcpy.management.Adjust3DZ(in_features=Z_Maaiveld,
    reverse_sign="NO_REVERSE", adjust_value="Z_Maaiveld", from_units="", to_units="")[0]
42. # Process: Feature Class To Feature Class (2) (Feature Class To Feature Class) (conversion)
43. Z_Leiding =
    arcpy.conversion.FeatureClassToFeatureClass(in_features=Water_Line_Vertices_AHN_Laye
    _6_, out_path=FME_TOOLS_gdb, out_name="Z_Leiding", where_clause="",
    field_mapping="Join_Count \"Join_Count\" true true false 0 Long 0
    0,First,#,Water_Line_Vertices_AHN_Laye,Join_Count,-1,-1;AHN_Join_Distance
    \"AHN_Join_Distance\" true true false 0 Double 0
    0,First,#,Water_Line_Vertices_AHN_Laye,AHN_Join_Distance,-1,-1;TARGET_FID
    \"TARGET_FID\" true true false 0 Long 0
    0,First,#,Water_Line_Vertices_AHN_Laye,TARGET_FID,-1,-1;ASSETGROUP \"Asset group\"
    true true false 4 Long 0 0,First,#,Water_Line_Vertices_AHN_Laye,ASSETGROUP,-1,-
    1;ASSETTYPE \"Asset type\" true true false 2 Short 0
    0,First,#,Water_Line_Vertices_AHN_Laye,ASSETTYPE,-1,-1;CREATIONDATE \"Creation
    date\" true true false 8 Date 0 0,First,#,Water_Line_Vertices_AHN_Laye,CREATIONDATE,-
    1,-1;LASTUPDATE \"Last update\" true true false 8 Date 0
    0,First,#,Water_Line_Vertices_AHN_Laye,LASTUPDATE,-1,-1;aanleg_datum \"Datum van
    aanleg\" true true false 8 Date 0 0,First,#,Water_Line_Vertices_AHN_Laye,aanleg_datum,-1,-
    1;aanleg_geschat \"Aanleg geschat\" true true false 2 Short 0
    0,First,#,Water_Line_Vertices_AHN_Laye,aanleg_geschat,-1,-1;gis_id \"GIS ID\" true true
    false 23 Text 0 0,First,#,Water_Line_Vertices_AHN_Laye,gis_id,0,23;wijze_inmeting \"Wijze
    van inmeting\" true true false 2 Short 0
    0,First,#,Water_Line_Vertices_AHN_Laye,wijze_inmeting,-1,-1;Z_Surface \"z\" true true false
    2048 Text 0 0,First,#,Water_Line_Vertices_AHN_Laye,Z_Surface,0,2048;Z_Maaiveld
    \"Z_Maaiveld\" true true false 0 Double 0
    0,First,#,Water_Line_Vertices_AHN_Laye,Z_Maaiveld,-1,-1;Z_Leiding \"Z_Leiding\" true true
    false 0 Double 0 0,First,#,Water_Line_Vertices_AHN_Laye,Z_Leiding,-1,-1;Z_Verschil
    \"Z_Verschil\" true true false 0 Double 0

0,First,#,Water_Line_Vertices_AHN_Laye,Z_Verschil,-1,-1;XY_ID \"XY_ID\" true true false 0 Double 0 0,First,#,Water_Line_Vertices_AHN_Laye,XY_ID,-1,-1", config_keyword="")[0]

44. # Process: Adjust 3D Z (2) (Adjust 3D Z) (management)
45. Z_Leiding_2_ = arcpy.management.Adjust3DZ(in_features=Z_Leiding, reverse_sign="NO_REVERSE", adjust_value="Z_Leiding", from_units="", to_units="")[0]
46. # Process: Merge (Merge) (management)
47. Z_Merge = "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge"
48. arcpy.management.Merge(inputs=[Z_Maaiveld_2_, Z_Leiding_2_], output=Z_Merge, field_mappings="AHN_Join_Distance \"AHN_Join_Distance\" true true false 0 Double 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,AHN_Join_Distance,-1,-1;ASSETGROUP \"Asset group\" true true false 4 Long 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,ASSETGROUP,-1,-1;ASSETTYPE \"Asset type\" true true false 2 Short 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,ASSETTYPE,-1,-1;CREATIONDATE \"Creation date\" true true false 8 Date 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,CREATIONDATE,-1,-1;LASTUPDATE \"Last update\" true true false 8 Date 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,LASTUPDATE,-1,-1;aanleg_datum \"Datum van aanleg\" true true false 8 Date 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,aanleg_datum,-1,-1;aanleg_geschat \"Aanleg geschat\" true true false 2 Short 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,aanleg_geschat,-1,-1;gis_id \"GIS ID\" true true false 23 Text 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,gis_id,0,23;wijze_inmeting \"Wijze van inmeting\" true true false 2 Short 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,wijze_inmeting,-1,-1;Z_Maaiveld \"Z_Maaiveld\" true true false 0 Double 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,Z_Maaiveld,-1,-1;Z_Leiding \"Z_Leiding\" true true false 0 Double 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,Z_Leiding,-1,-1;Z_Verschil \"Z_Verschil\" true true false 0 Double 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,Z_Verschil,-1,-1;XY_ID \"XY_ID\" true true false 0 Double 0 0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Maaiveld,XY_ID,-1,-1", add_source="NO_SOURCE_INFO")
49. # Process: Add XY Coordinates (Add XY Coordinates) (management)
50. Updated_Input_Features = arcpy.management.AddXY(in_features=Z_Merge)[0]
51. # Process: Calculate Field (4) (Calculate Field) (management)
52. Water_Line_Vertices_AHN_Laye_8_ = arcpy.management.CalculateField(in_table=Updated_Input_Features, field="XY_ID", expression="!POINT_X! + !POINT_Y!", expression_type="PYTHON3", code_block="", field_type="TEXT", enforce_domains="NO_ENFORCE_DOMAINS")[0]
53. # Process: Points To Line (Points To Line) (management)
54. Water_Line_Z_Quality1 = "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_Z_Quality1"
55. with arcpy.EnvManager(qualifiedFieldNames=True):
56. arcpy.management.PointsToLine(Input_Features=Water_Line_Vertices_AHN_Laye_8_, Output_Feature_Class=Water_Line_Z_Quality1, Line_Field="XY_ID", Sort_Field="", Close_Line="NO_CLOSE")
57. # Process: Spatial Join (2) (Spatial Join) (analysis)
58. arcpy.analysis.SpatialJoin(target_features=Water_Line_Z_Quality1, join_features=Water_Line_Vertices_AHN_Laye_8_, out_feature_class=Z_Kwaliteit_Output_Feature, join_operation="JOIN_ONE_TO_ONE", join_type="KEEP_ALL", field_mapping="Shape_Length \"Shape_Length\" false true true 8 Double 0

0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_Z_Quality1,Shape_Length,-1,-1;XY_ID \"XY_ID\" true true false 8 Double 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Water_Line_Z_Quality1,XY_ID,-1,-1;AHN_Join_Distance \"AHN_Join_Distance\" true true false 8 Double 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,AHN_Join_Distance,-1,-1;ASSETGROUP \"Asset group\" true true false 4 Long 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,ASSETGROUP,-1,-1;ASSETTYPE \"Asset type\" true true false 2 Short 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,ASSETTYPE,-1,-1;CREATIONDATE \"Creation date\" true true false 8 Date 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,CREATIONDATE,-1,-1;LASTUPDATE \"Last update\" true true false 8 Date 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,LASTUPDATE,-1,-1;aanleg_datum \"Datum van aanleg\" true true false 8 Date 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,aanleg_datum,-1,-1;aanleg_geschat \"Aanleg geschat\" true true false 2 Short 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,aanleg_geschat,-1,-1;gis_id \"GIS ID\" true true false 23 Text 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,gis_id,0,23;wijze_inmeting \"Wijze van inmeting\" true true false 2 Short 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,wijze_inmeting,-1,-1;Z_Maaiveld \"Z_Maaiveld\" true true false 8 Double 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,Z_Maaiveld,-1,-1;Z_Leiding \"Z_Leiding\" true true false 8 Double 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,Z_Leiding,-1,-1;Z_Verschil \"Z_Verschil\" true true false 8 Double 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,Z_Verschil,-1,-1;XY_ID_1 \"XY_ID\" true true false 8 Double 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,XY_ID,-1,-1;POINT_X \"POINT_X\" true true false 8 Double 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,POINT_X,-1,-1;POINT_Y \"POINT_Y\" true true false 8 Double 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,POINT_Y,-1,-1;POINT_Z \"POINT_Z\" true true false 8 Double 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,POINT_Z,-1,-1;POINT_M \"POINT_M\" true true false 8 Double 0
0,First,#,Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Z_Merge,POINT_M,-1,-1", match_option="INTERSECT", search_radius="", distance_field_name="")

59. # Process: Delete Field (Delete Field) (management)
60. Water_Line_Z_Quality_2_ =
arcpy.management.DeleteField(in_table=Z_Kwaliteit_Output_Feature,
drop_field=["AHN_Join_Distance", "ASSETGROUP", "ASSETTYPE", "CREATIONDATE",
"LASTUPDATE", "aanleg_datum", "aanleg_geschat", "gis_id", "wijze_inmeting", "Z_Maaiveld",
"Z_Leiding", "Z_Verschil"], method="KEEP_FIELDS")[0]
61. if __name__ == '__main__':
62. # Global Environment settings
63. with
arcpy.EnvManager(scratchWorkspace=r"Q:\ArcGIS\Projects\FME_TOOLS\FME_TOOLS\FME_TOOLS.gdb",
workspace=r"Q:\ArcGIS\Projects\FME_TOOLS\FME_TOOLS\FME_TOOLS.gdb"):
64. VerticalReferenceFeaturesLine(*argv[1:])

11.2.5. Create polygons on the vertical reference features (polylines)

```python
1.  # -*- coding: utf-8 -*-
2.  """
3.  Generated by ArcGIS ModelBuilder on : 2023-03-02 10:46:31
4.  """
5.  import arcpy
6.  from sys import argv
7.  def GroundSurfaceFeaturesPolygon(Length_of_the_ground_surface_polygon_features_2="0,2 Meters",
    Input_feature_Vertical_reference_features="Standaard_verticale_afstand_tot_maaiveld",
    Input_feature_Distribution_network="Water",
    Width_of_the_ground_surface_polygon_features_2="0,1 Meters",
    Output_data_Ground_surface_polygon="Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\
    MyProject1\\MyProject1.gdb\\Standaard_verticale_afstand_tot_maaiveld_vlak"):  # Ground
    Surface Features Polygon
8.  # To allow overwriting outputs change overwriteOutput option to True.
9.  arcpy.env.overwriteOutput = False
10. # Process: Buffer (Buffer) (analysis)
11. Standaard_verticale_a_Buffer =
    "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\Verticale_Lijn_Segmenten.gdb\\Standaar
    d_verticale_a_Buffer"
12. arcpy.analysis.Buffer(in_features=Input_feature_Vertical_reference_features,
    out_feature_class=Standaard_verticale_a_Buffer,
    buffer_distance_or_field=Length_of_the_ground_surface_polygon_features_2,
    line_side="FULL", line_end_type="ROUND", dissolve_option="NONE", dissolve_field=[],
    method="PLANAR")
13. # Process: Intersect (Intersect) (analysis)
14. Standaard_vertical_Intersect =
    "Q:\\ArcGIS\\Projects\\FME_TOOLS\\FME_TOOLS\\FME_TOOLS.gdb\\Standaard_vertical_Int
    ersect"
15. arcpy.analysis.Intersect(in_features=[[Standaard_verticale_a_Buffer, ""],
    [Input_feature_Distribution_network, ""]], out_feature_class=Standaard_vertical_Intersect,
    join_attributes="ALL", cluster_tolerance="", output_type="LINE")
16. # Process: Buffer (2) (Buffer) (analysis)
17. with arcpy.EnvManager(ZDomain="-100000 900719825474,099", outputZFlag="Enabled"):
18. arcpy.analysis.Buffer(in_features=Standaard_vertical_Intersect,
    out_feature_class=Output_data_Ground_surface_polygon,
    buffer_distance_or_field=Width_of_the_ground_surface_polygon_features_2,
    line_side="FULL", line_end_type="FLAT", dissolve_option="LIST", dissolve_field=["z_max"],
    method="PLANAR")
19. # Process: Adjust 3D Z (Adjust 3D Z) (management)
20. Afwijkende_verticale_afstand_tot_maaiveld_vlak_2_ =
    arcpy.management.Adjust3DZ(in_features=Output_data_Ground_surface_polygon,
    reverse_sign="NO_REVERSE", adjust_value="z_max", from_units="", to_units="")[0]
21. if __name__ == '__main__':
22. # Global Environment settings
23. with
    arcpy.EnvManager(scratchWorkspace=r"Q:\ArcGIS\Projects\FME_TOOLS\FME_TOOLS\FME
    _TOOLS.gdb",
    workspace=r"Q:\ArcGIS\Projects\FME_TOOLS\FME_TOOLS\FME_TOOLS.gdb"):
24. GroundSurfaceFeaturesPolygon(*argv[1:])
```