3D BIM-GIS for underground network management

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March, 2019

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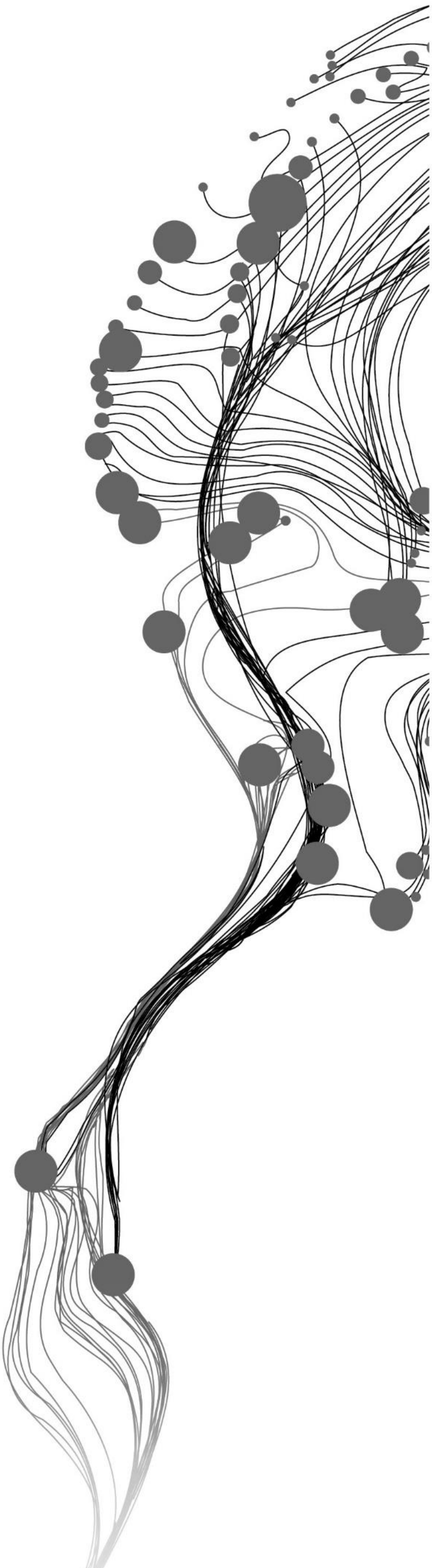

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SHEN NIE
Enschede, The Netherlands, March,2019

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfillment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Land Administration

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ABSTRACT

Old and deteriorating underground sewer systems are a problem in many large cities. To ensure normal urban activities, more and more sewer renewal projects are being put forward for urban management. With the complex distribution in vertical visualisation, the construction of the sewer system needs to consider not only the attributes of a sewer but also its interaction with the environment. Meanwhile, in sewer management, various stakeholders join the work with their software and data properties. This situation causes repetitive data processing and data conversion process, which would lead to data loss of underground construction. This study aims to develop and test a 3D model integrating BIM and GIS technologies to reduce data loss and promote data sharing among the different stakeholders. Right now, integrating BIM and GIS technology in urban planning is widespread, however, applying these two technologies in underground construction is rare.

Based on a sewer renewal project in Kleiweg, Rotterdam, this study is mainly composed of four stages. First, the expert interview is used to investigate the reason and content of data loss. Meanwhile, the data which will be used in later modelling work has been collected. Second, in the data preparation stage, the semantic and topological quality of data has been validated and modified separately. Actually, this stage mainly lays the foundation for the following modelling work. Then, considering the requirement of underground BIM, the 3D model is developed using CityEngine. CityEngine models the objects by using shapefiles which is widely used in 3D city modelling. To be mentioned, CityEngine provides an online platform to help the stakeholders share the data freely. The created 3D model is uploaded into the online web viewer for better data exchange, visualisation and sharing. At last, the model's usefulness is assessed by sending a questionnaire to experts. The usefulness of the model includes utility and usability. After analysis of the experts' feedback, it concludes that the 3D model promotes the data sharing among stakeholders and significantly support the sewer renewal work. However, the Level of Detail (LoD) of the sewer system should be improved in future work.

Keywords: underground BIM, GIS, data loss, 3D modelling, the CityEngine.

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Finally, my sincere thanks also go to my parents and friends who always encourage me during my thesis work.

Yours,
Shen Nie
Enschede, February 2018

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1. INTRODUCTION

Many large cities are faced with the problem of old, deteriorating integrated stormwater-sewer systems. With continuous urban development, the demand for services from underground utilities is also increasing. Thus, the collapse of sewer system must accompany with life inconvenience and higher potential damages. More and more sewer renewal projects are raised by municipalities (Koeper, Coble, & Coll, 1982). Recently, there is a sewer renewal project processing in Kleiweg, Rotterdam.

With its complex distribution in both horizontal and vertical dimensions, the sewer system construction needs to consider about not only the attributions of sewer itself (i.e. materials, depth, size, connection), but also the interaction with other objects (i.e. tree roots, road, surface building, soil) (Davies, Clarke, Whiter, & Cunningham, 2001). Therefore, the 3D city models storing and presenting geometric and semantic information are needed in sewer management (L. Zhu, Wu, & Liu, 2004). Although today there is various software for 3D city modelling, the data formats are proprietary for corresponding software. Actually, there is no single and universal application to preserve geospatial data in a 3D model (Mcgarva, Morris, & Janée, 2009).

In sewer management, multiple parties participate in the working chain with respective software and data formats. Hence this situation, repetitive data processing work and data conversion may reoccur during data transfer, which results in the loss of data and misunderstanding in construction work. Based on a sewer renewal project in Rotterdam, this research aims to reduce data loss during the data transfer by combining Building Information Model (BIM) and Geographic Information System (GIS) into an integrated 3D model to help efficiently share data among participators.

Focusing on the ongoing sewer construction that is used as a case study, this chapter describes the background and significance of the research, explains research problems which should be deeply investigated and addressed, and identifies the research objectives and sub-objectives. The last section of the chapter describes the structure of this thesis.

1.1. Research background

The complete urban infrastructure supports the operation of city functions. As an essential part of urban infrastructure, urban underground sewer system is the important carrier of waste disposal and flood reduction (Liu, 2016). With the acceleration of urbanization, the underground sewer system is suffering of great pressure from overground activities. Integrating the sewer renewal into urban planning strategies maintains the normal civil living and avoids the risk of flood problem.

For a sewer renewal process, integrated planning is required to consider the properties of sewers themselves and external factors (Davies et al., 2001). On the one hand, apart from the sewers, the underground environment which also includes various pipes, cables, plant roots and other facilities. The overlapping characteristic between sewers and other objects requires the sewer renewal project has concrete data and holistic 3D perspective (Zhou, 2016). On the other hand, the construction of sewer project is a complex work composed by a series of associative procedures which are controlled by the different participant (InfraGuide, 2003). For the practical sewer construction project, a comprehensive construction plan requires a common understanding based on shared information and spatial data during the whole work chain. However, with the existed difference in systems, data formats, data standard, application and software used, the efficient data sharing among various participants is still a problem (El-Mekawy, 2010). Considering the two aspects above, a common 3D city model integrates with BIM and GIS technology can provide a clear visualisation and less data loss for the sewer project (Bansal, 2014).

3D city models enable a digital visualisation of space and its related spatial objects in a city in which both the representation and relationships among spatial entities would be stored and modelled (Stadler & Kolbe, 2007). A key advantage of a 3D city model is that it can integrate different data sets together to analyse the environment with holistic insights (R. Chen, 2011). With the combination of GIS and BIM, the integrated model can achieve sharing the lifecycle data of objects relevant to urban planning and management processes among various stakeholders in different levels of detail (Ma & Ren, 2017). BIM provides detailed information about single objects, and GIS helps to present spatial information in large scale (Harris & Batty, 1993). For the underground pipeline network management, to be specific, BIM technology is mainly used in establishing a refined model with detailed attributes, providing multi-angle of view and organizing all the information for communication and decision making of participants (M. Chen, 2017). GIS focuses on providing the position of the pipeline network and displaying the spatial relationship (Zuo, Feng, & Cai, 2017). Therefore, the 3D city model with BIM and GIS technologies is possible to display the sewer system in both city and object level.

This research is based on an ongoing sewer project in the Kleiweg, Rotterdam. The next section explains the project detailed context and the problems related to this study.

1.2. Research problem

This study is based on a sewer renewal project in Kleiweg area and aims to reduce data loss among multi-participants. In this project, the multi-participants refer to the project advisor in the municipality of Rotterdam, the engineering company and the contractors. In order to support the sewer renewal process, the municipality hopes to transfer the data completely and effectively, however, there is a big gap between ideal and real data condition (Figure 1).

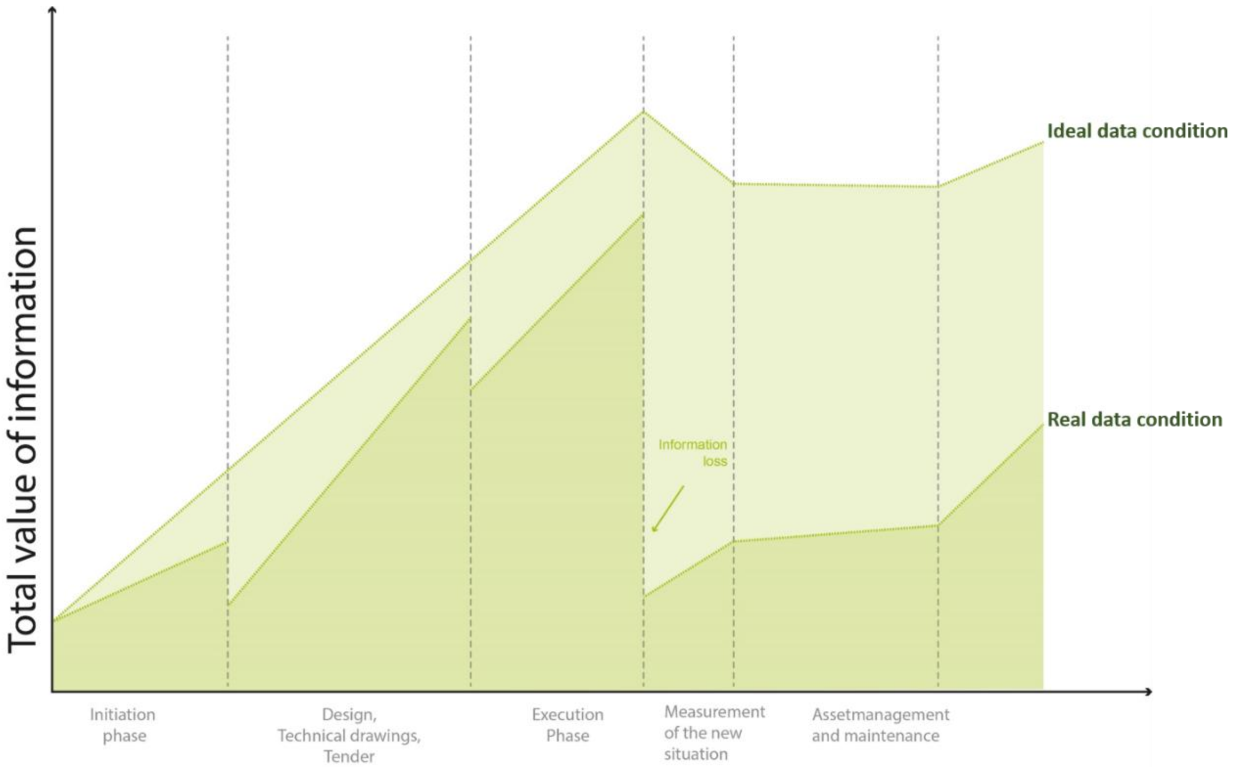


Figure 1 The data loss situation (Provided by the municipality of Rotterdam)

Two main reasons cause this problem. First, the existence in data conversion. Every time 3D data is transferred between two participants, the data needs to be converted to shapefiles. As the data conversion mainly concentrates on syntactics and excludes the semantics, the transfer process is always burdened by data loss (Raines, 1997). This data loss may cause misunderstandings between the involved parties in the project plan. Second, Relatics is a cloud platform which provides a common template of Systems Engineering to control all the project information (Relatics,2007). It is widely used in the urban planning and can directly link to various software (i.e. Esri, Autodesk). However, because of pure development of the software, it cannot link the 3D model and Systems Engineering fully. Every time data transfer happens, the participants need to re-check the data with the unique ID.

Therefore, this study hopes to develop an integrated model to solve these issues. Although the Relatics needs further improvement, this study focuses on finding a solution to reduce its' adverse impact rather than editing software. The next section explains the conceptual framework of this study.

1.3. Conceptual framework

As shown in Figure 2 below, the gray circles are on behalf of the sewer renewal project. For this project, the data problem about data loss and data sharing is existing. In order to deal with current data problems of this project, an integrated 3D model is put forward. This 3D model relies on integrating BIM and GIS to support the construction of sewer renewal project in multiple dimensions and scale levels (Sebastian, Böhms, Bonsma, & Van Den Helm, 2013). "Usefulness Evaluation" refers to the evaluation of the 3D model with two criteria: usability and utility. Usability mainly focuses on how easy this model can be accepted by the municipality, otherwise, utility refers to whether this model can provide functionalities which the project needs (Nielsen, 1993). With these two criteria, strength and weakness of the created 3D model will be shown. Considerably, the evaluation process requires considering the opinion of stakeholders who involve in the sewer renewal project. It would let the 3D model closely connect with the requirement of the project and satisfy the objective of this study. The more details of the research objectives will be explained in the following section.

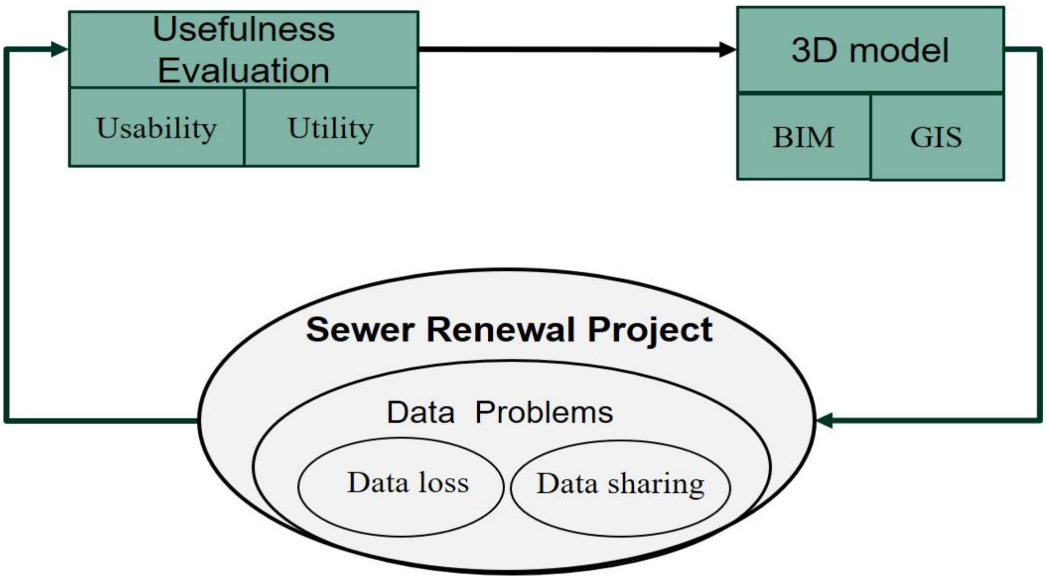


Figure 2 Conceptual framework

1.4. Research objective

1.4.1. General objective

To develop and test a 3D model integrating BIM and GIS technologies to reduce data loss and promote data sharing among the Rotterdam Municipality, the engineering company and the sewer contractors.

1.4.2. Specific objective

1. To investigate the characteristics and content of the original data and converted shape files.
2. To prepare a set of data which satisfy the demand of BIM underground for sewer renewal project.
3. To develop an integrated 3D model to reduce data loss.
4. To evaluate the usefulness of the 3D model with the specialist of Rotterdam Municipality, the engineering company and the contractor.

1.5. Research questions

1. To investigate the characteristics and contents of the original data and converted shape files.
   1.1 What is the detailed procedure of data transfer?
   1.2 How does the data conversion process operate?
   1.3 What data loss by comparing the contents of original data and shapefiles?
   1.4 What data formats involves in the conversion process?
2. To prepare a set of data which satisfy the demand of underground BIM for the sewer renewal project.
   2.1 What types of information are required for sewer renewal project?
   2.2 What Level of detail (LoD) is enough of this project to display the project information?
3. To develop an integrated 3D model of the underground environment.
   3.1 Which software is suitable to develop the 3D model?
   3.2 How to share the 3D model among different participants?
4. To evaluate the usefulness of the 3D model with the specialist of Rotterdam Municipality, the engineering company and the contractor.
   4.1 What performance elements will be selected to do the evaluation?
   4.2 What are the strengths and limitations of this model?

1.6. Thesis structure

This thesis contains six chapters in total. The detailed structure is described below:

Chapter 1 Introduction: explains the research background and significance, based on the characteristics of underground sewer network and the data problem of the sewer renewal project in Kleiweg area, provides the research objective and research questions of this study.

Chapter 2 Literature review: introduces an overview of previous studies on constructing an underground sewer network with 3D technology. The definition of underground BIM will be explained and some related works will be displayed. And explains the data loss and related methods to reduce data loss. The 3D modelling work will also be discussed.

Chapter 3 Field of study: introduces the background of the study area and explains the plan of the sewer renewal project in Kleiweg. The data used in this study will also be displayed.

Chapter 4 Methods: corresponding the procedure of the study, explains the methods used in this study. The methods refer to the quantitative and qualitative method. The whole workflow will also be presented in this chapter.

Chapter 5 Result and Discussion: explains the results and discussions of a different stage. Specifically, describes the result of the expert interview, presents the integrated 3D model and evaluates the usefulness of 3D model and data sharing platform.

Chapter 6 Conclusion: summaries and bring together the main result of each sub-objective, gives a final comment which includes making suggestions for future improvement.

1.7. Summary

This chapter summarises the relevant content of research and illustrates the desired research objectives. Right now, it is popular to use 3D technology to help underground construction work. This study is based on a sewer renewal project in Kleiweg area. Because of data conversion and pure development of software, the municipality of Rotterdam finds that there is data loss during the information transferring process of the project. To solve the data loss problem and promoting data sharing, this study develops a 3D model integrating BIM and GIS technologies. At last, the usefulness of the integrated 3D model would be evaluated.

The whole thesis includes six chapters. The subsequent study would base on the description in this chapter and concretely be explained in the following sections.

2. LITERATURE REVIEW

This chapter displays an overview of previous studies on managing underground sewer network. Consists of three sections, this chapter starts with introducing the essential concepts and content of underground BIM. To achieve the research objectives, the focus point of the underground project is sewer management. Then, the effective data transfer is explained in the following section, which includes the reason of data loss, previous studies on the measures of effective data transfer and the positive effect of using BIM and GIS technologies. At last, the third section focuses on explaining the related works and proper software selection of 3D modelling.

2.1. Underground BIM

In terms of BIM, the original proposal can be traced to the 1970s by the Pro. Chuck Eastman (Ballard, 2000), he defined BIM as "A single model that integrates all the model information, functional requirements and component performance of the building construction project throughout the life cycle. It also includes construction progress and process control information during the construction process." Although the origin of BIM was early, the implementation of BIM in Architecture Engineering Construction (AEC) industry started mid-2000s (Eastman, 2011). Then, with the development of BIM, its' functionalities became stronger, and the definition also was updated. The National Building Information Modelling Standards Committee (NBIMS) put forward a more comprehensive definition which explains BIM as " BIM is a digital representation of the physical and functional characteristics of the construction project, is a common knowledge resource and an information sharing process which provides a reliable basis of decision making during the whole life cycle, and also is a digital model based on an open interoperable standard to support cooperative work (NBIMSC, 2007)." Moreover, the McGraw-Hill Construction Company in the US organised a market survey and defined BIM in its survey report as "the process of design, construct and maintain a project with a digital model succinct (McGraw Hill Construction, 2015)." In recent years, BIM has become more and more popular in AEC industry, and Hardin (2014) thinks that BIM is a process and software rather than just a software, which means BIM not only provides 3D intelligent model but also support the whole project workflow and project delivery processes. From the above definitions, it can be concluded that BIM is an application of construction project which can provide refined information for the whole life cycle and support collaborative work in multi-party.

As one of the four underground resources, underground space is considered to have long-term potential to encourage sustainable urban development (H.-Q. Li, Parriaux, Thalmann, & Li, 2013). Nowadays, with the progress of urbanisation, dynamic urban environment and the subsequent space deficiency promote the increase of underground construction (Ghodsvali, 2018). For underground construction, having accurate information and a clear vertical view is the most valuable aspects of managing and protecting underground facilities (Davidson, 2016). The proposal of underground BIM not only support the management of underground construction but also improve communications and decision-making between project stakeholders (Acaddrafting, 2017). With the underground BIM technology, the topographic data, building information and underground utilities information must be seamlessly integrated into a comprehensive 3D digital model. This model is a powerful and intuitive tool to show different stages of construction used by all stakeholders (Plowman Craven, 2000). To be mentioned, Level of Detail (LoD) is an essential concept in underground BIM. It is always used to indicate how detailed information of objects will be simulated by the 3D model. In most countries, at least LoD 2 should be adopted for underground BIM services (Susan, 2017). Specifically, in LoD 2, the external and internal of objects would be modelled separately. Additionally, the outer surface should adjacent to the surroundings and display the connection relationships with other objects (Borrmann et al., 2015).

The underground infrastructures commonly include the physical piping, sewers, electric cables, telecom lines, underground water, underground traffics etc. (Acaddrafting, 2017). For underground pipeline network, the underground BIM requires a model that shows not only the distribution of network but also the connection with surface objects (Drogemuller, 2009). This study is based on a sewer renewal project in Kleiweg area. As a part of the underground pipeline network, applying BIM into the sewer construction project will promote the plan optimisation and increase the work efficiency (Zhou, 2016).

The following subsection describes the characteristics of sewer construction project, summarises the positive effect of integrating underground BIM technology in the sewer project, and explains recent related works in this field.

2.1.1. Sewer construction project

Sewer system is the infrastructure that collects and transport surface runoff and sewage. A complete sewer system includes sewer networks and technical installations (e.g. manholes and pumping stations) (Grundfos, 2010). The sewer network always overlaps and mess with the other underground network, which brings difficulties for sewer management and construction (Ballard, 2000). In general, the main characteristics of underground sewer construction are as follows (S. Zhu, Wu, & Li, 2009):

Invisible: In order to maintain city beauty and save ground space, the sewer system always is laid underground, it is hidden without excavation.

Complex: First, the sewers overlap with other pipes or cables underground. Second, the construction of sewers always involves various stakeholders and departments (Yin, 2017).

Professional: The whole life cycle of sewer construction needs professional knowledge.

Systematic: The sewer system is made up by various components, they interact with each other. Failure of anyone can seriously affect the normal operation of the whole system.

Considering the characteristics of sewer construction projects, the planning, design, construction and maintenance gradually are converted from 2D to 3D (Wan, 2015). Moreover, for some projects on the city level, they start using GIS technology to manage sewer information. However, the majority of current sewer GIS system are still based on 2D GIS system or CAD system, which lacks of the information of underground environment and cause the incompatibility between sewers and other infrastructure (Zhou, 2016). In order to solve these issues, the need of integrating BIM with the sewer construction project is growing (Isikdag, Underwood, & Aouad, 2008).

2.1.2. Integration of BIM and sewer construction

Based on the internal and environmental information of the sewer project, BIM establishes 3D engineering model which contains this information and provides a visible collaboration platform for all participants in the planning, construction, maintenance and management stages of sewer project (M. Chen, 2017). Comparing with traditional 2D technology, BIM technology has significant advantages in three aspects: data, visualisation, cooperation work. Table 1 below shows the result of the comparison.

Table 1 The comparison of Traditional 2D technology and BIM

		Traditional 2D	BIM
Data	Data content	• Sewer information	• Sewer information; • Spatial information: connection with ground objects; topological relationship with other pipes; environmental information etc. • Topographical information.
	Data analysis		• Clash analysis; • Construction simulation; • The user can design the analysis based on their needs.
	Data transfer	• Transfer the real 3D sewer data to planning 2D data, which causes data loss and construction deviation.	• Transfer 3D sewers to 3D model; • Link with the database, possible to store all the needed sewer information; • Be able to integrate with Web Service to establish a universal sharing platform.
Visualisation	Dimension	2D	3D, even 4D
	LoD	Low, only use points and lines to display sewers system.	At least LoD 2, based on the requirements of projects.
Cooperative work	Project stage		Based on the projects needs, provide the information of the whole life cycle.
	Stakeholders		• Bring all the information together and promote the communication and decision-making of all stakeholders; • All stakeholders use one universal model.

Source: Adapted from F. Li,(2016), M. Chen, (2017), Davidson (2016), Azhar, Khalfan, & Maqsood (2012),Liu (2016)

In reality, the sewer system contents the manholes and sewers. As for establishing the 3D BIM scene of the underground sewer system, the manholes can be assigned as 3D point layers, and the sewer network can be modelled as 3D polyline layers (Zuo et al., 2017). Information such as the sewers' materials, location code, manhole code and defect code can be added to each respective element on the model. Each element assigns a unique ID which the element's relative information is linked to (Marzouk & Othman, 2017).

With the widespread implementation of BIM in the underground pipeline project, Halfawy and Dridi (2008) made a comprehensive study on the sewer renewal planning process. They integrated both BIM and GIS technologies in 3D sewer model to help the municipality optimise the sewer renewal planning while reducing the project costs and risk of clashes of the sewer network.

Although not focused only on the sewer network, the research of Penusila and Reddy (2016) are also remarkable. They conducted a BIM technology application study on the case of an underground utility pipeline construction project in Dallas and Texas. Starting from the traditional 2D drawings, the BIM construction model is established to assist owners and contractors in managing the corridor construction project. Through practice, BIM technology can help to develop a more manageable construction plan and reduce construction rework.

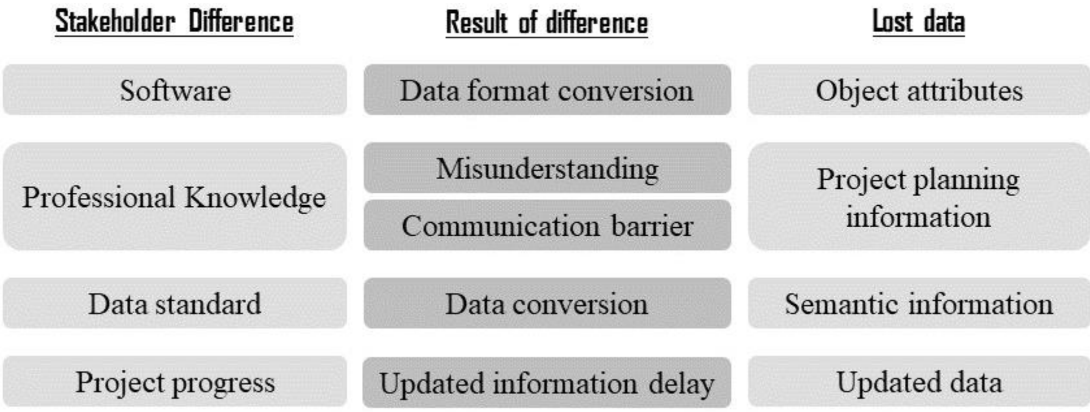
In summary, the application of BIM technology in sewer management project can not only guide the construction process but also promote the cooperative work of various stakeholders. Next section, 2.2, will provide an overview of data loss in the construction process, the overview mainly refers to investigating the method of data loss reduction from the previous related studies and researches.

2.2. Data loss in construction project

Construction projects become more and more complex and challenging to manage (Chan, Scott, & Chan, 2004). One reason of this situation is that the different stakeholders of the project affect each other, such as the contractor, engineer, project advisor and government administrators (Sears, Sears, & Clough, 2008). The various stakeholders dispersedly participate in the project in different stages. Large amounts of information exchanges and transfers with different formats in this process (Xu & Luo, 2014). In the AEC industry, the success of a construction project deeply relies on accurate and timely information transfer (Rojas & Songer, 1999). However, it is unfortunate that data loss exists between every stage of the construction project (Mangon, 2018). Cornick (1991) indicated in his book that "Two-thirds of the construction problems caused by insufficient coordination and inefficient transfer of project information and data." In conclusion, if there is no good way to solve the data loss problem, the construction performance will be incompetent in costs, quality and safety and so on (Dawood, Akinsola, & Hobbs, 2002).

As for various project stakeholders, the differences and gaps between them hinder the effective data transfer. The difference mainly refers to the domain, used software and data standard (El-Mekawy, 2010). Figure 3 below summaries the relations between these differences and data loss.

Figure 3 Summary of the relations of stakeholder differences and data loss



Source: El-Mekawy(2010);Raines(1997);Y.Li(2007);Wang(2018);Zhang&Guan(2000);Whyte, Bouchlaghem, Thorpe & McCaffer(2000); McHenry & Bajcsy(2008)

Data transfer is often associated with format conversion. As the conversion mainly concentrates on syntactic and forgets the semantics, the transformation process is always burdened by data loss (Raines, 1997). Considering this situation, D.Yuan and M. Xue (2018) suggested reducing data conversion times. The simplest way was doing data standardisation. They also proposed to build a unified information detection platform to insure the least data loss. However, the idea of the unified information detection platform did not put into practice.

In an overall view of data transfer in construction work, Al-Hussein (2000) explained the original communication and data transfer among stakeholders of the project as a "Node to Node" type, and suggested changing it to the new type, called "Interoperable Information Sharing". Shown as Figure 4 below. A "Share Project Model" links all the stakeholders together, the mode is based on unified data standard and simplify the complexity of data exchange. Actually, getting the help of Web Service and computer science, this interoperable communication type has been encouraged.

With the technological development, more and more projects used web service and computer science to support construction work (Martínez-Rojas, Marín, & Miranda, 2016). Based on the research of Howard and Levit (1989), with the help of these techniques, the construction projects aimed to integrate data transfer, decision-making and construction work together, which would reduce the data loss and improve the construction performance. Recently, the integration of BIM and GIS shows advantages in reducing data loss and promoting data sharing (Yamamura, Fan, & Suzuki, 2017).

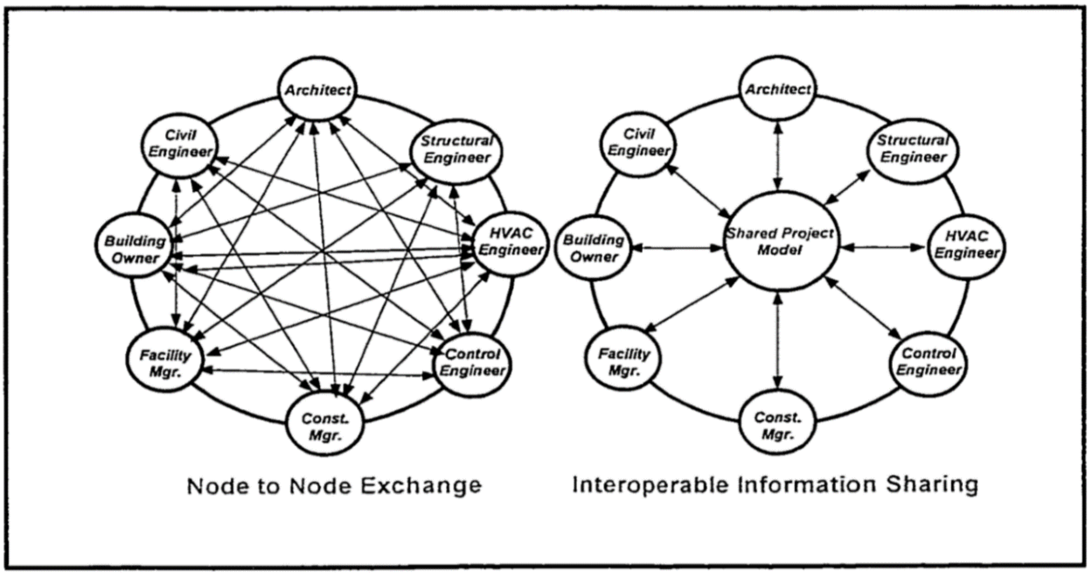


Figure 4 The comparison of two types of data transfer in underground construction (provided by Al-Hussein(2000)).

In the urban construction project, using BIM can achieve data sharing among various stakeholders on a common platform, which means the cost and loss of data sharing are much less (Deng, Cheng, & Anumba, 2016). Moreover, focusing on the city level, GIS plays a vital role in data integration, data visualisation and data application in urban construction (Clarke & Gaydos, 1998). Combined the strength of BIM and GIS, their integration can promote cooperative work of various stakeholders, especially with the help of Web Service (Wan Abdul Basir, Majid, Ujang, & Chong, 2018). As an example, Yamamura et al (2017) provided an energy planning system based on "GIS-BIM" to help to obtain the optimal solution for readjusting city infrastructure and developing a smart city. His study used Web Service to provide web view and a common sharing platform. The feedback from stakeholders indicated the excellent performance of the data transfer process.

2.3. 3D city modelling

The utility of 3D city modelling technology is becoming more and more popular and useful in the urban management process. By digitally representing the earth surface and spatial objects in a city, the 3D city models enable various types of urban application to create a detailed model in a specific area (El-Mekawy, 2010). Regardless of the type of urban industries, the use of the 3D model should focus on visualisation and spatial planning two functions (Biljecki, Stoter, Ledoux, Zlatanova, & Çöltekin, 2015). For an integrated model, it is not only important to considers the graphical or geometrical model, but also should understand the semantic part which defines the entities and the relationships among them. Overlooking the semantic and topological aspects will cause the model mostly used for visualisation purposes but lack interoperability between different stakeholders (Kolbe & Bacharach, 2006).

In the construction of 3D urban models, the factors, such as the expected output, clients, budget and the covered area, should be taken into account. Meanwhile, there are another three elements that should be considered alone with attention: "LoD", "Data requirements" and "Functionality" (El-Mekawy, 2010; Ghodsvali, 2018; Shiode, 2000). Same as mentioned in section 2.1, the "LoD" describes the complexity and fineness of 3D city models, which is associated with its application. Actually, the higher LoD does not mean the better, the increase in LoD occupies larger data sizes and costs more in money and time (Arroyo Ohori, Ledoux, & Stoter, 2015). “Data requirements” focus more on the required data collection, data formats and data standard, which will influent the later model transformation and interoperability (El-Mekawy, 2010). “Functionality” considers the application and user demand of the model, which will be evaluated its usefulness in practical working (Shiode, 2000).

With numerous nodes and lines, the 2D map of an underground piping network is difficult to distinguish different objects with the same x, y coordinates. This 2D visualisation may cause misunderstanding in filed construction. Therefore, mostly with the help GIS technology, the use of the 3D city model is increasing (Y Du & Zlatanova, 2006). For example, Du and his colleagues (2006) designed a 3D model to organise the 3D lines underground, The database stored the geometric attributes of utilities and also the relationships between various objects. The model also included the basic calculation of construction parameters.

With the development of 3D city modelling, the methods to be used and the developed software solutions had a great progress. As for integrating BIM into 3D city modelling, the CityEngine of Esri and the Revit of Autodesk are powerful in simulating the real urban situation (Pispidikis et al., 2018). CityEngine is an advanced 3D modelling software for producing huge, interactive and immersive urban environment (Esri, 1990). The CGA rules grammar is an essential property of the CityEngine, which reduce the complexity of the modelling process (Stavric, Marina, Masala, Pensa, & Karanakov, 2012). Revit is a professional 3D BIM software developed by Autodesk. It can be used in architectural design, MEP and structural engineering, and construction (Autodesk, 1989). The Revit can directly work with the other Autodesk product to provide further analysis functionality, for example using Navisworks for clash analysis.

To select a proper software of this study, Table 2 below shows the comparison of these two software. The box with blue texture means the more beneficial choice for this project. To achieve research objectives and conforms to the needs of sewer renewal project in Kleiweg area, the selection of comparison elements should pay attention to supporting sewer BIM in large scale and reducing data loss.

From Table 2, it is clear that the CityEngine is more helpful in creating an integrated 3D model of Kleiweg project in city level. It can directly import the data from shapefiles and provide an online data sharing platform with the help of Esri Online without coding process, which is in favour for reducing data loss.

Table 2 The comparison of CityEngine and Revit

Software		***CityEngine (CE)***	***Revit***
Characteristics	Platform	GIS	BIM
	Application scales	In city level	In small scale or a single building
	Rule grammar	CGA	C#
	Supported file formats	◆ CE native format: cej, 3ws, obj, etc. ◆ ArcGIS format: shp, gdb, etc. ◆ Image format: png, jpg, tiff, bmp, etc.	◆ Revit native format: rvt, rfa, rte, rft. ◆ CAD formats: dwf, dwg, dxf, etc. ◆ Image format: bmp. png, jpg, tif, etc.

Software		*CityEngine (CE)*	*Revit*
Functionality	Sewer BIM	Support, however, used more on overground BIM	Support and professional
	Data processing	Using other Esri products	Using other Autodesk products
	Modelling template	Yes, however, for the underground pipes/sewers, their templates are limited, users must create by themselves	Yes, the family file of Revit can provide detailed sewer template.
	Web Service	Yes, can directly export model in Esri Online. Provides Web Viewer and online data sharing platform.	No, need third-party software to provide web serve. Moreover, the user must be knowledgeable in WebGL.

Source: Esri (1990), Autodesk (1989), Pispidikis et al.(2018), M & O (2012)

In summary, this study develops an integrated 3D model with BIM and GIS technology to support the sewer renewal project in Kleiweg and reduce the data loss during transferring data between different participators. For this purpose, the CityEngine is used in the 3D modelling process.

2.4. Summary

Based on the previous studies, this chapter firstly gives an overview of the development of underground BIM. Also, by comparing with the traditional 2D technology, the advantage of BIM is shown clearly in Table 1. Then, recent analysis and solutions of data loss in the construction project have been summarised in section 2.2. The last section summarises the cases in 3D city modelling. Moreover, to select a proper software for this study, this section also compares the CityEngine and the Revit, which shows that the CityEngine is more suitable for helping achieve the objective.

The next chapter aims to introduce an overview of the study area and its sewer renewal project. Meanwhile, the collected secondary data will also be presented.

3. FIELD OF STUDY

This study develops and tests a 3D model integrating BIM and GIS technologies to reduce data loss and promote data sharing among actors engaged in sewer renewal projects. The municipality of Rotterdam identifies the data loss problem and are trying to solve this issue to improve the data exchange and communication between different stakeholders. A sewer renewal project in Kleiweg is used as a study area. This chapter focuses on the overview of the study area, and introduce the project contents. At last the collected secondary data will be described.

3.1. Study area

Figure 5 Kleiweg Area, Rotterdam (Image from the municipality of Rotterdam and Open street maps)

Kleiweg is located in the Hillegersberg - Schiebroek district, a historical area closed to natural scenery, in the Rotterdam city. Kleiweg area has obvious urban characters with several large connecting roads. The land cover of this area is mainly high-density buildings and small public green area (Gemeente Rotterdam, 2016).

Similar to the whole of Rotterdam, the underground space in Kleiweg is full of sewers, gas pipes, drinking water pipes, electric cables, and telecommunication cables. The tree root systems also take up great space. In general, the space under the roads and sidewalks is used for positioning the public sewers, pipes and cables. This measure is always good at managing underground space and beautifying overground scenery (Leidingenbureau Rotterdam, 2016).

Recently the municipality of Rotterdam initiated a sewer renewal and road maintenance project in this area. Annex 6 shows the underground sewer system of Netherland. Beginning in early October 2018, the project is undertaken by a local contractor, Jac Barendregt. The construction phase may be sustained five months ending in February 2019. Annex 2 shows the maps of the renewal plan provided by the engineer company.

3.2. Data description

This study requires professional information related to urban infrastructures and project planning. These mostly are secondary data which can be acquired from existing urban plans and spatial documents. The project stakeholder provides the official records and files. Table 3 below shows the details of collected data.

Table 3 Data description

Name	Contents	Data format	Source
Engineer design documents	The detailed plan of sewer renewal project	CAD file(.dwg)	Gebiedsmanagers B.V.
New sewer system	Position and attributes of new sewer and wells	Shapefile (point and polyline)	
Old sewer system to be removed	Position and attributes of removable sewer and wells	Shapefile (point and polyline)	
Building	Position and foot print of building	CAD file(.dwg)	
Building Height	Height of building	Store in excel file(.xlsx)	Google earth
DEM	Elevation information of study area	Raster(.tiff)	Rotterdam Municipality
Tree	Position, size and type of tree	Shapefile (Point)	
Light pole	Position, height and type of light pole	Shapefile (Point)	
Electric cable	Distribution, depth and material of cable	Shapefile (polyline)	
Telecom cable	Distribution, depth and material of cable	Shapefile (polyline)	
Television cable	Distribution, depth and material of cable	Shapefile (polyline)	Rotterdam Municipality
Drinkwater system	Distribution, size, Z value and material of pipes	Shapefile (polyline)	
Gas system	Distribution, size, Z value and material of pipes	Shapefile (polyline)	
Road	Position, size and type of road	Shapefile (polygon)	
Surface water	Footprint, position and area of surface water	Shapefile (polygon)	

3.3. Summary

This chapter briefly introduce the background of Kleiweg area. As a part of Netherland, its underground sewer system follows the requirement of national government. The details of sewer network can be found in Annex 6. Besides, the relevant data used by this study have been shown in Table 3. The primary source of data is the Rotterdam Municipality and Gebiedsmanagers B.V. (the engineer company).

4. METHODOLOGY

The overall approach of this study mixes qualitative and quantitative methods to achieve the specific objectives. To be specific, corresponding to each sub-objective, data collection, data processes and data analysis need to be considered to choose the most suitable methods. Table 4 shows the overall approach of this study.

	Data collection	Data processing	Data analysis
Requirement analysis	• Assess documents provided by the municipality • Expert interviews	• Data semantic quality assessment	
Data preparation	• Literature review	• Validate topology • Extract elevation	
3D modelling	• Literature review		• 3D modelling
Model evaluation	• Questionnaire		• Model assessment

Table 4 Overall approach

Data collection refers to the various stages of the process. On the one hand, this study requires professional information related to underground cables and pipes, surface and subsurface constructions, vegetation and green area, road condition, etc. These mostly are secondary data which can be acquired from existing urban plans and spatial documents from the municipality of Rotterdam. On the other hand, in order to know about the requirements of the municipality and the user needs, expert interviews are used to collect the requirements of the municipality which refers to required data and its quality, current work flow and faced data problems. The interviewees refer to knowledgeable staffs related to Kleiweg sewer projects (e.g. urban manager, project engineer, contractor, etc.), considering that the municipality plays a critical role in the sewer project and problem proposal, the interviewees from the other parties are introduced by the municipality. Last, the 3D model is evaluated by interviewing experts and collecting their suggestions. To be mentioned, in some steps, the literature review is used to get help from relevant scientific studies.

Data processing mainly exists in the early steps to lay a foundation for the later 3D model building. Firstly, it is vital to assess data quality to encourage the sharing, interchange and use of required data sets. Data completeness and logical consistency are two essential aspects of data quality. As ISO(2013) defines, the data completeness describes "the presence and absence of features, their attributes and relationships", and, the logical consistency refers to “the degree of adherence to logical rules of data structure attribution and relationships." Specifically, in this study, the data quality assessment is organised in semantic quality and geometric quality two parts. In regard to semantic quality, because the information and data attribute need translation and CAD files need transfer to shapefiles, the completeness and consistency of data attributes would be evaluated by expert consultation. And as for geometric quality, in view of the requirement of underground BIM, the topology validation is used to assess the relationships of sewer itself and with the other objects. Secondly, the height of building and elevation is extracted in this procedure for further 3D modelling.

Data analysis mostly uses quantitative methods including 3D modelling and Model assessment. With the help of the CityEngine, in 3D modelling process, GIS platform is used to display the position of objects in city level, and the sewer distribution and connection use BIM present in detail. In the end, model assessment is implemented to modify the integrated model by sending a questionnaire to relevant experts.

To be specific, the following sub-sections will introduce the methods in detail. And Figure 6 displays the workflow of this study.

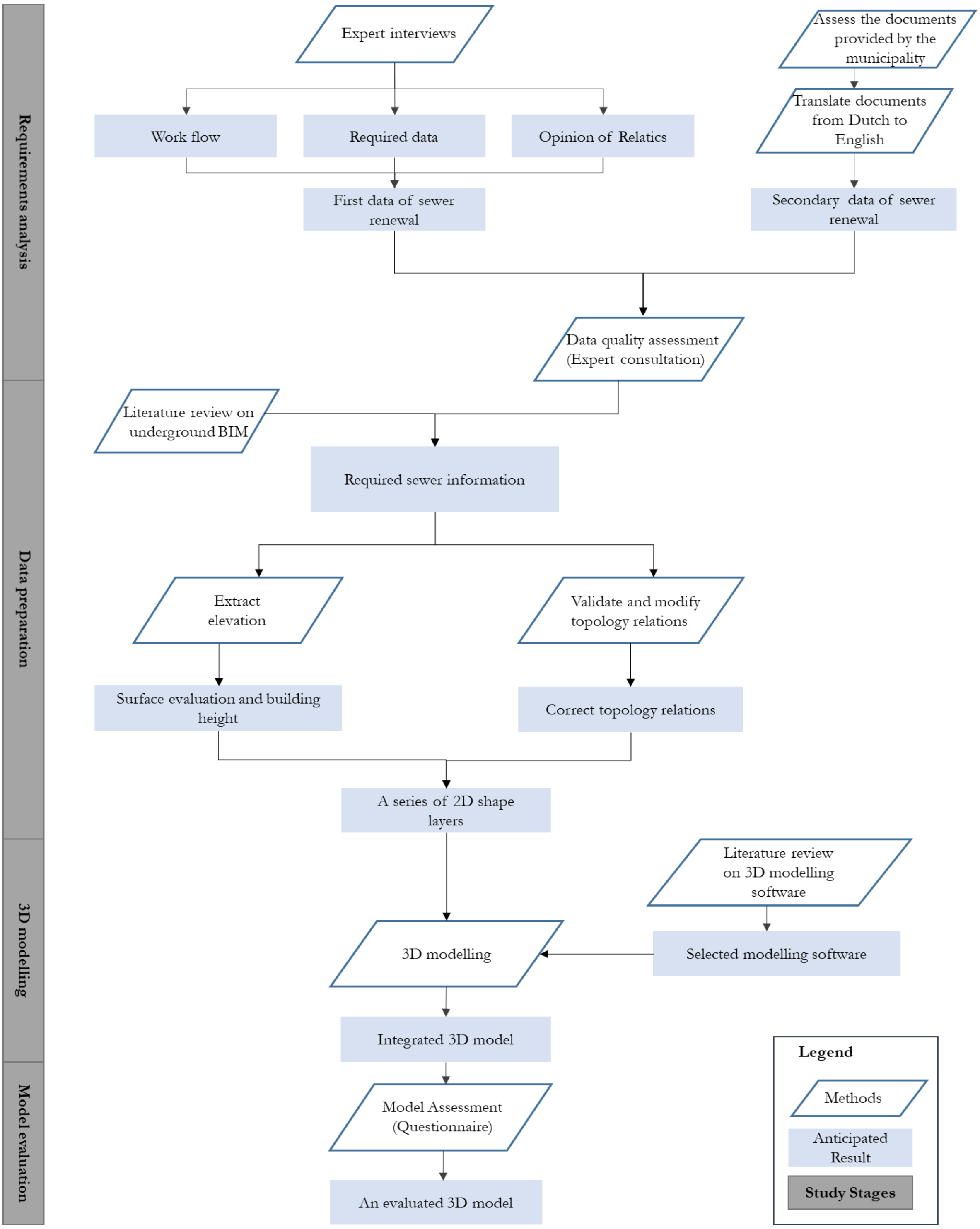


Figure 6 Work flow

4.1. Expert interview

The expert interview was used to obtain more information about the current workflow and data loss situation. To get high accurate information, the interviews were developed by structured questions. Since this study required to know about the concrete workflow and data characters, this method was advantageous to target the specific research domain by considering the scope of detail while designing the interview (Statistics Solutions, 2019). The interviewees were mainly knowledgeable professionals in this sewer project. The staff came from the municipality of Rotterdam, engineer company and contracting company. As they each had their own working background, the interview should try to avoid information gaps or overlaps among them. For different staffs, the interview questions might have a little difference (Annex 1 shows detailed interview questions in this study). The interview questions could be divided into two parts: work chain and data description. The interviewees answered the questions at first, based on their answer, more items would be added as supplementary. Then, categorised and summarised the response in a table; At last, considering about project situation, the critical point of data loss and the requirement of different stakeholders were found out.

4.2. Data semantic quality assessment

In this study, the planning documents and data attributes from the municipality were in Dutch, so information translation was needed in the early stage. First, Google Translate was chosen for translating Dutch to English. Then, in order to ensure the semantic quality of information, after translation, the result of translation would be assessed.

Besides, because some object layers were extracted from CAD files, CAD files were transforming to Shapefiles. ArcGIS was able to provide this functionality in its toolbox. However, in this step, some attributes lost and needed to be reimported. To ensure attributes completeness and logical consistency, the reimported attributes required to be assessed in quantity and type.

The data semantic quality assessment could be divided into two levels. Data producer implements the first level, and the second level is performed by the users' feedback (Srivastava, 2008). In this study, expert consultation would be prime methods of data quality assessment. The result of the translation was sent to the expert for checking. Moreover, for the transformed shape layers, the consultation of stakeholders determined what essential attributes would be reimported.

4.3. Method of data preparation

To ensure the precise 3D modelling process, the data preparation stage should integrate needed data layers with completed information. All the layers should be harmonised in same data format and projection. In this study, CityEngine uses shapefiles as basic data format, besides "RD_new" is chosen for the Netherlands local projection system. This section focuses on explaining two vital tasks in data preparation stage. One is exacting building height, and the other is using topology validation to ensure data accuracy.

4.3.1. Extract building height

As the building layers were converted from CAD file, part of its attributes were missing. For latter 3D modelling, the building height had to be collected separately and reimported. This study used Google Earth to help extract building height. In Google Earth, for Kleiweg area, 3D simple gray model with current building height existed. And there was "Ruler" functionality to measure the length of 3D path. The measurement process was implemented in street view (as the Figure 7 shows). To reduce the deviation of measurement, every building was measured three times and finally used the average value as the building height. Last, the value directly input in the attribute table of building layer in ArcGIS. In this study, since the terrain and elevation would be considered in the later modelling process, the measurement of building height specifically meant the distance from the surface to the top of 3D gray model.

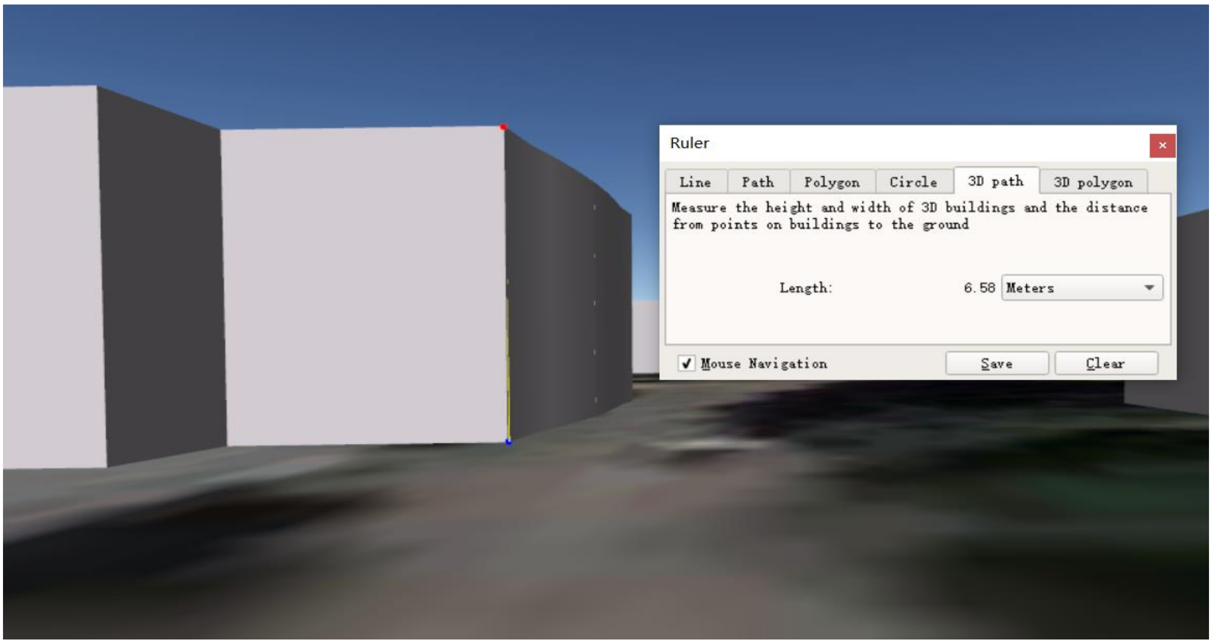


Figure 7 The measurement of building height in Google earth

4.3.2. Topology validation and modification

Topology refers to the spatial relationship between geographic features, and it is a set of behavioural rules which ensure the quality of spatial data (L. Li, Luo, Zhu, Ying, & Zhao, 2016). Especially for underground BIM, to correctly display the connection between different objects, the spatial relationship must be validated and modified.

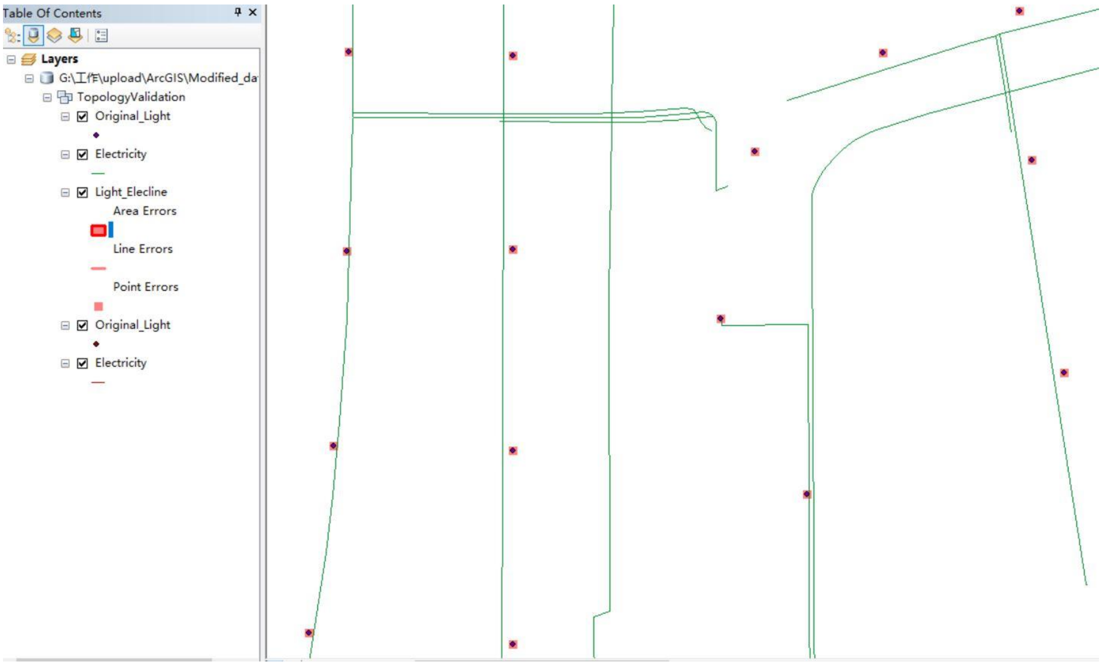


Figure 8 Example of topology validation between original "Light pole" layer and "Electricity network" layer.

In this study, the topology was divided into two types: the topology of one data layer and the topology between two data layers. Considering the object requirement and layer type, the topology rule was different. In ArcGIS, the topology was created based on geodatabase. Moreover, all features and database should be unified in the same coordinate system. The whole process mainly included three steps. First, since the topology validation required to proceed under a common dataset, all data that needs to be validated were moved into a new dataset and checked its coordinate information. And then, based on the topology rule, the topology relation was validated. The error of data would be displayed in red colour. In this step, the tolerance of error used the default value: 0.001. Last, all the error should be modified by using the tools in "Topology" toolbar and ArcGIS toolbox. In general, the detailed topology rules and modified approaches are presented in Table 5. And Figure 8 shows an example of topology validation for "Light pole" and "Electricity network".

	Layer name	Layer type	Topology rule	Modification method
One layer	Street	polygon	Must not have gaps.	Edited the node points of polygon.
	All cables/sewer/pipes	polyline	Must not overlap.	Deleted one of the overlapping lines.
Two layers	Light pole	point	Point must be covered by line.	◆ Used "Near" tools to add X and Y coordinate of the location on the polyline which is closest to the point; ◆ Exported the X and Y coordinate to .dbf table; ◆ Used "Add XY data" to import new point layer which follow the topology rule.
	Electricity network	polyline		
	Sewerage well	point	Point must be covered by line	
	Sewer	polyline		

Table 5 The topology validation and modification

4.4. Method of 3D modelling process

This section describes the process of using CityEngine to produce 3D underground BIM and realising data sharing. The whole model can be divided into two parts: the underground infrastructure and its external environment, each part having several objects. To be specific, the underground network contained electricity network, telecom network, television cable, drinking water system, gas system, sewage system and planned sewer. Besides the external environment included building, tree, light pole, street and water.

The following sub-section 4.4.1 explains the details of model generation, CityEngine and ArcGIS were used in this process. Also, section 4.4.2 focus on uploading the integrated 3D model online to achieve the data sharing among different stakeholder of Kleiweg sewer renewal project.

4.4.1. Model generation

CityEngine directly uses GIS vector data as the basic data of the modelling process, and makes full use of its attribute field information to simulate the reality. Based on CGA rules, CityEngine can change the appearance of 3D model by adjusting the parameter in the property file (*.cga). By dragging and dropping the rule file to the modelled data layer, the 3D model will be automatically generated in batches. This approach replaces the complex one-by-one modelling process, greatly improving the speed of modelling. Annex 3 displays the specific rule files for different objects. The following statements explain the 3D generation steps of each object type.

Underground Infrastructures:

- Electricity/telecom/television/drink water/gas/sewage network: These underground pipe/cable networks were presented in the respective line features with radius and depth information. Since CityEngine cannot form a transverse cylindrical pipe model, the first two steps were implemented in

ArcGIS. First, "Feature to 3D By Attribute" tool was chosen to create 3D feature using depth value of start and end point from the attribute table, this step located network distribution on Z coordinate. Then, the "3D Buffer" tool was used to form a cylinder shape based on the radius of pipes/cables. Last, the created multipath shapefiles would be imported into the CityEngine for further visualisation. To be mentioned, for better visualisation, the radius of pipes/cables used the average value. Moreover, different network was move to separated level for a clear 3D view.

- Planned sewer: Same as the other type of pipe/cable, the modelling step of sewer firstly used ArcGIS to produce the cylinder shape and then imported into CityEngine environment. The planned sewers had three types: existing sewer, removable sewer and new sewer. To provide a noticeable difference in visualisation, with different texture, the existing sewer and removable sewer were stored in one layer and the new sewer in another layer. These two layers were put into a new "Sewer renewal project" group, which can achieve comparison function in the latter web viewer.
- Well: The point feature of sewage wells was used in this step and connected them to the pipe/cable/sewer. Because the original data provided by the municipality didn't have depth and width attribute, the depth of wells used assumption value which can let them connect to the underground network tightly. Moreover, the width of wells used the corresponding pipe/cable/sewer radius as its width. "Extrude function" in CityEngine can be used to produce vertical cylinders which represented the wells.

External environment:

- Terrain: CityEngine can directly extract terrain information from the raster image by creating a new map layer. The coordinate value of raster image was used to clip satellite image from the Open street map, which would be set as the texture of the ground.
- Building: The buildings were divided into two types which shows in different colours: main building and auxiliary building. According to the height attribute, "Extrude function" was used to model 3D buildings in LoD1. To be mentioned, because of terrain, the bottom of building needed to be closely attached to the terrain. "Align Shapes to Terrain" in CityEngine applied to achieve this requirement.
- Tree: In this study, a static model (*.obj) was inserted for 3D modelling of trees. Due to the lack of tree height information, the radius of crown served as a reference for the size of the tree. The original point layer needed to align to terrain, moreover, the modelled 3D objects of trees should along be the world coordinate system's y-axis.
- Light pole: Considering about connection with electricity cables underground, the light poles had two components, surface pole and subsurface connection which would be modelled separately and merged into one layer. The static model of light pole was used in this study which represents the 3D object of surface pole, and the subsurface connection was modelled by generating a vertically downward cylinder. The depth of the cylinder was determined by the position of electricity cables.
- Street and water: These two objects were both presented by polygon feature, and only needed simple operation for attaching texture. Because lack of Z value, the polygon shapes must attach to terrain.

4.4.2. Model sharing online

CityEngine can let the users create, update and share the 3D model in a common platform. The platform is free, and only a user account of Esri is required. CityEngine can also allow different users to add comments and share their comments via e-mail. This functionality is beneficial for reducing losing update information. Also, CityEngine can also let the user view the 3D model online. With the Comparison function, the user can directly compare difference of the current sewer system and the new planned sewer system, which can help the user to understand the work plan fully.

Specifically, the first step was to register an account on the Eris website. To ensure the privacy of data sharing, a working group was established in a personal account. For latter data sharing, only the people in this workgroup was able to view and download the data. Second, the generated 3D model should be exported in the 3ws format which is the professional format for uploading online in Esri. Finally, the 3D model was uploaded to online account and edited its basic information. The accessibility was set as only be accessible to group members.

After finishing sharing 3D model online, it is necessary to validate the usefulness of the model and relevant result. This study aims to deal with the data loss and data sharing problem of the municipality of Rotterdam, hence the opinion of relevant stakeholder is important. The next section introduces the steps of model assessment.

4.5. Model assessment

The model assessment used a questionnaire to collect the feedback of the experts in this project. The expert mainly referred to the stakeholders of the Kleiweg project. To be specific, three experts from the municipality of Rotterdam, an engineering company and contractor company was chosen to participate in the evaluation work. However, because of time limitation and substantial work of experts, the assessment result may be not comprehensive, which is difficult to coordinate and avoid.

The whole assessment can be divided into three steps. First, a model introduction manual was written. The manual included the reason for choosing CityEngine, the legend of 3D model and the instructions of sharing platform. If the user required, the model could be presented via Skype. The manual would send to the experts to help them understand the integrated 3D model. Meanwhile, this manual also was able to download online in the project information web page.

Then, the feedback questionnaire was designed (Annex 4). The questionnaire mainly used Likert questions; the experts were asked to score the agreement of the specific statement. In this assessment, from 1 to 5, 1 means “Strongly disagree” and 5 means “Strongly agree”, besides 0 for “No idea”. The selection of questions referred to the definition of “Usability” and “Utility” by Nielsen (1993), the usability involved test the learnability, efficiency, satisfaction and errors rate of the model. As for utility, it was used to assess the functionalities of the model. Specifically, the first part of the questionnaire assessed the utility of the model, and question 1 to 5 were put forward to evaluate whether the 3D model satisfies the stakeholders’ requirement. This requirement included supporting professional work and solving data problems. Specifically, from question 1 to 5, the model’s data provision, the ability to reduce data loss, data sharing functionality, the quality of underground BIM and LoD were validated. Secondly, with respect to usability, the model should be easy to understand and promote work efficiency. In this part, question 6 to 8 assessed the interaction between the 3D model and the user; moreover, question 9 and 10 deliberated the impact of the 3D model on actual sewer renewal work. At last, this study used three open questions (Q11~Q13) to collect the experts’ opinions and suggestions of the integrated 3D model. At last, the received feedback would be calculated the score and summarised the opinion of open questions to conclude the overall result of model assessment.

4.6. Summary

Corresponding to the workflow, this chapter introduces the methods used in this study. Both quantitative and qualitative are included to achieve each sub-objective. More specially, the literature review is a primary method to collect information and previous experience in relevant studies. Besides, the expert interview is used to investigate the experts’ requirement and opinion of data loss. All the collected data which will be used to do 3D modelling needs quality assessment. The assessment focuses on semantic and geometric quality. Experts consultation and topology validation are implemented to ensure data completeness and logical consistency. And then, 3D modelling is accomplished by the CityEngine with the help of CGA rules. At last, model evaluation uses a questionnaire to get the experts’ feedback and analysis the usefulness of the integrated 3D model. The result of these processes will be shown in the next chapter.

5. RESULTS AND DISCUSSION

This chapter shows the results of this study. The work content of experts and its opinion of data loss are introduced at first; meanwhile, their comments about Relatics also are discussed. Then, the integrated 3D model is presented in two parts, the model visualisation and its common sharing platform. Moreover, the last part aims to summarise the feedback of experts and discuss the performance of the 3D model.

5.1. Result and discussion of data loss

In this case, in total three persons participated in the expert interviews. They come from different organisation and play different role in the Kleiweg sewer renewal project. Their interview results are devoted to describing the details of the data loss and showing the views on the Relatics. The interview starts with the expert in the municipality of Rotterdam who introduces the other two experts. Therefore, despite the limited number of interviewees, the good relationship between them makes they have a common concern on the Kleiweg project. Table 6 summaries the result of expert interview in three themes. Note, due to the busy work of the municipality expert, his answers to the interview were very delayed. Consequently, most of the latter requirement understanding and problem analysis are based on answers of the other two experts, the municipality's response is only a supplemental reference.

From Table 6, the interview result is categorised into three themes: work description, data loss and opinion on Relatics. The work description (with grey background) focus on knowing about interviewees' work duty and data properties. As for data loss (with pink background), the expert responses explain the reason and content of data loss, and introduces their recommended measures of reducing data loss. Last, the opinion of the Relatics part (with blue background) focuses on the usage and suggestion of the Relatics.

According to the interviewees, the municipality is responsible for preparing the work plan and building 3D model, and then the engineer creates a final draft of the project and makes feature layers in shapefile. Last, the contractor uses the shapefiles delivered by the engineer to manage the project in the field work. Autodesk' software and ArcGIS are popular in making maps and modelling project. Hence, CAD file (*.dwg) and shapefiles are widely used and transferred in their work process. Based on this workflow, the interviewees talk about the data loss during the life-cycle of the project.

By integrating interviewees' view on data loss, all the experts mention the problem of data loss during exchanging process. This exchange includes data format conversion during 2D to 3D conversion, and also includes transferring data and 3D model between different stakeholders. On the one hand, the municipality finds that data attributes loss a lot when exchange 2D data to 3D models. After transferring, only object ID can be kept, which will be used as key field to reimport data attributes from modelling software. On the other hand, the engineer and the contractor think that, due to lack of common shared database and differences in work method, the data loss happens more frequently between different stakeholders. They emphasize the missing of updated information and suggest to build common platform for data sharing.

As for the Relatics, to some extent, the poor development of software and query problem also influence the data loss. The experts use the Relatics to manage information completely and create an information environment for the contractor's fieldwork. However, the gap between the 3D model and the SE template causes that the data exchanging process always needed to relink the data and its corresponding attributes information. However, according to the municipality opinion, the weakness of the Relatics can only be improved by the software company, the user can put forward some suggestions. In summary, the improvement suggestions provided via interview mainly focus on two aspects. One is improving the functionality of the software, for example, adding verification functionality and expanding knowledge base. The other is improving the utility of software, which refers to modifying the user manual more friendly.

Position		BIM Advisor *Municipality of Rotterdam*	Engineer *Gebiedsmanagers.B.V*	Contractor *Van der Meer*
Work description	Duty	• Advising the project team on how to implement BIM workflows in the engineering of project; • Generated underground system; • Building 3D model and linking the attributes.	• Create final drafts of project; • Convert drafts to shapefiles and store them on a server; • Accompanying consultation.	Overall management of the project in the field work
	Software	• ArcGIS; • Auto Civil 3D • Navisworks; • Infraworks; • Relatics; • FME.	• AutoCAD (2D/3D); • Relatics; • ArcGIS.	• Relatics • ArcGIS • Microsoft programs SharePoint
	Data format	• CAD file (*.dwg); • Shapefile; • NWD file; • Relatics database.	• CAD file (*.dwg); • Shapefile; • Excel spread sheet.	Follow the format provide by the Engineer.
Opinion for data loss	Why?	In the exchange of maintenance data to the 3D models, the attributes can not be transferred completely in the modeling software.	• Do not have the linkage to sewage 3D libraries, which is owned by the municipality. The others can not get the completed 3D model after transfer. • Non-working Relatics query affects the data import.	• Information updating; • Different organization has own way of work; • Transfer data by email; • Human error.
	What?	Data attributes. When data format change, only the attributes of symbology and object ID keeps.	• Updated information; • The 3D sewage libraries from the Municipality.	• The last revision of design; • Updated information.
	How?	Using the corresponding ID's in modeling software to reimport the attributes.	Share the sewer system in common platform to the contractor.	• Use BIM; • Put the information in the cloud or common digital platform.
Opinion of the Relatics	Application	• Help linking SE and 3D models and support exchanging the data with Contractor; • It's not possible to link the 3d models and the SE model in 100%.	Create an environment in which the end user can operate.	Do verifications work of the demands from the municipality.
	Improvement	• Add the verification and validation in the SE template; • Only exchange the requirements which the contractor needs; • The improvement should be done by the software company.	• More clear explanation of the user manual; • Expand the knowledge base.	Use it the first time, don't see real issues of the software.

Table 6 Summary of expert interview

In conclusion, to reduce data loss during the life-cycle of the Kleiweg sewer renewal project, it is necessary to decrease the times of data conversion and build up a common sharing platform. This study uses CityEngine to create a 3D model integrating BIM and GIS technology. CityEngine uses shapefile as basic data format, which will reduce converting shapefiles to CAD files for modelling in Autodesk. Moreover, the CityEngine has free online platform for data sharing. Based on the requirement of underground BIM and limited time, the integrated 3D model display objects and environment in LoD1. The next section shows the result and discussion of the integrated 3D model.

5.2. Result and discussion of integrated 3D model.

In this study, an integrated 3D model with BIM and GIS technology has been created to reduce data loss during the life-cycle of Kleiweg sewer renewal project. Since the CityEngine is based on its own GIS platform, using it to achieve underground BIM should take care of the data semantic quality (Jia & Liao, 2017). Data semantical quality assessment has been finished in the preceding data preparation stage. With the prepared data and texture images, the modelling process mainly includes two steps: creating the 3D scene of model, and, sharing model on the common platform. According to these two steps, the result of the 3D scene and common platform will be presented separately in this section.

5.2.1. 3D scene

The whole 3D model integrates the objects above and below the ground with actual terrain. However, because this model is also designed to help the underground sewer renewal project, the 3D scene pays more attention to the distribution of underground infrastructures. The creation of the 3D scene is based on the CGA grammar which is put forward by Esri. The "insert (*)" and "texture (*)" grammar are used to invoke texture image or static model, which helps the symbolization work of 3D modelling. Since the CityEngine is not able to insert the legend of model, the selection of texture should be similar to the reality as far as possible. In the final, created integrated underground 3D model has been published on the CityEngine web viewer (shown in Figure 9). Using the web link can directly access to it (Link: CityEngine web viewer). In web viewer, the user can manage layers, search data, set sunlight and shadowing value, add comments and scan the model information.

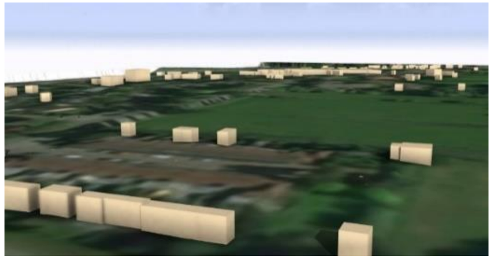
Figure 9 The integrated 3D model in web viewer

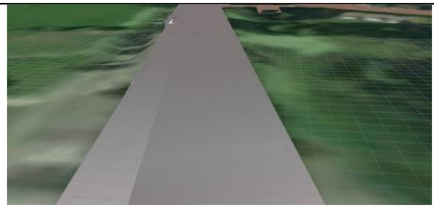
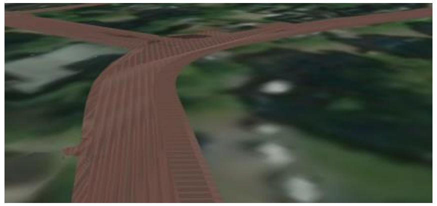
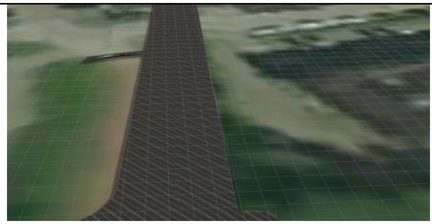
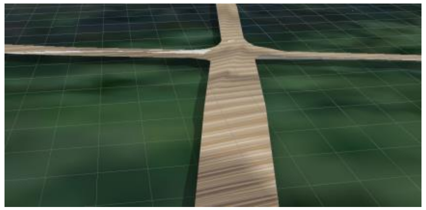
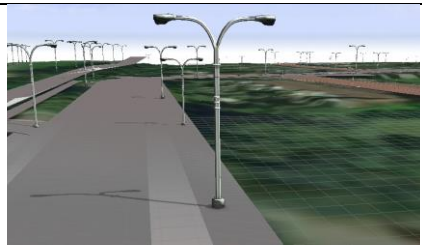
Same as a legend, Table 7 describes 3D objects of the model. For each layer, its visualisation is presented, and its major attributes are mentioned. As this model will be introduced to experts who are more familiar with Dutch, also the whole number of attributes is large, although some information has been translated into English in the previous step, the 3D model still chooses to show objects' information in Dutch. Besides, Table 7 also discusses the limitations of 3D objects. Since the constraints of time and data integrality, this study has a little problem in modelling the objects in higher LoD.

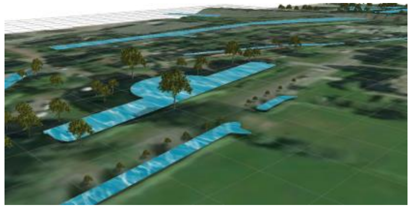
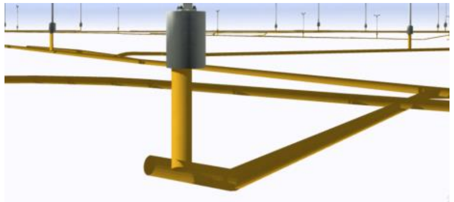
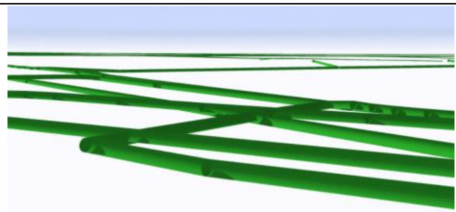
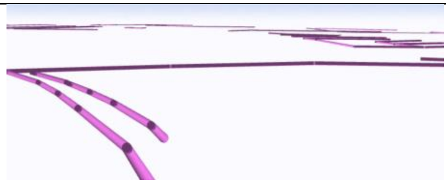
To be mentioned, in the web viewer page, "comparison mode" and "comment" functionalities are truly helpful in supporting sewer renewal work and sharing updated information. In the comparison mode, the user can compare the current sewer layers and the new Sewer layers directly (shown in Figure 10). Besides, the "comments" functionality allows the user to add the descriptions of model or the updated information, moreover, the comments can be directly shared via e-mail to the other stakeholders.

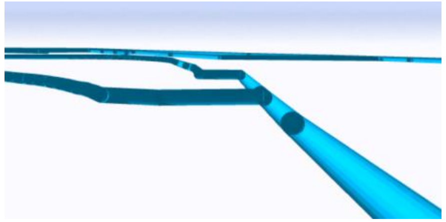
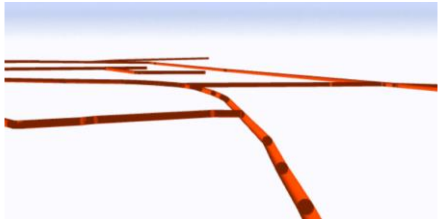
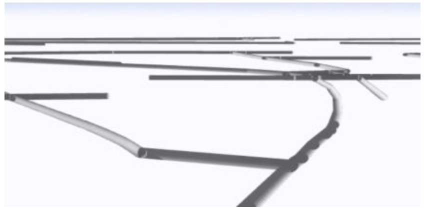
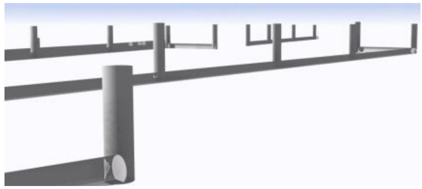
Figure 10 "Comparison mode" of Web Viewer

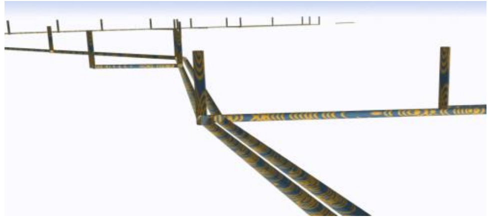
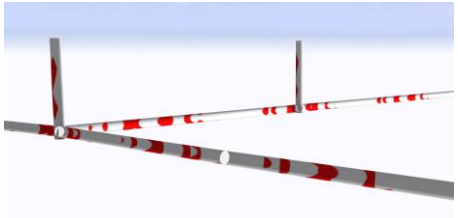
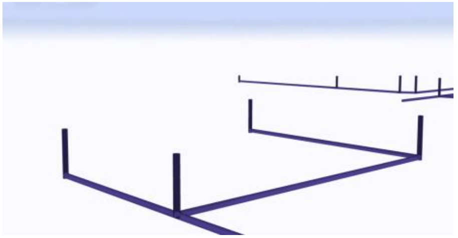
Table 7 The description of 3D objects refer to layers

Layers	3D Objects	View	Information provision	Annotation
Building	Building		◆ Building height; ◆ House number; ◆ Street Name; ◆ Area of the footprint.	◆ The original data lacked height value, the height value was extracted from Google Earth by measuring. So, the building height has a deviation.
	Annexed Building		◆ Building height; ◆ Area of the footprint.	◆ Lack of height value; ◆ The annexed building which can be found in Google Earth had been measured, the others were assumed to a unified value (3 meter).
Tree	Tree		◆ The diameter of the crown; ◆ The diameter of the trunk; ◆ The position of the tree. ◆ Type of tree.	◆ The visualisation of the tree is not the same as the real condition; ◆ Lack of height value, the tree was modelled by the radius of the crown; so, the size of trees was not as same as the real world.

Layers	3D Objects	View	Information provision	Annotation
Street	Main road (Wykontsluitingsweg)		◆ Type of Road; ◆ The position of Road. ◆ Road name; ◆ Road material.	◆ Lack of Z value, the street cannot completely attach to the terrain. ◆ The texture of road is not the same as reality.
	Residential street (Woonstraat)			
	Industrial road (Weg in industriegeb)			
	Recreation area road (Recreatiegebied)			
Light pole	Light pole		◆ The height of light pole, ◆ The position of the light pole; ◆ The connection with electricity cables.	The visualisation of the pole is not the same as the real condition;

Layers	3D Objects	View	Information provision	Annotation
Water	Water		The profile and position of water.	Lack of depth and Z value, the water cannot completely attach to the terrain.
Electricity network	Electricity lines		◆ Distribution, diameter and depth of electricity cables; ◆ The connection with the light pole.	◆ The connection of light pole and cables were modelled by the location of the light pole. ◆ Lack of the specific position of building and electricity cables, so the connection with the building do not display.
	The connection with the pole			
Telecom network	Telecom cables		◆ Distribution, diameter and depth of telecom cables.	◆ In reality, cables are too thick to model, so the radius of cables in the model has been zoomed in. ◆ Lack of the specific position of building and telecom cables, so the connection with the building do not display
Television network	Television cables		◆ Distribution, diameter and depth of television cables.	

<table>
<tr><th>Layers</th><th>3D Objects</th><th>View</th><th>Information provision</th><th>Annotation</th></tr>
<tr><td>Drink water system</td><td>Drink water pipes</td><td></td><td>◆ Distribution, radius and depth of drink water pipes.</td><td rowspan="2">◆ The radius of pipes is used the average value (0.53m). The real value will be reported in attributes.</td></tr>
<tr><td>Gas system</td><td>Gas pipes</td><td></td><td>◆ Distribution, radius and depth of drink water pipes.</td></tr>
<tr><td rowspan="2">Sewage system</td><td>Sewage sewer</td><td></td><td rowspan="2">◆ Distribution of sewage sewer;
◆ The visualisation of sewage wells at an assumed depth.</td><td rowspan="2">◆ The radius of the sewage sewer was assumed by the literature review of other construction files.
◆ The data of the sewage system was provided by the municipality, some objects were not in line with the reality and had been modified.</td></tr>
<tr><td>Sewage wells</td><td></td></tr>
</table>

Layers	3D Objects	View	Information provision	Annotation
New sewer	New sewer and its well		◆ The length, size and elevation of newly planned project sewers. ◆ Visualize the new planned sewage wells.	◆ For better visualisation, the radius of sewers and wells were assumed. The real value will be reported in the attributes.
Current sewer	Current sewer and well will be maintained		◆ The length, size and elevation of current sewerage system; ◆ The distinguishable visualisation of removed sewers.	
	Current sewer and well will be removed			

5.2.2. Common platform

CityEngine provides a free online platform for the users sharing data. With a web account of Esri, the generated 3D model can be uploaded online platform and directly share the whole model file to other stakeholders. Figure 11 shows the project information webpage of Kleiweg sewer model. The project information page displays the description of the model and provides some data share functionalities. The model publisher has the accessibility to edit all the information or update the model, which the other users are not able to do. (Link to: Project information page)

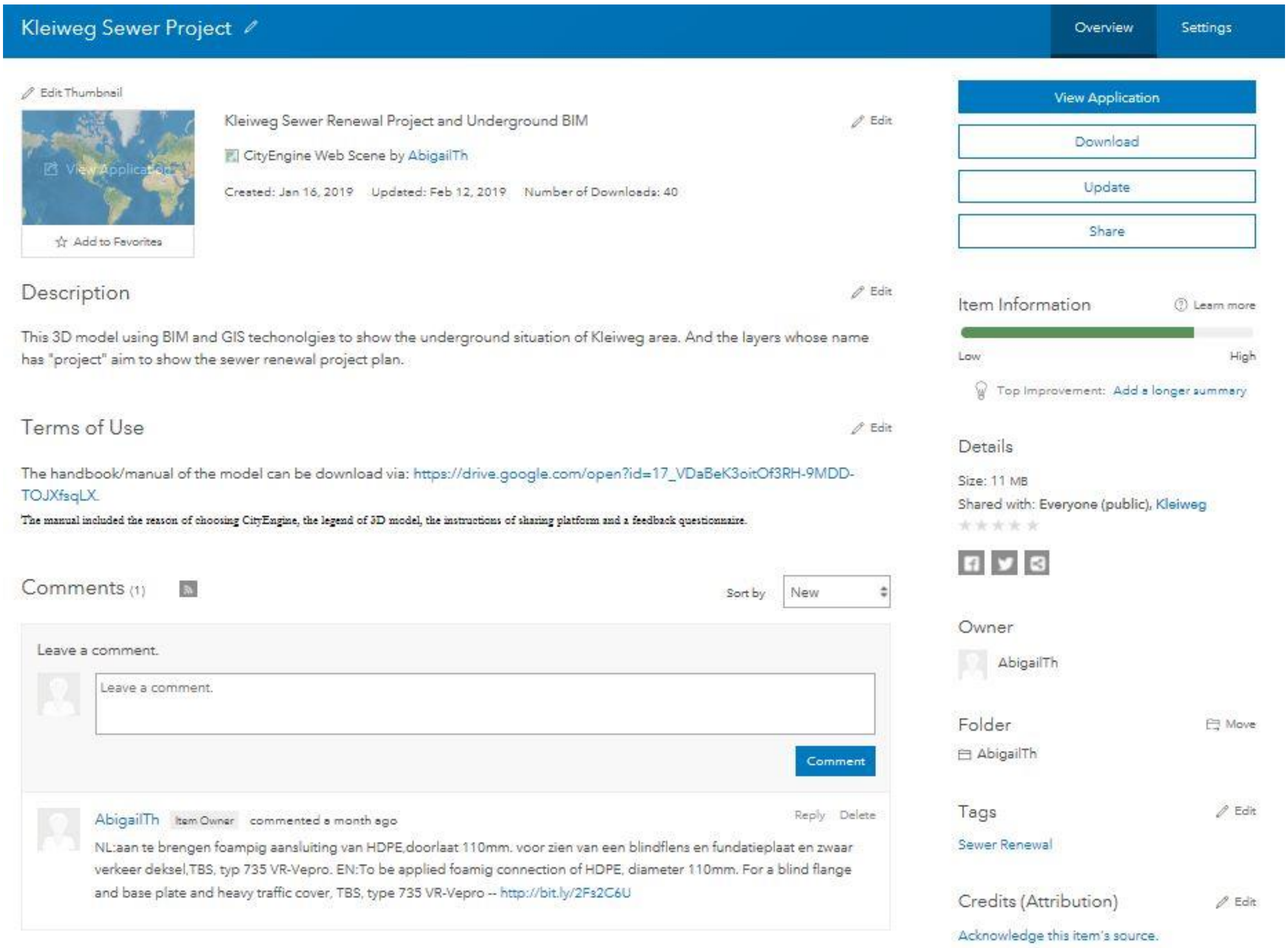


Figure 11 The screenshot of project information page

To enable the user to easily understand the model, the manual for Kleiweg 3D model has been uploaded to the information page. After finishing editing the project information, every user who is allowed access to this model can download the model in 3ws file to your computer and import in CityEngine. The 3ws file contains the basic feature layers, texture image and CGA rule files (Annex 3), which assists the user to modify and manage the 3D model for supporting their professional work. Besides, for information sharing, not only the model, but also the comments of the 3D model can be shared with the other users via a short URL. With this URL, users can directly access to the project information page or the comment's position on web viewer page.

The result of 3D modelling also is presented in the manual and sent to the stakeholders of Kleiweg project for model assessment. The next sub-section illustrates the result and discussion of model assessment.

5.3. Result and discussion of model assessment

The model assessment uses a questionnaire (Annex 4) to collect the stakeholders' feedback. Regarding the usefulness of 3D model, the utility and usability are evaluated with corresponding questions. The questionnaire used Likert items, the analysis result of the interviewees' response shows how satisfied the stakeholders are with the model.

The questionnaire uses Likert Scale, for every question, the experts give a score to express their attitude on the 3D model statements (the number "1~5" means "strongly disagree" to "strongly agree", "0" means "No responds"). By calculating the sum, average and variance of the score, the experts' responses are analysed. However, in this study, due to the small number of experts, the overall conclusion of the 3D model's usefulness is limited. Especially the expert from the municipality of Rotterdam is really busy, up to now, its feedback has not collected. Although it cannot be avoided, this problem causes the limitation of this study. Therefore, this study only calculates the sum of the score, which is used to evaluate the model performance. Figure 12 shows the concluded result of feedback. To be mentioned, the questions shown in the Figure 12 are capsules, the intact questions can be found in Annex 4.

			Engineer	Contractor
Utility	Q1	Data provision	3	4
	Q2	Data loss reduction	2	4
	Q3	Data sharing functionality	4	3
	Q4	Underground BIM quality	4	3
	Q5	LoD	3	4
		Sum	16	18
Usability	Q6	Learnability	4	5
	Q7	Interaction with the model	5	5
	Q8	Visualisation	3	4
	Q9	Helpful for work	3	4
	Q10	Valuable to promote	4	4
		Sum	19	22

Legend	
0	No idea
1	Strongly disagree
2	Disagree
3	Neither agree nor disagree
4	Agree
5	Strongly agree

Figure 12 The analysis of experts' feedback

In Figure 12, the darkness of colour indicates the agreement of the experts. The darker background of the cube, the higher score of this question, which means this expert is more satisfied with the model performance. Overall, from the darkness of the table background, it can conclude that the 3D model is useful for the experts to manage the sewer renewal project. Moreover, based on the sum of score, both the engineer and contractor think model's usability is better than utility. In particular, the users can easily understand the 3D model and friendly interact with it. In addition, it is valuable to implement the 3D model in actual work and promote it in a more extensive field.

Furthermore, the model utility still needs more improvement. On one hand, as serving the sewer renewal project, the 3D model should focus more on the sewer system itself. The sewer system in the Netherland includes three types, and it would be nicer to distinguish them in model visualisation. Also, the direction of sewage flow cannot be observed in the 3D model. In the further model modification, it is better to mark the sewage direction on the texture. Or complexly, the 3D model tries to simulate the flow of sewerage. On the other hand, it is obvious that the lowest mark is provided in the data loss evaluation by the engineer, which is owing to that they found this model focus more on the usage of the municipality. Since the municipality raises the data loss problem, this 3D model only considers one-way information flow which is from the municipality to the contractor. Moreover, the limited experts are introduced by the staff from the municipality, this study only considering partial data loss of interviewed stakeholders. However, as for the whole project, in reality, the information transfer which is same as a cycle includes more stakeholders and stages (Shown in Figure 13). In Figure 13, the orange arrows are on behalf of the project phases considered by this study. Apparently, some phases are ignored, especially the crucial information transfer from the contractor to the municipality after finishing execution. Hence, to reduce the data loss of the whole project and apply the 3D model in the entire project life-cycle, this matter needs further consideration about the data flow among other stakeholders.

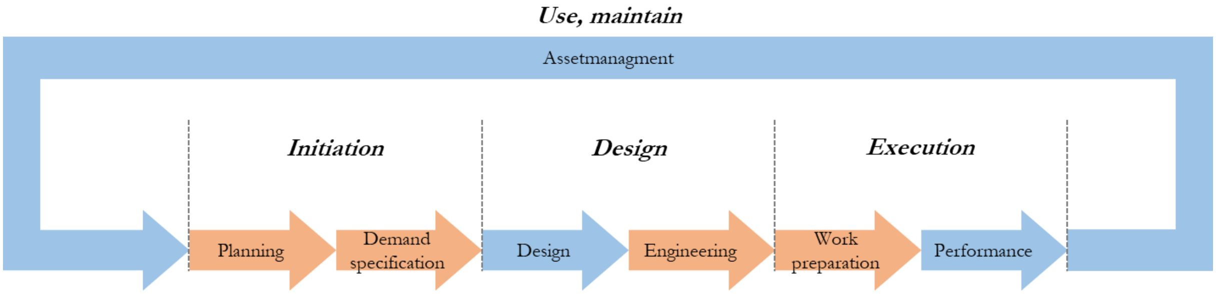


Figure 13 The whole workflow of the sewer renewal project

According to the answer of open questions, Table 8 summarises the advantages, disadvantages of the 3D model in supporting sewer project and reduce data loss. In addition, the suggestions from the experts about the 3D model improvement are also illustrated.

Table 8 The summary of experts' evaluations and suggestions

Advantages	◆ Easy to understand; ◆ Provide basic information of the Kleiweg project; ◆ Provide a good way to present and share the project to stakeholders. ◆ The "comparison mode" is really useful.
Disadvantages	◆ Lack of legend; ◆ The model is too big to run quickly; ◆ Ignore the bidirectional information flow.
Suggestions	◆ Adding legend of the 3D model; ◆ Adding "clash control" functionality to check the conflicts of the sewer system; ◆ Distinguish the sewer based on different type of sewer system.

5.4. Limitation

This section describes the limitations of this study, which may cause operation error and affect the results. The limitations mainly include four points:

- Time limitation: Due to the initial delayed response of the municipality of Rotterdam, this study changed the research area and research project. This loss of time has reduced the time for a more comprehensive study.
- A small number of experts: Actually, the experts are busy in their work, it is difficult to find a sufficient number of experts to participate in the interview. Moreover, sometimes it is difficult to get their feedback on time.
- Translate Dutch: The translation is done by Google Translation, although the result is checked with experts, there may still exist some deviation.
- Information reliability: Part of missed information was collected by the author (i.e. building height), which cannot avoid data error.

5.5. Summary

This chapter displays the results of expert interview, 3D modelling and model evaluation. In sum, the experts answer can be organised into three themes (Table 6): work description, the opinion of data loss and opinion of Relatics. As for data loss, apart from the loss in format conversion, the missing of updated data is mentioned by most experts. Then, the created 3D model is presented in the 3D scene and common platform two parts. After that, the 3D model evaluated by analysing and calculating the score of questionnaires. In general, the 3D puts up a good performance in usefulness, especially in the usability part. However, the LoD and the target stakeholders should improve. The 3D model is better to consider more working stages of the renewal project. In addition, the last section describes the limitation of this study.

The next chapter will describe the conclusion of this study and put forward some suggestions for further study.

6. CONCLUSION AND RECOMMENDATION

Refer to research specific objectives and their questions, this chapter summarizes the conclusion of whole study. Moreover, some recommendations are also put forward for further study.

6.1. Conclusion of each sub-objective.

This study aims to develop a 3D model integrating BIM and GIS technology to reduce data loss and promote data sharing between stakeholders. Based on the sewer renewal project in Kleiweg, this model should visualise the sewer system and present its external environment. As for reducing data loss, the feasible way is unifying data format and decreasing the times of data conversion. In addition, the exchanging of 3D model is not as easy as 2D datasets. Because of its enormous data volume, the 3D model has high requirements for the convenience and completeness of data exchange. By comparing the functionalities of various modelling software, this study chooses CityEngine to modelling objects with shapefiles and achieving data sharing on its common online platform. The results of specific research objectives are shown below, and the detailed research questions can be found in section 1.5.

- *To investigate the characteristics and content of the original data and converted shape files.*

Investigating the reason and content of data loss is the foundation of this research. By an expert interview, it can be concluded that, starting from the planner in the municipality, the required data is transferred to the engineer, and then the contractor gets the data and prepares the field work. In this process, Autodesk (in dwg files) and ArcGIS (in shapefiles) are the two most commonly used software of all the stakeholders. Notably, in this sewer project, when dwg files convert to shapefiles or vice versa, only the ID of objects can be saved. All the other attributes need to be reimported and manually check its integrality. Moreover, the delay of updated information should not be neglected as a part of data loss. For this problem, both the experts and previous studies suggest decreasing the times of data conversion and creating common data sharing platform. Also, the opinion of the Relatics software also collected via the interview.

- *To prepare a set of data which satisfy the demand of underground BIM for the sewer renewal project.*

Based on data availability and the requirement of underground BIM, the underground networks should show not only its distribution and characteristic but also the interaction with objects in the external environment. In this study, apart from the sewers of Kleiweg project, the other underground infrastructures and relevant surface objects are modelled. Because of the limitation of time and data availability, LoD1 is used to display the project information.

- *To develop an integrated 3D model of the underground environment.*

By comparing with Autodesk Revit, the CityEngine is suitable to develop the integrated 3D model. CityEngine can directly import shapefiles to achieve batch modelling. As for the sewer renewal project, its "Comparison mode" can compare the difference between the current and new sewer system. Besides, CityEngine is able to provide common data sharing platform with the help of Esri online. Its sharing platform has the “Share” and “Comments” functionalities, which allow the users to communicate in real-time and share the updated information directly by e-mail. This characteristic significantly promotes the updated information exchanging and ensures the information integrity of the whole project. Hence, the 3D model would be upload to Esri online after the modelling, which allows the relevant stakeholders to download and use the 3D model on their computers.

- *To evaluate the usefulness of the 3D model with the specialist of Rotterdam Municipality, the engineering company and the contractor.*

For the model evaluation, the usefulness of the created 3D model is assessed regarding utility and usability. By using and analysing questionnaire, the integrated 3D model is excellent in supporting sewer renewal project and expediently sharing data. However, the assessment also indicates that the model needs to improve its LoD of the renewal sewer system. Furthermore, as for reducing data loss, the 3D model only considering partial phases which are associated with the municipality but ignores the loss in the whole project lifecycle. The integrated 3D model may be more helpful for reducing data loss of the municipality. For supporting the sewer renewal work, the 3D model should be more comprehensive in the whole project lifecycle.

6.2. Recommendation

Based on current research results, the recommendations below provide the possible directions for future studies:

- Investigating the way to reduce data loss during data format conversion process;

  In this study, the CAD files are converted to shapefiles in one step with the help of tools in the ArcTool Box. Actually, there is not only one way to data conversion work. Apart from direct conversion, it is possible to use E00 file as an intermediary file which the CAD file is exported in and the shapefile is converted from. Also, FME is also a popular software which allows the format conversion between CAD file and shapefile (N. Chen, Li, Zhou, & Wu, 2012). To find the best way for low data loss, further study can compare the information change after converting data format by these three methods. The comparison should consider both the geometric information and attribute information. Moreover, the data quality assessment is necessary for converted data.
- Using BIM technology to support underground construction in high LoD;

  Considering the characteristics and requirements of BIM, the 3D model with higher LoD should include more details about the underground infrastructure. These details refer to the information required by underground construction work. As the experts' suggestion mentioned in section 5.3, the different types of sewer system could be distinguished by their visualisation. Also, the sewer/cable/pipe can be modelled their inside and outside separately with real texture. Furthermore, it is important to show more connection with the overground objects, especially buildings and electrical equipment. However, attainable data integrality and sufficient data accuracy are tasks of further study.
- Developing 4D model to present the whole life-cycle of construction project.

  The 4D model can be defined as a time-varying 3D model (Schindler & Dellaert, 2012). In a construction project, these various times are on behalf of the different work stages of the project. The main point of implementing 4D in project management is building a connection between the 3D model and the working schedule. This connection ensures the 3D models are consistent with the schedule in both time and space (J. Zhang, Han, Li, & Lu, 2006). The working schedule can be planned by WBS (Work Breakdown Structure), which can be achieved by Microsoft Project (J. P. Zhang, Cao, & Zhang, 2005). Moreover, since IFC is proposed for the construction industry and is widely used, it is more suitable to build the 4D management system based on the IFC standard.

  To be mentioned, the development of the 4D model is a complex process. It is not just various 3D model in different periods, but a platform which includes a database, 3D models and WBS together. The development of the 4D model in construction management needs sufficient time and professional experts, for example, construction planner, software programmer, network engineer and so on are required. Moreover, the coding technology is also essential for building the 4D model in construction work.

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Appendix 1 Template of expert interview

Interview Form

Name: Profession:

Organization/Company: Department:

Tel: Email:

Date:

1. Work Chain (For your System Engineer work in Kleiweg-west project)

1.1 Can you describe what are your main duties and concreate tasks in your work related to the sewer renewal project in Kleiweg area?

1.2 What is the main software you are using in your daily work? (For clear correspondence, you can fill the answer in the table below)

1.3 What are the main results/products you are aiming to achieve in your work? (For clear correspondence, you can fill the answer in the table below)

Software	Result/Product

1.4 For the software Relatics in System Engineer work:

- What is your opinion on the software Relatics in System Engineer work?
- Do you think there are some not well-developed parts in this software? Please give an example.
- As for the not well-developed parts, what improvements would you suggest?

1.5 When you are transferring data, I understand that all the original data have to be converted to shapefiles. Please explain the detailed data conversion steps.

- Overall procedure:
- Specific procedure (Please fill in the table below):

Original data format	Method	Used software

2. Data Description

2.1 For your System Engineer work in Kleiweg-west project, which data standard for data creation and data exchange that you are currently using?

2.2 For your System Engineer work in Kleiweg-west project, what data is needed*? In which level of detail? Using which data format?

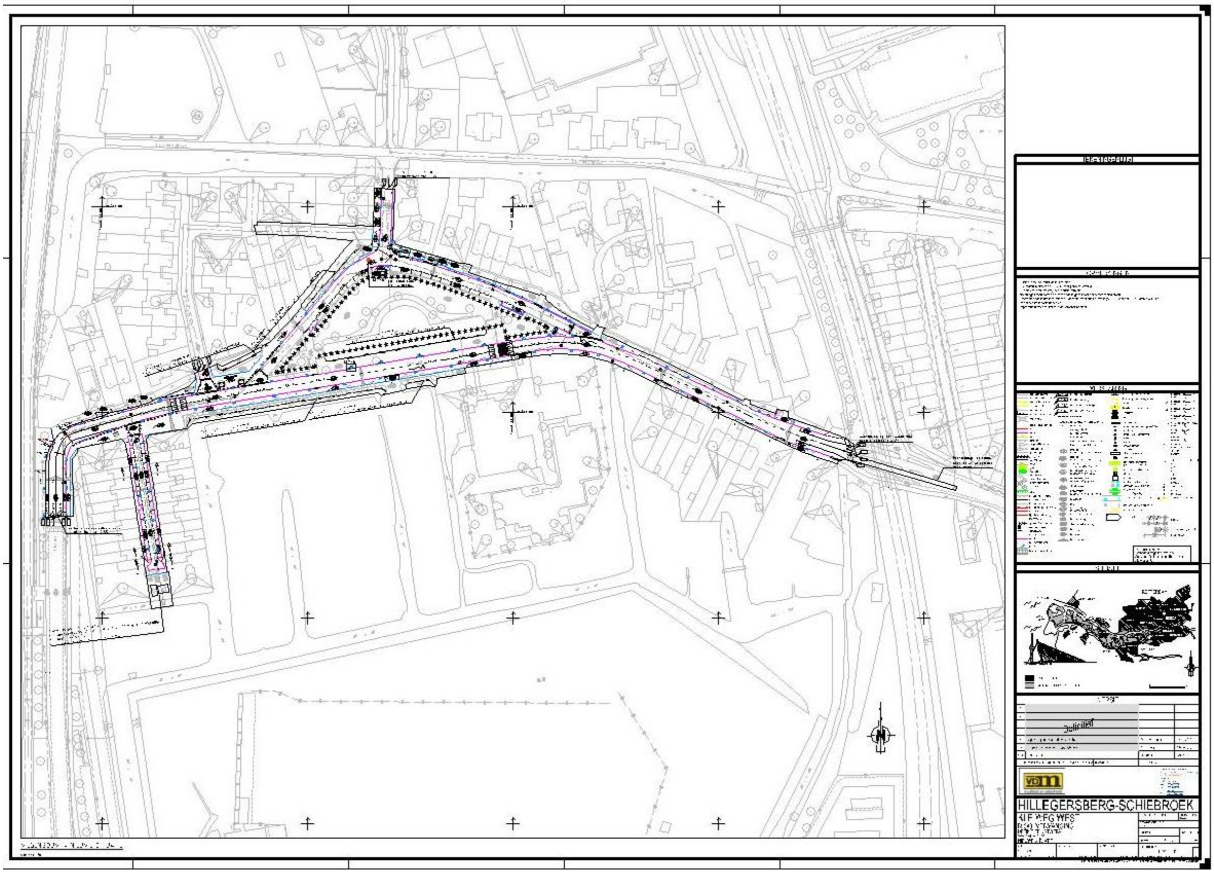
	Data	Level of Detail	Data format
2D Data			
	…		…

	Data	Level of Detail	Data format
3D Data			
	…		…

2.3 Do you think that there is data loss problem when you exchange data with the contractor for your work in Kleiweg-west project?

- If yes, can you explain what data do you think is being lost during this process?
- If yes, why this data loss problems are happenings?
- If yes, what methods would you recommend to avoid data loss?
- If no, would you describe what can be the reason for having data loss?

Appendix 2 Maps of sewer renewal plan



Appendix 3 The CGA grammar for 3D modelling

```
/**
 * File:    Building.cga
 * Created: 1 Jan 2019 00:10:11 GMT
 * Author:  s6036805
 */

version "2018.1"

##Buildings##
//Color//
Tan="#D2B48C"
AnnexeWheat="#F5DEB3"
//Attributes//
attr Building_height=10 #Building height comes from the Google Earth
attr House_street="Kleiweg"
attr House_number=""
attr type=""
attr A_Height=3

Buildings -->
case type=="Building":
  extrude(world.up.flatTop,Building_height)
```

```
  color(Tan)
else:
   extrude(world.up.flatTop,A_Height)
   color(AnnexeWheat)
   report("Height:", A_Height)

##Trees##
//Attributes//
attr Branch_Diameter=1.0
attr Crown_Diameter=10.0
attr STRAAL_KRO=4.0 #the radius of crown.

Tree-->
  extrude(world.up.flatTop,STRAAL_KRO)#The height of the branch is assumed
  s(0,STRAAL_KRO,0)
  i("assets/tree/tree_whole.obj")
  report("Branch Diameter:", Branch_Diameter)
  report("Crown radius:",Crown_Diameter)

##Light Pole##
//Attributes//
attr Pole_Height=7.2
//Color//
ElecYellow="#DAA520"

LightPole -->
  extrude(world.up.flatTop,Pole_Height)
  s(0,Pole_Height,0)
  i("assets/LightPole/Light_pole.obj")
  report("Pole Height:",Pole_Height )

LightConnection -->
  color(ElecYellow)
  extrude(world.up.flatTop,-1.0)
  primitiveCylinder(16,0.1,-1.0)
  s('1,'1,'1)

##Water##
//Texture//
WaterTex= "assets/texture/water.jpg" #Texture definition

Water_way -->
  setupProjection(0,world.xz,15,75)
  #the set of texWidth(15) and texHeight(75) just for beauty
  texture(WaterTex)
  projectUV(0)

##Street##
//Texture//
MainRoad="assets/texture/MainRoad.png"
ResidentialTexture="assets/texture/Residential.jpg"
IndustrialTexture="assets/texture/Industry.png"
RecreationTexture="assets/texture/RecreationRoad.jpg"
//Attributes//
attr TypeNum=3
```

```
attr TypeName=""
attr Function=""
attr StreetName="Kleiweg"

Street -->
  case TypeNum==3:
  texture(MainRoad)
  tileUV(0,10,'0.5)
  projectUV(0)
  case TypeNum==4:
  texture(ResidentialTexture)
  projectUV(0)
  case TypeNum==7:
  texture(IndustrialTexture)
  projectUV(0)
  else:#The rest are street in Recreation area.
  texture(RecreationTexture)
  projectUV(0)

##Underground infrastructure##
@InMesh
// Color Definition//
DrinkBlue="#00BFFF"
GasRed="#FF4500"
ElecYellow="#DAA520"
TelGreen="#32CD32"
TVPurple="#DA70D6"
DirtyGray="#D3D3D3"

#Generated by 3D Analyst in ArcGIS, thr pipes ara import in 3D form
#For a better visualisation, the show of different pipes are in different Z level
#The real depth will be displayed when you click the objects.
//Arrtibutes//
attr DrinkZ=-5.0
attr GasZ=-5.0
attr ElecZ=-1.0
attr TelZ=-1.0
attr TVZ=-1.0
attr DrinkRadius=1.5
attr GasRadius=1.0
attr ElecDia=0.05
attr TelDia=0.05
attr TVDia=0.05
#This part gives the depth value of various pipes,the number is default value at first
#The true vale will link to depth value in the attributes later

Drinkwater -->
  color(DrinkBlue)
  translate(rel,world,0,-6.0,0)
  report("Depth:",DrinkZ)
  report("Radius:",DrinkRadius)

Gas -->
  color(GasRed)
  translate(rel,world,0,-7.0,0)
```

```
  report("Depth:",GasZ)
  report("Radius:",GasRadius)

Dirty_water -->
  color(DirtyGray)
  translate(rel,world,0,-6.25,0)

Electricity -->
  color(ElecYellow)
  translate(rel,world,0,-1.0,0)
  report("Depth:",ElecZ)
  report("Diameter:",ElecDia)
Tel_cables -->
  color(TelGreen)
  translate(rel,world,0,-1.0,0)
  report("Depth:",TelZ)
  report("Diameter:",TelDia)

TV_cables  -->
  color(TVPurple)
  translate(rel,world,0,-1.0,0)
  report("Depth:",TVZ)
  report("Diameter:",TVDia)

##The sewer refer to Kleiweg sewage renewal project##
//Color and texture//
RioolwaterDark="#483D8B"
RemoveTexture="assets/texture/Remove_sewage.jpg"
NewTexture="assets/texture/New_Sewer.jpg"
//Attributes//
attr SewageSta="Current"
attr InsideDiam=0.5
attr OutsideDiam=0.64
attr Length=""
attr Elevation=""
attr WellSta="Current"
attr WellElev=""
attr C_depth=-4
attr R_depth=-4.75
attr N_Elev=""
attr N_InDia=""
attr N_OutDia=""
attr N_Length=""
attr NW_Elev=""

#PWell means the well will used in this maintainence project.

Sewage -->
  case SewageSta=="Current":color(RioolwaterDark)
                          translate(rel,world,0,-6.25,0)
  #In this project, the tubes need to be removed
  else:texture(RemoveTexture)
       setupProjection(0,world.xz,2,2)
       projectUV(0)
       translate(rel,world,0,-6.25,0)
```

```
 report("Inside Diameter:",InsideDiam)
 report("Outside Diameter:",OutsideDiam)
 report("Length:",Length)
 report("Elevation:",Elevation)

Wells -->
 case WellSta=="Current":color(RioolwaterDark)
      extrude(world.up.flatTop,C_depth)
      primitiveCylinder(16,0.25,C_depth)
      s('1,'1,'1)
 else:texture(RemoveTexture)
      extrude(world.up.flatTop,R_depth)
      primitiveCylinder(16,0.25,R_depth)
      s('1,'1,'1)
 report("Elevation:",WellElev)

New_sewer -->
  texture(NewTexture)
  setupProjection(0,world.xz,2,2)
  projectUV(0)
  translate(rel,world,0,-6.25,0)
  report("Inside Diameter:",N_InDia)
  report("Outside Diameter:",N_OutDia)
  report("Elevation:",N_Elev)
  report("Length:",N_Length)

New_wells -->
 texture(NewTexture)
      extrude(world.up.flatTop,R_depth)
      primitiveCylinder(16,0.25,R_depth)
      s('1,'1,'1)
      report("Elevation:",NW_Elev)

##Sewage well##
//Color definition//
DarkGray="#A9A9A9"
LightGray="#D3D3D3"
//Arrtribute//
#The width,radius and depth of  the wells based onthe assumption
#The assumptions are based on product model from Google
attr PuttenType="Rioolwater Putten"
attr P_depth=-4.25

Rioolwater_Putten -->
 color(LightGray)
 extrude(world.up.flatTop,P_depth)
 primitiveCylinder(16,0.5,P_depth)
 s('1,'1,'1)
```

Appendix 4 The template of questionnaire

Feedback Questionnaire

After finishing investigate the 3D model, please answer the following questions. Your feedback will help me evaluate and optimize the model. Thanks!

The following questions focus on testing the utility and usability of the 3D model of Kleiweg. Please rate each item, and the criterion is shown below:

0 —— No idea; 1 —— Strongly disagree; 2 —— Disagree; 3 —— Neither agree nor disagree; 4 —— Agree; 5 —— Strongly Agree.

Utility

The model can effectively provide required information for the sewer renewal project in Kleiweg.

[ ]

The model based on Esri platform can effectively reduce the loss of updated data.

[ ]

The model based on Esri platform can help the users share data effectively and conveniently

[ ]

The model can satisfy the requirement of underground BIM.

[ ]

Level of detail of the model can sufficiently shows the underground situation of Kleiweg area.

[ ]

Refer to the utility of this model, please give some suggestion or opinion.

Usability

Based on the introduction text, the model is easy to get familiar with.

[ ]

It is easy to interact with the model via the Web viewer facilities.

[ ]

Assigned color, texture and geometry design of objects make the model easy to be understandable.

[ ]

Once the user has learned the model, the 3D model is helpful for his/her work.

[ ]

The integrated 3D model is valuable to promote in different projects and study area.

[ ]

Refer to the usability of this model, please give some suggestion or opinion.

Suggestion

Please explain the major advantage of the model you have found;

Please explain the disadvantages of the model you have found;

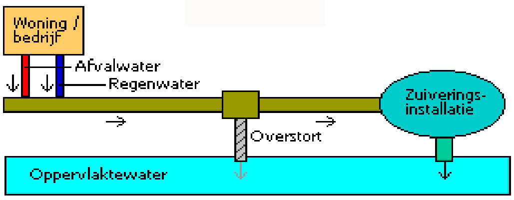
Please provide any suggestions you think are helpful for further optimizing the model.

Appendix 5 The type of sewer system in Netherland

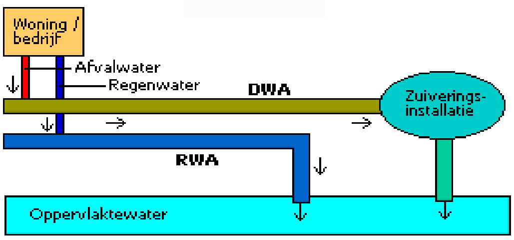
The sewerage system in Netherland is consists of sewers, pumping stations and sewerage wells. This system collects and disposes wastewater (from households and businesses) and rainwater. According to the sewerage system, those water transfer to the central waste water treatment place (Gemeete Rotterdam, 2018). There are three types of sewerage system used by the Netherlands (Unihorn, 2016), Figure 6 provided by (Wikipedia, 2019):

- Hybrid sewage system (Gemengd Stelsel, GWA): In this system, the rainwater (Regenwater) and wastewater (Afvalwater) is collected into one sewer and subsequently transported to the treatment place.
- Separated sewage system (Gescheiden Stelsel, GS): In this system, there are two types of sewer working separately, the DWA (droogweerafvoer) is used to transport wastewater in a dry environment, and the RWA (neerslagwater op bestrating) is used to transfer rainwater.
- Improved separated sewage system (Verbeterd Gescheiden Stelsel): In this system, the rainwater from roof will be collected by SWA (Schoonwater), and the RWA just collect the rainwater on the road (Lelystad & Oost, 2010). There is a valve (Klep) used to shunt the rainwater.

GWA



GS



Improved GS