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Prototyping a domain-task ontology for facilitating strategic decisions of asset managers of public sewerage systems

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PROTOTYPING A DOMAIN-TASK ONTOLOGY FOR FACILITATING STRATEGIC DECISIONS OF ASSET MANAGERS OF PUBLIC SEWERAGE SYSTEMS

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EXECUTIVE SUMMARY

Introduction

The current research stems from the motivation of reducing the information loss that asset managers face in the operation & maintenance phase of the project. Most of the public infrastructure assets' condition nowadays deteriorate due to ageing and municipalities confront challenges to manage their portfolios effectively by adopting proactive management strategies. To succeed the highest possible value from assets, asset management is being adopted as an industry practice in the Dutch construction sector. Successfully managing assets requires managers at the handover stage to acquire accurate, explicit, and complete information from the earlier stages (Design and Construction phase). Only with reliable information they can make the right decisions about costs, performance, and risks which are the pillars of asset management theory. However, the information in the operations stage is incomplete or invalid and dispersed in various sources. This is an obstacle to reuse knowledge as asset managers have to identify information from various sources leading to secondary costs. Significant barriers are the asset managers' limited involvement from the project's beginning. That makes their needs less explicit for contractors and reduces the level of understanding of what information they have to deliver. This thesis works towards providing a more reusable and flexible method in the construction industry for capturing and structuring the strategic information needs of asset managers in a machine and human-understandable way.

Research Design

The research addresses to the problem that asset managers of public spaces face, namely receiving incomplete information from the construction phase. The research follows the steps that Verschuren and Dooerwaard (2010) suggested that a practice-oriented project should take. First part of the process focuses on problem analysis. An exploratory study was conducted to identify the problem of inadequate delivery of information. Based on findings from academic and industry context, the main research question was formulated to arrive at the final solution.

"How can we capture and structure the strategic information needs of the asset owner from the earlier phases towards operation & maintenance phase for a portfolio of assets?"

The second part focuses on identifying and analysing the background theories and causes of the problem. Besides the literature review, interviews are conducted to validate the causes of the problematic transfer of information at the handover stage in the Dutch Infrastructure sector. Moreover, interviews provided a first insight into the information needs of asset managers. The third part starts with a stakeholder analysis and the elicitation of needs to requirements is taking place. That forms the scope of the designed solution and produces its main concepts. The fourth part describes the design and evaluation of the solution. It presents how we build it with an editor tool and how we evaluate its structure and content with structural metrics, tools and use cases from the practice. Finally, the fifth and last chapter presents the main conclusions of the research, its limitations and recommendations for the developed solution and the industry.

Problem Exploration & Definition

This stage of the research includes the theoretical background of the research and the examination of the information loss causes. A literature review with the

main concepts of the research is presented and a first identification of the causes that hinder asset managers to obtain complete information in order to create value for their assets. The literature identified several problems in the current transfer process of information and subsequently those causes were validated by experts from the industry. Few of the important causes identified are: the lack of formal asset requirements, not reusable information because of the absence of a common structure and poor definition of the information and the reception of irrelevant information from the earlier phases. Furthermore, the problem exploration revealed that an ontology provides the input to solve the above mentioned problems . Ontology is a generic information model in which information is described, defined and organised in a structured way. An ontology can be used as a blueprint of asset owner's information needs. Its reusable and adaptable nature can ensure that asset information requirements will be defined from the beginning of the projects.

Development of the Ontology

This development phase of the solution starts with introducing the methodology of Zhou et al. (2016) that was adopted in order to develop the prototype ontology. Firstly, the scope and purpose of the ontology are defined. The domain is public space and, more specifically, the sewerage systems. The ontology intends to solve the identified problems. It aims to: 1) enhance the communication between the client and the contractor by making explicit the information needs of the client from the beginning of a project, 2) facilitate the contractors to transfer only the relevant information and 3) aggregate the information from diverse sources resulting in reusable information and reduction of secondary costs. Then, the execution of a stakeholder analysis and elicitation of the prototype's structural, functional and environmental requirements shapes the scope of the design (see Table 4.3). Finally, after the review of existing standards and combined with academic literature and the interviews, a conceptual model was presented, which facilitates understanding of how the diverse knowledge is interrelated. It is consisted of the eight main concepts and the relationships between them (see Figure 4.5a). Four of them (sewerage system, related party, object, function) are coming from existing ontologies while four new ones (location, risk, operation & maintenance, state) are proposed for the description of necessary knowledge. The conceptual model helps to create the backbone of the ontology (taxonomy) and classify the rest of the identified concepts, enabling the representation of more specialised knowledge.

Construction of the Ontology

This chapter introduced the steps adopted to develop the solution for capturing and structuring the information. Linked data and semantic web technologies were used to capture and structure the information. The information was stored and structured in three linked data pieces (subject-predicate-object). This format can take any subject and link it to any object by using the predicate to show their relationship. Firstly, an editor tool was selected which can support most ontologies' formats (e.e RDF, OWL etc.). OWL was selected to be the language of the ontology as it can restrict the properties, define the meaning better, and ensure that the ontology will not provide contradictory knowledge. Most ontologies are described using classes, properties or relationships, restrictions and individuals. Therefore, firstly the concept or class hierarchy is established. Then, the object relationships are modelled. The properties can link the concepts and establish the generic knowledge that the ontology aims to represent. However, asset managers need more information for every concept to facilitate their decision-making. Data and annotation properties can describe this information and need to be established as well. Finally, the restrictions of properties and individuals are modelled. Restrictions prevent our ontology from providing contradictory knowledge to the users while individuals illustrate its use cases.

Ontology Evaluation

Ontology is a powerful tool to represent the knowledge for a domain. However, to be useful, the intended users need to be confident that its concepts and relationships represent the domain accurately. Thus, the structure, the knowledge representation of the ontology and its ability to cover the defined scope have to be evaluated. To evaluate the ontology eight criteria are established after consultation of the literature. The defined functional, structural and environmental requirements of the solution's design are assigned to the relevant criterion. For the evaluation, four different methods are followed. Technically the ontology is evaluated by structural metrics and an online tool. The content of the ontology is validated against three use cases from the practice. The relevant missing terms are added to the model and then, the ontology's technical competence is evaluated once more. The created queries using a programming language proved that the ontology returns information that covers the defined scope. The described process assessed the scope, structure and knowledge representation of the developed prototype and revealed its technical soundness and an acceptable level of domain's knowledge representation. It also reveals that the ontology prototype represents a wide variety of concepts in the domain but not expanding them into detail. That makes the designed solution easily adaptable and extendable in case of future use.

Conclusion

In conclusion, the research demonstrated a way of identifying, capturing and structuring asset information needs with which users can communicate effectively using a common language. The ontology can aggregate information from diverse sources and enhance the communication between parties by provide them a common understanding given a specific scope. In this way, the information needs of asset managers can be explicitly defined from the beginning of a project, resulting to complete and reusable information and the reduction of secondary costs. This research project comes also with some limitations. An extra validation with domain experts would help to increase the clarity of the defined terms. The study also was conducted using terms in the English language. The use of the developed solution in the Dutch language needs to be researched. The research concludes with recommendations for the developed solution and the industry. The recommendations concern the implementation of the proposed ontology and the adoption of common standards in the industry for the automation of the transfer of information and the reduce of information loss.

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This report is the result of the last seven months of research into Information Management in the construction industry. This report has been written to conclude my studies in the masters program Construction Management and Engineering and fulfil its graduation requirements. The research was conducted in collaboration with the Transportation and Mobility division of Sweco B.V. This research stems from my motivation to contribute to tackle the information loss in the construction industry and it has been a roller coaster ride. However, the help and support of a few people made possible the completion of the goal to obtain my master's degree. Therefore, this space on the report is devoted to expressing my gratitude to these people.

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I hope you will enjoy reading this thesis, and it may inspire you to contribute to improving and digitising the construction industry.

Apostolos Barekas
Delft, Novemeber 2022

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ACRONYMS

[AEC] : Architecture Engineering and Construction

[AM] : Asset Management

[AIM] : Asset Information Model

[GIS] : Geographical information system

[IAM] : Infrastructure Asset Management

[ILS] : Information Delivery Specification

[KM] : Knowledge Management

[OTL] : Object Type Library

[O & M] : Operation & Maintenance

[SAM] : Strategic Asset Management

[SAMP] : Strategic Asset Management Plan

[SSI] : Semi-Structured Interview

[WIAM] : Water Infrastructure Asset Management

[IMBOR] : Informatiemodel Beheer openbare ruimte (Information model for Public Space Management)

[GWSW] : Gegevenswoordenboek Stedelijk Water (Urban Water Data Dictionary)

[WWW] : World Wide Web

[URL] : Uniform Resource Locator

[URI] : Uniform Resource Identifier

[HTTP] : Hypertext Transport Protocol

[HTML] : Hypertext Markup Language

[LOD] : Linked Open Data

[RDF] : Resource Description Framework

[W3C] : World Web Consortium

[RDFS] : Resource Description Framework Schema

Part I

IDENTIFYING THE PROBLEM WITH INFORMATION LOSS

1 INTRODUCTION

The Chapter 1 introduces the current information problem faced by asset managers in the Dutch public space sector. This chapter entails background information and the problem definition that explain the issues that asset managers confront to acquire accurate information from the previous phases that they need to operate and manage their assets (Section 1.1 a nd Section 1.2). The next section (Section 1.3) states the gap that this research is oriented to fill in the academic and industrial content. In Section 1.4, the research objective is underlying the importance of creating a framework that will define asset managers' information requirements/needs from the earlier phases of a project. The main research question is oriented to answer the research objective, whilst the sub-question provide guidance in order to incrementally draw up a solution to the problem (Section 1.5). Finally, in this chapter, a sketch of the report's structure is provided in the Section 1.6. It depicts how the chapters are connected and the methods that have been applied to elicit an answer to the main question and produce meaningful conclusions.

1.1 SUBJECT INTRODUCTION

Most of the public infrastructure assets' condition nowadays deteriorate due to aging and municipalities confront challenges to manage effectively their portfolios by adopting proactive management strategies (Halfawy, 2008).

For the assets it is critical to assess value from a complete life perspective to get the most out of them (Ashworth, 2016). Thus, asset managers at the handover stage must acquire accurate, explicit, and complete information from the earlier stages (Design and Construction phase). Only with reliable information asset managers can make the right decisions about costs, performance, and risks which are the pillars of asset management theory (Haase and van Belzen, 2016).

This thesis works towards identifying a set of asset information requirements by focusing on urban water systems (specifically on public sewerage systems). That ensures that the information that public authorities need from construction phase for making strategic decisions and satisfying their business needs, is clearly defined by the beginning of the process. Then, that information needs can be included in an ontology (or Object Type Library). The ontology will allow asset owners to define the information they need from the earlier phases and enable the actors to work with the same standards and data. By succeeding a common understanding of requirements, asset-related data is gathered in accordance with the needs of asset managers for strategic decisions and by formalising them with an ontology, the performance of capital investment decisions, risk management and operational performance during the asset portfolio's lifetime will be enhanced, affecting productivity (Heaton et al., 2019). In addition, an ontology enhances the involved parties' communication, reducing the failure costs of information transfer and retrieval time.

1.2 PROBLEM DESCRIPTION

Infrastructure asset management (IAM) of urban water systems is the collection of processes that utilities should include to ensure the highest possible infrastructure performance cost-effectively during its lifecycle (Alegre and Coelho, 2012). To facilitate infrastructure asset management, the information delivered in the handover stage should include accurate, complete and up-to-date data related to infrastructure assets for effective operation and maintenance (Farghaly et al., 2020). However, according to Bosch et al. (2015), 30% of the information in the operations stage is incomplete or invalid, leading to secondary costs as managers are looking for relevant information.

Despite that, several works (Ashworth, 2016; Becerik-Gerber et al., 2012; Carbonari et al., 2015) have criticised the lack of connection between the information delivered and the owners' goals and requirements for AM. Fang et al. (2022) argued that there is no clear method to create, exchange, and manage the asset data from construction to the O&M phase. The beneficial effects of the integrated asset management information transfer are still unrevealed because the engagement of asset managers in the design and construction phase is limited (Fang et al., 2022). Therefore, there is a need to improve the handover of asset information from the earlier stages of the projects to the operation and asset management stage as this process malfunctions at present (O'Keeffee et al., 2017). This can be achieved by defining the information needs/requirements of the public authorities and enable them to speak the same language with the contractors of the earlier phases. In this way, the contractor will be able to understand the information that is needed to deliver to the party responsible for the management and operation of the asset.

The literature identifies several problems with the capture of the information from the design and construction phase and its delivery to asset managers.

- Designers and construction managers do not clearly understand the information needs of asset managers.
- Incompetence of clients to clearly define their information requirements early in a project to facilitate their inclusion in the delivery process.
- Asset managers do not need all the information that is generated during the design and construction to execute their strategic tasks.
- Asset managers spend time to identify the relevant information to disperse sources. That leads to secondary costs and makes difficult to reuse the information.

1.3 RESEARCH GAP

1.3.1 Academic Context

Asset management covers the process of optimising return by examining performance and making critical strategic decisions at all stages of an asset's lifespan (Too, 2010). However, because of the problems that were mentioned in Section 1.2, there is a need for the early involvement of asset managers in the whole life asset process. In order to deliver the best value from assets, it is essential to consider value from a whole life perspective.

The operational & Maintenance phase is responsible for the 60% of the costs of a project (Akcamete et al., 2010; Ashworth, 2016; Ashworth et al., 2017, 2018; Patacas et al., 2016; Sadeghi et al., 2018). Early involvement by AM is beneficial for the whole life design process as "up to 80% of the operation, maintenance and replacement costs of a building can be influenced in the first 20% of the design process" (International Organization for Standardization, 2017).

The literature review has indicated a lack of understanding of what information should be captured from the earlier stages to facilitate asset management strategies at a portfolio level. The problem becomes even more significant because of the unclear content of handover documents that should include the client's information exchange requirements (Ashworth et al., 2017). Thus, research has to be conducted in order to enhance the quality of information that has to be collected for asset managers, as not all the data stored from the construction and design stage is relevant to the asset management phase (O'Keeffee et al., 2017).

According to Ashworth et al. (2018), research has to focus on establishing a support method for asset managers to develop solutions for exchanging information that satisfies their wider asset management strategy. Currently, some researchers have focused on ontology methods in order to provide a solution to the information exchange problem between the AEC industry and AM. However, there are very few ontologies developed for the water domain (Varga et al., 2022).

An opportunity exists here to develop an approach that will capture, store and formalise the information requirements that have to be delivered from construction to the operational phase for managing a portfolio of assets. A prototype of a domain-task ontology that will facilitate the knowledge retrieval of asset managers' information requirements from the pre-operation & maintenance phase is proposed in this research.

1.3.2 Company Context

Sweco is a consultancy firm that provides asset management advice and guidance to public and private clients. They have developed an asset management software called Obsurv, which keeps track of municipalities' assets, and with frequent inspections, they assess their condition. After research from the municipalities of Almelo and Utrecht, it is evident that 50% of an object's information that an asset manager needs is lost in the earlier phases of an asset's lifecycle. For example, a 2D CAD drawing from the design and build phase is transferred to the organisation responsible for the operation and maintenance, where it is stored using their own asset management software, which is portfolio based. But, the two software have different levels of detail for the required information and the asset management software does not need all the information that was assigned to objects during the previous phases. The required information for asset managers is stored manually, an error-prone activity that can result in distortion and loss of the information. In conclusion, municipalities confront challenges with managing public space assets due to missing or incorrect data, leading to wrong investment decisions and unnecessary costs.

1.4 RESEARCH OBJECTIVE

The current research stems from the motivation of reducing the information loss that asset managers face in the operation & maintenance phase of a project. The problem described in Section 1.2 can be translated into various objectives that can guide this research project. First, the most important objective is to get insight into the information needs that organisations responsible for managing the public space have at a portfolio level. Then another important objective is to get a further understanding of the best tools and standards to capture and structure the information requirements that an asset owner has for managing his assets. Once all these have been identified, the next and most important objective to be achieved is developing a new model. The model should be able to capture and make explicit what information is required to be transferred to the asset managers from the initial stages of the projects. That would contribute to more accurate, upfront information for managing a portfolio of assets than the current practices. In summary, the main objectives of this research project are:

- The identification of asset owners' information needs from the construction phase of a project in order to enhance the communication with the related parties (construction managers, designers etc.).
- Identify and use the best standards and tools for capturing and structuring of the necessary knowledge in order to be available from the beginning of the projects.
- Use the right technologies to aggregate information from diverse sources and make it reusable and easily extendable. That would reduce the time retrieval of information from asset managers leading to reduction of secondary costs.
- Develop a prototype of a domain-task ontology that includes only the relevant concepts and relations for facilitating the cost-effective strategic decisions of asset managers of sewerage systems.

1.5 RESEARCH QUESTION

The above-mentioned objectives can be reached by answering several research questions that can guide this research. The main research question can be formulated as follows:

"How can we capture and structure the strategic information needs of the asset owner from the earlier phases towards operation & maintenance phase for a portfolio of assets?"

In order to answer this question, several sub-questions need to be answered. These can be expressed as:

1. "What are the drawbacks of the current process of project information transfer between the organisations managing the public spaces and the contractors?"
2. "What information the organisations managing public spaces need from the earlier phases for strategic decision making?"
3. "How can we translate the information needs to requirements and which are the main concepts of the ontology?"
4. "How should the ontology be constructed?"
5. "How can the ontology be evaluated?"

1.6 RESEARCH OUTLINE

This report is divided into five main parts and it is further decomposed in seven chapters. This Section will elaborate on the contents of each chapter and on which chapter are answered the research questions as shown in Figure 1.1.

- Part I: This part consists of chapters one and two. The first chapter introduces the research project, while the second refers to the research methodology followed to answer the sub-research questions and finally answer the main research question.
- Part II: This part includes the problem analysis, providing the theoretical background. The theoretical background offers an insight into the existing literature related to the main concepts that this research consists of Strategic Asset Management, Information & Asset Management, and Ontologies. The

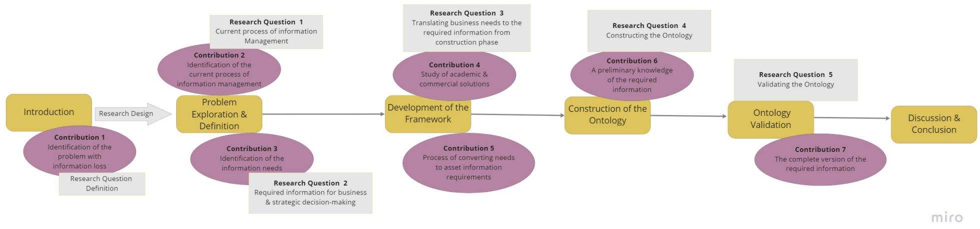


Figure 1.1: Report Structure

chapter ends with the presentation of the results of the exploratory interviews. The interviews were conducted to understand the current process of information documentation and exchange of information in the public space projects, the verification of the problem and the identification of information needs for the development of the prototype ontology.

- Part III: This part focuses on developing the prototype that will capture the information needs that asset managers require for strategic decisions. It starts with explaining the need for such a model and continues by presenting the information needs identified through the interviews and the study of various existing sources that can be used to construct the ontology as they include relevant information. Finally, the chapter also discusses how the requirements were elicited from the needs and the conceptual model and the categorisation system that was used to provide a hierarchy of those needs and requirements.

- Part IV: This chapter presents the ontology modelling. Firstly, provide the description of the used tool to construct the prototype. In continuation, the chapter explains the steps for creating the prototype. Finally, it presents the evaluation process and the final version of the ontology.

- Part V: The final chapter answers the research questions of the graduation project. The limitations of the proposed framework and future work recommendations for the industry and academic sector are also proposed.

1.7 SUMMARY

To operate their assets effectively and create value for the organisations, asset managers need to have complete, accurate and up-to-date information (Farghaly, 2020). To succeed that, their information requirements from the previous stages must be clearly defined from the beginning of the projects. However, the information needs of the asset managers are not formalised yet, and a clear framework has not been defined. Hence, an approach for capturing, defining and structuring the asset owners' requirements is needed. This research focuses on developing an ontology to satisfy the need for precise asset owner requirements for strategic decisions.

2 RESEARCH DESIGN

2.1 INTRODUCTION

This chapter aims to describe the methodology and strategy that the project adopted to provide a solution. Section 2.2 describes the methods and approach followed. Public authorities manage various assets in the domain of public spaces, hence it is essential to limit the scope to a particular type of assets. This is analysed in Section 2.3. Finally, summary of the second chapter is provided in Section 2.4.

2.2 RESEARCH METHODOLOGY

The research intends to contribute towards the solution of the problem that asset managers of public spaces face, namely receiving incomplete information from the construction phase. Therefore, drawbacks to the current process and information needs were identified. Consequently, a solution is suggested after revising existing solutions and technologies. This research follows the steps that Verschuren and Dooerwaard (2010) suggested that a practice-oriented project should take, more specifically:

- ***Problem Analysis***: At this stage, the problem must be stated and become clear for everyone. Three fundamental questions have to be ordered to make the problem transparent to everyone: ***what*** is the problem, ***why*** it is a problem and ***whose*** problem it is.
- ***Diagnosis***: After identifying the problem, the theoretical background and the causes can be examined. If the nature of the problem and its causes are understood, an effective solution can be drawn.
- ***Design***: At this stage, the intervention plan can be formulated to solve the examined problem. The information of the previous step is important to initiate the solution's design.
- ***Intervention/change***: Only the design is insufficient to provide a definite solution to a problem. A set of changes must be implemented.
- ***Evaluation***: The final stage consists of the verification of the developed solution. If the solution does not solve the problem or create new problems, the previously mentioned steps have to be repeated from the beginning.

This research study adopted the above process. The activities performed were grouped by phases, and they are explained below and represented graphically in Figure 2.1:

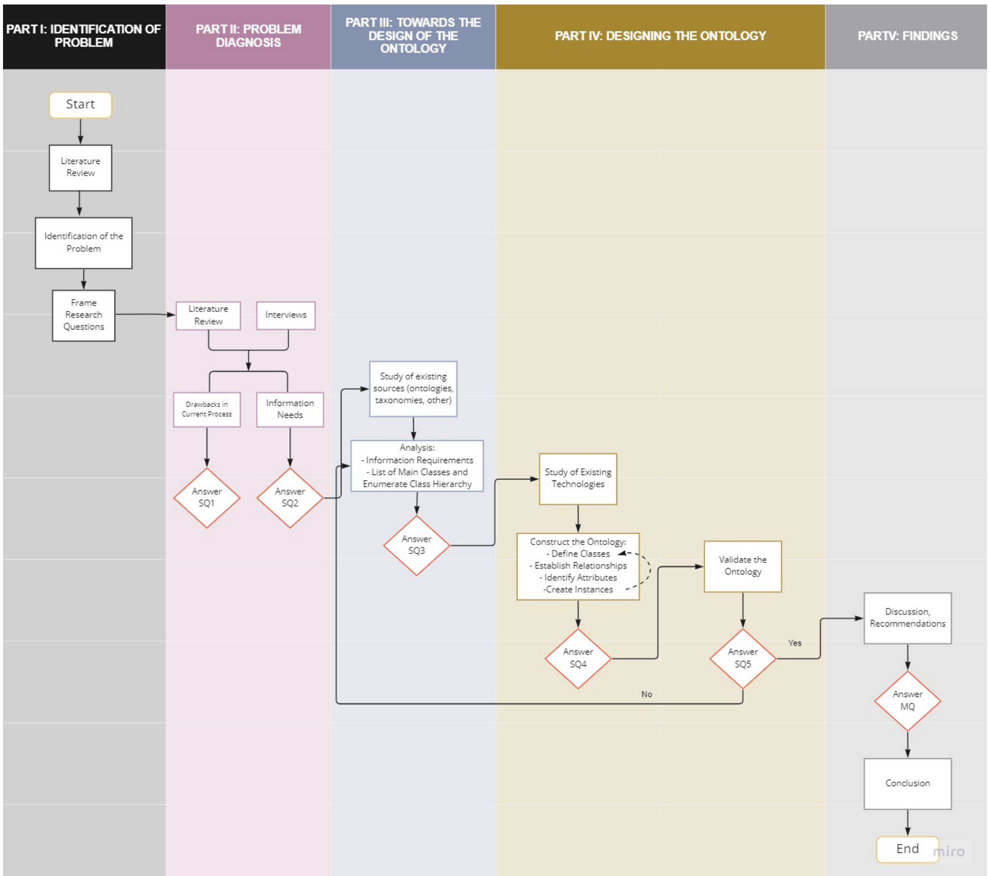


Figure 2.1: Research Methodology

The first stage of the practice-oriented process, i.e. Problem Analysis, is elaborated in Part I. The chapter answers the three fundamental questions (what, why and whose is the problem) to analyse and describe the problem. More specifically, an exploratory study is conducted to identify the problem of information inadequate delivery (Section 1.2) and why it is a problem in academic and industry contexts. The latter is described in Section 1.3 as it underlines the absence of a solution that clearly defines the information requirements of asset owners. That results in incorrect data and costly investment decisions. Finally, from the beginning of Section 1, it is mentioned that the asset owners of public spaces face the problem of information loss.

Part II focuses on identifying and analysing the background theories and causes of the problem. Besides the literature review (academic literature, standards and best practice guidelines), interviews are conducted to identify and verify the causes of the problem and the information that asset managers need from the construction phase.

The information identified will be used in Part III to start the solution's design and answer the third sub-research question. The process starts with a stakeholder analysis and eliciting information needs to information requirements. That forms the scope of the designed solution. Then, combined with examining existing solutions, the formulation of the main concepts of the solution is gained.

Part IV starts with the description of the tool that can capture and structure the information requirements. Then, the modelling of the solution by using the preferable technology is described, and the solution is evaluated by commercial tools, structural metrics and use cases from the practice. At the end of the process, in Part v a feasible solution is proposed for the early definition of the information required by asset owners for strategic decision-making.

2.3 RESEARCH SCOPE

This graduation research is fulfilled to satisfy the requirements for the Construction Management and Engineering degree at TU Delft. The graduation project is conducted in collaboration with Sweco B.V., a European engineering consulting company that provides services such as the analysis, calculations, studies, and the planning, design, and construction of buildings and community infrastructure.

The research focuses on the identification, capture, and structure of information requirements that asset managers of public spaces have to satisfy their business needs. After identifying asset owners' information needs and eliciting information requirements, this thesis works towards developing a prototype of an ontology to include the required strategic information from the design and construction phases and link it with the objects of a public sewerage system. That means that the prototype is oriented to include the knowledge for the point that wastewater leaves the boundaries of a building property or enters a road's gully, to the point it is discharged to into a treatment facility. The overall goal of the thesis is to enhance the information delivery process as the project stakeholders will know from the beginning what information should be delivered to the organisations managing the public spaces.

2.4 SUMMARY

This chapter has attempted to explain the research design that was followed by this graduation project. The current research is more practice-oriented, trying to suggest a solution for the definition of the information requirements of the public authorities for a sewerage system. Due to the fact that the proposed solution is adaptable, modular and consistent can help towards to the creation of a complete model that can tackle the information loss problem in the Dutch authorities managing the public spaces. The method proposed by Verschuren and Dooerwaard (2010) is adopted as a research methodology for the current project. The research is divided into five parts which content was analysed in detail. To conclude this chapter, the research scope of the project was stated to clarify the aim of the research and its boundaries.

Part II

PROBLEM DIAGNOSIS

3 PROBLEM EXPLORATION & DEFINITION

3.1 INTRODUCTION

This chapter explains the concept of Strategic Asset Management and the Information asset managers need to manage their assets and effectively create value for their organisations. The chapter also explores the topic of Ontologies and their adoption to capture, structure and transfer knowledge amongst related parties. The insights from the literature review will form the basis for the interviews and the developing prototype. Moreover, the interviews will verify the problem of incomplete handover of information between the phases. They will further provide a preliminary insight into the information attributes for the design of the prototype as well. This chapter answers the sub-research questions 1 & 2 about the current information management process and asset owners' information needs from the construction phase.

Section 3.2.1 underlines the importance of Public Water Infrastructure for the society. Section 3.2.1.1 introduces Strategic Asset Management as a concept and gives a first impression what knowledge managers need to make effective strategic decisions. Having discussed the theory of Strategic Asset Management and the considerations that public space managers have for making strategic decisions, the required asset information has to be explored. The chapter moves on to Section 3.2.2 which details asset information forms and formats that asset managers receive at the handover of projects. However, these deliveries often comes with incomplete information. The causes of are explained in the Section 3.2.3. In Section 3.2.4 the ontology concepts are explained and why they are a solution of capturing and structuring information.. The chapter is concluded with the presentation of the exploratory interview analysis. The interviews were conducted to identify the current information exchange process between the contractor and the municipalities. In addition, they intended to verify the process' drawbacks and get a preliminary insight into information attributes that asset managers need to make long-term decisions.

3.2 THEORETICAL BACKGROUND

3.2.1 Importance of Public Space Management for Society

A significant portion of public life is conducted in public spaces. Public space includes assets like roadways, railroads, parks, retail malls, public green areas, stations, and utility infrastructure that isn't apparent to the naked eye (van Capelleveen and Bruijn, 2022).

The Physical infrastructure that provides the public with resources and critical services is crucial to the social and economic success, development and welfare of human society (Schraven et al., 2011; Uddin et al., 2013). Water systems in urban areas are the most important component of global public infrastructure, and public authorities are tasked with managing and enhancing them for current and upcoming generations (Alegre and Coelho, 2012). The management and enhancement of public infrastructure becomes more and more complex because there is an emerging need for replacement of the aging infrastructure and due to climate adaptation and energy transition (Duivenvoorden et al., 2021; van Capelleveen and Bruijn, 2022)

This thesis will focus on Water and Wastewater Public Infrastructure. This category of Public Infrastructure includes (Uddin et al., 2013):

- Water supply (pumping stations, treatment plants, main water lines, wells, mechanical/electric equipment)
- Structures (dams, diversion, levees, tunnels, aqueducts)
- Agricultural water distribution (canals, rivers, weir, gates, dikes)
- Sewers (main sewer lines, septic tanks, treatment plants, stormwater drains)
- Stormwater drainage (roadside gutters and ditches, streams, levees)

In the Netherlands, the annual cost of managing and maintaining the municipal domain's artefacts in public space ranges between $7 and $8 billion. Additionally, provincial domain administrators spend 1.5 billion annually (van Capelleveen and Bruijn, 2022). Focusing on water urban systems, according to Wijnia and Croon (2015), in the Netherlands 415 municipalities and 25 water boards are responsible for collecting and treating wastewater. These authorities have a cost-cutting pact in place. A major element to this agreement is to: "reduce the cost of the water chain by €380 million per year, on the total annual expenditure of about 3,000 million euro".

Asset management implementation is anticipated to be crucial in this cost-cutting effort (Ouertani et al., 2008a). To facilitate that, the information delivered in the handover stage should include accurate, complete and up-to-date data related to infrastructure assets for effective operation and maintenance (Farghaly et al., 2020). The report of van Capelleveen and Bruijn (2022) supports that this can be achieved by: "Better information management, information provision, prevention of information loss, and better information for asset management."

3.2.1.1 *Strategic Asset Management*

WHAT IS STRATEGIC ASSET MANAGEMENT? Strategic asset management aims to achieve long-term organisational goals and effectiveness by dynamically aligning the essential infrastructure assets to meet and face changing circumstances (Too et al., 2006). The strategic viewpoint of infrastructure asset management strives for successful performance of the portfolio of assets by taking into account the long-term service needs of the costumers and the expectation of stakeholders for return on their investment (Too, 2010). To succeed cost-efficient asset management, Vanier et al. (2001) came up with six questions that asset owners need to answer. Figure 3.1 shows the six whats of asset management according to Vanier et al. (2006a):

- **What do you own?** It is essential for asset managers to know what assets are in their portfolio and where are they located. An inventory of all the assets with clear categorisation of the usage, location and design,construction, and operational and maintenance records is required (Zhang et al., 2009).
- **What is worth?** There different methods to assess the value of an asset. Vanier et al. (2001) mentions that asset managers usually use six terms to describe the value of an asset: 1) The historical cost or the original "book value" of an asset. The book value is the amount of money that the shareholders would receive if the asset were sold and liabilities were paid off. 2) The historical cost calculated in present day dollars, taking into account inflation or deflation. 3) The current replacement value of an asset 4) The "performance in use" value which is is the prescribed value of the actual asset for the user, 5) The deprival cost is the "the cost avoided as a result of having control of an asset". 6) The market value is the value of the asset if it were sold on the open market today.

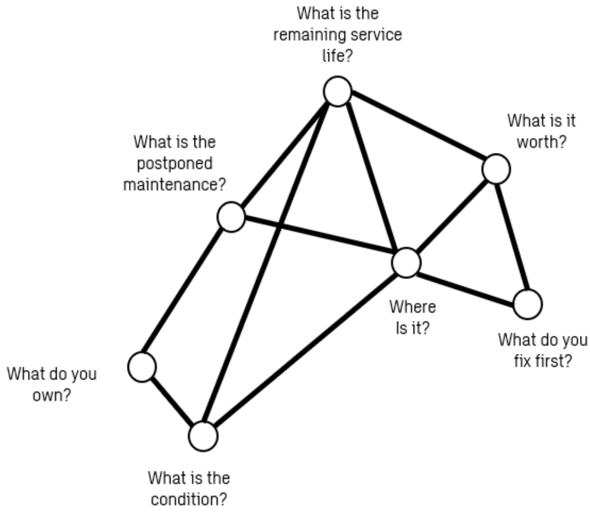


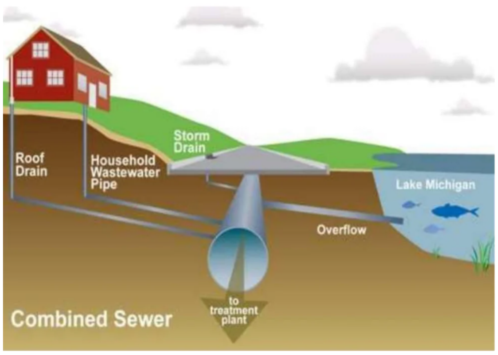
Figure 3.1: The six asset management questions (Adapted from Vanier et al. (2006a))

- **What is the postponed maintenance?** Asset managers should have clear information for the projects, repairs and maintenance actions that have been postponed or disregarded. That would give them a preliminary estimate of problematic assets and an indication where to focus their resources.
- **What is its condition?** A clear understanding of the asset's present condition compared to the overall portfolio by comparing it to other assets in the portfolio. This information need to serve as the foundation for estimations of the remaining useful life of the structure and help in organising maintenance procedures and reinvestment choices.
- **What is the remaining service life?** After asset managers have identified what assets their portfolio possess, their value and condition, the next step is the determination of assets' remaining life. That will enable the estimation of the life-cycle costs (LCC) for different maintenance, repair, and renewal strategies.
- **What do you fix first?** The significance of the systems under consideration in relation to the asset in which they are installed must be taken into account in the planning process that establishes priorities for maintenance, repair or reinvestment scenarios. Except from the significance of the systems, the value of the assets and their importance within the portfolio must be assessed as well before the final strategic decision.

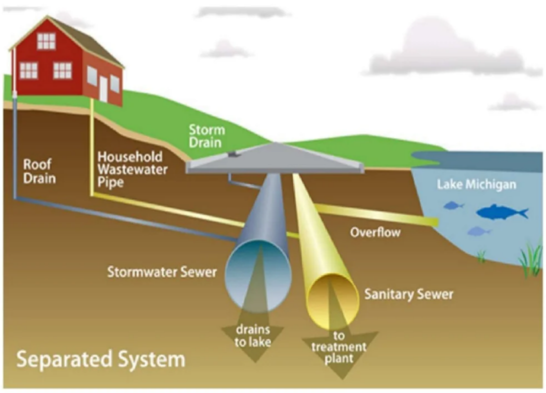
SEWER SYSTEM MANAGEMENT This thesis works towards the identification of the information needs that public authorities have in order to make long-term decisions of their assets. The asset of interest is a sewerage system. Sewers reduce the chance of humans coming into touch with harmful microorganisms that can deteriorate their health condition. Sanitation refers to the complete process of collecting, transporting, and treating blackwater (wastewater containing human faeces) (Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009). According to Nlingenieurs Sewer Systems Workgroup and RIONED Foundation (2009) the sewerage system is part of the wastewater system which includes:

- Interior Sewerage
- Exterior Sewerage
- Pumping stations and pressure pipes
- Wastewater treatment plants

Interior sewerage in the Netherlands is responsibility of the owner of the building (Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009). On the other hand, the exterior sewerage which function is to transport the wastewater away from the source, is responsibility of the municipalities. Municipalities are asset owner and asset manager of the sewerage systems (Van Riel et al., 2014). The exterior sewerage is consisted of underground pipes, manhole, service pipes that they carry the water to the public sewers, storm drains, overflows, weirs, pumping stations, storage basins and in some areas streams or culverts (Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009). Figure 3.2 shows the two different types of sewerage systems. Sewerage systems can be combined or separated. The combined system transfers the sewage and the rainwater with the same pipe while the latter one uses two different pipes (van de Ven, 2016)



(a) Combined Sewerage (Retrieved by (Ramprasad, 2017)



(b) Separated Sewerage (Retrieved by (Ramprasad, 2017)

Figure 3.2: The two different types of sewerage systems

Municipal sewerage networks are complex, public infrastructure systems that has an influence on modern societies' economic, environmental, and social aspects (Emera et al., 2012). These systems facing an emerging need for replacement of the aging infrastructure due to climate adaptation and energy transition (Duivenvoorden et al., 2021; Uddin et al., 2013). Moreover, the higher consumer demands and security concerns, combined with the declining maintenance budgets, impose challenges on the asset owners and managers to sustain an acceptable performance-demand ratio (Emera et al., 2012). These challenges create the need to municipalities to make effective strategic decisions.

STRATEGIC AND POLICY ACTIVITIES FOR A SEWERAGE SYSTEM The management of the exterior sewerage system is described in the European Standard NEN-EN 752 (NEN (2017)). Figure 3.3 shows the framework that the European Standard provide for the design, construction, operation & maintenance and rehabilitation of drain and sewer systems outside buildings.

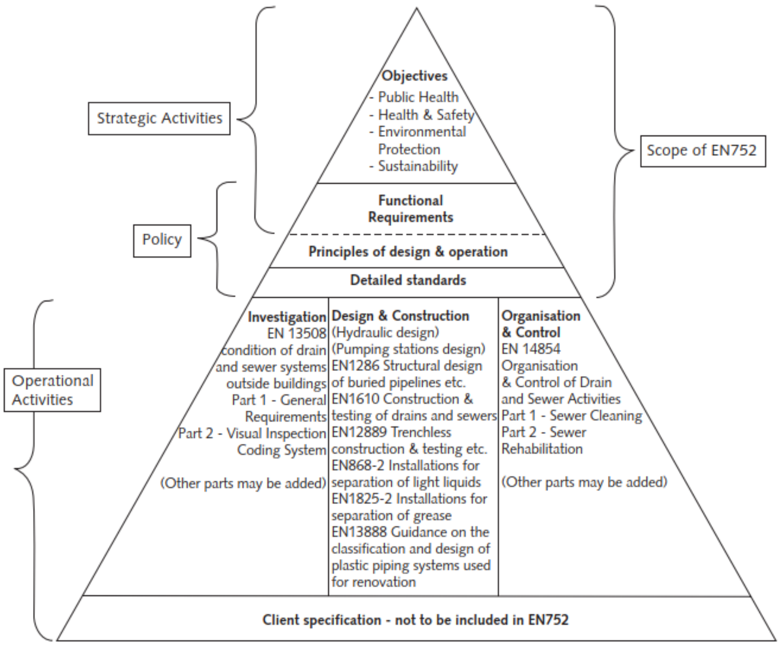


Figure 3.3: Sewer management activities according to NEN752 (Retrieved by (Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009))

NEN (2017) supports that the main objectives for sewerage systems are : 1) public health & safety, occupational health & safety, environmental protection and sustainable development. Therefore, the municipalities in order to satisfy those objectives have to prepare effective policy plans (investigate and decide the right measures) and allocate their budget (which is generated by the taxes) to the assets or objects of assets that need it the most. (Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009). Figure 3.4 shows the activities involved in the relationship between strategy and policy activities.

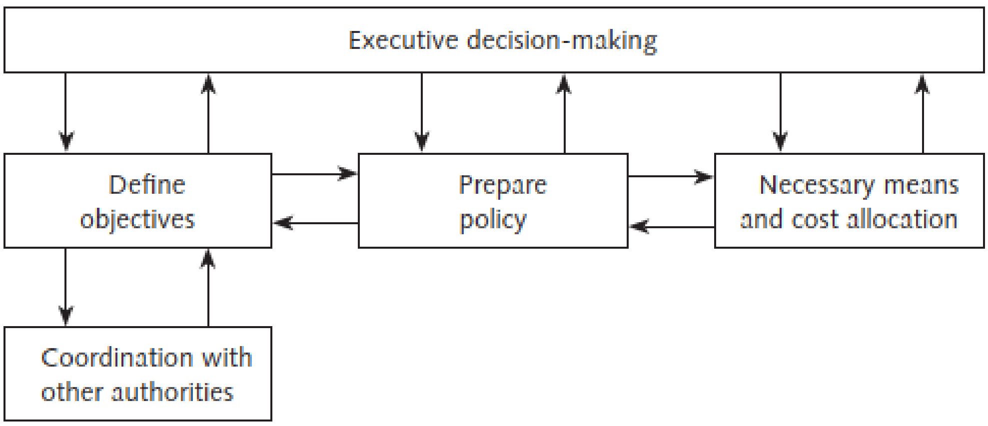


Figure 3.4: Relationship between strategy band policy activities (Retrieved by (Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009))

IMPORTANT INFORMATION FOR SEWER SYSTEM STRATEGIC DECISIONS For a sewerage system municipalities strive to satisfy their strategic objectives by ensuring that the system operates within its limits and completes its main task (collection and dispose of the sweage) (Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009). Information management is the central process of the organisation's crucial tasks. It aims to satisfy the previously mentioned tasks by providing relevant information that will allow to asset managers decide the right measure and generate value for the organisation and its stakeholders. According to Too (2010) and Nlingenieurs Sewer Systems Workgroup and RIONED Foundation (2009), asset managers need to collect data about the:

- Designs and revisions of sewer system objects
- Location of the asset
- Local conditions affecting the service life (i.e nature of the wastewater, geometry of the object (location and depth), local infrastructure, soil structure etc.)
- Object conditions
- Sewerage system performance
- Financial condition (service potential,risks and liabilities)

The above data provide information to facilitate the distribution of the organisation's resources for deciding the right management measure (maintain, repair, renovate or replace).

#	Measure	Object Condition	System Performance
1	Maintenance-Inspection-Local Repair	Do not improve structural condition	Restores original performance
2	Renovation	- Improves structural condition - Alters future deterioration rate	Restores original performance
3	Replacement	- Re-sets structural condition - Re-sets asset's age	Restores original performance

Table 3.1: Impact of management measures to asset condition and system performance

3.2.2 Information & Asset Management

DEFINITION OF ASSET INFORMATION Asset information is critical for businesses because it reflects the collective knowledge required to manage assets as well as generate and deliver goods and services to stakeholders (Ouertani et al., 2008a).

IMPORTANCE FOR A LIFE-CYCLE APPROACH The practice of asset management consists of the whole life cycle of an asset and its supply chain (O'Keeffee et al., 2017). In this research, the main goal is to connect the information that the Operation & Maintenance phase needs from the previous phases. In order for asset managers to answer the six questions that were mentioned earlier, a collection of information is then necessary, such as design requirements, reliability data, location and environmental conditions, to make efficient decisions that aim to maximise the asset's utilisation throughout its life (Ouertani et al., 2008b). Generally, the construction industry has adopted four life-cycle stages: Initiation or Planning, Design, Build or Construction and Operation & Maintenance (Hoeber and Alsem, 2016). Figure 3.5 shows the phases of an asset's life-cycle and the exchange of information between the different stakeholders. Boyes et al. (2017) supported that information from the Design and Construction phase can help asset owners to achieve considerable savings during the Operation & Maintenance phase.

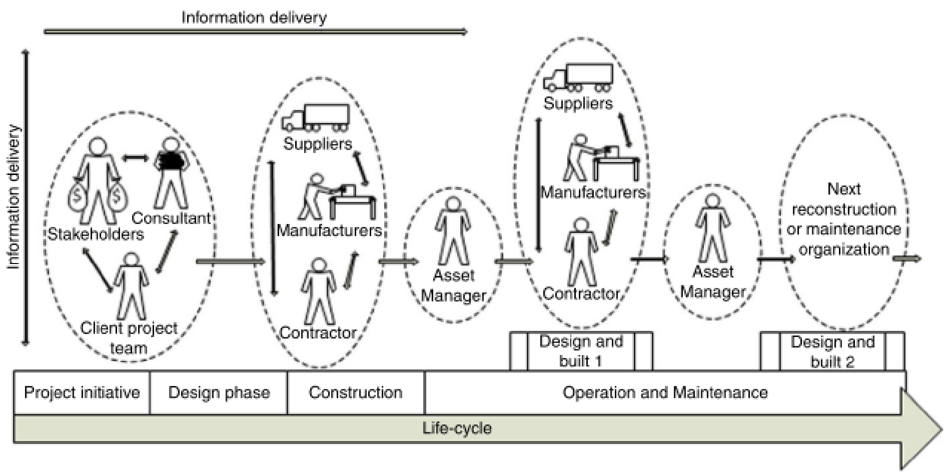


Figure 3.5: Information exchange in the life-cycle of a construction project (Retrieved by Hoeber and Alsem (2016))

INFORMATION FORMS AND FORMATS The construction industry is moving towards transforming the handover processes from paper-based to digital. Hence, asset managers need deliverables that include virtual 3D models, documentation with drawings, and tabulated data. These deliverables together are referred to as the asset information model (AIM) (Barnes, 2020).

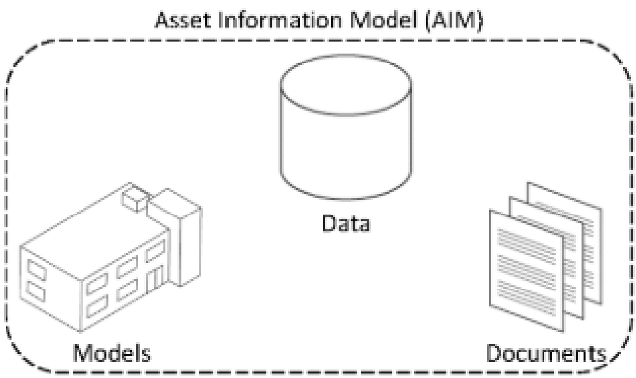


Figure 3.6: Digital Deliverables for Asset Management (Retrieved by Barnes (2020))

According to Alvarez-Romero (2014) a significant amount of the information delivered to the asset owners is not in a structured format resulting to slow transfer and prone to error or omission during the transcription process. However, some new approaches can provide structured and machine-readable information. These approaches enhance productivity and reduce the errors and will be discussed in Section 3.2.4. Figure 3.7 shows that the structuring of information helps the information to be re-used and information standardization enhances the longevity of the information.

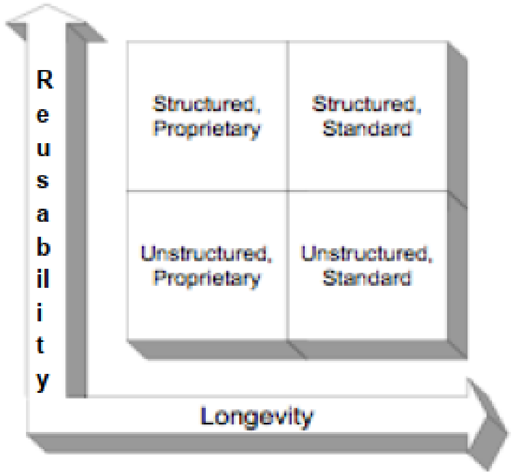


Figure 3.7: Information formats (Retrieved by Alvarez-Romero (2014))

Alvarez-Romero (2014) supported that the information that asset managers receive into their deliverables can be divided into four main categories (Figure 3.7):

- **Proprietary Format:** The information of a proprietary file format contains data that is ordered and encoded according to a specific encoding-scheme. The interpretation of the information is possible only by using the same software that was used for the production of the information (Alvarez-Romero, 2014).

- **Standard Format:** There are two categories of standard formats :

  - "Ad-hoc" standards may have been developed from a single vendor but afterwards they are commonly adopted by the practice (i.e. the Portable Document format or PDF).

  - "Formal" standards have been developed by standardization organisations and they are based on the information requirements of multiple organisations. A relevant example for this research is IMBOR, an open standard for standardizing the names of all objects in the public space and the data that can be recorded from the management phase for each type of object. The term "open" means that the standard is freely available for everyone to adopt, use and even update it.

- **Structured Data:** Structured data can be interpreted and used directly by computer applications. According to Barnes (2020) the structured data has five main characteristics:

  Firstly, they use **a single location** for storing the data in order to avoid duplication. Secondly, they are **linked** in a useful way. For example, information about an asset's space can be linked with information for its financial performance. Thirdly, the organisation of information is **object oriented**. That means that the information is organised around objects (i.e representations of real world objects). This differs from the conventional file-based approach in which information for the same object has to be searched in several locations. The difference can be seen in Figure 3.8.

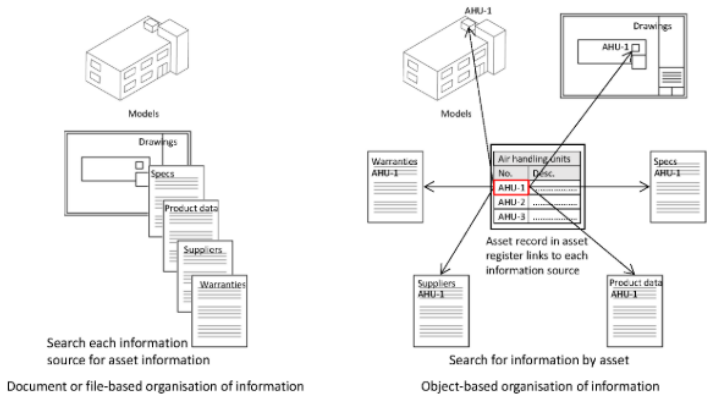


Figure 3.8: Object-based vs File-based organisation of information (Retrieved by Barnes (2020))

Fourthly, the data is **based on a schema**. Schema is a conceptual framework that aids communication and understanding by providing a plan of the relationships between different concepts. Computer applications need a common schema in order to exchange data and communicate. Finally, structure data must take advantage of **metadata**. Metadata provide information for other data. For example the file size, the creation date or the author of a PDF file, are its metadata.

- **Unstructured data:** It is the information that is not arranged in a defined schema and consequently, it can not be interpreted by computers.

3.2.3 Limitation in current practice

Currently, asset managers confront the challenge of improving and standardizing the quality of the information they have at their disposal, both to execute the daily operational tasks as well as to provide reliable information to facilitate top managers to make strategic decisions (Dias and Ergan, 2016; Gnanarednam and Jayasena, 2013).

There are several reasons identified by the literature why asset information management is ineffective and asset managers receive incomplete, outdated, inaccurate and not reusable information. One reason is because the data collected and created by the different parties (e.g., architects, contractors, and manufacturers) and methodologies are heterogeneous (Fang et al., 2022; Hoeber and Alsem, 2016). That means that the data has a proprietary format and can be understandable only by the software that was created (O'Keeffee et al., 2017). Moreover, O'Keeffee et al. (2017) and Hoeber and Alsem (2016) in their works mentioned that information is not (re)usable because it is: document-based (unstructured, having poor meaning/semantics hence being multi-interpretable), structured in incompatible ways, represented in incompatible formats, stored in incompatible systems and/or databases. Last but not least, is that asset in the construction & maintenance phase receive a vast amount of information at the operation & maintenance phase which is not directly relevant to execute their tasks (Barnes, 2020; O'Keeffee et al., 2017; Yuan et al., 2016). Consequently, all the above reasons lead the asset managers to make manual modifications to input the relevant data into their systems (Matarneh et al., 2019). This a prone-error activity that leads to information loss between the phases that is visible on the Figure 3.9.

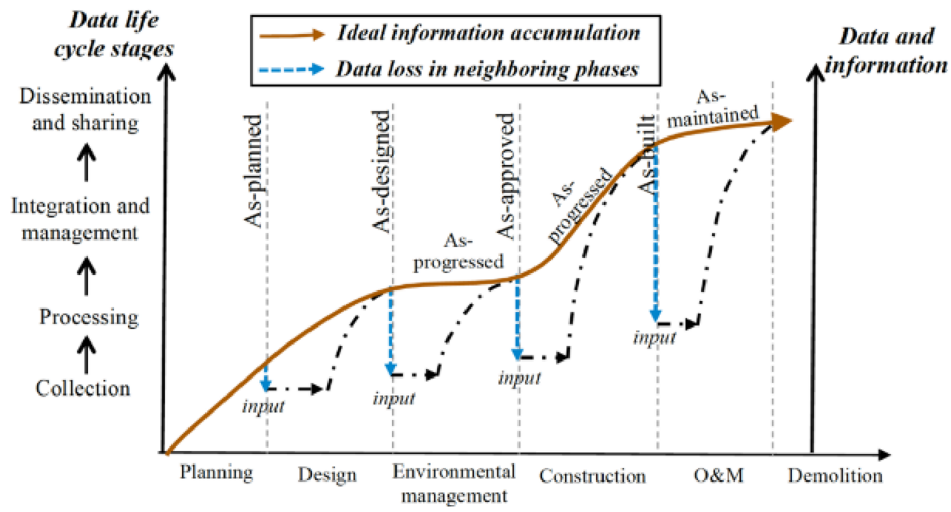


Figure 3.9: Integration of data lifecycle and infrastructure asset lifecycle (Retrieved by Yuan et al. (2016))

Another reason for the incomplete information is that there is still a lack of understanding and development of operational information requirements that asset owners needs during the O&M phase to satisfy their business needs and create value (Becerik-Gerber et al., 2012; Munir et al., 2020b). Moreover, there is a lack of knowledge how to transfer this information seamlessly into existing asset management software (Matarneh et al., 2019). To overcome incomplete and not accurate information from the design and construction stages to the operation and maintenance phase, asset-related life-cycle information shall be properly captured, used and stored by standardizing it and make it interoperable (Bonanomi, 2016).

3.2.4 Ontology and the Semantic Web

Section 3.2.3 identified that one of the reasons contributing to the information loss is that asset owners have not explicitly defined their information requirements. Information requirements should be identified at an early stage to facilitate a seamless data exchange between pre-operation and AM systems (Matarneh et al., 2019). An ontology provides the input to achieve that. An Ontology (or OTL) is a generic information model in which objects are described, defined and organised in a structured way. An ontology can be a blueprint of asset owner's information needs (Haase and van Belzen, 2016).

3.2.4.1 Ontology

WHAT IS AN ONTOLOGY According to O'Keeffee et al. (2017):

> *An object type library (OTL) is a library with standardised object-types names (e.g. road, viaduct) and properties or specifications. An object is described with its object-type data, geometry data and metadata, Metadata are data (or information) about the data of objects. Metadata are needed because each object type has its own properties. How the object types are grouped is called an ontology. The OTL can be linked to a data dictionary, with the definitions of object-types*

Ontologies are used to describe knowledge, and establish a common understanding by acting as a point of reference between the different parties (Bassara, 2007). They can create a common vocabulary for these parties who need to search or share information in an agreed form (Frolov et al., 2010; Noy et al., 2001). The most common existing definition in the literature originally proposed in 1993 by Gruber (1993). The definition suggests that ontology is the conceptualization of terms and their relations in a domain (Ding et al., 2016; Gruber, 1993; Zhou et al., 2016). Farghaly (2020) on his research mentioned that Borst (1999) added to more terms to the definition. He stated that an ontology should be formal. Hence, it should be written in a machine language in order to be easily processed and shareable, which means that it is created based on an agreement between the experts of the knowledge domain in order to be usable in different applications.

An ontology often comprises a hierarchically organised set of classes, instances, relations, functions, and axiom (Campos, 2007). It can be described as a combination of a dictionary (which gives meaning to terms) and a taxonomy (a hierarchical classification scheme which gives a structure and relations to terms) (Farghaly, 2020). Ontology engineering is emerging to enhance interoperability from semantic and technical aspects: at semantic level, they create shared concepts and common unambiguous meanings between different stakeholders; at technical level, in their digital form, ontologies guarantee consistent machine-readable data formats for enabling the communication amongst systems (Frolov et al., 2010; Polenghi et al., 2019; Zheng et al., 2021).

ONTOLOGY CLASSIFICATION Farghaly (2020) on his work argued that knowledge engineering ontologies can be classified into **taxonomic** and **semantic ontologies**. A taxonomic ontology formalises the hierarchical relationships among terms. It provides the distinction into ordered categories. Therefore it is a classification which can be used as the skeletal foundation for the development of several ontologies for a domain. (Farghaly, 2020).

Semantic ontologies represent a domain knowledge more thorougly and impose additional constraints on domain terms and relations (Farghaly, 2020). Gómez-Pérez et al. (2006) categorised semantic ontologies based on two categories: the richness of their internal structure and the subject of conceptualisation. According to the richness of their internal structure ontologies can be classified to **lightweight** and **heavyweight**. Lightweight ontologies are consisted of classes, relations between classes, classification of the classes (taxonomy), individuals and attributes or properties. Heavyweight ontologies poses more restrictions and axioms to the lightweight ontologies to define better the meaning of classes and relations.

In the second category of the semantic ontologies, the classification is based on the level of knowledge that they provide for the domain. Below they are listed from general concepts to more application-oriented description of knowledge (Polenghi et al., 2019). According to Gómez-Pérez et al. (2006) they can be classified into: **General ontologies**, **Top-Level Ontologies**, **Domain Ontologies**, **Task Ontologies**, **Domain-Task Ontologies**, **Method Ontologies**, **Application Ontologies**.

- **General Ontologies:** They represent basic knowledge used in multiple domains. For example, Standards-Units Omtology, which defines units of measure.
- **Top-Level Ontologies:** They include the main concepts of a domain and provide general instructions how the terms of the domain ontologies can be linked (Gómez-Pérez et al., 2006).
- **Domain Ontologies:** They are more specific than top-level ontologies and they provide specific definitions and relations of the connected concepts. For example the word card has many different meanings depending the context. An ontology for the domain of football would model the "card of the referee" while an ontology for the banking domain it could model a "credit card" or a "debit card"
- **Task Ontologies** They provide a detailed description of individuals to explain the solution of problems of the same or different domains.
- **Domain-Task Ontologies:** Their difference with task ontologies is that they can not be used to solve problems of other domains.

- **Method Ontologies:** They contain the relevant terms, their definitions and relations in order to describe a process that is used to achieve a task (Gómez-Pérez et al., 2006). A recipe for making a cake would belong into this category.

- **Application Ontologies:** They contain the relevant terms, their definitions and relations in order to describe the knowledge for a particular application. For instance, we could create an application ontology for a structural engineer specialized in concrete buildings.

ONTOLOGY COMPONENTS There are several representation languages for developing an ontology and each of them uses different components to create an ontology (Farghaly, 2020; Gómez-Pérez et al., 2006). However, most ontologies are described by using classes, instances, properties or attributes, relations, and axioms. Scholars (Farghaly, 2020; Gómez-Pérez et al., 2006; Gómez-Romero et al., 2015) on academic publications defined ontologies' elements as:

- **Classes:** They determine sets that classify domain objects.

- **Instances or Individuals:** are concrete occurrences of classes. There are the elements that the ontology describes (Farghaly, 2020). For example, Netherlands is the instance of the class Country.

- **Attributes or Properties:** They represent a feature, a characteristic, property of a class or an instance. Their value is a datatype (i.e string, float etc.)

- **Relations:** They are the type of association between the classes or the individuals of the ontology. For instance, Chardonnay "is a" Subclass_Of White wine and these relationships can create the taxonomy of the ontology.

- **Axioms/Restrictions:** They establish restrictions over classes, instances and properties that characterize their features. They enable the distinction of hierarchical and semantics that satisfy the ontology rules from those that do not.

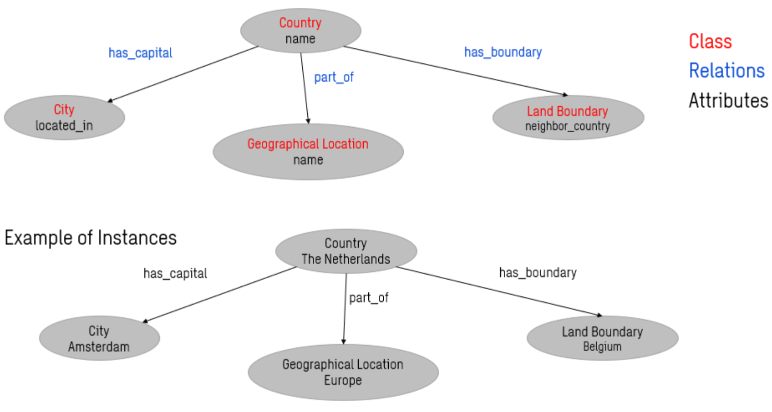


Figure 3.10: Example of an Ontolgy's Components

WHY AN ONTOLOGY According to Zhou et al. (2016) the construction industry is behind in the research and implementation of ontologies compared to other sectors despite the significant problems confronted such as lack of information interoperability and low productivity because of rework, lack of automation and inability to reuse knowledge. Uschold and Gruninger (1996) suggested that ontologies can act as a unifying framework and solve this problems. They classified their roles as follows:

- **Communication:** between people and organisations by enable them speak the same language.

- **Interoperability:** among software or systems. An ontology can unify different languages and software tools and make them communicate.

- **System engineering benefits:** ontologies can support software systems by providing knowledge but with other ways as well:

  - Re-usability: An ontology when is represented in a formal language can be a re-usable component in a software. Moreover, it can act as basis for new larger ontologies as it has already depict a part of a domain's knowledge.

  - Reliability: It facilitates automating consistency checking.

  - Specification: The ontology can assist the process of identifying requirements and defining a specification for an IT system.

3.2.4.2 An introduction to the Semantic Web

The Semantic Web Term was first conceptualised by Tim Berners-Lee, the founder of the World Wide Web (WWW) in 2001. The World Wide Web, is the well-known Web, an information system that facilitates the searching and assessment of information, documents or other items of interest over the Internet (W3C, 2009). The Semantic Web is an extension of the World Wide Web and its aim is to structure and give meaning to the content that exists in WWW (Berners-Lee et al., 2001). According to Shadbolt et al. (2006) the semantic web is a *"Web of actionable information derived from data through a semantic theory for interpreting the symbols"*.

The data in the traditional web is interpretable only by humans, a computer can handle them but not understand its meaning. However, by structuring and giving a well defined meaning (semantics) to the information, computers will be able to manipulate meaningfully to the Web, understand the data and execute sophisticated tasks for users. That will improve the cooperation between humans and computers (Berners-Lee et al., 2001). That is achieved by developing ontologies which are conceptual schemas and are one of the main components of the Semantic Web (Moreno et al., 2015). Berners-Lee et al. (2001) in his paper gave an example of the sophisticated tasks that could be achieved through the Semantic Web. He described that a computer would be able to retrieve information from a patient's prescribed treatment and provide options for scheduling an appointment with relevant providers. That would be able to be realised in the Semantic Web as the document prescription would be linked with associated providers, their location, schedule etc. This is the essence and purpose of the semantic web. Hence, the universality of data and data linking with the help of hypertext links enables "anything to be linked to anything" (Berners-Lee et al., 2001). The rules that someone should apply to link the information are explained in the next paragraph.

LINKED DATA RULES The Semantic Web is about making links in order a person or a machine can explore it. Therefore, with linked data when you have identified something you can find other relevant data (Berners-Lee, 2006). The basis of linked data are founded on the World Wide Web, where three elements describe its architecture. These elements were explained by Frystyk (1994) and Berners-Lee et al. (2004):

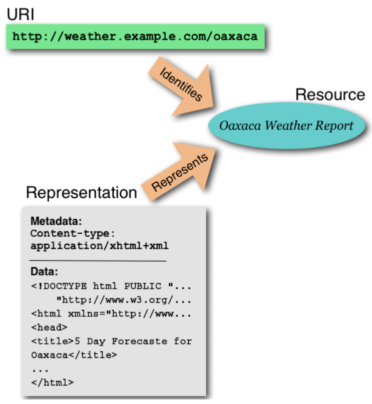


Figure 3.11: The relationship between the elements of WWW (Retrieved by (Berners-Lee et al., 2004)

URI/URL: a URL (Uniform Resource Locator) and a URI (Uniform Resource Identifier) are used to provide to every information object (or resource) a unique name or identifier.

HTTP: HTTP (Hypertext Transport Protocol) is a protocol which describes how one can interact with the Web to request and retrieve information. It provides access to the things that someone needs from the Web.

HTML: HTML (Hypertext Markup Language) is the language which describes how the information is presented and linked. However, it is not a semantic language resulting in the inability of computers to understand the meaning of the information.

The evolution of World Wide Web led to the creation of the semantic web or "Web of Data" (Linked Open Data (LOD) cloud). It builds upon the main principles of WWW with the difference that it adds semantics (meaning) to the data. It is a decentralised, global database of information that can be understandable by the computers (Petrova and Pauwels, 2021). Berners-Lee (2006) defined four rules for the effective publishing of data in the Linked Data Format:

- Use URI as names for things (a unique ID for information objects).
- Use HTTP URIs so people can look up this things on the Web.
- Use standards (like Resource Description Framework (RDF), SPARQL query language, etc.) to provide useful information when someone looks up a particular URI.
- Include links to URIs, so that people can discover more things

Based on the four principles, Berners-Lee suggested a star rating scheme in order to assess how well the actors publish their data according to the linked data principles. Figure 3.12 explains the five star scheme and provides a relevant example from the domain of interest (operation & maintenance domain).

Star	Requirement	Acronym	Format	Example
★ OL	Available on the Web under an open licence	OL: On-Line	Any	PDF of Asset specifications
★★ OL RE	Available as machine-readable Structured data	RE: Readable	E.g. Excel	Product Data Template in Excel
★★★ OL RE OF	Available in a non-proprietary open format	OF: Open Format	E.g. CSV	Product Data Template in CSV
★★★★ OL RE OF URI	Available in URIs to denote things	URI: Universal Resource Identifier	E.g. RDF/SPARQL	Ontology in RDF
★★★★★ OL RE OF URI LD	Link data to other data to provide context	LD: Linked Data	-	Linked with other Ontologies

Figure 3.12: The five starts of Linked Data Scheme Rating

LINKED DATA LANGUAGES AND TECHNOLOGIES The Semantic Web of Data requires standards to enable a highly linked network with a well-defined meaning for the data (Farghaly, 2020). Therefore, standards organisations like the World Web Consortium (W3C) or the Internet Engineering Task Force created a set of languages for sharing meaning and support the development of the LOD and link the different sources of information (Farghaly, 2020; Shadbolt et al., 2006). The collection of these standards is called semantic web stack and can be seen in Figure 3.13.

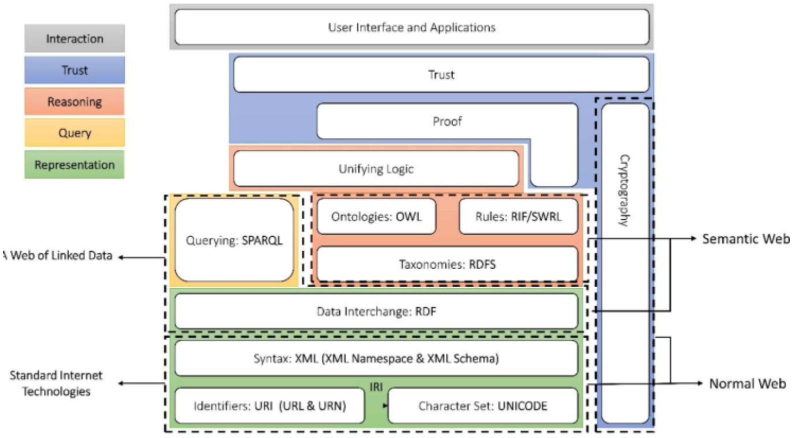


Figure 3.13: The Semantic Web Stack (Retrieved by (Farghaly, 2020))

The semantic Web stack has several layers that form its structure. The first layer is consisted of standard technologies that help the provision of data to the World Wide Web. The combination with the Cryptography which secures information and communication on the Internet by preventing unauthorised access to the information and verify its reliability (Farghaly, 2020; IBM Coorporation, 2021). The basic language to represent knowledge and manage distributed data in the Web of linked data is the Resource Description Framework (RDF) and all the other Semantic Web Standards build upon it (Allemang and Hendler, 2011). RDF is a general and adaptable language that allows for the display and integration of data from many knowledge areas (Farghaly, 2020). It builds upon the the architecture of the World Wide Web, thus every resource (it can be anything that someone wants to talk about it) should be identifiable and referenceable via its unique URI (Shadbolt et al., 2006). The knowledge in RDF is expressed by in sets of triples (Berners-Lee et al., 2001). An RDF triple is consisted of the terms: subject-property-object which form a graph of the data and every term has its own URI (Farghaly, 2020). An RDF graph model can be seen in Figure 3.14 where every knowledge element is represented by a node and it is linked with other pieces of knowledge by lines. RDF can be expressed by using various sytntaxes such as XML, N-Triples, JSON-LD and Turtle amongst others.

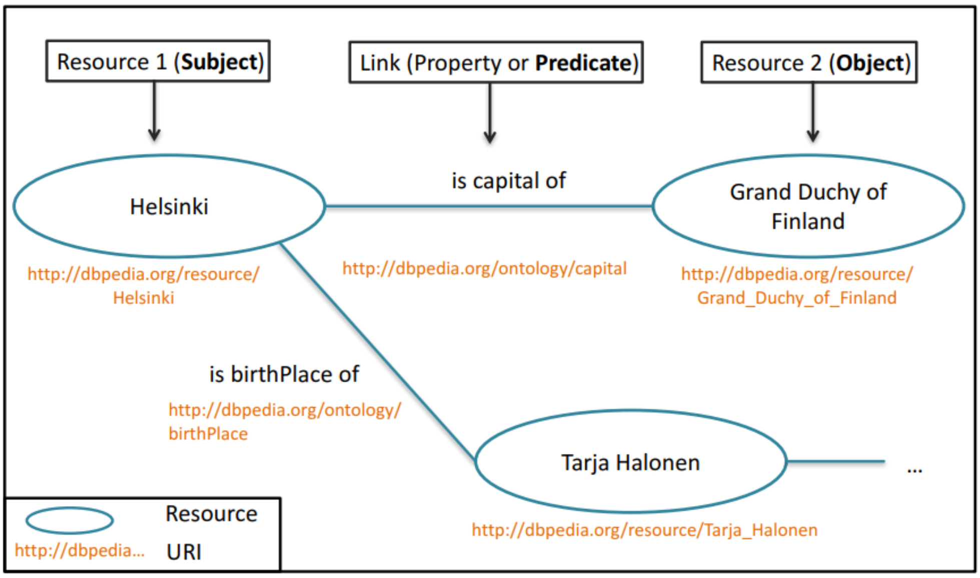


Figure 3.14: Example of Linked Resources on the Web using URI and the RDF syntax for their identification and representation (Retrieved by (Bernard, 2019))

The RDF Schema (RDFS) can encode only the lightweight ontologies (see 3.2.4.1), thus it contains only classes, relations between classes, sub-classes and attributes or properties. On the other hand, OWL is more advanced in possibilities by allowing the encoding of heavyweight ontologies which results in better definition of the meaning and greater machine interpretability. It is the language that gives logic to the Semantic Web (Allemang and Hendler, 2011). That means that allows the modelling of subclasses, disjunctive relations, cardinality constraints, transitivity, uniqueness, and invasiveness (Farghaly, 2020; van der Pas, 2022).

To conclude this section, the linked data technologies include the RDF which stores knowledge, RDFS and OWL as ontology languages, other ontologies that define the meaning of other parts of the semantic web. Finally, SPARQL language facilitates the standard access to RDF data as well as RDFS and OWL languages and retrieve the necessary knowledge (Allemang and Hendler, 2011; Berners-Lee et al., 2001; Farghaly, 2020; Shadbolt et al., 2006; van der Pas, 2022)

3.3 INTERVIEWS

3.3.1 Introduction

This section describes the results that were produced from the Thematic Analysis of the interview data. Six interviews were conducted with public authorities practitioners to gain a preliminary insight into the information that asset managers need and the process they follow to document the information for making long-term decisions to manage their assets. In addition, the interviews were conducted to verify the drawbacks of the current process and the information that was identified from the desk research activity. The results presented in this section will be complemented by interview segments.

The processes and methodologies that were followed for conducting the interviews can be found on Appendices. Appendix A presents the interview purpose, content, structure and questions. Appendix B provides the list of interviewees which includes their role and the public authority they represent. Finally, Appendix C the theory behind the collection and the analysis of interview data.

In order to conduct the analysis interview transcripts were thoroughly examined. During the coding process data segments from the transcripts that considered interesting and relevant to the research objective were identified and highlighted. Then, the codes were grouped into three main themes addressing the two first research questions. The themes are presented in sequential order in Figure 3.15.

Figure 3.15: The themes generated by interview data

The first theme **"Information Needs"** identifies the information that asset managers of the municipalities need from the constructors in order to make long-term decisions and manage effectively their sewerage systems. The second theme is the **"Current process & Drawbacks"** which discusses the process of information management in the industry and which are the problems that it poses to asset managers.

Finally, the last theme is **"Future Solutions"**. This theme discusses the interviewees' ideas on how the existing challenges can be tackled.

3.3.2 Results of the Thematic Analysis

Information Needs

The **"Information Needs"** theme attempts to capture and understand the long-term decisions that asset managers make to create value for their organisation. Moreover, it tries to identify important information attributes that the objects of a sewerage system should have in order to facilitate these decisions. This theme was mostly highlighted in the interviews through discussions about the role, responsibilities and the decisions that the heads of public authorities management departments make. The interviewees also mentioned which information attributes are important for the operation and maintenance of a sewerage system. Hence, the "Information Needs" is represented in two main subthemes: **the decisions** and **information attributes**.

Decisions

By the definition of asset management, it is clear that its main objective is to create value for an organisation through its assets. In order asset managers manage cost-effectively their assets their decisions are based on **the allocation of the budget to the critical (based on risks) projects**, **choosing the right time to intervene to the assets (improve, repair or replace)** and **sustainability**.

Resource Allocation & On time Intervention

The asset managers need to distribute the financial resources of the municipality to the assets that will create the most value to the organisation. Thus, they need to spend money in the right asset at the right time to optimize the return on investment.

In the Netherlands, as a municipality, we have to make a maintenance plan for every asset (...) "in the coming five years we need 2 million euros per year for paving the road, we need 1 million for green, we need 6-9 million for replacing the sewerage system. So, it is on that level but it is only one part. I2

It is more like a technocratic view on what we have and when we need to replace it. I2

We are looking to the risks more than the old ways. The old ways were just more time-based. We had intervals for maintaining and now we are looking more to risk-based, when is the right time to maintain objects. I3

Yeah, so for example, two years ago, we say that the maintenance of our trees was not on the right level. So, we decide to make a proposal to our board to as them for more money. That kind of intervention is my job. I4

It is always negotiation when to dispose of our assets because in this part of the Netherlands (i.e. Rotterdam) the sewerage system does not fail because of technical or structural malfunction because it is subsiding. I3

Sustainability

Besides the allocation of budget to the right assets and the decision to intervene to the assets at the optimal moment, sustainability seems to significantly affect the long-term decisions of asset managers. The upcoming years energy transition and climate adaptation create a need for a shift towards circular economy. For instance, public authorities need to choose the right materials that will extend the lifespan of the objects and reduce the management costs in the long term.

You need the drawings and the materials because we need to know what type of materials we are using to make our city circular. So when we change something, we also know what material is in it and what we can reuse. I2

The sewage system is long, but when you look at the pumps or drainage, I think those things have a shorter lifetime. I think we have to renew a pump after 10-15 years, drainage 30 years depending on what kind of investment you have made. Because when you use coconut shells, it degenerates in 10 years, while if you use plastics, that is not good, it will degenerate in 30-40 years. So, it depends on the type of material we use and the type of pump. A pump has a much shorter lifetime than a concrete pump.

Information Attributes

In the previous section, the interviewees elaborated on the long-term decisions that have to make within the terms of asset management. For the facilitation of the resource allocation and the effective decision making, asset managers need to obtain the suitable information. During the interviews, the information attributes that practitioners highlighted were **the location**, **the condition**, **type of materials**, **year of construction** and **life expectancy**.

The location of the sewerage system components it is very important. Asset managers need their X,Y, Z coordinates in meters. The depth is the most important coordinate as it is an indication for how well the system is functioning and if it needs maintenance.

It is measured at the position of the sewerage system both horizontally and vertically because we need to have what I have said the depth of the system which is important. I3

We measure the depth of the sewerage system, how much had been sunk. It is because the depth of the sewerage system is an indication of how well it is still functioning. When we are putting a service system into the ground and it needs to be at a certain level. It is always in slope because this is how it functions but in some parts of Rotterdam it sinks a little bit faster and then it will be blocked. All the waste is getting stuck into the switches and we have to clean it more often. That is an indication that is getting worse as well. At a certain point, it is below the groundwater level so it is full of groundwater and it cannot function correctly. That is the time when we have to dispose of the sewerage system. I3

Then we define what kind of sewer it has to be. So, is it a separate system or is it a combined system and where it is? Does it connect with the open water? Where is it connected with other sewer systems? And the height of the sewer system. So, I do not know if you know the term BOB, and it means the lowest point of the sewer. I5

Except from the location, the condition of an object is important. The asset managers need to know how well it is functioning and if there are any defects.

We also need them to give is some kind of inspections. They ride with a camera through the sewerage system to show us that it is well built so no leakage and no cracks on it. I think these are the most important parts of information that we need because the situation of the sewerage system is important because it is a whole network. Everything has to be in the right position in order to find the network is functioning ok. I3

Yeah. And they translated into what we call beheer system, so it is an asset management system for maintaining the sewerage system. So, you have the as-built situation and then you go to the maintenance so every 9 to 10 years you measure again and you get an idea of *how the sewage system is functioning and when it is about to fail and you have to maintain it or dispose it and build a new one. I3*

Finally, the practitioners mentioned that they need to know the material of the objects, the year of construction and its life expectancy in order to decide their strategy and when to dispose an asset.

It depends. For the Nota kapitaalgoederen you need the year of completion, so when the asset is built. You need the life expectancy, it is 60 years, 20 years or 30 years. You need the drawings and the materials because we need to know what type of materials we are using to make our city circular. I2

Yeah sorry, all these details are the as-built drawings, so ***materials***, ***the year of building***, *the depths and all kinds of stuff. I3*

They want to know where is the manhole, where it is located, where is the sewer pipe, what is the height of it, what is the location of it, what is the dimension of it, what is the time that is constructed and that kind of things. I5

Current Process & Drawbacks

The **"Current Process & Drawbacks"** theme express the barriers that obstruct the public authorities and contractors from achieving interchanging complete information for the post-construction phase. This theme was mostly highlighted in the interviews through discussions about how the definition and exchange information currently is implemented in the industry, the difficulties that the process creates and the reasons behind them. The "Current Process & Drawbacks" are represented in five main subthemes: **workflow**, **formats**,**standards**, **drawbacks** and **reasons**.

Workflow

During the interviews, an attempt to understand how the asset managers obtain the required information was made. Once a project is completed, the personnel of the municipalities **1. inspect the constructed artefact to identify if there are any defects.** If any defects are spotted, additional work has to be done by the contractor to remedy the situation. When the as-built situation conforms with the designed specifications and there are no defects, **2. transfer of information can take place**. Most of the data attributes that asset managers require for a sewerage system from the contractor has been defined by a revision drawing. They supply it to an AutoCAD format to the contractor and they receive a PDF by e-mail. Before the acceptance of the dataset and the project handover for the operation or maintenance phase, public authorities **3. assess information's completeness and readability for their asset management systems.** After that, they **verify the obtained information with the as-built situation**. This action verify which objects has to be added or remove to the asset management system. The last step of the process is **4. the manual entry of the data to the asset management systems.** The process is shown in Figure 3.16.

You have supervisors on the work that our people on the street. The company that is working for us delivers the information to the supervisors and they will bring it inside. Inside is the asset and data managers. Then the asset managers pick up the information and control the data if it is correct and after it is correct, they send it to the data management department which investigates if it is readable and usable for our systems. When all of that is complete, we go back to the project and we check if the data is in agreement and now we proceed to the maintenance of this part of the city. I2

So, the constructor makes the new sewer and when he is ready, he gives the sign to a director of the municipality and the director checks and confirms if everything is built as the *constructor says. Then, someone at the engineering office is checking if the delivered PDF is the right way drawn and if the values and signs are right. When it is ok, they give a sign to the measurement party and they go and look outside where the covers of the manholes are. So there is a new one, here another one and so and so. Then there is the information manager like these are all points measured and we think it is all our manholes and the new ones. They get a PDF from the engineering office and they look at and they type all the information in the asset management system. I5*

Formats of the received Information

Most of the valuable information that asset managers need to put into their systems is included into a PDF revision drawing. However, this is not the only information format that they ask to be inside the deliverable. The most common formats in the current process are: **PDF documentation including drawings**, **3D/2D Models** and **tabular data**.

PDF documentation including drawings

The most important thing is the data sets such as the drawings, the review taken in drawing and specific asset management information (e.g the type of the material, installation guide of a pump). I2

Yeah sorry, all these details are the as-built drawings, so materials, the year of building, the depths and all kinds of stuff. You know the sewerage system is built from one manhole to the other manhole and in those metals there are the depths that we measure and that is a very important indicator for us.

Yes, we have a template for the as-built drawings. The information that the contractor is giving back is translated to the template, so it is all how we like it to be so it can be translated easily into our system. It is an AutoCAD format and tells in which layer you have to draw a certain information I3

Nowadays, we have PDF and I think is a nice format to exchange information because without a specific software you can look at a PDF. But when you actually want to exchange data we have to look to other formats and we are looking for XML, GML or maybe RDF. But RDF is the Linked Data world and that is really experimental at the moment. I5

- Interviewer: Do you define the format that the contractor has to provide the information to the municipality?

Yes, we define it and at the moment it is PDF. We have the first examples of a constructor that delivers OroX and that is the RDF of GWSW. And that data that not only a human can read but also a machine can read. That can give a lot of opportunities to automate the revision process. I5

2D/3D Models

In 95% of the cases, the information is in a digital format like drawings in .dwg .gis in different setups. (...) I think you are mostly focusing on the information that the asset manager wants, and not on the project itself. So it is mostly drawings, a list with the measurements, and sometimes a GEO database, it depends on the project. I1

Tabular Data

*I think you are mostly focusing on the information that the asset manager wants, and not on the project itself. So it is mostly drawings, **a list with the measurements**, and sometimes a GEO database, it depends on the project. I1*

*Yes, it is digital and not hard copies. **Sheet files**, Pdf and information BGT. I4*

The workflow of the project transfer and the formats that were identified fromm the interviews can be seen in the Figure 3.16.

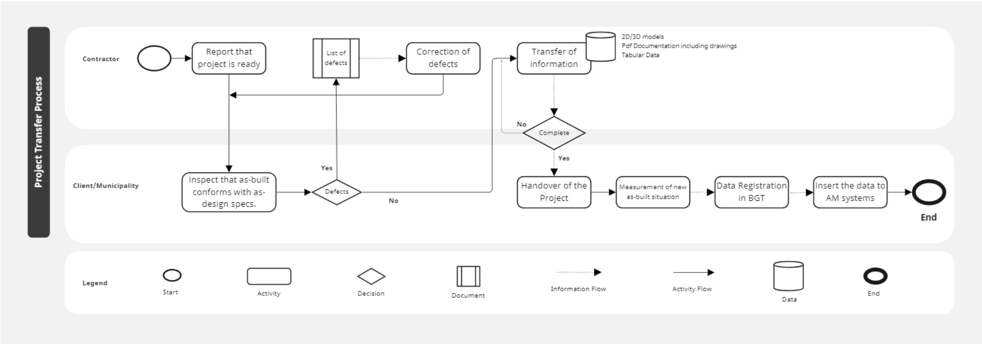


Figure 3.16: The Project Transfer Process

Standards

Two main ontologies were identified as important in the domain of urban water management and the management of public spaces. The Urban Water Data Dictionary (**GWSW**) is an ontology , a special data structure that describes systems and processes in the field of urban water management (RIONED, 2022). The second ontology is **IMBOR**. The Information Model for Public Space Management (IMBOR) is an open standard for standardizing the names of all types of objects in public space and the management data that can be recorded for each type of object (CROW, nd). The difference between the two standards is that GWSW describes the objects of urban water systems in a greater detail and is more relevant for the engineering world. On the other hand, IMBOR includes the fixed characteristics that are relevant for management (i.e construction year, material etc) (RIONED, 2020). It is fully in line with the Basisregistratie Grootschalige Topografie (BGT)[1] and the Information Model Georgraphy (IMGeo)[2] and . IMGeo supplies the geometry which is enriched in IMBOR with management information. Finally, the another standard that was identified is the NLCS[3]. Based on this standard are defined the revision drawings that municipalities provide to the contractors and they return it in a PDF format.

This year, IMBOR was standardized and we want to use it and we need it very badly but it is not implemented in Rotterdam yet. We hope to do it this month, and then we have the FME script. At that moment we could do the OTL and ILS together. So it is a lot of work to plan these activities and needs a lot of work to make them work.I1

IMBOR is one of the things that is important. I think it hangs together with BORIUS and it is still in development. But, I think the software companies and CROW are coming together to build BORIUS, I do not know exactly what it will be. I2

Yes, we use GWSW and NLCS. And the NLCS is the Netherlands CAD Standard and we use it in our drawings, engineering drawings. But, most of the time the amount of detail that we need in the engineering phase is much higher than the detail that is needed for the asset manager. So we have to look at how we can map the information to other information in other standards. Do you understand what I am trying to say?. I5

I think IMBOR is not the only standard that can fix it. I think the OTL like GWSW is better. Why is it better? Because it not only describes the concept as a sewer pipe but it

1 BGT is a digital map of the Netherlands where buildings, roads, waterways, sites and railways are unambiguously recorded. BGT standards are legally required in the Dutch industry.
2 IMGeo is an extention of BGT standards. It includes the mandatory BGT standards plus more detailed features of topographical objects.
3 NLCS is the Dutch CAD standard for the civil engineering sector. The goal is the uniform construction of digital drawings throughout the sector and convert the drawings into a carrier of standardized, reliable and reusable (geometric) information about civil engineering objects.

gives to the concept different levels of detail. So when I make a sewer pipe, it's constructed by many tubes. And I can only order tubes and buy a producer. I cannot order a whole pipe. Do you know what I mean? So, I order ten tubes and I make one pipe. But the asset manager wants to know where is the pipe and he does not want to know what tubes in the pipe are. But there are moments in the lifecycle of an asset that you have to know what the tubes in the pipes are. And most of the time we do not have the information anymore. So we have to dig the street, open it and look what we will find. Because we cannot connect data in language A to the data in language B. Yes, and I think IMBOR is a good language for the asset manager but it is not a good language for the engineer. I5

Drawbacks

There are several negative impacts that public authorities have identified in the current process of the information that they obtain from the construction phase. The most common ones are: **incomplete or not accurate information** and **the information is not delivered on time**.

Incomplete or not accurate information

It is what I mentioned before. The drawings are coming too late or the survey(inspection) was already in place but the project was not delivered adequately and the survey has to be done again. The information is not correct or complete. I1

No most of the time the information is delivered in the required format. The problem is the completeness of data and not forgetting something in the data. I2

Yes, but I don't think that only technology will solve the problem because we also have the problem of the constructor who delivers sometimes the wrong information. I5

Delayed delivery of the information

But the biggest challenge is to deliver the information on time. The constructor is late compared to the contract time or they do not have the information or they deliver it too late. I1

But there are too many people and processes involved and nowadays we need a lot of time to obtain information, sometimes even a year, especially with the sewerage system.

For example, in some difficult projects, it may take weeks before we have all the things back into our maintenance system. And you wanted to be days, I hope, but not as long as it takes now. You want the information to get as fast as possible into your system because today it is built and then you want to know that is actually built, so it has to be in the system. You want that time between the building and maintenance system to be as short as possible. That is I think the main goal. I3

Reasons

The current process is time consuming and error prone resulting to delayed delivery. The main reason is that it relies so heavily **on manual inspection and entry of data to the applications**. In addition, the **lack of expertise**, **the difference in the level of detail of the information** and **the lack of defined information requirements** seem to contribute to the missing information that asset managers obtain.

Manual Work

I think what is taking a lot of time now is because what I said, the information is taken from the construction site, goes to the supervisor, to my colleague and it is all done by e-mail *or by hand. And all the controlling is also done by hand, so it takes a lot of time and there is room for mistakes. That is what is wrong with it. So, when you automate things, you can rule out those mistakes. I think this is something that we would like to change. I3*

There is not an organisation that does not have this problem. It is just people working and making mistakes, it is not a strange thing. I2

Lack of expertise

Manual work results into loss of information or not accurate information. A solution could be the utilization of open standard exchange formats that can enable the communication between different software. However, the lack of expertise seems to be an obstacle to the implementation.

The main reasons mostly are because they do not have the right people or they lose information, they are sloppy or they think that it is not important because they are builders and not information managers. I1

And we have a struggle with that because as a municipality (..) So what we do is to exchange in a way that is not any kind of software but you can translate it to any kind of software, like GML or IFC, etc., etc. But when we do that we see it is, even more, harder for constructors to understand what we are doing than if we just give a DWG to them. I5

When you have to understand GML or OroX or IFC or CityGML or any of the standards that are software independent, it is a kind of IT job and that is really hard and really technical. And a constructor what he can do well is make a sewer, he is not an ICT man. I5

Different Level of Details

Another reason that contributes to the information loss is the absence of communication between the different lifecycle phases. Engineers and Asset Managers speak different languages and they need different level of detail of information to perform their tasks. The absence of a common language between them results to asset managers making manual modifications to the information as they do not need all the information that constructors deliver. In addition, it reduces the level of communication and understanding of information needs between the actors and increases the delays.

There are four phases: the design phase is a total world separated from engineering, operation and maintenance. In these 4 worlds must be implemented a lot of changes and enhance communication between them. OTL's can enhance communication but they have to be simple and to use the right tone of voice and take into consideration the people that you are speaking to. It is always a thin line between simplicity and technical. Communication is very important, I think. I1

Yes, and why doesn't want the asset manager to the kind of detail that we produce? Because he doesn't speak the language and it's too much work for him to translate all the information. I think when we know each other language and we can make some kind of automation. I5

Lack of defined information requirements

Yes, we are missing information in our processes. So, we do not receive the information from the contractors because we do not define it in the beginning phase. I4

Future Solutions

"Future Solutions" discusses possible measures that can be used or have been used to address the Drawbacks mentioned in the previous theme. This theme was mostly highlighted in the interviews through discussions about the problems of the current process and how they can be overcome in the future. The main aspiration of the interviewees is the elimination of manual work which is time-consuming and prone to errors. Therefore the automation of processes such as the exchange and control of the information is the main goal for the future. The interviewees mentioned that **the standardization** is an important principle and **integrated systems** may be another solution.

Standardisation of Information Exchange

A uniform data registration is a first step towards the automatic data exchange without information loss by achieving semantic interoperability (Karimi et al., 2004). Semantic interoperability can be achieved by two ways: Applications share a common vocabulary or creating mappings between their different vocabularies (Ushold and Menzel, 2005). The other two parts are the usage of exchange standards which describe how data should be structured for sharing. Finally, a standard for guidance which formalises the information exchange process is the last principle. It defines when, how often, what information and in which format has to be exchanged (Hoeber and Alsem, 2016) between the contractor and the client.

My personal opinion is that we need to standardize the delivery standards. I1

The most important is the different systems to use one type of dataset like IMBOR, the data warehouse as we call it. In this way, we will not depend on the software to build the data set. I2

I think that there has to be a standard, national or international that not only the municipality of Rotterdam but also other municipalities say that I want to use in their super(mega) projects. And the construction party will know what they will get from the municipality and what they have to give back to the municipality. I5

From the answers of the practitioners it is evident the need of the standardisation of information exchange process. They underline the necessity of using a common language (a common OTL or Ontology) and the standardisation of deliveries. In this way, the contractors not only will use uniform data but also will know what, how and when will need to get or deliver the information to the municipalities.

Integrated Systems

The other idea that was mentioned was shared systems between the contractor and the client. By using this systems, the contractor could deliver the required information and it would be automatically processed to be understandable by the asset management systems and assessed for its completeness.

We need to put some systems in place in the municipality of Rotterdam so that the contractor can log in, insert the data, and then we check if they are complete. But there are too many people and processes involved and nowadays we need a lot of time to obtain information, sometimes even a year, especially with the sewerage system. So, if we could have a system where the contractor could log in and in the system we have prepared it for the right information that we need and we could check that is complete, that would be a win-win situation for all the parties involved. I1

Yes, I hope in the future that the contractor can get the information he needs straight out of our system and when he has built the sewerage system, then he can put it back into our system and the system controls and converts the information. So, there are not activities that are done by hand. I think that could be a good step for us. I3

3.4 SUMMARY

Asset management is still an emerging theory and literature indicated that specifically WIAM has not yet aligned strategic decisions with operational activities. In addition, asset managers confront challenges of improving and standardizing the quality of the information they have at their disposal, both to execute the daily operational tasks as well as to provide reliable information to facilitate top managers to make strategic decisions (Dias and Ergan, 2016; Gnanarednam and Jayasena, 2013). This feature contributes to the misalignment of operational activities and strategic decision-making. Moreover, manual work seems to be the parameter identified by the literature and the interview of practitioners, contributing the most to the loss of valuable information for asset managers which could improve the situation.
Section 3.2.3 documented why scholars argue that asset managers receive incomplete information. The interviews with public authorities practitioners verified most of the reasons. Table 3.2 summarizes the reasons contributing to information loss that were identified in the literature and the interviews.

Literature	Interviews
Not standard structure of the information (O'Keeffee et al., 2017)	Public space does not use a standard structure of information (not a common language)
Not common Formats of the information (O'Keeffee et al., 2017)	-
Lack of expertise to seamlessly exchange the information (Matarneh et al., 2019)	Lack of expertise to seamlessly exchange the information
Different Levels of Detail of the information between the life-cycle phases (Barnes, 2020; O'Keeffee et al., 2017; Yuan et al., 2016)	Different Levels of Detail of the information between the life-cycle phases
Lack of formalising asset information requirements to enable strategic decisions (Becerik-Gerber et al., 2012; Munir et al., 2020a)	Lack of defined/formal asset Information Requirements
Manual Work (Matarneh et al., 2019)	Manual Work

Table 3.2: Reasons contributing to information loss

As manual work is the most important parameter for the information loss, automation is a necessity for the industry. This need was highlighted both in literature and the interviews. Scholars and practitioners also agreed that uniform data registration is the first step toward automatic information exchange. In this way, the related parties and systems will speak the same language resulting in the enhancement of communication and understanding of the information needs. The formalisation of an OTL for making strategic decisions, besides the uniform data registration, would help the contractors to know from the beginning of the project what information they should include per object into their deliveries. Table 3.3 shows a first overview of the information needs that the developing prototype should include based on the interviewees' suggestions.

#	Identified concepts for the prototype		Interviewee	Explanation
1	**Physical Objects**	Pipes Manholes	*They want to know where is the manhole, where it is located, where is the sewer pipe. I5* *The sewerage system is built from one manhole to the other manhole. I3*	
2	**Information Attributes**	Position (X,Y,Z coordinates)	*It is measured at the position of the sewerage system both horizontally and vertically because we need to have what I have said the depth of the system which is important. We measure the depth of the sewerage system, how much it had been sunk. It is because the depths of the sewerage system is an indication of how well it is functioning. I3*	
		Maintenance Level (Ongoing, Planned, Postponed)	*For a sewerage system, we need to know its depth, where it starts and where it finishes or which is its maintenance level. I2* *You have the as-built situation and then you go to the maintenance, so every 9 to 10 years you measure again and you get an idea of how the sewerage system is functioning and when it is about to fail and you have to maintain or dispose it and built a new one. I3*	
		Type of materials	*We need to know what kind of materials we are using to make our city circular. I2*	
		Physical and Functional condition	*They ride with a camera through the sewerage system to show us that it is well built ,so no leakage and no cracks on it. I3*	
		Year of Construction Dimensions	*They want to know where is the manhole, where it is located, where is the sewer pipe what is the height of it, what is the location of it, what is the dimension of it, what is the time that is constructed. I5*	
3	**Information Documents**	Sewer Inspection Report	*We also need them to give in some kind of inspection. I3*	The measurements refer to the topographical data required for the BGT
		Drawings	*All these details are the as-built drawings, so materials, the year of building, the depts. I3*	
		List of Materials	*You need the drawings and the materials because we need to know what type of materials we are using to make our city circular. I2*	
		List of Measurements	*It is mostly drawings, a list with the measurements and sometimes a GEO database. I1*	
		Revision Drawings	*The most important thing is the drawings, the review taken in the drawings and specific asset management information. I2*	
4	**Related Standards**	IMBOR GWSW	*This year, IMBOR was standardized and we want to use it and we need it very badly. I1* *I think the OTL like GWSW is better. It not only describes the concept as a sewer pipe but it gives to the concept different levels of detail, (...) I think IMBOR is a good language for the asset manager but it is not a good language for the engineer. I5*	Related Standards that have already defined and register concepts relevant to the public space and sewerage management. They can be used in order an ontology (OTL) use the same vocabulary with other parties in the sector.

Table 3.3: Identified concepts for the developing prototype from the interviews

Part III

TOWARDS THE DESIGN OF THE ONTOLOGY

4 DEVELOPMENT OF THE ONTOLOGY

4.1 INTRODUCTION

This chapter aims to describe the methodology and strategy that was adopted to design the ontology. Section 4.2 describes the methods and approach followed. In its subsections the first three steps are analysed and explained and the conceptual design of the ontology is presented. More specifically, the identification of the ontology's stakeholders is discussed and the requirements that are derived based on their needs. These two activitied contribute to the definition of the solution's design scope. Then, after the review of existing ontologies from the literature and Dutch public asset and water management sector, the main concepts that describe the necessary knowledge are explained. Finally, a summary of the fourth chapter is provided in Section 4.3.

4.2 METHODOLOGY FOR THE DEVELOPMENT OF THE ONTOLOGY

Based on the literature review and the examination of ontology development methodologies, a list of methodological steps were created for the successful development of a domain ontology. It is good to mention that there is not one correct way to model a domain (Noy et al., 2001). It was selected to follow the methodology described on the work of Zhou et al. (2016). This method integrates the advantages of various ontology development methodologies and it is focused on the construction industry. Figure 4.1 illustrates the systematic framework for the building of the ontology.

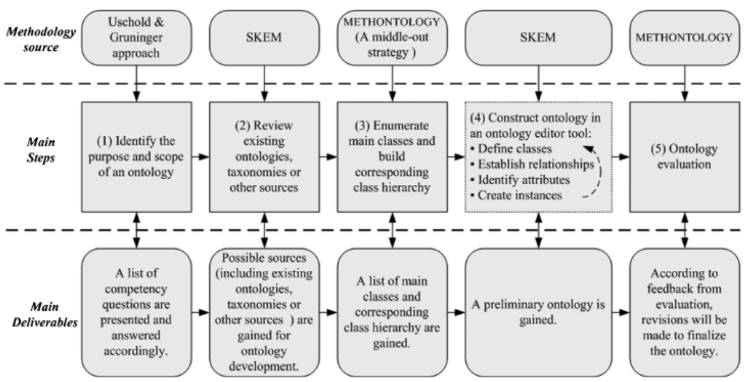


Figure 4.1: Methodology for ontology Building (Retrieved by Zhou et al. (2016))

Based on the above systematic framework, the following steps were identified which will be discussed on the rest of the chapter:

1. **Define the domain and scope of the ontology**
    - Sketch a list of competence questions.
    - Derive functional, structural and environmental requirements.

2. **Review of existing standards and other sources**
   - Possible sources that can be reused by adding or excluding from them elements. It is often suggested as a shortcut to the process but also can offer advantages to the interoperability.
3. **Initial Structuring of the Ontology**
   - A list of main classes and the taxonomy are gained.
4. **Building the Ontology**
   - Choose the right ontology editor
   - Choose the modelling language of the ontology
   - Construct the Ontology in the editor tool
5. **Evaluate and Refine Ontology**

4.2.1 Defining the Domain and Scope of the Ontology

In the previous parts of the document (Part 1 & 3), a desk research study and semi-structured interviews were conducted for identifying and describing the problem to be treated. These research activities were conducted in order to analyse the problem (what is the problem, why it is a problem and whose is the problem), make a diagnosis and gather information for the design of the solution (see Section 2.2). This section will elaborate on the Goal & Scope of the solution, thus the stakeholders of the domain of interest, the aims and objectives, the scope and the requirements that are produced will be described.

4.2.1.1 *Stakeholder Analysis*

To investigate the problem, the first step is to identify the domain of interest and its stakeholders. After the initial literature review, it was decided the domain of interest to be the public space and more specifically the sewerage systems. The reason was that asset managers in the Netherlands argue that they have identified that they obtain incomplete or not accurate information from the previous phases. They believe that a reason is the absence of a uniform registration of the data fulfilling their information needs and accurately describe their domain (Gemeente Almelo and Gemeente Utrecht , 2021). Therefore, the stakeholders of the domain of public sewerage systems will be mentioned and secondly, the identified stakeholders will be mapped according to the onion model of Alexander (2005).

STAKEHOLDER IDENTIFICATION A stakeholder is a person influenced by the solution of a treated problem and can has the power to impact the outcome (Reed et al., 2009). They are one of the sources of goals within a project, goals that the produced solution has to satisfy. Consequently, they are one of the sources of project's requirements (Wieringa, 2014). Their identification along with the technological opportunities, previous research and solutions, ensure that all requirements are included to the design of the end-product (Johannesson and Perjons, 2014). The stakeholders of this project are described within the Table 4.1 together with the goals and constraints.

#	Stakeholder	Description	Goal(s)	Constraints
1	Designer	Msc student of TU Delft, responsible for the development of the domain ontology.	- Acquiring master's degree.	- Project duration of 6 to 8 months.
2	Public Authorities	Organisations with ownership and responsible to operate & maintain the sewerage systems.	- Complete, accurate & up-to-date as-built information of their sewerage systems. - Enhancing the quality of obtained information from the previous project stages. - Easy to use ontology.	- Development of a solution that will capture all the required information for their needs. - A complete common language for the public domain
3	Contractors	Collaborated parties responsible for the construction of the sewerage system.	- Obtain and understand the information requirements of the client from the beginning of the project. - Easy to use ontology.	-
4	Standardisation bodies	Organisations concerned with the information modelling of public utilities (such as IMBOR).	- A complete set of requirements for the sewerage system. - Improving system interoperability amongst actors of public space projects.	- Conformance with existing standards.
5	Software developers	Organisations developing asset management related software.	- Development of sector-wide asset management software for the sewerage systems.	- Development of a solution suitable for the existing software in the industry.
6	Sewerage system users	End-user of sewerage systems.	- Reliable and effective sewerage systems.	-

Table 4.1: Stakeholders within the project

STAKEHOLDER MAPPING The mapping of the stakeholders follows the onion model of Alexander (2005). This way of stakeholders mapping is more focused to the end product rather than the relation of stakeholders' power-interest. The taxonomy that Alexander (2005) created to classify stakeholders has an immediate impact on identifying and validating the roles of stakeholders in requirements elicitation. That helps to address all the requirements, hence the risk of failure of the end-product is reduced. The mapping of the stakeholders can be see in in Figure 4.2.

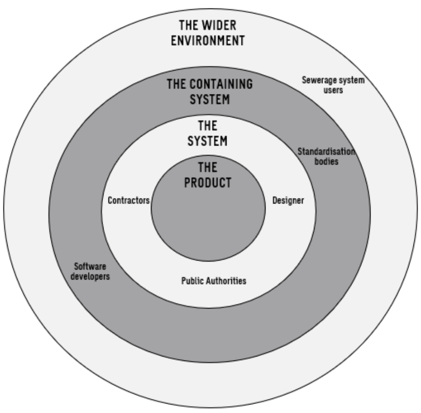


Figure 4.2: Stakeholder Mapping following Alexander (2005) onion model

Figure 4.2 shows the project's stakeholders within the onion model. The inner circle **"The Product"** is the item under development. In our case, this is the domain ontology for the sewerage system. The next circle **"The System"** consists of the stakeholders that can influence the design requirements, and eventually they might be the ontology users. These are the Public Authorities whose information needs will be captured by the ontology and the contractors who will need to use it in order to understand those needs and transfer the correct information. The circle of **"The Containing System"** includes beneficiaries that are indirectly involved in the design procedures. That means that they can not impose changes to the design, however they do have an influence on that. For example, the standardisation authorities have provided object type libraries (or ontologies) that can be used as a guidance for the development of the end-product. Finally, the **"The Wider En-**

vironment" all the other identified stakeholders. Sewerage system users belong to this circle as they may benefit from the use of an ontology. As it was identified from the interviews (see Figure 3.16), the handover of the project is not completed until the Public Authorities will have a complete information set for their need operate & maintain the artefact. The end-product could enhance communication, leading to contractors transferring quicker complete information resulting to less down-time of the utility.

4.2.1.2 *Problem that the Ontology Aims to solve*

The problem investigation and diagnosis (see Part 3) showed several problems (Table 3.2) contributing to the information loss that an object has between the life-cycle phases of a project. The main problems that the need to be solved are:

1. **The lack of structured knowledge for strategic decisions in the domain of public sewerage systems.**

2. **The lack of formal information requirements of sewerage systems owners' to facilitate their strategic decisions.**

3. **The reception of irrelevant information from earlier phases forcing the asset managers to search in disperse information sources which leads to secondary costs.**

4.2.1.3 *Opportunities and Challenges*

Currently, in the industry there is not a language which describes adequately the information needs of asset managers for the operation & maintenance of a sewerage system. In the construction industry, usually the related parties collaborate only during the execution of a project rather than establishing long-term relationships with clearly defined process (Borrmann et al., 2018; Hoeber and Alsem, 2016). Ultimately, this leads to different information requirements at every project and fragmented models. That makes the transfer of the needed information prone to errors, confusion and miscommunication between the related parties (Hoeber and Alsem, 2016). Therefore, the aim of this research is:

The development of a domain-task ontology that includes the relevant concepts and relations for enabling strategic decisions for the operation and maintenance phase of a sewerage system.

In this way, the related parties and systems will speak the same language resulting in the enhancement of communication and understanding of the information needs. The formalisation of an OTL for making strategic decisions, besides the uniform data registration, would help the contractors to know from the beginning of the project what information they should include per object into their deliveries. The contribution of the domain ontology to the sector of public water utilities is:

- **To enhance the communication between the client and contractor by making explicit the information needs of the client from the beginning of a project.**

- **Facilitate the contractors to transfer only the relevant information that asset managers need in the operation & maintenance phase to make strategic decisions.**

- **Aggregate the needed information from diverse sources resulting in reusable information and reduction of secondary costs.**

4.2.1.4 *Requirements of the Ontology*

After having identified the stakeholders of the project, conducting interviews to understand their goals and information needs, now it is time to proceed to the elicitation of ontology's requirements. To elicit the requirements, various methods were applied: (1) creation of a list with the competency questions (2) translation of the stakeholders' goals and needs towards requirements, (3) document study and literature review

COMPETENCY QUESTIONS Besides the stakeholder mapping and interviews, one way to define the scope of the ontology is to create a list with questions (Noy et al., 2001). The end-product should be able to provide the information to answer those questions (Noy et al., 2001; Sure et al., 2009; Uschold and Gruninger, 1996). By answering the competency questions corresponding functional requirements can be gained for the design of the ontology (Zheng et al., 2021; Zhou et al., 2016). In addition, competency questions can be used and as an evaluation tool to check whether the ontology contains enough information to answer them and fully cover its scope (Corcho et al., 2003; Noy et al., 2001). Therefore, the competency questions are focused on satisfy the goal of the public authorities, which is to have complete, accurate and on-time information in order to make strategic decisions for their sewerage systems.

The formulation of the competency questions is related with the uses of the ontology. Within the context of this research thesis, a use is seen as a decision that the asset manager should have the relevant information to create value for the organisation in the long term. Therefore, these decisions and the information that satisfies them supported the creation of the (informal) competency questions. The term informal comes up by the fact that the questions are not expressed in the formal language of the ontology (Uschold and Gruninger, 1996). In accordance with the goal of the research thesis, its scope and the stakeholders demands, eight use cases were identified. Altogether, the uses cases were formulated to satisfy long-term decisions for the whole lifecycle of an asset in the domain of operation & maintenance of a public sewerage system. Consequently, the competence questions were formulated and categorised to a particular use case. The theory of Strategic Asset Management (see section 3.2.1.1 and the analysed interviews (see the theme **"Information Needs"** in section 3.3.2) helped towards the formulation of the competency questions. The following questions were specified as a starting point for the design of the ontology:

1. **Identification of the sewerage system.**
   - What is the ID of the sewerage system and/or its components?
   - What is the year of construction of the sewerage system
2. **Identification of the related parties of the sewerage system**
   - What is the name of the client organisation of the sewerage system?
   - What is the name of contractor organisation of the sewerage system?
   - What is the name of the administrator of the sewerage system?
   - What is the name of the responsible person of the contractor organisation for the sewerage system?
3. **Identification of the location of the sewerage system**
   - What is the municipality that the sewerage system is located?
   - What is the city of the sewerage system ?
   - What is the neighborhood of the sewerage system ?
4. **Assessment of the dependencies between (1) the sewerage system and its components (2) components.**

- How the sewerage system and its components relate to each other?
- How the components of the sewerage system are related to each other?

5. **Assessment of the functioning and usage of the sewerage system and/or its components.**
   - What is the function of the component?
   - What is the functional state of the component? Is the function performs according to the designed specification?
   - What is the physical condition/state of operation of the system and/or its critical components? Is there any defect?
   - What is the severity of the defect to the physical state?

6. **Mapping the risks that might cause deterioration of the state or performance of the sewerage system and its components.**
   - Is there any risk to the state of the sewerage system due to soil subsidence?
   - Is there any risk to the state of the sewerage system due to vegetation?
   - Is there any risk to the state of the sewerage system due to corrosion?
   - Is the sewerage system or a component in high risk?

7. **Identification of the sewerage system's and/or its components' characteristics which influence its state**
   - What is the maximum capacity of the system or its components?
   - How many years the system or the component is in operation?
   - Which is the position in the (1) x-, (2) y- or (3) z-coordinate of the sewerage system and/or its critical components (manhole, sewer pipe?)
   - What is the shape of the sewerage system component?
   - What is the type of the material of the critical components (sewer pipes, manholes) of the sewerage system?
   - What are the dimensions of the critical components of the sewerage system?
   - What is the soil type of the sewerage system?

8. **Planning of operation & maintenance activities.**
   - What is the available budget for the execution of operation & maintenance activities?
   - When was the last inspection performed?
   - When was the last maintenance performed?
   - What was the last maintenance or inspection method?
   - What is the status of the activity?
   - What is the cost of the activity?

It is wise to mention that these competency questions are an initial draft to help the elicitation of the requirements. However, ontology development is an iterative process and the list of the questions, the requirements and consequently the ontology can be refined during the validation phase.

LIST OF REQUIREMENTS Johannesson and Perjons (2014) distinguishes three categories of requirements; functional, structural and environmental requirements. A functional requirement can be defined as a function that the end solution should satisfy depending on the needs and wants of the stakeholders. Therefore, these are the requirements that describe the knowledge that the ontology needs to represent (Fernández-Izquierdo and García-Castro, 2019). An example is the assessment of the performance of the sewerage system. In contrast, a structural requirement aims to structure and environmental requirements are related to form an environment for the solution that is more generic. Examples of structural requirements could be that the ontology should have a coherent and modular design. Examples of environmental requirements could be that the ontology should be supported by existing languages or existing modelling standards.

An ontology is successful only when depicts the knowledge of a specific domain by creating a shared set of conceptualisations (Gruber, 1993). Therefore, to elicit the functional requirements the focus was on the needs of asset managers. This was achieved through: 1) interviews and 2) literature. The interviews helped to understand the long-term decisions that asset managers need to make. In addition, they offered a preliminary insight into the information needs that the managers of sewerage systems need to make these decisions. The literature provided a more in depth insight into the long-term visions and goals of the municipalities. Altogether, these sources helped to formulate the competency questions and reflect upon the stakeholder goals.

In addition to the functional requirements, structural and environmental requirements were defines as well. These were elicited from literature review and document study. Seven papers were reviewed that described structural characteristics for an adequately design of an ontology (Chimalakonda and Nori, 2020; Corcho et al., 2006; Costin and Eastman, 2014; Lovrenčić and Čubrilo, 2008; Missikoff et al., 2002; Noy et al., 2001; Uschold and Gruninger, 1996). Subsequently, eight criteria were defined: 1) accuracy, 2) adaptability (modularity/extensibility), 3) clarity, 4) completeness, 5) conciseness, 6) consistency and 7) reusability (by leveraging existing knowledge such as using standard practises (languages) or standards).

The requirements were written down by distinguish them into two categories 1) Industry's Operations and 2) System/Product. This distinction was used in order to categorise the requirement to the ones that will satisfy needs and goals that were derived by the industry's practices while the latter category describes the (structural or environmental) characteristics that the solution should have. The complete list of requirements can be seen in Table 4.3 . The second-last column indicate whether the requirement was taken into consideration while the last one indicates whether the requirement was validated or not.

#	View	Goals	Needs	Requirements	Scope	Validated
1.1	Industry's Operations	Improved long-term decision making	More information-based decisions for on-time intervention	The solution should provide life-cycle information that will allow asset managers to prioritise which asset need to intervene and when		
1.2			Better allocation of the budget	Should provide life-cycle information that will allow asset managers to allocate the budget to the right project of their portfolio		
1.3			More information-based decisions for climate adaptation	Should provide life-cycle information from the earlier phases that will allow asset managers to make sustainable decisions		
2.1		Improved Communication between the public asset owners and the contractors	Reduce costs	Should reduce the secondary costs that are produced by the delay of the handover of an incomplete set of information		
3.1		Improved interoperability of public space data	Reduce miscommunication and misinterpretation of information needs	Should provide a unified and uniform set of concepts and relations based on shared conceptualizations of the end-user.		
3.2			Reduce the load of manual work and consequently the information loss	Should reduce the manual work (translation of terminologies, inputting data from contractor to their databases, translating standards) and the risk of information loss		
4.1	System/Product	Improved transfer of information at the handover stage of a project	Complete	Should cover all relevant concepts and relation within the domain of operation & maintenance of sewerage systems		
4.2			Accurate	Should cover the information needs of the asset owners with the right level of detail		
4.3			Consistent	Should include consistent definitions and no contradictoyr knowledge can be inferred		
4.4			Concise	Should not include redundant or irrelevant concepts and relations		
5.1		Ontology is future-proof	Modular	Should allow new elements to be added without changing its existing core		
5.2			Adaptable	Should be easy to adapt in case of changes of information needs of the users		
6.1		Easy utilisation of the ontology	Clear	Should include a defined, explained and documented taxonomy and hierarchy		
				Should include a defined, explained and documented vocabulary of terms and		
6.3			Instructions	Should provide instructions on how to apply the ontology which are easy to read,learn and apply		
6.4			User-friendly	Concepts and relations must be easily traceable by the user		
7.1		Supported by the existing environment	Supported by ontology modelling languages	Should comply with existing ontology languages to be compatible with ontology modelling tools		
7.2			Supported by the industry's modelling standards	Should comply with existing sewerage system data as modelled in existing standards (i.e. IMBOR, GWSW, IMKL)		

Figure 4.3: Ontology Requirements

4.2.2 Review of existing standards & other sources

An activity that is worth to spend time during the building of an ontology is the review of existing standards. This is also the second step of the applied methodology towards the development of the prototype. It is possible that someone has already modelled a part of the domain that we intend to cover. In this way, we can check if we can refine or extend existing ontologies in order to achieve the representation of the required knowledge for our task (Noy et al., 2001). One advantage is that the modeller will not have to reinvent the wheel and a significant amount of time will be saved. Moreover, it can enhance the interoperability between systems. Noy et al. (2001) mentioned that if our system has to communicate with other systems that have already committed to certain ontologies or restricted vocabularies, reusing existing ontologies may be required. For the development of this prototype only Dutch ontologies were reviewed as the scope of the thesis includes only the Dutch public sewerage systems.

4.2.2.1 *IMBOR*

IMBOR intends to become the common language of public space. It was create in such a way in order to have similarities with other national and models of the domain. To achieve the best possible coordination and eventually linkage and becomes the common language of the public domain, an attempt has been made to connect its taxonomy with other models (CROW, 2022a).

Figure 4.4 shows the current situation in the industry. Throughout the years the information needs and uses of industry's parties have been translated into standards, which can be modeled into ontologies which describe the knowledge for a particular application. For instance, an application ontology for an asset management of public lights who wants to execute an energy performance analysis of a light system or an ontology for an asset management software.

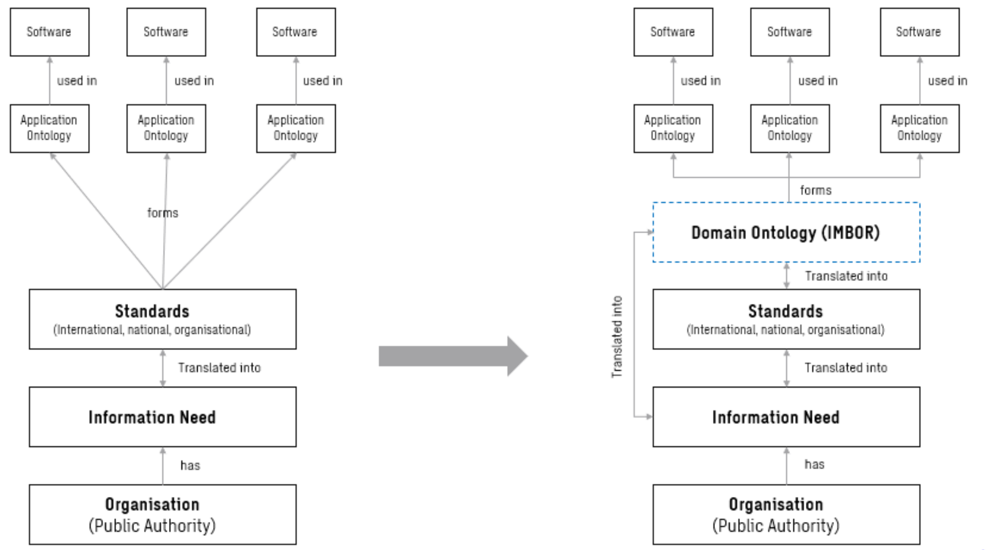


Figure 4.4: The place of a domain ontology in the industry (left as-is situation, right with the as-intended by adopting a domain ontology)

The inclusion of a domain ontology can act as an intermediate layer. Organisations can be create their own onotlogies based on this common domain ontology, and therefore become interoperable one with each other.

By using IMBOR due to its conformance with other standards such as NEN 2660-2 ensures that the data structures are more comparable and easier to link. Therefore, it provides a better reusable and applicable solution for the practice and it is an important step to achieve integration for data from different sources.

4.2.2.2 GWSW

GWSW or the Urban Water Data dictionary, is an open mandatory standard for the uniform recording, exchange and reuse of data in urban water management (Forum Standaardisatie, nd). As an open standard (free for use from anyone), GWSW is part of the semantic Web and is modeled in the W3C web language RDF/RDFS/OWL-2 (RIONED Strichting, 2022). It is an ontology (common language for the domain of urban water management) which describes the objects, systems and basic management processes in sewer and urban water management (RIONED Strichting, 2022). However, according to the interviewees, GWSW is more suitable for the engineers as it describes the domain of sewer management in a greater detail than an asset manager need (see section 3.3.2, paragraph of ***Standards***). Thus, not all the concepts or attributes inside the dictionary is needed for an asset manager. A comparison between the two standards is available in the Table 4.2. The comparison was based on six elements:

1. **Focus:** focus (purpose) of the standard
2. **Scope:** scope of the standard
3. **Users:** the targeted end-users of the standard

4. **Data:** the application schema that are modelled
5. **Origin:** the country that the standard is applied and modelled for
6. **Reference:** the reference that was used for the analysis

#		IMBOR	GWSW
1	Focus	The aim is to create become the common language for Public Space Management. It standardizes concepts for all the fields of public space management (Water, Roads, Green, Public Lights etc.) and the management data that can be recorded per of object.	The GWSW is an ontology (a semantically rich data model) for the data exchange in the field of sewerage management and urban water.
2	Scope	IMBOR contains only fixed object data. It does not describe dynamic data (condition measurements, inspections, planning & budget data). This is done for the field of sewerage management in GWSW.	Applies to activities of urban water and sewerage management. This concerns urban water tasks: the collection, transport and processing of rainwater, groundwater and waste water, both underground and above ground. This mainly concerns the data on the characteristics, condition and functioning of the objects and systems and the work processes for that urban water management.
3	Users	Targeted users are public domain authorities. It is intended to be the common language for all the disciplines of Public Space Management.	Almost all organizations that are professionally active in the field of urban water management are benefactors, including almost all municipalities, all water boards, some provinces, private sewerage managers, many consultancies, including all leading engineering firms, supply companies, contractors and sewerage inspection companies.
4	Data	IMBOR is available in both MS Access and Linked Data.	It is part of the Semantic Web and is modeled in RDF/RDFS/OWL-2.
5	Origin	The Netherlands	The Netherlands
6	Reference	IMBOR Technische documentatie (CROW, 2022a)	Agenda item 3D - Intake advice GWSW version 1.5.1 (Stuurgroep Open Standaarden, 2020)

Table 4.2: Comparison between the two standards

The literature review and the interviews showed that asset managers confront challenges of improving and standardizing the quality of the information they have at their disposal, both to execute the daily operational tasks as well as to provide reliable information to facilitate top managers to make strategic decisions (Dias and Ergan, 2016; Gnanarednam and Jayasena, 2013). The interviewees underlined the necessity of a common language (ontology) for the domain of public space that will solve this problem amongst others. IMBOR is an initiative that intends to register all the objects in the public space and their related management data. However, this information model is still incomplete for the sewerage system and in addition it includes only static information for the objects (CROW, 2022b). Thus, it does not describe dynamic data such as condition descriptions (inspections, condition measurements etc.), planning and budget data that an asset manager needs for making long term decisions. Literature and interviews mentioned that GWSW is a more complete ontology for the sewerage system and includes this type of information. Nonetheless, it describes the information in greater detail which may result in asset managers to obtain more information than they need from the previous phases (Barnes, 2020). An overview of the two standards and their relation with other standards is provided in the Appendix D.

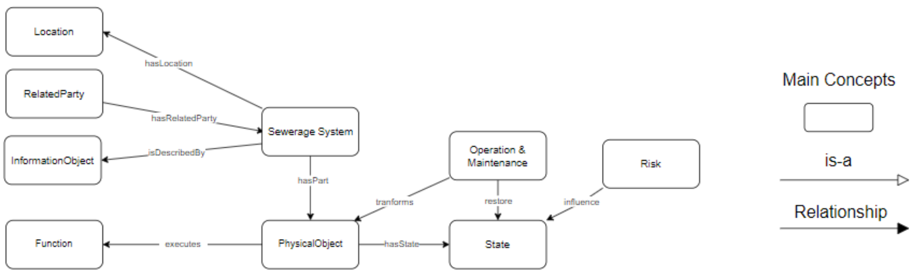
4.2.3 Conceptualisation

The end goal of the prototype ontology is to provide the information that satisfies the asset managers' need for cost efficient asset management (see section 3.2.1.1). After the review of existing ontologies and relevant literature eight main concepts were created to achieve the end goal and create the conceptual model which is the the outcome of the third step of the methodology of Zhou et al. (2016) (see section

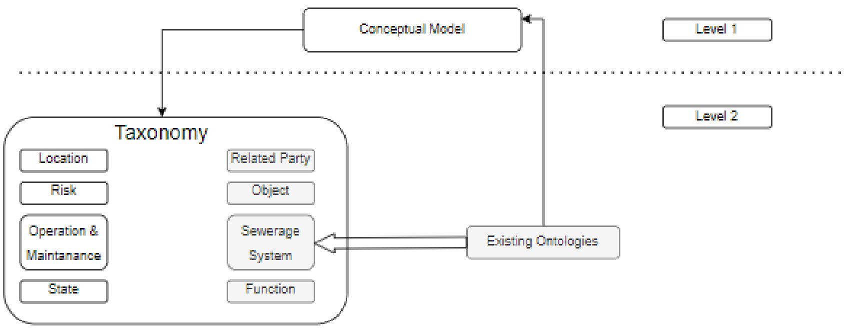
4.2. The creation of the conceptual model represents key concepts at the abstract level aiming to accomplish two objectives (Zeb, 2020):

1. to facilitate the understanding of how the diverse knowledge is interrelated
2. to categorise easily the knowledge to lower levels of detail

The development of the prototype ontology followed the the approach of Gómez-Pérez et al. (2006) by adopting a layered architecture. Except from the conceptual model which represents the generic knowledge at level 1, a second level was also developed. Level 2 represents the specialised knowledge by developing or reusing existing ontologies/taxonomies (Zeb, 2020). Figure 4.5 illustrates the conceptual model and the existing ontologies highlighted that were used for this research work.



(a) Conceptual Model



(b) Ontology Architecture (Adapted by (Zeb, 2020))

Figure 4.5: Ontology Architecture and Conceptual Model

The conceptualisation of the model starts with the system/asset of interest (sewerage system), which is owned, operated or managed by a related party (organisation or person). The scope of this research is focused on the effective long-term decisions these parties should make to manage their assets cost-efficiently. Therefore, they need to know the location of their assets (Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009; Vanier et al., 2006b). Moreover, to decide which asset measure has to be applied, the asset owners need to know the physical and functional state of the objects which form the system and if they fulfil their designed function (Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009; Vanier et al., 2006b). In addition, they need to have the history of asset maintenance and if a measure has been deferred causing the deterioration of the state (Vanier et al., 2006a). Finally, to assess the criticality of the system and decide on which asset they will allocate their budget, the risks that may cause significant deterioration of their assets' state have to be mapped (Kapelan, nd; Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009).

Based on the logic mentioned above, eight main concepts were defined along with the relationships between them to formalise the knowledge for the facilitation of asset owners' long-term decisions. More specifically, the long-term decisions concern the selection of which measure (maintenance-inspection-local repair, renovate or replace) they have to apply and on which asset. To easily categorise the knowledge, 4 taxonomies are built, whereas the rest are captured from existing ontologies. Table 4.3 includes the eight main concepts and their relation to the ontology. Table 4.4 shows the reused taxonomies and their sources.

#	Concept	Relation with the Ontology
1	Sewerage System	Asset managers need to know which assets they posses as they are entities which have the potential to create value for their organisation.
2	Related Party	Identifies who is the owner of the asset and responsible for the appliance of Operation & Maintenance measures. Moreover, it identifies which organisation is the contractor and which individual is responsible for the project from contractor's side.
3	Location	It is essential for asset managers to know which is the location of the assets of their portfolio.
4	Object	Asset Managers need to know which are the important Physical Objects that may influence the physical condition or the performance (functional condition) of the asset. Moreover, during the handover process they ask from the contractor Information Objects which include the necessary knowledge for their needs in the Operation & Maintenance Phase.
5	Function	The Functions are executed by the Physical Objects. If a function does not fulfil its designed purpose, asset managers need to apply Operation & Maintenance measures.
6	State	Asset Managers need to know which is the physical and functional state of the system and if it performs the required level of service. Defects could compromise health and safety.
7	Risk	Underground utilities confront risks such as vegetation or soil subsidence that eventually can cause the deterioration of the system's performance and condition. These risks have to be identified in order to assess if an asset is critical and a priority for the appliance of Operation & Maintenance measures.
8	Operation & Maintenace	During this phase of a system's or object's lifecycle managers need to take decisions on what strategy (local repair, renovate or repair) they will follow that will enable the system to provide the required level of service and will be cost-efficient for the organisation.

Table 4.3: Main concepts of the ontology

#	Concept	Source	Explanation
1	Related Party	El-Diraby et al. (2009)	-
2	Object	IMBOR/NEN 2660/GWSW	IMBOR and NEN2660 argue that objects can be classified to Physical and Information Objects. The next level of the taxonomy is created by two classes, Construction Component (IMBOR) and Sub-System Objects(own introduction). The last level was created by concepts identified from the interview discussions, provided documents from the municipalities and existing standards.
3	Function	IMBOR/NEN 2660/GWSW	Functions are a subclass of the proposed Top Concept Activity of NEN2660 standard.
4	Sewerage System	GWSW	Follows the taxonomy of GWSW of the concept "Rioolstelsel".

Table 4.4: Reused taxonomies and their standards

4.3 SUMMARY

This chapter introduced the methodology that was adopted in order to develop the prototype ontology. Firstly, the scope and domain of the ontology were defined. A stakeholder analysis and the elicitation of the structural, functional and environmental requirements that the prototype should satisfy shaped the scope of the design. Finally, after the review of existing standards and in combination with academic literature and the interviews, a conceptual model was presented which facilitate the understanding of how the diverse knowledge is interrelated. Moreover, the conceptual model helps to create the backbone of the ontology and in the next chapter to classify the rest of the identified concepts and represent more specialised knowledge by creating taxonomies for every main concept.

Part IV

DESIGNING THE ONTOLOGY

5 CONSTRUCTION OF THE ONTOLOGY

This chapter describes the steps followed in the editor tool to build the ontology. For the build of the ontology, Protégé editor was used, due to its free of and easiness to use characteristics. Section 5.1 describes the features of the editor tool. Section 5.3 describes the steps followed to model the ontology. After the modelling, the preliminary format of the ontology is presented (section 5.4). The term preliminary is used, as in the next chapter, the ontology's structure and content have to be validated in order to finalize its format. Finally, a summary of the fourth chapter is provided in Section 5.5.

5.1 TOOLS FOR THE BUILD OF THE ONTOLOGY

Although ontologies can be written as code, ontology developers usually take advantage of editor tools which facilitate and enhance the development process (Farghaly, 2020). There are several ontology editor tools. However, for this thesis project Protégé is used to code the knowledge representation formally. Protégé is a freely available-to-use editor tool developed by Standford University in collaboration with the University of Manchester (Noy et al., 2001). It was selected because of its ability to a) read and save ontologies in most ontologies formats: RDF, RDFS, OWL etc. (Slimani, 2015), b) build and process large ontologies in an efficient manner (scalability and extendability) (Alatrish, 2012). c) support reasoning tools for the evaluation of ontology's structure, d) support add-on applications for knowledge representation (Zeb, 2020), e) allow the creation of rules and queries that can test the reasoning capabilities of the ontologies (Farghaly, 2020).

Protégé ontology editor has three main components which are classes, properties and individuals (Horridge and Brandt, 2011). The explanation of the components are provided in Table 5.1 and their relations can be seen in Figure

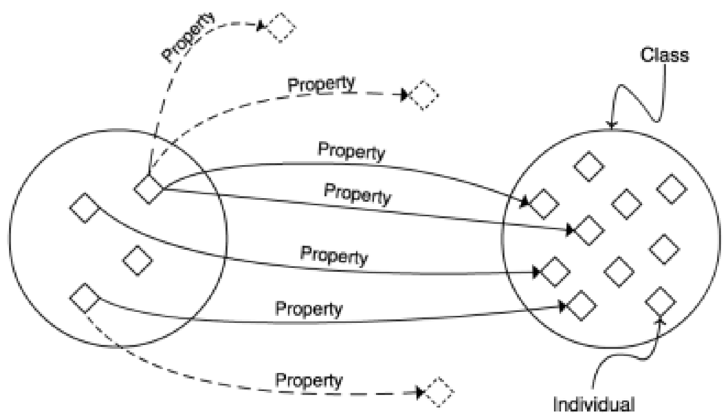


Figure 5.1: Main components in Protégé (Retrieved by Zhu (2015))

#	Components in Protégé	Explanation
1	Class	Sets contain individuals. Every set share similar characteristics.
2	Properties	Binary relationships between individuals or between an individual and a value. They can be: - Object Properties: linking two individuals. - Annotation Properties: they add information (i.e. metadata). - Datatype Properties: they describe relationships between an individual and data values. Characteristics of Properties: - Functional: there can be at most one individual that is related to the individual via the property. - Transitive: if the property relates individual a to individual b, and also individual b to individual c, then we can infer that individual a is related to individual c via property P. - Symmetric: If a property P is symmetric, and the property relates individual a to individual b then individual b is also related to individual a via property P. - Assymetric: If a property P is asymmetric, and the property relates individual a to individual b then individual b cannot be related to individual a via property P. - Reflexive: A property P is said to be reflexive when the property must relate individual a to itself. -Irreflexive: If a property P is irreflexive, it can be described as a property that relates an individual a to individualb, where individual a and individual b are not the same.
3	Individual	Objects in the domain of interest, they contain the knowledge to be shared.

Table 5.1: Main Components in Protege

5.2 ONTOLOGY LANGUAGE

An ontology establishes a common vocabulary in a domain which can be reusable, shareable and understandable both from humans and machines (Frolov et al., 2010; Noy et al., 2001; Polenghi et al., 2019; Zheng et al., 2021). Borst (1999) stated that an ontology should be formal. Hence, it should be written in a machine language in order to be easily processed and shareable. Therefore, standards organisations like the World Web Consortium (W3C) or the Internet Engineering Task Force created a set of languages for sharing meaning. These languages were described in section 3.2.4.2.

In this research, we selected OWL (ontology web language) as the formal language to represent the prototype ontology for the following reasons:

- OWL is more advanced in possibilities by allowing the encoding of heavy-weight ontologies which results in better definition of the meaning and greater machine interpretability.
- OWL is the language that most of the ontologies are built (Vrandečić, 2009)
- Protégé using guide (Horridge and Brandt, 2011) is written for modelling OWL ontologies. Thus, the editor tool fully supports OWL formal syntax.

5.3 BUILDING THE ONTOLOGY

5.3.1 Define Classes

In this section, the building of class hierarchy is presented. Once the main concepts have been defined, the internal structure of the concepts must be described (Noy et al., 2001). The building of a class hierarchy as a structure helps to breakdown the main concepts and categorise easily the knowledge in lower levels of detail. There are several methods to develop a class hierarchy: a) a top-down approach starting from the most general concepts and subsequently someone can derive more specialised concepts, b) a bottom-up which starts from the most specialised concept with subsequent grouping of these into more general concepts, and finally c) a combination of the two approaches (Noy et al., 2001). For the building of the hierarchy of the main concepts of these ontology, we followed a combined approach. As it can be seen in Table 4.4 existing ontologies were revised in order to gain top level or bottom level concepts. The ontologies were not imported into the ontology editor. Instead, their naming conventions and hierachies were followed as explained in the following example, which describes the combined approach.. The combined approach can be seen in the taxonomy of objects where the first, second and third level were adopted by existing ontologies, while the third-intermediate level of the Physical Object class was created in order to classify them in sub-system and component level objects. That step was taken in order to follow the typology of El-Diraby and Osman (2011) who classifies the utility infrastructure objects in system level/top-level objects, subsystem level objects and component level objects. A brief explanation follows:

1. System Level - Objects that are on top of the hierarchy
2. Subsystem Level - Intermediate level of the classification. Objects that can be further decomposed and are consisted from other objects.
3. Component Level - Objects that can not be furthered decomposed

Therefore, with the help of existing ontologies, the literature and our logic an hierarchy for each main concept was gained which can be seen in Table 5.2 and Figure 5.2. More specifically, Nlingenieurs Sewer Systems Workgroup and RIONED Foundation (2009) mentioned:

1. Sewerage System - The coherent collection of sewer pipes, manholes and other facilities used for the collection and transport of foul water and/or rainwater
2. Subsystem Level - A sewer system includes:
    - Sewer (interconnected pipes) and manholes. Each length of sewer piping between two manholes is known as a section.
    - Domestic drains and road gullies that discharge the wastewater and runoff from the connected properties, sites and, roads into the sewer sections.
    - Storage and storage/settling facilities that together with the overflows minimise the impact on the population and the environment.
    - Sewer pumping installations that pump the sewage (wastewater) through the sewer systems and to the seage treatment plant.
3. Component Level - Objects that can not be furthered decomposed and were identified through existing ontologies or literature.

An indication of the decomposition of the sewerage system can be seen in Figure 5.3.

#	Top Level	2nd Level	3rd Level	4th Level	5th Level
1	SewerageSystem				
2	RelatedParty	Organisation			
		Individual			
3	Location				
4	Object	InformationObject	DigitalDrawings ListOfMaterials ListOfMeasurements RevisionDrwaing SewerInspection		
		PhysicalObject	SubSystemObjects	Connection	
				SewerPipe	
				Manhole	
				Structure	StorageSettlingBasin OverflowStructure PumpingStation
			ConstructionComponent	Compartment FlushingDevice Gutter ConnectionPipe FlowProfileDevice MeasuringInstrument Valve Pump MechanicalValve AirVent ClimbingIron ConnectiengPiece DivingShot Foundation Grate Inlet Lid LiftingDevice OdourFilter OdourTrap OverflowSill PipeUnit Pond ReleaseValve SafetyGrid SandTrappingDevice SewerValve ShieldWall	
5	Function	They will be modelled as instances			
6	State	PhysicalState			
		FunctionalState			
7	Risk	CorrosionRisk			
		SoilSubsidenceRisk			
		VegetationRisk			
8	Operation & Maintenance	Activity	Adjustment		
			Maintenance		
			Investigate		

Table 5.2: Class hierarchy

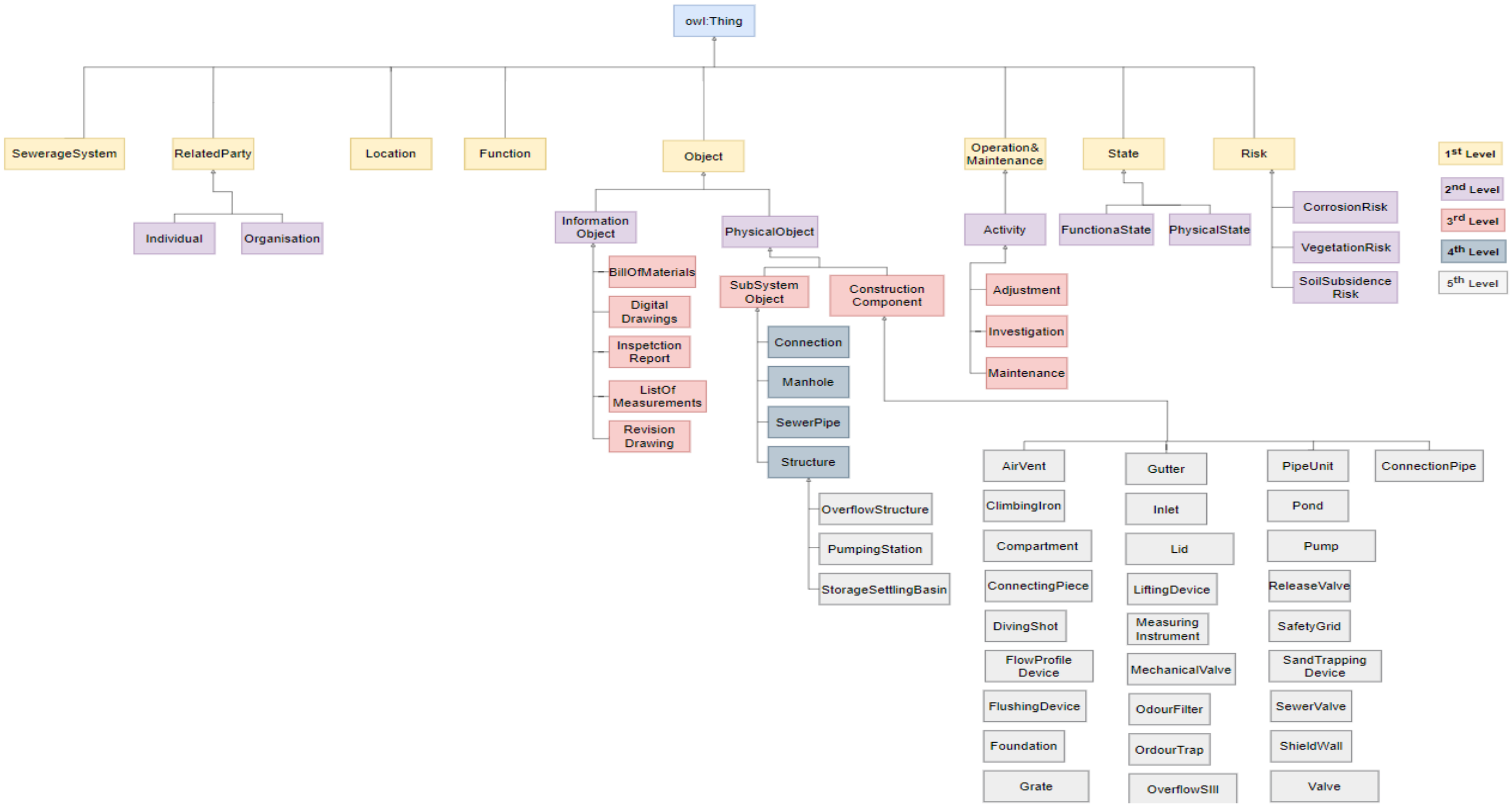


Figure 5.2: Class Hierarcy/Taxonomy of the Ontology

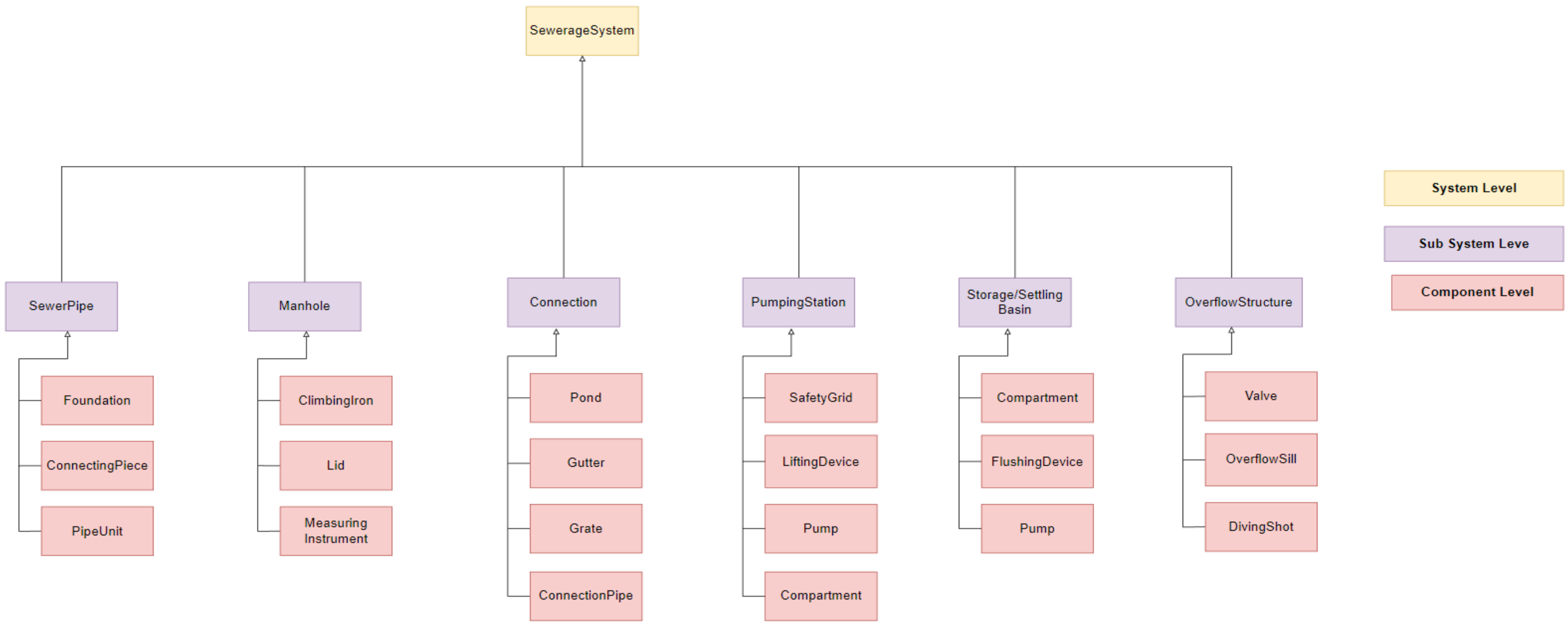


Figure 5.3: Decomposition of the Sewerage System

5.3.2 Establish Relationships

In this section, we are going to define how the individuals of each class relate to each other or relate to data values. This will be done by establishing properties (or relationships) and property restrictions. By establishing restrictions, we enable Protégé to do the auto-classification and reasoning of the ontology.

5.3.2.1 Add Properties

OBJECT PROPERTIES A property restriction is a special kind of a class description. It describes more thoroughly our domain of interest, by providing rules for which individuals can belong to this special kind of class (Bechhofer et al., 2004; Horridge and Brandt, 2011). It allow us to describe classes in terms of other things we have already modelled (Allemang and Hendler, 2011). Therefore, firstly we need to define the main relationships that have been identified to represent the generic knowledge of the domain in the conceptual model. From literature and standards, seven relationships were identified:

- **hasPart:** The hierarchical relationship, also called composition relationship. A decomposition relation between concrete concepts (NEN, 2021)
- **executes:** The activity or function is executed by a concrete concept (NEN, 2021)
- **hasState:** The state of an entity in a certain point or period of time (NEN, 2021)
- **isDescribedBy:** The information object that describes something (NEN, 2021)
- **transforms:** The object transformed by an activity (NEN, 2021)
- **hasRelatedParty:** include individuals and organisations who own, operate and manage sewerage systems. (Zeb, 2020)
- **restore:** Operation & Management Measures restore the original performance (Nlingenieurs Sewer Systems Workgroup and RIONED Foundation, 2009)

In addition to the seven relationships, we add three new relations: one between the sewerage system and the location, one between the subsystem objects and the component objects and one between the risks and the condition. After adding these new properties, and data properties for a preliminary version of ontology's properties has been gained.

As showed in Table 5.3, we try to mostly use the format hasRelation and isRelation of desppite the fact that there is on a strict naming convention for properties (Horridge and Brandt, 2011). However, it is recommended the properties to prefixed with "has"or "is" because it makes is understandable for humans and conforms with the format that W3C follows (Allemang and Hendler, 2011; Horridge and Brandt, 2011). Properties link the individuals from the domain to the individuals from the range and this can be seen in Table 5.3 where every object in the medium column links the first column (domain individuals) with the last column (range individuals). Each object property may have a corresponding inverse property (Horridge and Brandt, 2011), for example isPartOf is the inverse of hasPart.

#	Domain	Property Name	Range	Explanation
1	Sewerage System	hasSubSystemPart	SubSystemObject	It is similar with hasPart relation.
2	SewerageSystem	hasLocation	Location	
3	SewerageSystem	hasRelatedParty	RelatedParty	
4	SewerageSystem	hasPart	PhysicalObject	
5	SewerageSystem	isDescribedBy	InformationObject	
6	PhysicalObject	isPartOf	SewerageSystem	
7	SubSytemObject	isPartOfSystem	SewerageSystem	
8	Location	isLocatedIn	SewerageSystem	
9	RelatedParty	isRelatedPartyOf	SewerageSystem	
10	SubSytemObject	hasComponentPart	ConstructionComponent	It is similar with hasPart relation.
11	ConstructionComponent	isPartOfSubSytem	SubSytemObject	
12	PhysicalObject	executes	Function	
13	Functions	isExecutedBy	PhysicalObject	
14	PhysicalObject	hasState	State	
15	PhysicalObject	hasFunctionalState	FuntionalState	
16	PhysicalObject	isTransformedBy	Operation&Maintence	
17	State	isStateOf	PhysicalObject	
18	SewerageSystem	isDescribedBy	InformationObject	
19	Operation&Maintence	transforms	PhysicalObject	
20	Operation&Maintence	restores	State	
21	State	isRestoreBy	Operation&Maintence	
22	Risk	hasInfluenceOn	State	
23	State	isInfluencedBy	Risk	
24	Investigation	investigatesTheConditionOf	PhysicalObject	

Table 5.3: Object Properties

DATA PROPERTIES Object Properties established the relationships between the main concepts of the developing ontology. This enabled the conceptualisation of the generic knowledge that the ontology aims to represent. However, asset managers need more information for every concept to facilitate their decision-making. Data and annotation properties can describe this information. For example, asset managers need not only to know the relation that operation & maintenance transforms a physical object and that it can restore its physical and functional condition. They need to have the history of asset maintenance and if a measure has been deferred, causing the deterioration of the condition. Therefore, except from the **"transforms"** relationship, we added additional data properties to the concept of Operation & maintenance, such as the status of the implemented measure (planned, cancelled, etc.) and the date of the last implementation of the measure. Table 5.4 shows the data properties that we created in order to represent the necessary knowledge:

#	Domain	Property Name	Range	Explanation
1	Sewerage System	hasSystemID	N/A	
2	Sewerage System	hasYearOfConstruction	N/A	
3	Organisation	hasClientOrganisationName	N/A	Subclass of RelatedParty
4	Organisation	hasContractorOrganisation Name	N/A	
5	Individual	hasAdministratorName	N/A	Subclass of RelatedParty
6	Individual	hasResponsibleContractor Name	N/A	
7	Location	hasCityName	N/A	
8	Location	hasMunicipality	N/A	
9	Location	hasNeighbourhood	N/A	
10	Object	hasDate	N/A	*Note that the properties of a superclass can be inherited and to the subclasses. Therefore, a construction component will have also an ID and a value can be assigned for his unique ID.
11	Object	hasObjectId	N/A	
12	SewerPipe	hasBob	N/A	Altitude relative to NAP of the inner bottom of the tube of the pipe. It is the lower point of the pipe and an indication of soil subsidence which affects hydraulic performance.
13	SewerPipe	hasPipeDiameter	N/A	
14	SewerPipe	hasPipeHeight	N/A	
15	SewerPipe	hasPipeLength	N/A	
16	SewerPipe	hasPipeWidth	N/A	
17	SewerPipe	hasPipeShape	N/A	
18	SewerPipe	hasPipeType	N/A	
19	SewerPipe	hasPipeMaterial	N/A	
20	SewerPipe	hasSoilType	N/A	Influences the hydraulic performance
21	SewerPipe	hasStartManhole	N/A	Municipalities want to know with which manholes the pipeline is connected. Manholes are assigned with specific numbers and coordinates by the municipalities. That enables them to know the position and the depth of the pipeline.
22	SewerPipe	hasEndManhole	N/A	
23	Manhole	hasManholeHeight	N/A	
24	Manhole	hasManholeMaterial	N/A	
25	Manhole	hasManholeWidth	N/A	
26	Manhole	hasShape	N/A	
27	Manhole	hasXcoordinate	N/A	
28	Manhole	hasYcoordinate	N/A	
29	Manhole	hasZcoordinate	N/A	
30	PhysicalState	hasDefect	N/A	Subclass of Condition (Main Concept)
31	PhysicalState	hasDefectSeverity	N/A	The inspector also judges the severity of each individual defect by a one (no damage) to five (severe damage, replacement required) classification system, which is also described in the EN 13508-2.
32	FunctionalState	isFunctionExecuted	N/A	
33	Operation& Maintenance	hasAvailableBudget	N/A	
34	Activity	hasCost	N/A	Subclass of Operation&Maintenace (Main Concept)
35	Activity	hasInterval	N/A	
36	Activity	hasLastDateOfImplementation	N/A	
37	Activity	hasMethod	N/A	
38	Activity	hasStatus	N/A	
39	Risk	hasRisk	N/A	Risk has subclasses: Corrosion Risk, VegetationRisk and SoilSybsidenceRisk.
40	Risk	hasCriticality	N/A	

Table 5.4: Data Properties

In Table 5.2 it can be seen that in our ontology, we have included more sub-system and construction components than those we have assigned data properties. Therefore, there is a need to explain this design choice. The main reason for this choice is that from the Interviews and Literature, it was identified that for strategic choices (allocation of budget to measures, replacement of objects/system etc.), pipes are the most critical object. To make such a choice and develop management plans, asset managers need to know the structural and hydraulic performance of the system (Van Riel et al., 2014). The structural or physical condition is affected by the pipe age, soil characteristics or protruding roots (Van Riel et al., 2014). These information attributes can be seen in rows 10,20 and 39. Kapelan (nd) explained using a cause effect-approach how these factors influence the deterioration of asset performance:

- Wastewater leads to corrosion, loss of structural strength and finally collapse of the sewer.
- Protruding roots, lead to reduction of flow area, hydraulic capacity and subsequently in spills,pollution and flooding.
- Protruding roots increase blockages and result in flooding and pollution.
- Ground subsidence is responsible for opening of joints which results to leakages and loss of storage.

Moving to hydraulic performance, pipe dimensions are a critical parameter. For example, changing the hydraulic properties of a sewer system by decreasing the diameter of several pipes will inevitably change the hydraulic performance (Van Riel et al., 2014). Also, hydraulic performance is assessed by soil type and soil subsidence rate. These two are covered by the object data properties soil type and hasBob property which shows the depth of the pipe at each manhole location and, with the years, can sow if the pipes have been sunk (this is for gravitational systems). Finally, the Continuity equation and the Manning equation for steady-state flow is used to calculate the flow in a sewer pipe. Continuity Equation Q = V*A, where:

- Q = the volumetric flow rate,
- V= the mean velocity,
- A= the cross sectional area of the pipe.

The sewer line capacity needs the dimensions of the sewer pipeline to be calculated. This is why asset managers need to know the dimension of the pipes. They need to know the estimated flow and see if the system operates according to designed specifications.

5.3.2.2 Restrict Properties

As it was mentioned above, a property restriction is a special kind of a class description. A restriction is a class defined by describing the various existing properties and values that apply to all members of the class (Allemang and Hendler, 2011; Horridge and Brandt, 2011). The properties and property restrictions can narrow down the variability of individuals relationships and define it more thoroughly. Noy et al. (2001) and Horridge and Brandt (2011) mentioned on their works the below property restrictions:

- Cardinality Restrictions - Restricting the number of the values.
  - **Min:** specifies the minimum number of relationships that a class of individuals has with other individuals or values.
  - **Max:** specifies the maximum number of relationships that a class of individuals has with other individuals or values.
  - **Exactly:** specifies the exact number of relationships that a class of individuals has with other individuals or values.
- Quantifier Restrictions - The relationships that an individual can participate in.
  - **The existential restriction** describes the set of individuals which has at least one relationship with an individual of a specified class. It is also known as ”someValuesFrom”. In Protégé, the keyword **”some”** is used to define existential restrictions.

  - **The universal restriction**, also known ”allValuesFrom”, describes the set of individuals which all values of a relationship come from a specific class. In Protégé, the keyword **”only”** is used to define universal restrictions.

- hasValue - The relationships which links an individual to another specific individual.

- Value types of data properties:
  - **String** which is consisted from a sequence of characters. It is used for dataproperties such as name.
  - **Number** (float, integer, etc.) it describes numeric values.
  - **Boolean** it describes Yes or No (”true” or ”false”) values.
  - **Date** it describes values that contain date (date is specified in the form ”YYYY-MM-DD”)

Let’s take the example of a sewerage system in order to understand the way that restrictions work. During the interviews asset mangers mentioned that they need to know the year of construction if the system. Therefore, in our model we connected with the sewerage system class a data property called *hasYearOfConstruction*. Someone can fairly assume that the system can not have different date of constructions. For this reason, we restricted this property with a cardinality restriction:

- *SewerageSystem hasYearOfConstruction exactly 1 xsd:date*

To this example, a value type restriction of a data property as visible as well. This restriction make the hasYearOfConstruction to can accept only values that have dated format ”YYYY-MM-DD”.

Moving to the rest of the restrictions, a sewerage system is consisted of sewer pipes, manholes, connections (road gully or house connections), pumping stations and a storage settling/basin and overflow structures. All these objects have been defined as classes in our ontology. Therefore, an individual (concrete occurrence, an actual sewerage system) should have at least one sewer pipe, one manhole etc. in order to be a sewerage system and belong in this class in our model. That is accomplished by using existential restrictions:

With the same way we connected the components to the sub-system parts. To construct a sewer network the sewer pipes (a sewer pipe is consisted of tube parts/pipe units) have to be placed on special shaped ground and connected with other sewer pipes.

- *SewerPipe hasComponentPart some Foundation*

- *SewerPipe hasComponentPart some PipeUnit*

- *SewerPipe hasComponentPart some ConnectingPiece*

The same logic was followed for the rest of sub-system parts to accomplish the decomposition of the system. Finally an example for a has value restriction will be given. A sewer pipe in a sewerage system transports the waste water, this is the function that fulfills:

- *SewerPipe executes value TransportOfWastewater*

A better clarification of the quantifier restrictions and hasValue restriction can be found in Appendix E.

5.3.3 Create Instances/Individuals

The last step before gaining a preliminary ontology is to create instances or individuals. The application of instances will illustrate the use cases of our ontology. Most of the data is from a revision drawing obtained from the municipalities' interviews. But, still not all the the information is relevant for our scope. Therefore, to find as much as possible relevant and realistic data, we consulted Sweco's asset management software. Wherever it was not possible to create realistic instances, we defined indicative values for illustrative purposes.

As it was identified from the interviews (see Table 3.3) and literature, the most critical parts of the system for making strategic decisions are the pipes and manholes. Therefore, we created instances only for these two physical objects. The below Figure 5.4 give an impression on what information the municipalities need from the contractor for a sewer pipe. The Table 5.5 has detailed all the object, data and annotation properties that are included in the ontology for a sewer pipe. For the rest of the concepts, Appendix F which includes all individuals, their related properties and values.

Pipe R001-001 subsystem part of R001:

Note: The names, neighborhood, monetary values and dates are indicative.

#	Class of Individual	Individual	Relationship	Individual 2/ Value	Annotation
1	SewerPipe	R001-001	executes	TransportOfMatter	
2	SewerPipe	R001-001	isPartOfSystem	R001	
3	SewerPipe	R001-001	hasState	PhysicalState	
4	SewerPipe	R001-001	hasFunctionalState	FunctionalState	
5	SewerPipe	R001-001	isTransformedBy	LastMaintenance	
6	SewerPipe	R001-001	isTransformedBy	LastAdjustment	
7	SewerPipe	R001-001	hasDate	2020-03-03	The date that the object started to operate or the information object was created. ValueType: [yyyy-mm-dd] xsd:date
8	SewerPipe	R001-001	hasPipeType	Combined	The type ofwater that the the sewer pipe transports. ValueTypes: (Combined, Wastewater, Rainwater, Drainage, other)
9	SewerPipe	R001-001	hasSoilType	Sand	ValueType: (Gravel,Clay,Clay+sand,Heavy clay, Sand, Sand+Gravel, Other) [GWSW] Soil type in which the part is located.
10	SewerPipe	R001-001	hasManholeHeight	1250	ValueType: [mm] xsd:integer: min=500 max=4000 [GWSW] The internal height (vertical, from the side view). The distance from the inside bottom to the inside top of the manhole construction (including bottom box).
11	SewerPipe	R001-001	hasBob	-3.04	Altitude relative to NAP of the inner bottom of the tube of the pipe at the location of the starting point of the system. It is the lower point of the pipe ValueType: [m] xsd:decimal
12	SewerPipe	R001-001	hasPipeMaterial	Concrete	[EN13508-2+A1] The material of the fabric of the sewer, in accordance with Table C.4. Where the pipeline has been lined the material recorded is the material of the original pipeline. ValueType: (Asbestos cement, Cement mortar, Concrete, Epoxy, Glass fibre reinforced plastic, Reinforced concrete, Cast iron,Steel).
13	SewerPipe	R001-001	hasPipeShape	Ovoid	[EN13508-2+A1] The shape of the cross-section of the pipeline as follows. ValueType: [Other,Ovoid,Ovoid inverted, Parabolic, Horse shoe section, semi-eliptic section, semi-circular section, U-shaped section, rectangular section)
14	SewerPipe	R001-001	hasPipeHeight	700	EN13508-2+A1] The height of the section in millimetres. [mm] xsd:integer: min=63 max=4000
15	SewerPipe	R001-001	hasPipeLength	18.7	The length of a pipe from one manhole to the other. [m] xsd:decimal: min=1 max=75
16	SewerPipe	R001-001	hassPipeDiameter	400	[GWSW] The length of the centerline of the circle that describes the inside or outside of the pipe cross-section. For plastic this length is the outer size, for the other materials the inside size. This also applies to (the plastic) Polypropylene (PP), although in practice the inner size is sometimes used for this. https://data.gwsw.nl/1.5.2/Basis/index.html?menu_item=classes [mm] xsd:integer: min=63 max=4000
17	SewerPipe	R001-001	hasPipeWidth	950	[EN13508-2+A1] The width of the section in millimetres. (Not required where both dimensions are the same -e.g. circle). Value Type: [mm] xsd:integer: min=63 max=4000
18	SewerPipe	R001-001	hasStartManhole	G7	The manhole that the pipeline starts. Municipalities assign to every manhole a unique number as identifier e.g. G01 G= manhole for mixed sewer V= manhole for wastewater sewer H= manhole for rainwater sewer S=manhole for connection sewer I= manhole for infiltration sewer P = manhole for press sewer D= manhole for drain sewer
19	SewerPipe	R001-001	hasEndManhole	G4b	The manhole that the pipeline ends.

Table 5.5: Individual of Sewer pipe

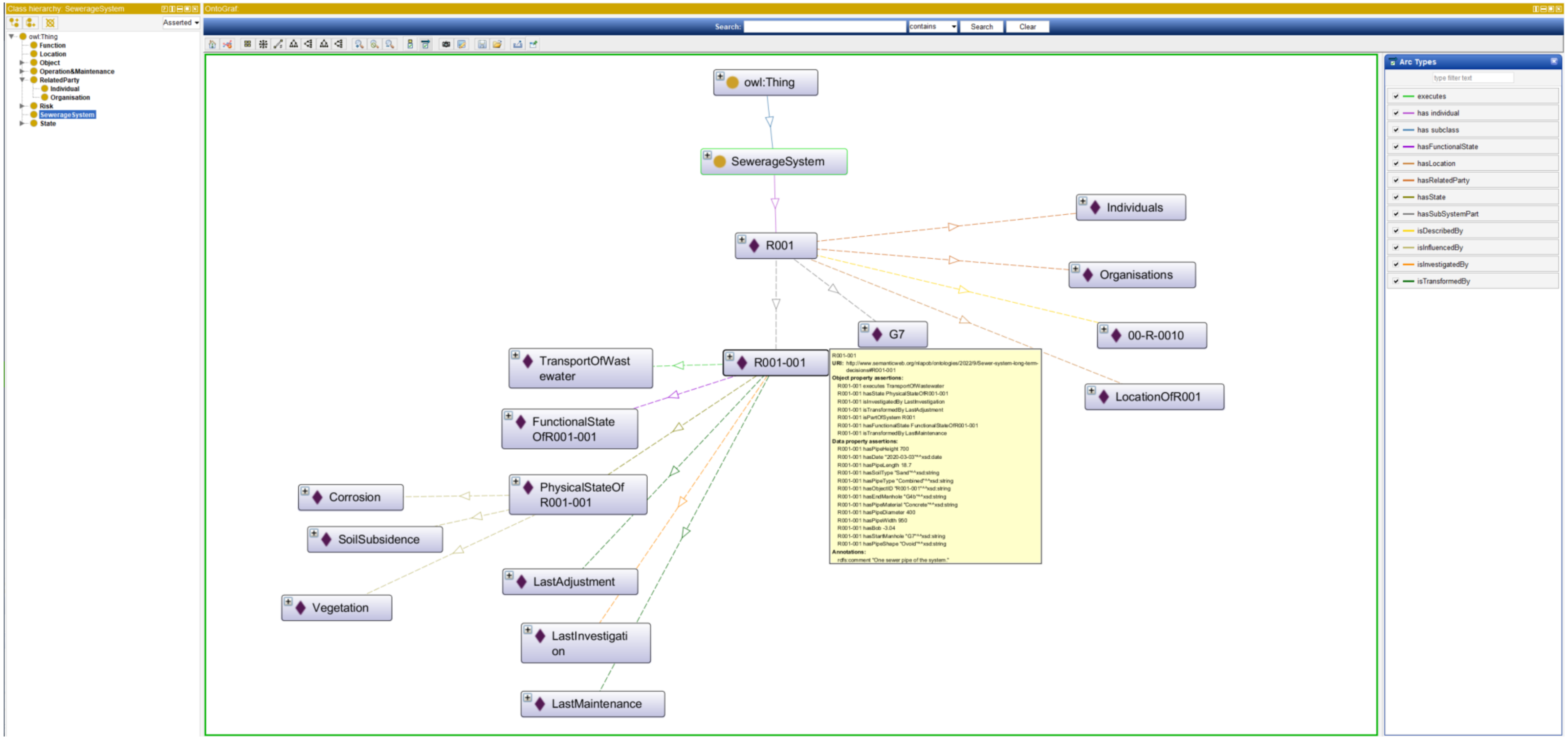


Figure 5.4: Individuals of the Ontology

5.4 PRELIMINARY ONTOLOGY

After the definition of the class hierarchy, properties, property restrictions and instances, a preliminary structure of our prototype has been gained. This chapter discussed the steps of building and formalising the prototype ontology on an editor tool. The developed prototype is consisted of 8 main concepts and their respective hierarchies (taxonomies, see table 5.2). These concepts and their individuals were linked with object, data and annotation properties which subsequently were restricted in order to provide a better representation of the domain of interest. To summarize the contents in this section, a high level overview of the prototype ontology can be seen in figure 5.5. Note that in the graph not all the classes and data attributes for making strategic decisions are visible.

5.5 SUMMARY

This chapter introduced the steps adopted to develop the prototype ontology. Firstly, an editor tool was selected which can support most ontologies' formats (e.e RDF,OWL etc.). Then, a class hierarchy and their relationships were established. Next, the ontology attributes were identified and linked to the relevant concepts. Finally, individuals were created to illustrate the use cases of the prototype ontology. After following these steps of Zhou et al. (2016) methodology, a preliminary version of the ontology was gained. In the next chapter, the prototype will be validated, aiming to achieve the prototype ontology's final structure, which facilitates the strategic decisions of public sewerage systems asset managers.

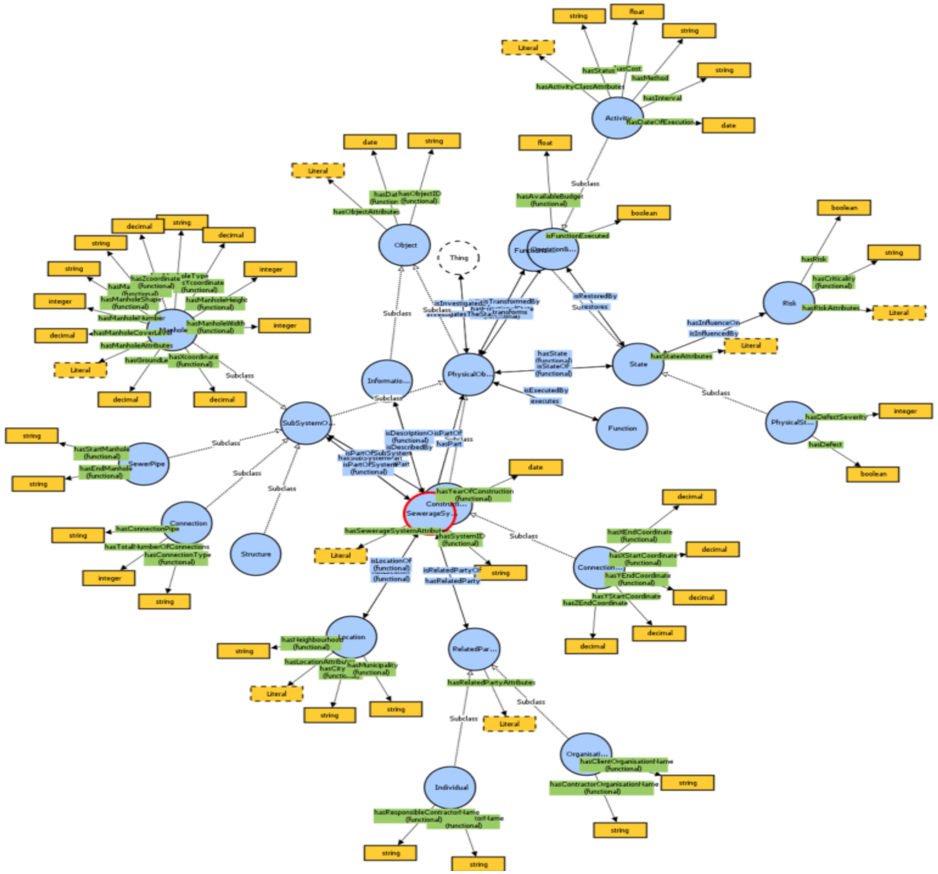


Figure 5.5: Ontology for strategic decision in public sewerage systems

6 ONTOLOGY EVALUATION

6.1 INTRODUCTION

In the previous chapter, we created the first version of the ontology, which represents the domain knowledge asset managers need to make strategic decisions for public sewerage systems. This chapter will evaluate and validate the ontology, aiming to answer the fifth and last research question. Section 6.2 explains briefly the theory of the evaluation. Section 6.3 describes the criteria and methods used for the evaluation. Section 6.4 presents and interprets the verification methods and their results. Then, in section 6.5 a proof that the model describes the real world is provided. Finally, a summary of the sixth chapter is provided in Section 6.9.

6.2 EVALUATION THEORY

An ontology is a powerful way to capture and structure the information in a domain. However, it is important the users to be confident that the model represents the real world. Confidence can be gained by evaluating the ontology for its scope, structure and knowledge representation with respect to the real-world concepts (Anand, 2015). Ontology evaluation is: " a technical judgement of the content of the ontology with respect to a frame of reference" (Gómez-Pérez et al., 2006). For these project, the frame of reference are the competency questions and the requirements that were formulated in section 4.2.1.4. Lovrenčić and Čubrilo (2008) argued that ontology evaluation is consisted of two parts:

- **Verification:** the concepts' structure must be as consistent and complete as possible, and its definitions should correctly implement the ontology requirements and competency questions.
- **Validation:** refers weather the ontology models the real world and requires content evaluation.

Therefore, to assess how much (quantity) and how good (quality) the prototype model represents the real world, we will evaluate it:

- against the competency questions and requirements which define the ontology's scope.
- by estimating quantitative parameters which reveal how much (quantity) the ontology's structure represents the real world.
- by using tools to check the quality of the ontology concepts and their relations. The tools assure that there are no modelling mistakes that can make the model inferre contradictory knowledge.
- by checking against reference data from the real practice, how good (quality), correct and accurate the model represents the domain knowledge.

6.3 EVALUATION CRITERIA AND METHODS

The ontology's requirements are based on the work of Johannesson and Perjons (2014). The functional requirements were derived by interviews with domain experts and the literature. Combined with the competency questions, they intend to cover the necessary knowledge to facilitate long-term strategic decisions. The structural and environmental requirements were derived from the review of seven articles (Chimalakonda and Nori, 2020; Corcho et al., 2006; Costin and Eastman, 2014; Lovrenčić and Čubrilo, 2008; Missikoff et al., 2002; Noy et al., 2001; Uschold and Gruninger, 1996). Subsequently, based on the literature as mentioned earlier and the work of Vrandečić (2009), eight criteria were defined to evaluate the ontology. These criteria are: 1) accuracy, 2) adaptability (modularity/extensibility), 3) clarity, 4) completeness, 5) conciseness, 6) consistency and 7) reusability (by leveraging existing knowledge such as using standard practises (languages) or standards). Table 6.1 gives the interpretation of the evaluation criteria.

#	Criteria	Interpratation
1	Accuracy	The definitions and description of ontology's classes, properties and individuals comply to the expertise of one or more users of the domain of interest.
2	Adaptability	The ontology offers the conceptual foundation for the anticipated uses and allows new elements and changes without changing its existing core.
3	Clarity	The ontology effectively communicates the intended meaning of the defined terms by providing objective definitions.
4	Completeness	The ontology covers the necessary knowledge for the domain of interest by answering the defined competency questions.
5	Conciseness	The ontology does not include redundant or irrelevant concepts and relations.
6	Concistency	The ontology should include consistent definitions and no contradictory knowledge can be inferred.
7	Reusability	The ontology should leverage existing standard practices (modelling languages) or ontologies.

Table 6.1: Ontology evaluation criteria (Adapted bye (Vrandečić, 2009))

In addition, the format of ontology's requirements Table 4.3 was refined and provided in Table 6.2. The ID or number of the requirements has remained the same in order to avoid confusion. The intention is to be clear in which category every requirement belongs to and which criterion intends to satisfy. We remind to the reader that according to Johannesson and Perjons (2014):

- *Functional Requirement:* depend on the problem to be tackled and the needs of the stakeholders
- *Structural Requirement:* refer to the structure of the end solution.
- *Environmental Requirement:* refer to the environment and are more generic requirements for the design of the solution.

The method of evaluating the 7 criteria and their corresponded requirements are provided in Table 6.3.

#	Category	Criteria	Requirement Interpretation	Scope	Validated
1.1	Functional	Completeness	The solution should provide information that will allow asset managers to prioritise which asset need to intervene and when.		
1.2	Functional	Completeness	Should provide information that will allow asset managers to allocate the budget to the right project of their portfolio.		
1.3	Functional	Completeness	Should provide information from the earlier phases that will allow asset managers to make sustainable decisions.		
2.1	Functional	Completeness	Should reduce the secondary costs that are produced by the delay of the handover of an incomplete set of information.		
3.1	Functional	Accuracy	Should provide a unified and uniform set of concepts and relations based on shared conceptualizations of the end-user.		
4.1	Functional	Completeness	Should cover all relevant concepts and relation within the domain of operation & maintenance of sewerage systems for enabling strategic decisions.		
4.2	Functional	Accuracy	Should cover the information needs of the asset owners with the right level of detail.		
4.3	Structural	Consistency	Should include consistent definitions and no contradictory knowledge can be inferred.		
4.4	Structural	Conciseness	Should not include redundant or irrelevant concepts and relations.		
5.1	Structural	Adaptability	Should allow new elements to be added without changing its existing core.		
5.2	Structural	Adaptability	Should be easy to adapt in case of changes of information needs of the users.		
6.1	Structural	Clarity	Should include a defined, explained and documented taxonomy and hierarchy.		
6.2	Structural	Clarity	Should include a defined, explained and documented vocabulary of terms and names.		
6.3	Structural	Clarity	Should provide instructions on how to apply the ontology which are easy to read,learn and apply.		
6.4	Structural	Clarity	Concepts and relations must be easily traceable by the user.		
7.1	Environmental	Reusability	Should comply with existing ontology languages to be compatible with ontology modelling tools.		
7.2	Environmental	Reusability	Should comply with existing sewerage system data as modelled in existing standards (i.e. IMBOR, GWSW, IMKL).		

Table 6.2: Requirements for Evaluation

#	Criteria	Method	
		Qualitative	Quantitative
1	Accuracy	Use cases	
2	Adaptability		Structural Metrics
3	Clarity	Use cases, Tool	
4	Completeness	Use cases, Competency questions	Structural Metrics
5	Conciseness	Use cases, Tool	
6	Consistency	Reasoner, Tool, Competency questions	
7	Reusability	This criterion was satisfied by the selection of Protégé editor tool. It supports most ontology languages (RDF,OWL etc.) and by using existing standards for the relationships, decomposition and ontology concepts.	

Table 6.3: Evaluation Methods

The consistency and conciseness of the ontology was constalnty evalueted during modelling process by using **the reasoner of Protégé**. The reasoner of Protégé enables the automatic classification and consistency checking (Horridge and Brandt, 2011). It can check whether all the definitions and statements are mutually consistent and recognise which concepts should be included under every definition (Horridge and Brandt, 2011). Treatment requirements mainly involved 4.3

In addition, the web-user interface of **OOPS! (OntOlogy Pitfall Scanner!)**, a tool for detecting pitfalls in ontologies (Poveda-Villalón et al., 2014) will be used. The tool provides the ability to evaluate the structural, functional and usability-profile dimension of the ontology. Moreover, it enables the evaluation of ontology aspects such as consistency, clarity, understanding, language, requirements completeness (more relevant to conciseness and consistency and not in completeness criteria) and application context. The evaluation dimensions and aspects of the tool can be seen in Figure 6.1. Treatment requirements mainly involved 4.3, 6.1 to 6.3 and 7.1.

Then, the completeness and adaptability of the ontology's hierarchy/structure was assessed by applying **numerical metrics**. They can inform potential users how much information has been captured from the model and the nature of the structure; if it covers a wide range of domain's information (generic) and easily adaptable or too detailed and need more effort to be extended/adapted without changing its existing core. Treatment requirements mainly involved 4.1, 5.1 and 5.2.

For assessing whether our ontology has fully (completeness) modelled the defined scope, queries were formed that answer the competency questions. That was implemented through the **SPARQL Query tab of Protégé's editor tool**. Treatment requirements mainly involved 4.1 to 4.4.

Finally, the ontology was checked with real world examples to evaluate its accuracy and completeness. Validation refers to the real world, hence the ontology was compared with **documents from the practice.** to assess how good (quality),correct and accurate the model represents the domain knowledge. Treatment requirements mainly involved 1.1 to 1.3, 3.1 and 4.1 to 4.4.

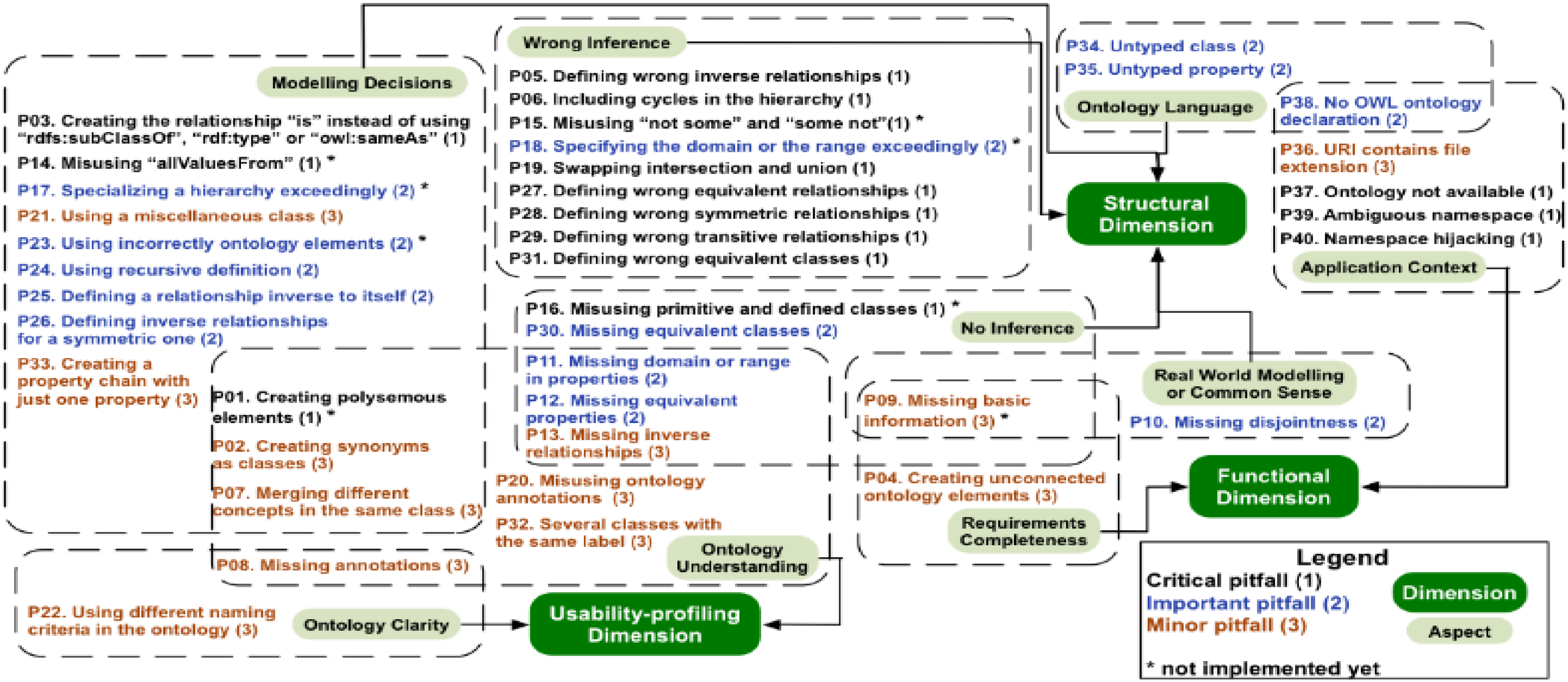


Figure 6.1: Pitfall classification by ontology evaluation dimensions and aspects (Retrieved by (Poveda-Villalón et al., 2014)

6.4 VERIFICATION METHODS

6.4.1 Evaluation with the Tool

The first step to this evaluation method was to run Protégé's Hermit reasoner. It indicated only suggestions for the inclusion of more disjoint classes which were subsequently added to the ontology. The reasoner did not provide errors; therefore, a second method for ontology's consistency and clarity was followed (OOPS! (Ontology Pitfall Scanner!)). The system tracks every pitfall and provides an indicator for each (critical, important, minor). After the first running of the tool, we obtained the below results (Figure 6.2):

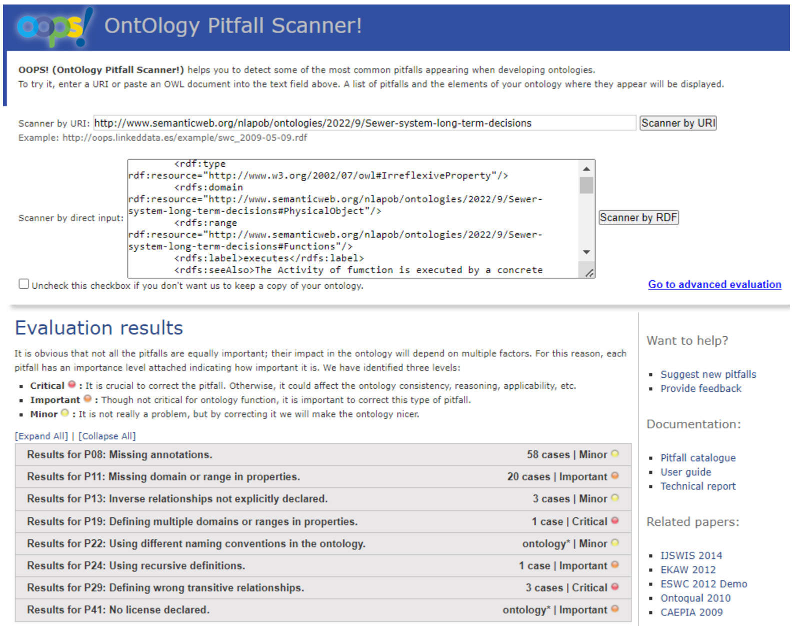


Figure 6.2: Results of Oops! Evaluation Tool after the first running

The Ontology has 6 critical pitfalls. Three of them was that the object relationships hasPart, hasSubSystemPart, hasComponentPart and their inverse properties were wrong defined as transitives. The other critical error was identified on the hasObjectID relationship where we have assigned an additional unnecessary restriction to the domain. After the corrective actions, the tool evaluated our ontology as it can be seen in Figure 6.3.

The results obtained by the evaluation were free of critical pitfalls. Pitfalls can be classified in two categories, remain and repair (Yusof and Noah, 2019). The first category includes modelling pitfalls due to real world factors and its representation (e.g creating synonyms as classes). The evaluation of our ontology did not produce this kind of pitfalls. All the pitfalls felt under the repair category which were due to researchers omissions. All the pitfalls were repaired except P22, which is a minor one and could not be spotted.

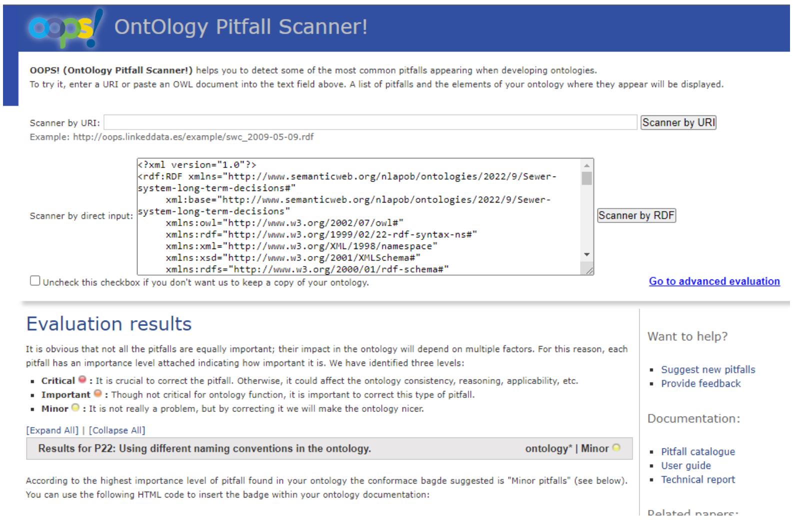


Figure 6.3: Revaluation Results

6.4.2 Quantitative Evaluation - Structural Metrics

Ontologies' structural dimension focuses on the structure and formal semantics (Gangemi et al., 2005). Gangemi et al. (2005) and Tartir et al. (2005) provide metrics for the evaluation of the design and knowledge representation richness. Five metrics of their work will be used which measure the ontology's: depth, breadth, relationship richness, inheritance richness and attribute richness.

- **Average Depth:** the average number of nodes for all paths. The cardinality of paths takes into consideration only is-a arcs of the ontology's graph. A path starts from a root node (concept in the top hierarchy, i.e. condition,object or sewerage system in our ontology) and ends at a leaf node (concept in the last level of the taxonomy's hierarchy, it is not a supercalss of another concept, e.g AirVent). Therefore, the average depth is the number of nodes in each path divided by the number of paths.

- **Average breadth:** the average size (number of classes) of the levels of the ontology (Fernández et al., 2009) . A level is consisted from nodes that have the same distance from the root node in the graph (Gangemi et al., 2005). Our ontology is consisted of 63 nodes(concepts) distributed in 5 levels.

- **Relationship Richness:** the number of non-inheritance relationships (non class-subclass relationship) divided by the total number of relationships/properties. According to Tartir et al. (2005), a relationship relates concepts non-taxonomically. Therefore, for Protégé the non-inheritance properties are the modelled object properties, disjoint and equivalent classes.

- **Inheritance Richness:** represents the average number of subClassOf relationship per class (Class count).

- **Attribute Richness:** the average number of data properties per class. Attributes relate concepts with literal values (Tartir et al., 2005).

Figure 6.4 helps to understands the terms that were mentioned above and the Table 6.4 explain the meaning of metrics' results.

The Ontology metrics from the Protégé editor can be seen in Figure 6.5. The equations of the structural metrics and the evaluation results can be seen in Table 6.5.

#	Metric	Explanation
1	Depth	Describes the level of detail of the main concepts.
2	Breadth	Describes what level of detail of the domain's relevant concepts the ontology is able to cover.
3	Relationship Richness	Describes the diversity of the types of the relations of the ontology.
4	Inheritance Richness	Describes the nature of the ontology (generic (horizontal, swallow) or specific (deep, vertical)).
5	Attribute Richness	Describes the average level of knowledge that the classes possess.

Table 6.4: Explanation of Terms (Adopted by (Anand, 2015))

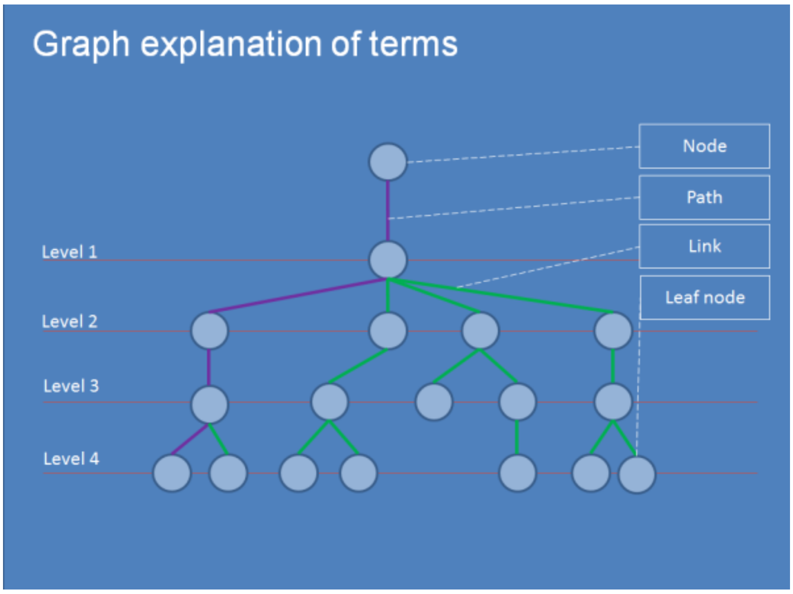


Figure 6.4: Graph explanation of terms (Retrieved by (de Vries, 2013))

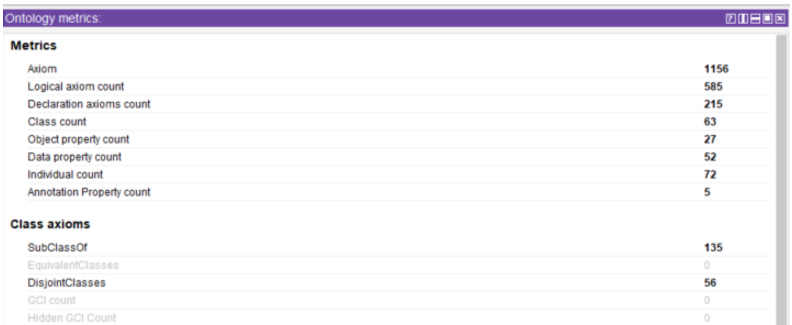


Figure 6.5: Ontology Metrics in Protégé editor tool

6.4.2.1 Interpretation of Structural Metrics Results

The prototype ontology of this research was created with the aim of representing information that helps asset managers to make strategic decisions in the domain of public sewerage systems. Structural ontological metrics were applied to evaluate the appropriateness of the taxonomy (Lourdusamy and John, 2018). A taxonomy is the backbone of an ontology and is used to organise classes and instances of an ontology that are interconnected with relations (Lourdusamy and John, 2018). These quality metrics evaluate the success of a taxonomy in modelling a real-world domain (Tartir et al., 2005). More specifically, the AD, AB represent the width and depth and are related to the graph of the ontology. The ontology has an average

Evaluation Metric	Parameter A	ValueA	Parameter B	ValueB	Formula	Result
Average Depth(AD)	Cardinality of paths	193	Number of paths	58	A/B	3.32
Average Breadth(AB)	Cardinality of levels	63	Number of levels	5	A/B	12.6
Relationship Richness(RR)	Non-inheritance relationships	84	Inheritance relationships	135	A/(A+B)	0.38
Inheritance Richness(IR)	Inheritance relationships	135	Total Number of classes (Class count)	63	A/B	2.14
Attribute Richness(AR)	Total number of data properties	52	Total Number of classes (Class count)	63	A/B	0.83

Table 6.5: Structural Metrics

depth of 3.32. That indicates that each path of the ontology is expanded by 3.32 subclasses. The average breadth of the ontology is 12.6, which means that each level has on average 12.6 classes. The high Average Breadth (AB) value suggests that our ontology has a wide variety of concepts to describe the domain of interest. However, the low Average Depth (AD) value indicates that these concepts were not analysed or expanded in detail.

The result of the Relationship Richness (RR) metric is a percentage representing the level of the connection of the ontology with rich relationships. The term rich describes relationships that add information to an ontology compared to the SublassOf relationships, which only classify and group the concepts. Therefore, numbers close to 1 indicate ontologies with richer relationships than a taxonomy (0 value). Our ontology has a low score of 0.38, indicating that the ontology provides less information on how the different classes are interconnected.

The metric Inheritance Richness (IR) describes the information's distribution to the ontology's subclasses. The result is a real number where its high values indicate a horizontal nature of the ontology while low values represent an ontology of vertical nature (Tartir et al., 2005). A vertical ontology means that the domains have been described in detail, while a horizontal one represents a wide range of general knowledge with a low level of detail. For example, our ontology has a value of 2,14, meaning its nature is horizontal. Every class contain, on average 2.14 subclasses and covers the domain at a generic level.

Finally, the Attribute Richness (IR) metric describes the amount of information that can be inherited from the instances (Tartir et al., 2005). It gives an insight into the knowledge level that the ontology classes possess. We assume that the more slots-attributes defined, the more knowledge the ontology conveys (Tartir et al., 2005). With 0.83 distinct attributes per class, the ontology gives limited details about the domain.

Our ontology can be described as horizontal and wide based on the above metrics. Such an ontology can be easily extended and adapted for anticipated and unanticipated tasks without changing its existing core. Moreover, the scores of the RR, IR and AR metrics are related to the design decisions we took within this research project's scope and time limit. The main aim of this project was to create a prototype ontology that would be easily adapted and extendable in the future. For that reason, we defined rich relationships only for the ontology's top concepts and the two most critical sub-systems (pipes-manholes) components. We have not assigned data properties to the rest of the system's components, and for that reason, our ontology has a more generic nature.

6.4.2.2 Limitations of Structural Metrics Results

The quantitative results of the metrics cannot indicate if the design of the ontology is good or bad. To do so, we should compare them with a reference ontology (or a similar structure) of the domain that could be considered as a standard. In the absence of such an ontology, we can conclude that our ontology is horizontal or shallow from the fact that the average breadth is greater than the average depth. In combination with the low scores of RR and AR, it can be derived that our ontology contains a wide variety of concepts but these concepts have not been expanded in great detail due to its generic nature.

6.4.3 Testing the Ontology – Queries of Competency Questions

The main objective of the developed ontology is to capture and structure information in order asset managers will be able to retrieve information for making long-term decisions. To test whether the ontology can model the information that is asked for the competency questions formed to define the its scope were applied. The ontology was evaluated two times against the competency questions. The ontology was evaluated twice against the competency questions. The first iteration performed after the preliminary design. The second iteration was performed interviews after the validation with documents from the practice. All in all, the defined queries show that the ontology can provide all the needed information for the asset managers.

The result of this evaluation method provides mostly an insight into the coverage of the ontology's scope. When a question could not be answered by the ontology, the ontology was modified accordingly. This method mainly treats the requirements 4.2 to 4.4. The queries can be seen in Appendix G.

6.5 VALIDATION METHODS

6.5.1 Qualitative Evaluation – Use Cases

The last part for assuring that our modelled prototype can represent knowledge from the real world is a validation with examples from the practice. The validation of the prototype ontology was an iterative process. First, the ontology was validated against the document, Report expanded GRP - Municipal sewerage plan Delft 2022-2026 (Dutch: Rapport verbreed GRP - Gemeentelijk rioleringsplan Delft 2022-2026). A list of the terms relevant to the ontology were identified and placed to the first column of a table. Then, a second column was created with the respective classes of the ontology that covers these terms. The same procedure was applied for two more use cases. Two revision data [1] transfer checklists were obtained from the Municipalities of Delft and Rotterdam and were used for assessing how good (quality), correct and accurate the model represents the domain knowledge. After the comparison of the ontology terms with the three use cases, the terms that were not covered by the ontology were examined once more. If there was no justification for their omission, they were added to the ontology.

6.5.1.1 Validation with Report expanded GRP – Municipal sewerage plan Delft 2022-2026

Dutch municipalities are responsible for the management and operation of the sewerage systems. Thus, the are obliged to prepare a strategic plan for their sewerage

1 The revision data are collected after the construction and describe the constructed situation in detail. The construction of the asset is based on the specification drawings.

systems every five years. This document describes the strategies and costs for managing the sewerage system. Thus, it was considered a great fit for the scope of the ontology and helped that the case has not been used during the development phase.

Within the report of Municipal sewerage plan Delft 2022-2026. there are 6 sections that stand out:

1. Available Facilities
2. State of the sewerage system
3. Functioning of the system
4. Strategy development
5. Investment & Management Activities

Table 6.6 presents the comparison of the terms of the use case and against the ontology concepts and properties.

Term of Strategy Plan	Ontology Concept
Available Facilities	
Wastewater sewer pipe	SewerPipe. hasPipeType. This relationship can capture the different types of pipes With the help of annotation, we also give to the user the different types of sewer pipes that can type.
Combined sewer pipe	-//-
Rainwater sewer pipe	-//-
Pressure pipe (transport)	-//-
Sewerage pumping stations	-//-
Inspection pits	Manhole
Main sewerage pumping stations	PumpingStation
Overflows	OverflowStructure
Valves	SewerValve
Swirl	Release or ReleafValve
Rainwater outlets separated system	-
Line Gutters	Gutter
Water-permeable pavement	-
State of the sewerage system	
State	State
Inspection	Investigation Inspection is a type of investigation and it has been modelled as an annotation to the class of Investigation.
Damage pattern	Defect
High priority damage pattern	hasDefectSeverity

Categorising risk sewers and non-risk sewers	hasCriticality. Data property that allow to classify the risk as Low,Medium,High.
Measures	Activity
Performance of the system	-
Current situation against functional requirements	isFunctionExecuted. With this data property the user can state if the object executed its function according the specifications.
Locations	Location
Odor filters	OdourFilter
Strategy Development	
We identify risks and we take measures to prevent social damage due to settlement/ subsidence	SoilSubsidenceRisk
Connections (plot, gully, faulty)	-
Costs of Measures	hasCost
Maximum capacity of the system	-
The use of recycled raw materials is important for the sewerage system	hasPipeMaterial and hasManholeMaterial.
Flow rate	-
Pumping station capacity	-
Technical Condition of the sewer pipe, pumping station, the pressure pipe etc.	FunctionalState
Investments & Management Measures	
Masures/Activities	Activity
Improve To repair To replace Renovate	They have been included in the ontology in the class Adjustment by using annotation to inform the user that can insert as a method to the operation & maintenance activities.
Inspect	They have been included in the ontology in the class Investigation by using annotation to inform the user that can insert as a method to the operation & maintenance activities.
Energy costs pumping stations	-
Cleaning free-fall mixed and dirty water sewers, rainwater sewers	They have been included in the ontology in the class Maintenance by using annotation to inform the user that can insert as a method to the operation & maintenance activities.

Table 6.6: Comparison between the Municipal strategic sewerage plan and the Ontology

6.5.1.2 *Validation with revision data transfer checklist from the Municipality of Rotterdam*

With the completion of the construction phase and the installation of the sewerage system, the contractor has to transfer the data of as-built situation to the client (the process can be seen in figure 3.21). These data are called revision data and is the information that the asset managers need from the previous phases in order to operate and maintain the asset. Municipalities provide a checklist to contractors with what information they want them to transfer. In this section, the checklist of the Municipality of Rotterdam will be compared against the concepts of the prototype ontology. Any relevant term that is missing from the ontology and within its scope will be added to the model. Table 6.7 presents the comparison of Rotterdam's checklist terms against the ontology concepts and properties.

Term of revision checklist of Municipality of Rotterdam	Ontology Concept
Year of construction of pipes	hasDate
Material type of pipes	hasPipeMaterial
Manhole dimensions (width x height in mm)	Modelled as data attributes(hasManholeWidth, etc.)
X & Y coordinated of the manholes	hasXcoordinate and hasYcoordinate
Z coordinate: inside bottom tube altitude in m relative to NAP	hasBob
Z coordinate: manhole cover level in m relative to NAP	-
Foundation of wells, pipelines, overflows, etc. (shown in the revision drawing).	Foundation
Pile plan of foundations in the revision drawings	-
Valves	Valve
Spindles	-
Control box of pumping stations	-

Table 6.7: Comparison between revision Rotterdam's data transfer checklist and the ontology

6.5.1.3 Validation with revision data transfer checklist from the Municipality of Delft

A revision data transfer checklist was also obtained from the Municipality of Delft. Two sections stand out and they are relevant for the sewerage systems:

- Sewer revision. It is divided in three parts (Main sewers, Manholes and House-/Gully Connections)
- Pumping station and pressure pipes

In section 5.3.2.1, we explained that for the long-term decisions of the asset managers (disposal, replace etc.), the performance and structural condition are the most important parameters. Thus, the sewer pipes and their interconnected manholes were the physical objects that we focused and assigned data properties in this research work. Therefore, the data properties of the pumping stations that we identified during the validation process will not be included in the model. The comparison of the ontology against the checklist of the Municipality of Delft can be seen in the below Table 6.8.

Term of revision checklist of Municipality of Delft	Ontology Concept
Sewer pipe revision	
1. Manholes	Manhole
Street level measured in relation to NAP	-
X and Y coordinates measured in RD	hasCoordinateX and hasCoordinateY with annotation that has to conform with coordinate system RD
Manhole size	hasManholeWdth and hasManholeHeight
Manhole material	hasManholeMaterial
Manhole type (standard, internal, external overflow, etc.)	hasManholeType
For overflows, the threshold length and height are indicated	-
Manhole cover material	-
Pit number in accordance with municipal numbering	hasManholeNumber
2. Main Sewer pipes	Pipe
Pipe Dimensions	hasPipeLength, hasPipeWidth, hasPipeHeight
Pipe Material	hasPipeMaterial
BOB's pipeline measured in meters compared to NAP	hasBOB and annotation that indicates that has to be compared to NAP
Type of water that the pipe transports (mixed, dirty water, rainwater or drainage)	hasPipeType and annotation for the different types
Sewer foundation	Foundation
x and y coordinated measured in RD	
Pipe shape	hasPipeShape
3. House Connections/Gully Connections	Connections
Sewer connection size in meters	-
Connection pipe material	-
Connection pipe material color (dirty water red, rainwater blue).	-
Location (coordinates) of sewers and connection to the main sewer.	-
The House number of the connection clearly stated in accordance with the municipality numbering.	hasManholeNumber

Table 6.8: Comparison between revision Delft's data transfer checklist and the ontology

6.5.1.4 *Missing Terms*

After the examination of the use cases, the missing terms were collected and examined once more. If there was no justification for their omission, they were added to the ontology. It is wise to mention that the scope of the ontology is to capture and structure information from earlier phases that enable strategic decisions for public sewerage systems during operation & maintenance phase. Therefore, information that can be captured from the operation & maintenance activities was not taken into consideration. The missing terms, the reason of the omission and the decision for their inclusion in the ontology can be seen in Table 6.9.

At this point, we will present the rationale behind the selection of the modelled missing terms. The scope of the ontology is to facilitate long-term decisions of sewerage asset managers. From the interviews and the literature, it was identified that these decisions concern the replacement or not (other intervention or maintenance) of the sewer pipes, the allocation of budget and the selection of materials in order to create more circular cities. Moreover, from the same sources, it was identified that for this scope, the most relevant information for an asset manager is: location data, cost data, the differed maintenance and in general, parameters that influence the physical and functional condition of the sewer pipes (section 4.2.3, explains more

Missing Terms	Reason of omission
Water-permeable pavement	Not in scope
Performance of the system	The number of households connected to the system indicator is the only one that can be transferred from previous phases. It will be modelled as data property and linked in the Connection class.
Connections (plot,gully,faulty)	The class Gully connection will be changed to a more generic Connection class. Data property hasConnectionType will be added with an annotation property. Annotation property will indicate to the users which are the types of the connections.
Maximum capacity of the system	It can be calculated by sewer pipe dimensions. They have been already included in the model.
Pumping station capacity	Not in scope.
Energy costs pumping stations	Not in scope.
Z coordinate: manhole cover level in m relative to NAP	Not encountered in sources before, will be added as data property.
Pile plan of foundations in the revision drawings	Not in scope'.
Spindles	Not encountered in sources before, will be added as subclass of construction components. Moreover, a restriction hasComponentPart some Spindle will be added in the Storage/SettlingBasin class to connect them.
Control box of pumping stations	Not encountered in sources before, will be added as subclass of construction components. Moreover, a restriction hasComponentPart some ControlBox will be added in with the PumpingStation class to connect them.
For overflows, the threshold length and height are indicated	Not in scope.
Manhole cover material	Not important for the scope.
Street level in relation to NAP	Not encountered in sources before, will be added as data property.
Sewer connection dimensions in meters	Not encountered in sources before, will be added as data properties.
Location (coordinates) of start and end point of connection pipe	Not encountered in sources before, will be added as data property.
Connection pipe material	Not encountered in sources before, will be added as data property.
Connection pipe color	Not in scope, referring to the revision drawing color lines.
House number of the connection clearly stated in accordance with the municipality numbering.	Not encountered in sources before, will be added as data property.
Swirl	Not encountered in sources before, will be added as subclass of construction components. Moreover, a restriction hasComponentPart some Swirl will be added in with the Manhole class to connect them.

Table 6.9: Missing terms from the three use cases and the reason why

detailed the line of thought). Therefore, after the evaluation, we added the ontology terms only relevant to the defined scope.

In the tree use case, 96 terms should be inside the ontology. From the 96 terms, 18 had not been modelled in the created prototype. That means that the ontology covered 81,25% of the documents. This an acceptable level. Adding the missing terms to the ontology, the classes will be increased from 63 to 66, an increase of only 4,8%. The other terms will be included as data properties combined with necessary modifications.

6.6 EVALUATING THE STRUCTURE OF THE ONTOLOGY AFTER THE VALIDATION

After the addition of the new terms in the ontology, another round of evaluation with structural metrics and the OOPS! (OntOlogy Pitfall Scanner!) will be held. The reason is to check again how much and how good (detect any pitfalls during the modelling of the added terms) the ontology represents the domain knowledge after the additions of terms from the real world. Moreover, the consistency and conciseness of the ontology during the modelling of the additions was checked again continuously with the reasoner of Protégé.

Again the evaluation with he OOPS! (OntOlogy Pitfall Scanner!) gave only one minor pitfall. The tool argues that all the concepts ion the ontology do not follow the same naming convention, despite the fact that we tried to follow the format that W3C follows. The result can be seen in figure 6.6

Moving to the structural metrics, the old values of ontology parameters were compared with the new ones after the validation with the three cases. Table shows 6.10 that the values do not change significantly comparing to the preliminary version of the ontology. This is an indication that the ontology's structure and relationships did not need a lot of modification to represent the real world.

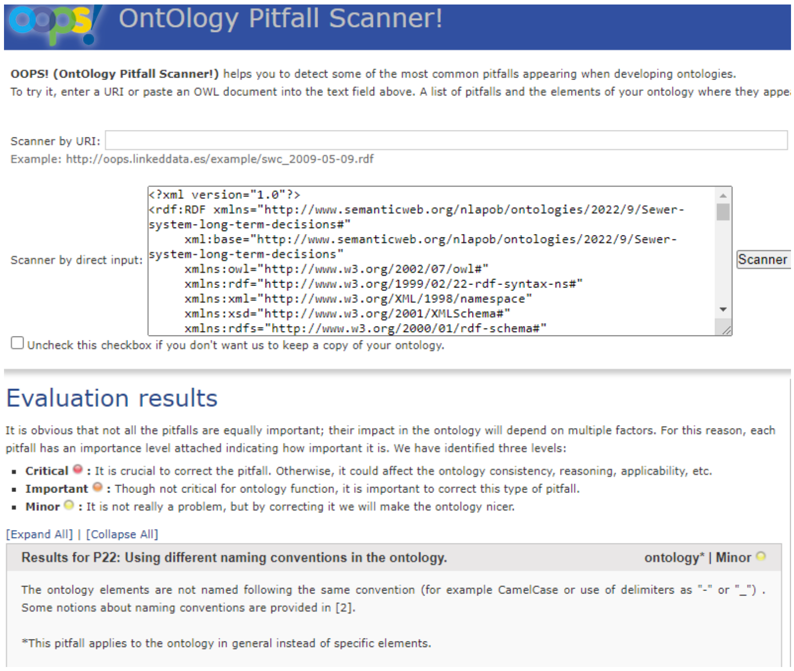


Figure 6.6: Evaluation with OOPS! (OntOlogy Pitfall Scanner!) after the validation

Evaluation Metric	Pre-validation input	Old result	After-validation input	New/ result	Change
Average Depth(AD)	193/58	3.32	205/61	3.36	1.20%
Average Breadth(AB)	63/5	12.60	66/5	13.20	4.76%
Relationship Richness(RR)	83/(83+135)	0.38	95/(95+145)	0.40	5.26%
Inheritance Richness(IR)	135/63	2.14	143/66	2.17	1.40%
Attribute Richness(AR)	52/63	0.83	63/66	0.95	14.5%

Table 6.10: Structural metrics after validation

6.7 SYNOPSIS OF THE EVALUATION

As it was explained in Section 6.2, users must be confident for the ontology's technical and content competence. Thus, the structure, the knowledge representation of the ontology and its ability to cover the defined scope was evaluated in this chapter.

The evaluation with the Hermit reasoner in Protégé editor tool showed that our ontology is consistent and concise. The additional check with the OOPS! (OntOlogy Pitfall Scanner!) increased our confidence that the ontology is consistent, concise and clear as only one minor error came up as result. The structural metrics indicated that our ontology is horizontal and wide in nature. That means that our ontology represents a wide variety of concepts in the domain but not expanding them into detail. That makes our ontology easily adaptable and extendable in case of future use.

The validation with documents from the real practice revealed that the ontology use term definitions and descriptions that the experts use in practice, thus our ontology can be characterised as accurate. Moreover, the comparison with the use cases showed that ontology covered 81,25% of the experts' terms. This is an acceptable level of completeness as an ontology can not be 100 % complete. The information needs of the users can change over time. A high percentage like that, in combination with the adaptability feature enable our ontology to be easily shaped and represent a satisfactory level of knowledge.

Finally, the created queries proved that the ontology can cover the defined scope. The scope was identified with by interviewing experts and the help of the literature. Then, it was expressed in the form of functional, structural and environmental requirements. The functional requirements were also expressed in the form of competency questions which were answered by the created queries. The table below shows whether we incorporated the requirements defined during the definition of the scope activity. A check indicates that the requirement was incorporated. The last column indicates by a check mark whether the requirement was validated.

#	Category	Criteria	Requirement Interpretation	Scope	Validated
1.1	Functional	Completeness	The solution should provide information that will allow asset managers to prioritise which asset need to intervene and when.	✓	✓
1.2	Functional	Completeness	Should provide information that will allow asset managers to allocate the budget to the right project of their portfolio.	✓	✓
1.3	Functional	Completeness	Should provide information from the earlier phases that will allow asset managers to make sustainable decisions.	✓	✓
2.1	Functional	Completeness	Should reduce the secondary costs that are produced by the delay of the handover of an incomplete set of information.	✓	x
3.1	Functional	Accuracy	Should provide a unified and uniform set of concepts and relations based on shared conceptualizations of the end-user.	✓	✓
4.1	Functional	Completeness	Should cover all relevant concepts and relation within the domain of operation & maintenance of sewerage systems for enabling strategic decisions.	✓	✓
4.2	Functional	Accuracy	Should cover the information needs of the asset owners with the right level of detail.	✓	✓
4.3	Structural	Consistency	Should include consistent definitions and no contradictory knowledge can be inferred.	✓	✓
4.4	Structural	Conciseness	Should not include redundant or irrelevant concepts and relations.	✓	✓
5.1	Structural	Adaptability	Should allow new elements to be added without changing its existing core.	✓	✓
5.2	Structural	Adaptability	Should be easy to adapt in case of changes of information needs of the users.	✓	✓
6.1	Structural	Clarity	Should include a defined, explained and documented taxonomy and hierarchy.	✓	✓
6.2	Structural	Clarity	Should include a defined, explained and documented vocabulary of terms and names.	✓	✓
6.3	Structural	Clarity	Should provide instructions on how to apply the ontology which are easy to read,learn and apply.	✓	✓
6.4	Structural	Clarity	Concepts and relations must be easily traceable by the user.	✓	x
7.1	Environmental	Reusability	Should comply with existing ontology languages to be compatible with ontology modelling tools.	✓	✓
7.2	Environmental	Reusability	Should comply with existing sewerage system data as modelled in existing standards (i.e. IMBOR, GWSW, IMKL).	✓	✓

Table 6.11: Validated Requirements

Requirements 2.1 and 6.4 were not validated. The first one requires the ontology to be applied in a real-life project, which was not possible during this project due to time limitation. The latter requirement can only be validated by domain experts. Interviews or experts' panels would let asset managers navigate the ontology and assess if they find the needed information easily. This requirement does not address if the relationships represent adequately the real world. It is about the user-friendliness of the ontology, namely how easily a user can find the relevant terms and navigate through the ontology. Due to time and resource limitations, that was not possible.

6.8 FINAL VERSION OF THE ONTOLOGY

This chapter presented the evaluation of the ontology. The content and structure of the ontology were evaluated and additional terms of the practice were added. From the evaluation process an acceptable level of confidence was gained that the developed prototype is technically and content wise competent. That enabled the finalisation of the design of the prototype ontology. The classes and properties can be found in Appendix H while the individuals in Appendix F.

6.9 SUMMARY

In this chapter the ontology evaluation was presented. The evaluation is consisted of two parts; the verification and the validation. For the evaluation, four different methods were followed. Technically the ontology was evaluated by structural metrics and an online tool. The content of the ontology was validated against three use cases from the practice. The relevant missing terms were added to the model and then, the ontology's technical competence was evaluated once more. The created queries proved that the ontology covered the defined scope. The described process assessed the scope, structure and knowledge representation of the developed prototype and revealed its technical soundness and an acceptable level of domain's knowledge representation. Finally, we do not claim that the ontology fully represents the domain. However, with sewerage asset managers starting using and adding more classes or even properties, will make the developed model more powerful in terms of content and details.

Part V

FINDINGS

7 DISCUSSION, CONCLUSION AND RECOMMENDATIONS

This chapter starts with discussion on the proposed framework for capturing and structuring information needs, implementation approaches in the industry and the contribution of this research work. This is elaborated in Section 7.1 along with the limitation of the current research. The next Section 7.2 answers the research question and concludes the research. Finally, Section 7.4 provides recommendations for Sweco and future research in this domain.

7.1 DISCUSSION

This research aimed to propose a method to identify, capture and structure the information sewerage asset managers need from earlier project phases for making long-term strategic decisions. Moreover, the solution should be future-proof, therefore easily extendable, adaptable and reusable.

The research started with identifying the problem in the current process of transferring information from the earlier phases of a project to the operation & maintenance phase. Various academic sources were studied to identify and understand why asset managers do not receive complete and accurate information. Then, the identified issues were validated by interviews with domain experts who also gave a first insight into the most important information that would facilitate their strategic decision-making. In the construction industry, the different actors have their own language to communicate. That results in the lack of a common structure of the information and the transfer of incomplete and not accurate information. The current process in the industry creates secondary costs, as asset managers spend time finding relevant information across various information sources. This thesis proposes a framework for capturing and structuring the information needs using a semantic model (ontology or OTL). An ontology is a knowledge model describing objects and what information is recorded. It can provide a structure for the required information to the different parties of the industry and enhance their communication by providing a common language for humans and computers. This makes understanding of what information has to be transferred to asset managers easier, that is reusable[1] and unambiguous, resulting in the time reduce retrieval of information and secondary costs.

The model was developed by following the steps of Zhou et al. (2016). After the definition of the model's scope and preliminary information from the interviews, existing standards (adopted ontologies by the industry) were studied along with literature to gain the main concepts of the ontology's structure that would better satisfy the needs of asset managers. Then, the identified information from the previous stages was attached to the main concepts using linked data principles, and a preliminary version of the ontology was gained. The developed prototype provides a decomposition of the objects of a sewerage system. Moreover, it defines and links to the objects what information has to be transferred from the contractor in order asset managers to make strategic decisions (e.g. replacing the asset's critical objects or disposing of the system).

1 An obstacle to reuse knowledge is that actors have to identify information from various sources. An ontology could aggregate information given a specific scope from diverse information sources.

An ontology is a powerful tool to capture and structure knowledge of a domain of interest. Thus, its scope, structure and knowledge representation has to be evaluated. In this way, users will be confident that the models describes correct the needed knowledge and it can be used in practice. Therefore, the developed prototype was evaluated by structural metrics, tools testing technical errors and using a programming language to check if the model provide information according to the scope. Then the correctness and accuracy of the knowledge that the model describes was validated by examples from the real practice. The results showed that the prototype is technically sound and easily adaptable and represents the domain knowledge in an acceptable level. Thus, it could be used in the practice from the related parties. However, we do not claim that the developed prototype fully represents the domain. Sewerage asset managers have to start using it and adding more concepts, will make the developed model more powerful in terms of content and details.

The developed ontology can be used with various ways. First of all, the project's main aim was to provide a common understanding and structure of the terms that contractors have to transfer to the asset managers of municipalities. Therefore, it can be used as a knowledge document to define what information and format contractors must deliver. This method can support a complete and accurate information/knowledge flow amongst the parties. In addition, providing a common understanding of the terms can facilitate software developers to develop consistent applications. They can use the ontology as a specification to develop asset management applications, and asset managers will use these applications for making strategic decisions. An example of these decisions is the selection of which asset is the most critical to allocate their budget for intervention activities. Finally, an ontology can also share a common understanding between software agents. The related parties in a construction project usually use different applications to manage the information. Suppose they agree on to make their applications to commit in a common ontology. In that case, they could enable the applications to communicate and exchange information, even if applications use various languages and data structures. The major contributions of these research are highlighted below:

- The identification of the drawbacks in the current transfer process of information in municipal sewerage projects and their reasons.
- The identification of what information sewerage asset managers' need for making strategic decisions from the earlier phases of a project.
- A conceptual model which facilitates the understanding of the needed knowledge for making strategic decision for a sewerage system.
- Methodological steps on how to identify and structure domain knowledge.
- A reusable, extendable and easily adaptable prototype model which captures and structures the information and enhances the communication between the contractor and the client.

The below section mentions some of the limitations of the research:

- The provided solution was developed based in the context of the Dutch construction industry. Therefore, the identified information needs and drawbacks of the transfer process describe only the Dutch utility sector.
- The examined literature, documents and ontologies for creating the concepts of the ontology was initially in Dutch language and translated into English. In order to be implemented in the Dutch industry, the accurate translation of the terms has to be explored.

- The initial motive of this research was the incomplete and not accurate information that asset managers obtain making difficult to apply cost effective strategic decisions. The research was focused on the information loss between the client (municipality) and an external contractor. However, information is also lost internally, between the various departments of the municipalities. Further research has to be conducted on this area.
- This research work developed a prototype ontology. Due to limitation of time and resources, not all the different components of a sewerage system were modelled.
- The research focused on attaching the relevant information to the main concepts and to the most critical physical objects. Further research needed to identify and add the information for the rest asset components of the model if it is needed in a specific use case.
- The ontology was developed based on the conceptualisation and information needs of the asset managers. Due to time and resource limitations, the side of the contractor was not taken into consideration. Thus, the ontology has to be tested if it is comprehensible from the contractors as well.
- The content of the ontology was validated against use cases of the public sewerage asset management domain. A validation with domain experts would enhance the clarity of the ontology and make it more user-friendly.

7.2 CONCLUSION

The incomplete and not accurate information that asset managers receive from the earlier phases of a project was the main driver for this research. The absence of structured information which describes the information needs of asset managers identified to be the major obstacle for the transfer of complete information. Thus, a main research was formulated about identifying and structuring asset managers' information needs. Five sub-research questions were formulated to help answer the main research question. The answers to sub-questions based on the findings of the research are discussed below:

What are the drawbacks of the current process of project information transfer between the organisations managing the public spaces and the contractors?

This research question answered by studying the current transfer of information process in projects where the municipalities act as the client. The illustration of public projects transfer (Figure 3.16) was arrived based on the workflow adopted by municipalities in order to obtain the needed information by the contractors. Asset mangers and a leader of a data management team of three municipalities were interviewed to identify the process and its drawbacks. The workflow was further validated by documents that asset managers provided to the interviewer after the sessions. The projects of public assets are not over until the municipalities obtain all the needed information. When the contractor notifies that the project is ready, inspections are carried out to confirm that the as-built situation conforms with the as-design specifications. If defects are detected, the contractor has to correct them and the process starts from the beginning. When everything is according to the specifications, the contractor has to deliver the required information. Then, the new situation is measured and registered in the Topographic Map of the Netherlands and the final step is the insertion of the data to asset management software.

The current process comes with some drawbacks that contribute to the information loss. First of all, pubic space projects do not have formal asset requirements and they do not use a standard structure of the information. Therefore, there is a lack of clear understanding from the designers and construction managers to what information they have to deliver. Another reason that contributes to the information loss is the absence of communication between the different lifecycle phases. Engineers and Asset Managers speak different languages and they need different level of detail of information to perform their tasks. The absence of a common language between them results to asset managers making manual modifications to the information as they do not need all the information that constructors deliver. Manual work results into loss of information or not accurate information. A solution could be the utilization of open standard exchange formats that can enable the communication between different software. However, the lack of expertise seems to be an obstacle to the implementation.

What information the organisations managing public spaces need from the earlier phases for strategic decision making?

This research question answered by interviewing domain experts and studying relevant literature. Asset managers were asked to elaborate on what strategic decisions make to create value for their organisations and what information they need to accomplish it. They argued that to manage cost-effectively their assets they need to have relevant information for deciding the allocation of the budget to the right projects, the right time to intervene to the assets (improve, repair or replace) and create sustainable assets. They also provided a first insight on what information is needed for the developing solution. The interview questions were focused in public sewerage systems. Therefore, they highlighted the importance of sewer pipes and the manholes and that they need information for their location, physical and functional state, maintenance status, dimensions, year of construction, type of materials. Literature helped to further understand their information needs and important parameters for sewerage systems. Asset owners need to know where their assets are located and which areas citizens they serve. The depth is the most important coordinate as it is an indication for how well the system is functioning and if it needs maintenance. To decide which asset measure has to be applied, the asset owners need to know the physical and functional state of the objects which form the system and if they fulfil their designed function. In addition, they need to have the history of asset maintenance and if a measure has been deferred causing the deterioration of the state. Finally, to assess the criticality of the system and decide on which asset they will allocate their budget, the risks that may cause significant deterioration of their assets' state have to be mapped. Dimensions are important for the hydraulic performance of the system and materials of the objects are important to accomplish the goal of municipalities for more circular cities. Finally, the asset's year of construction and its life expectancy help them to decide their strategy and when to dispose an asset.

How can we translate the information needs to requirements and which are the main concepts of the ontology?

This an important step towards the development of the end solution. The shaped solution has to include the needs of the asset managers and successfully depict the knowledge of the domain. The needs were translated into three requirement categories: functional, structural and environmental. A functional requirement can be defined as a function that the end solution should satisfy depending on the needs and wants of the stakeholders. Therefore, these are the requirements that describe the knowledge that the solution needs to represent. To elicit the functional requirements we based on the interviews and the literature. The interviews helped to understand the long-term decisions that asset managers need to make. In addition, they offered a preliminary insight into the information needs that the managers of sewerage systems need to make these decisions. The literature provided a more in depth insight into the long-term visions and goals of the municipalities. Altogether, these sources helped to formulate the competency questions and reflect upon the stakeholder goals. Competency questions is related with the uses of the ontology. Within the context of this research thesis, a use is seen as a decision that the asset manager should have the relevant information to create value for the organisation in the long term. Altogether, the uses cases were formulated to satisfy long-term decisions for an asset in the domain of operation & maintenance of a public sewerage system. With the formulation of the competency questions (they can be seen in paragraph 4.2.1.4) and the use cases of the ontology, the main concepts of the ontology could be derived (see in Table 4.3). In addition to the functional requirements, structural and environmental requirements were defines as well. These were elicited from literature review and document study. The structural requirements refer to the structure of the end solution while the environmental are more generic requirements for the design of the solution. The requirements were written down by distinguish them into two categories 1) Industry's Operations and 2) System/Product. This distinction was used in order to categorise the requirement to the ones that will satisfy needs and goals that were derived by the industry's practices while the latter category describes the (structural or environmental) characteristics that the solution should have. The complete list of requirements can be seen in Table 4.3.

How should the ontology be constructed?

This research question refers to the steps that we followed to construct the prototype ontology. To achieve that, we followed the methodology of Zhou et al. (2016).

First, as it was explained in the previous research question, the scope of the ontology was defined by conducting interviews with asset managers of municipalities and consulting literature. From this step, a list of requirements and the competency questions were gained which form the direction for the end-solution.

Second step was to examine existing ontologies to gain sources for the ontology development. It is possible that someone has modelled a part of the domain that we intend to cover. We checked if we could refine or extend existing ontologies in order to achieve the representation of the required knowledge for our task. The existing ontologies that we examined can be seen in Section 4.2.2.

After the review of existing ontologies and relevant literature, eight main concepts were created to achieve the end goal and create the conceptual model which is the the outcome of the third step. Except from the conceptual model which represents the generic knowledge, ontology's architecture was also developed. It represents the specialised knowledge by developing or reusing existing ontologies/taxonomies. By finishing the third step, a list of main classes and their corresponding hierarchy was gained (see Figure 4.5 and Table 5.2).

Fourth step is the build of the ontology in an ontology editor tool. First, the classes and their hierarchy were modelled in the tool. Then the relations between the main concepts that were identified in the conceptual model were modelled as object properties (see 5.3). In this way, we connected the concepts by making meaningful statements using triples and provided a structure to the information. However, asset managers need more information for every concept to facilitate their decision-making. Data and annotation properties can describe this information and they were assigned to the relevant concepts (visible in 5.4). Then the object and data properties were restricted. In this way, we defined how many relationships an individual of a class can have, the relationships that an an individual can participate in and what values can be assigned to the data properties. By restricting the properties, better definition of the meaning can be gained and we assure that the ontology will not provide contradictory knowledge.

The final step before gaining a first version of the ontology is the creation of individuals or instances for the classes. The application of instances illustrates the use cases of our ontology and the knowledge it can capture. In Appendix F all the created individuals are presented. The final step of the followed methodology is the evaluation of the ontology. The evaluation process will be presented in the answer of the next and final research question.

How can the ontology be evaluated?

An ontology is a powerful way to capture and structure information. However, it is important the users to be confident that the model represents accurate information for the real world. Confidence can be gained by evaluating the ontology for its scope, structure and knowledge representation. The evaluation was based on eight criteria derived from the literature: 1) accuracy, 2) adaptability (modularity/extensibility), 3) clarity, 4) completeness, 5) conciseness, 6) consistency and 7) reusability (by leveraging existing knowledge such as using standard practises (languages) or standards). Then the defined functional, structural and environmental requirements were assigned to the relevant criterion and the two evaluation parts were followed. One part is the verification of the ontology which assesses the completeness, conciseness and correct implementation of the requirements. The consistency and conciseness of the ontology was constalnty evaluated during modelling process by using the reasoner of Protégé. The web-user interface of OOPS! (Ontology Pitfall Scanner!) (a tool for detecting pitfalls in ontologies) was used to check the quality of the ontology's concepts and relations. The tool evaluated aspects such as as consistency, clarity, understanding, language, requirements completeness (more relevant to conciseness and consistency and not in completeness criteria) and application context. The tool ensure that there are no modelling mistakes which cause the inference of contradictory knowledge. The completeness and adaptability of the structure was assessed by structural metrics. They can inform potential users how much information has been captured from the model and the nature of the structure; if it covers a wide range of domain's information (generic) and is easily adaptable or too detailed and need more effort to be extended/adapted without changing its existing core. Finally, to assess whether the ontology fully modelled the defined scope, queries were formed that answer the competency questions. This part of the verification was implemented through the SPARQL Query tab of Protégé editor tool.

Validation is the latter part of evaluation process. It refers whether the ontology models the real world and requires content validation. Ontology was checked against three documents from the practice. First it was validated with the strategic plan of Municipality of Delft for their sewerage system. This document describes the strategies and costs for managing the sewerage system. Thus, it was considered a great fit for the scope of the ontology. After the insertion of the missing terms the ontology was validated against two documents that the municipalities of Delft and Rotterdam use to describe what information has to be transferred to them from the contractor. Identified missing terms were added to the ontology and the structure was evaluate once again to be sure that the added terms did not create pitfalls.

After answering the five sub-questions, the main research question is answered as well:

"How can we capture and structure the strategic information needs of the asset owner from the earlier phases towards operation & maintenance phase for a portfolio of assets?"

Explicitly defined and structured asset information requirements are necessary to transfer complete and accurate information to asset managers. An ontology can describe and structure the required information and make explicit to the contractors what information they have to deliver to asset managers.

Strategic asset information needs from earlier phases were identified and elicited into requirements (see Table 4.3). To avoid ambiguity, we clearly described the concepts involved in the domain of interest (Section 4.2.3). We used linked data and semantic web technologies to capture and structure the information. The information is stored and structured in three linked data pieces (subject-predicate-object). This format can take any subject and link it to any object by using the predicate to show the relationship between them (e.g. SewerageSystem hasCity Rotterdam). The set of interlinked triples creates a graph, which is more efficient as the human can understand it more quickly than a traditional sheet file or a database. Moreover, when the information is structured in this way, it can also be machine-understandable.

Defining the concepts of strategic decision-making of a sewerage system in such a clear format allows for sharing a common understanding of the information that asset managers need and the logic behind it. Now the information can be stored in a single location, and asset managers will not look for relevant information in various documents. Moreover, the applied metadata offering explanation for every concept reduces the possibilities for misconception and the transfer of wrong information. Now the understanding of what information has to be transferred to asset managers is more straightforward, reusable and unambiguous, resulting in reduced time retrieval of information and secondary costs.

7.3 REFLECTION

The operational & maintenance phase is responsible for the 60% of the costs of a project (Akcamete et al., 2010; Ashworth, 2016; Ashworth et al., 2017, 2018; Patacas et al., 2016; Sadeghi et al., 2018). Early involvement by asset managers is beneficial for the whole life design process as "up to 80% of the operation, maintenance and replacement costs of a building can be influenced in the first 20% of the design process" (International Organization for Standardization, 2017).

To facilitate asset management's cost-cutting effort, the information delivered in the handover stage should include accurate, complete and up-to-date data related to infrastructure assets for effective operation and maintenance (Farghaly et al., 2020). However, according to Bosch et al. (2015), 30% of the information in the operations stage is incomplete or invalid, leading to secondary costs as managers are looking for relevant information. The literature review has indicated two main obstacles for the complete transfer of information to the operation & maintenance phase. Firstly, there is a lack of understanding of what information should be captured from the earlier stages to facilitate asset management strategies at a portfolio level. Engineers and asset managers need different information for an asset and in different level of detail. That leads to a lack of shared understanding concerning of what information is important to be transferred at the handover stage of an asset. Therefore, asset owners want to have a comprehensive set of digital information about their assets that describes what information they need to manage and create value for the asset in the long term. Secondly, the relevant information is dispersed in various sources and applications with different formats and meaning. That makes the different applications not able to communicate and asset managers spend a significant amount of time to identify the relevant information and make manual modifications to insert the data into their systems (Matarneh et al., 2019). Therefore the created ontology can solve these problems by acting as common language between the contractors and asset managers. That may contribute better communication and to the transfer of complete information which will help asset managers to make well-informed decisions and create value for their organisation in the long-term. Moreover, it can serve as an interlingua between different applications and enable the exchange of information between them or act as specification for the development of new sophisticated asset management software.

7.3.1 Enhancement of communication between the actors

The public space domain currently lacks of a standard which will describe the required information with emphasis on life-cycle information which facilitates long-term strategic decisions. During these research, it was found that within the sewerage system domain, there are different modelling practices (GWSW, IMKL, IMBOR etc.) to model domain knowledge. These information models provide the vocabulary to create ontologies or OTLs for specific purposes. However, these practices describe the sewerage public sector using different attributes, formats, relations and semantic terms. From the literature there was a clear indication that there is not a standard framework that describes what information is needed to be stored and delivered to asset owners, especially for strategic decisions for public water sewerage systems. The absence of a digital modelling standard-i.e domain-task ontology, leads to confusion and misunderstandings when exchanging information at the handover of the projects.

Following the ontology's principles, all data instances can have meaning and context since the ontology stipulates certain rules for describing data objects and their labels. By connecting a data instance to a specified class in an ontology, or to another instance, or both, semantic technology enables context-awareness. Because an ontology offers robust terminology based on natural language, the context of data can be described clearly and unambiguously. As a result, it makes data storage and retrieval convenient. The ontology's focus on semantics reduce the amount of work that is needed to find out what data means comparing to other means of data storage-e.g. relational database (Uschold, 2015). Additionally, because it defines domain knowledge in human language and can be represented graphically, even non-experts may easily get data through it (May et al., 2022). Therefore, the actors could now store, transfer and understand the relevant information using one mean, not several documents or files. The access of asset managers to unambiguous and structured information may decrease the time of retrieval and the produced secondary costs.

The developed domain-task ontology offers to the actors a structure alongside they can store their information for their sewerage systems. Besides that, the stored information could be exploited for strategic decisions during the operation & maintenance activities. The ontology can enable digital practices such as predictive maintenance. The predictive maintenance works by gaining access to information on the status and condition of assets and concentrating on the knowledge that may be learned from the information. In this way, asset managers could enhance the reliability and service life of their assets by recognizing possible difficulties and giving early warning of problems and crucial events. That would help to prevent he occurrence of catastrophic failures during the functioning of a system (May et al., 2022). For a sewerage system the structural or physical condition is affected by the pipe age, soil characteristics or protruding roots (Van Riel et al., 2014). How these difficulties or risks are captured by the ontology can be seen in Section 5.3.2.1 (page 67). For example, the ontology can store information for:

- *R001-001(sewer pipe) hasState PhysicalStateOfR001-001*
- *PhysicalStateOfR001-001 hasDefect True*
- *PhysicalStateOfR001-001 hasDefectSeverity 3*
- *PhysicalStateOfR001-001 isInfluencedBy Corrosion(Subclass of Risk)*

Moreover, to the sewer pipe more concepts are connected such as the status of maintenance, the last applied measure, its cost, its date of execution etc. Therefore, the ontology can store relevant information that asset managers can use it for applying predictive analytics for operation & maintenance purposes and allocate their budget for intervention activities.

7.3.2 Enhancement of communication between the applications

Another feature that ontologies can enhance according to the academia is the communication of software tools by achieving semantic interoperability. Semantic interoperability ensures that the content of information is understood in the same way by the software tools throughout the exchanges between them (Karimi et al., 2003; Turk, 2020). In the construction industry, from the design and build phase towards the operation of the asset, the tools used in processes are very diverse and can not share information seamlessly (Fang et al., 2022). For example the needed information for our ontology could be produced by a CAD application (e.g. dimensions), a project management application (e.g. materials and costs) or a GIS software (spatial data and coordinates). According to (Ciocoiu et al., 2001) ontologies can help with two basic approaches for enabling the different applications to communicate. One is the standardization approach where all applications use the same ontology (common vocabulary and conceptualisation) to represent the information. The other approach is to use an ontology as interlingua when the software use different ontologies. The concept is to have a common ontology and use it as a reference vocabulary for translation between the software local ontologies (Ciocoiu et al., 2001). This can be achieved by a specification of how classes and properties of one ontology are related to classes and properties of the target ontology. For example, a property can indicate that two classes are "equivalent" (V-Con, 2016). However, some datasets produced by the software and used by the actors may not be in W3C Linked Data formats. Those datasets will need to be translated to the selected linked data formats (V-Con, 2016). For example a SPFF to an OWL format. As it was identified by the interviews, contractors is highly possible to not use W3C Linked Data formats. Therefore, it is expected that the datasets should be firstly translated without changing their structure(semantics) and then link the terms to the equivalent terms of our ontology. Lastly, as most of the software that the actors use in today's practice are already developed and can not be built by using the vocabulary and the conceptualisation of our ontology, the second approach is more relevant for achieving semantic interoperabilty in a public sewerage system project.

7.3.3 Acting as a specification for software development

Finally, the created ontology could help to develop asset management software for sewerage systems. Firstly, the ontology provides a vocabulary and a conceptualisation of the domain which facilitates the requirements elicitation and analysis (Gonzalez-Perez, 2017). The phase of the requirements engineering deals with gathering and understanding the functionalities that the system should provide to the costumers (Happel and Seedorf, 2006). For the creation of the ontology is phase is already covered. Domain experts were interviewed to analyse the problem and explain what is important for them in order to make strategic decisions. Then, an ontology was created that offers a decomposition with the objects that an asset manager wants for a sewerage system and the relevant information attached to the most critical objects. This domain-task ontology can be used as a staring point from software developers on which they will built their applications. According to Gonzalez-Perez (2017) software developers learn about the domain faster and make fewer mistakes when supported by an ontology rather than relying on discussions with domain experts. Therefore, the use of the ontology may lead to the reduce the analysis time and to a fit-for purpose (i.e. enabling the long-term management of public sewerage systems) software.

7.4 RECOMMENDATIONS

The recommendations provided in this section is based on observations during the analysis of the problem, the design process and the evaluation process of the developed prototype.

First recommendation is about the prototype's validation. The prototype was quantitatively evaluated with metrics related to the structure. Moreover, the structure was further evaluated with tools. The content of the ontology was validated against use cases. It would be beneficial to be evaluated by domain experts as well. This would improve the user-friendliness of the prototype and the clarity of the definitions.

Second recommendation is related to the implementation of the prototype. Sweco can use the developed ontology as a specification for building applications for facilitating its clients (municipalities) making strategic decisions.

Third recommendation is related to the implementation of the ontology. Sweco can make its asset management software to conform with the ontology's vocabulary and data specifications. In this way, the company will have a clear specification of the meaning and data type for every term. That may lead to an easier communication between software applications as it was explained in Section 7.3.2.

Fourth recommendation is about the representation of knowledge of the developed solution. Despite the fact that the evaluation showed an acceptable level of knowledge representation, if sewerage asset managers start using and adding more classes or even properties, will make the developed model more powerful in terms of content and details.

Fifth recommendation is about the standardisation of public space domain vocabulary. The industry have to work in a standardised language which will describe the information needs of the asset managers in the right detail. Such an initiative is IMBOR but it is not yet completed. By using IMBOR as the common language of the public space to create ontologies for specific tasks, the data structures will be more compatible with each other and the computer applications will be easier to communicate with each other.

Sixth recommendation is about the future of automated transfer of information to reduce information loss between the lifecycle phases. Industry should stop rely on the tradition way of transferring document based information. That implies the use of OTLs for using the same standardised specification of assets, information exchange formats and a formal information exchange specification defining when, how often, the content and the format of information.

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A INTERVIEW PROTOCOL

RESEARCH OBJECTIVE This research aims to standardise and make explicit the information that is required to be transferred to the asset managers from the initial stages of the projects for making long-term decisions. That would contribute to more accurate, upfront information for managing a portfolio of assets than the current practices.

PURPOSE OF THE INTERVIEWS The interviews are mainly focused to gather data to answer the first two research questions. Semi-structured interviews with professionals from the municipalities, will provide useful insights for the development phase of this research. The interview questions are based on the following sub-research questions of the project.

1. "What is the current process of information management within the organisations managing the public spaces?"
2. "What information the organisations managing public spaces need from the construction phase for business and strategic decision making for a collection of assets?"

The interviews will take place to understand the information needs of organizations managing public spaces to make strategic decisions. The first objective is to understand the current process of information management (RQ1). The second objective is to understand which information asset managers need to obtain during the handover stage (RQ2). The needed insights are how the information documentation is applied, the technologies, the standards, and the formats used for documenting the information in the current process. Moreover, a helpful insight would be to understand the issues in the current process and get an insight into the solutions that the professionals consider helpful for managing the information in the asset management field.

Interview Set Up

A Checklist for Interview Researcher

Preparation

- Conduct a literature review on the topic of interest. Sources to be used include journal articles, books/monographs, and conference papers.
- Conceptualize the literature around the topic. Look for themes emerging from the literature that may be applied to the research.
- Based on the topic and the review of literature, make an interview plan(substantive frame) of interviewees and content.

Logistic Considerations

- Develop a budget for your research.
- Prepare materials necessary for interview: tape recorders, microphones, tapes, and notepads, among others.
- Prepare a schedule of research.
- Check with Institutional Review Board (IRB) concerning research regulations, and secure IRB approval if required.
- Develop a consent form

Developing an Interview Protocol

- Be clear about the goals to be achieved in the interview.
- Determine a time limit for each interview.
- Develop interview questions.
- Develop an interview protocol.
- Do some preliminary interviews to try out your protocol

Respondents

- Identify respondents:
    - Key informants: people who are experts in an area, or people who are key witnesses to an event.
    - Sample of representatives: selection of people from a population.
    - Convenience sampling: selecting respondents because they are what we can get.
- Recruit respondents:
    - Be prepared to explain to potential respondents about the study.
    - Consider various recruiting strategies: phone calls, email, formal letter, or a combination of these.
    - Some kinds of sponsorship may be needed in some cases in order to approach a potential respondent.
- Schedule interviews with your respondents who agree to participate.

Interviewing

- Getting started

  - Introduce yourself and your project to the respondent.
  - Ask the respondent for permission of taping.
  - Ask the respondent to sign the consent form, explain to her/him if necessary.

Data Analysis

- Issue-Focused Analysis: what could be learned about specific issues from the respondent.
- Coding: link what a respondent says to the concepts and categories of the study
- Sorting: organizing excerpts of interview according to concepts and categories
- Integration: Making sense of the sorted interview data

Report Writing

- Keep your audience in mind: academic, professional, clients who commissioned your study, general reader, or a mixture of these?
- Watch your tone: you can be an advocate, a critic, or a detached reporter.
- Use excerpts as illustration and evidence of your arguments.
- Keep confidentiality of your informants.

(Standford University, 2003)

Interview Structure and Content

A. General Information
   - Relation of the Public Organisation with Asset Management
   - Relation of the Interviewee with Asset Management
   - Partners of Public Organisations in the Projects

Expectations: The expected information from these questions is to understand how asset management is applied by public authorities.

B. Information Needs
   - The Information that asset managers need from the construction phase (for urban water systems) for managing a collection of assets
   - Data formats and standards that are used in the current process
   - Actors involved in the handover and transfer of information at the completion of a project
   - Tools\Software used for AM activities from the public authorities
   - Drawbacks and their reasons in the current process

Expectations: The expected information from these questions is to understand what information the asset managers need from the construction phase, how they communicate their needs and when they do it. In addition, the questions will try to gain an insight to the reasons of information loss.

C. Future Needs
   - Organisation's vision for the next five years
   - Relevant Developments in the Information Technology
   - Future trends in Asset Management that influence the Information Solutions
   - Software or Applications useful in the future

Expectations: The expected information from these questions is to get insight to solutions that the professionals consider useful for the information management in the asset management field.

Interview Questions

A. General Information

Q1. What is your organisation's scope in relation to asset management?

Q2. What is your role in the organisation and your responsibilities?

Q3. What decisions do you have to make for executing the long-term strategy of your organisation?

Q4. What type of organisations do you typically cooperate with on infrastructure projects?

B. Information Needs

Q5. What information do you need from the organisations operating in the construction phase for planning the operation and maintenance of your assets?

Q6. Can you describe the typical format of this information?

Q7. Do you use any standard or a template to define the information that you need from the contractor?

Q8. How the information from the construction phase is delivered to you? Can you describe the process that you follow to transfer the information from the site into your systems?

Q9. Has your organisation identified any missing information from the construction phase? If yes, which are the main reasons?

Q10. What are the problems that you face when you process this information and place to the software?

Q11. Do you have any information such as guidelines or a handbook for structuring the information and putting it into your system?

C. Future Needs

Q12. What is your (or your organisation's) vision for the next 5 years?

Q13. Do you see any relevant developments in Information Technology?

Q14. Is there any specific software or applications that you are using or want to use in the future. Why do you think that they are useful?

Q15. Do you see any trends in asset management that can influence the information solutions?

D. Closure

Q16. Do you have any recommendations for additional literature that may help my research?

Q17. Do you have any recommendations for additional topics that were not covered during the interview?

These interview questions might seem general because they were structured in such a way as to avoid leading the interviewee towards specific topics and answers. The interview goes to further details by making follow up questions based on the interviewee's answers to the main questions.

B LIST OF INTERVIEWEES

ID	Role	Organisation
I1	Team Leader of Data Management Team of Public Space	Municipality of Rotterdam
I2	Program Manager of Public Space	Municipality of Delft
I3	Asset Manager (Sewerage System)	Municipality of Rotterdam
I4	Asset Manager of Public Space	Municipality of Zwolle
I5	Project Leader & Advisor of Engineering Projects	Municipality of Rotterdam

Table B.1: The list of Interviewees

C SEMI-STRUCTURED INTERVIEWS

Semi- structured interviews (SSIs) were conducted with professionals involved in the management of public spaces to gather data. The aim was to understand the information needs and the current process of the information management in the public authorities. SSIs include a mix of closed- and open-ended questions, which are frequently supplemented with why or how questions (Adams, 2015). This allow to gather in-depth data that help to understand the "what", the "how" and "why", thus the context of researcher's study (Saunders et al., 2003).

According to Adams (2015), some of the situations that SSis can help is:

- If the research wants to conduct some in-depth survey before constructing an overall research strategy
- If the research wants to understand the independent thoughts of the interviewees.
- If the research deals with an uncharted area the interviewer needs the freedom to explore and identify issues.

These three cases are relevant for the context of this research. Practitioners of the public authorities play an important role to the implementation of new solutions. They are responsible for the management and maintenance of public spaces, thus their information needs must be satisfied by the developed solution. Moreover, the asset management and OTL's are relatively new topics and SSIs provide the needed latitude to understand the context of the topic.

C.1 THE INTERVIEW PROCESS–DATA COLLECTION

After discussing the theory of SSIs and explaining their suitability for this research, this section describes the methodology of the interview process as shown in Figure C.1

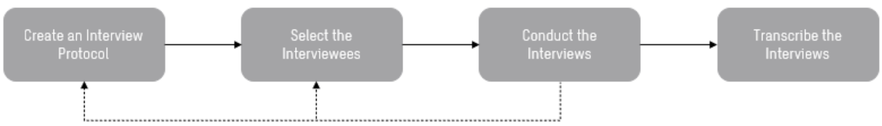

Figure C.1: The Process of the Interviews

CREATING AN INTERVIEW PROTOCOL The first step of the interview process is drafting an interview protocol. The interview protocol acts as a guide for the researcher/interviewer to prepare and plan a list of questions that need to be asked. It clarifies the goal of the interviews, which was formulated based on the research topic and the subsequent research questions. As it is created at the beginning of the process, no matter how detailed it is, it has to be considered a work in progress

(Adams, 2015). The last part of the interview is requesting feedback on the interviewee's experience. After each interview, the interviewer can evaluate the process based on the feedback or weak points during the interview. For instance, some questions may need to be added to cover emerging topics,or the sequence of questions might be rearranged, or even some questions might have to be excluded. Figure C.1 depicts this as a feedback loop between the steps of the interview process. Finally, the Interview Protocol of this research is described in Appendix A. It includes the research objective, the purpose, the structure and the content of the interview sessions.

SELECTING INTERVIEWEES The second step is to identify the target groups, set the selection criteria, and schedule the interviews. Since the research is focused on the information needs of Dutch public authorities, the main target group is the asset managers of public space. Hence, the interviewee parameters of selection were as follows:

1. **Disciplines:** The research topic needs insight from professionals with different areas of expertise. The purpose of the interviews is to understand the information that managers need from the Design & Construction phase (engineers) to manage the public space and the current process of information exchange of public authorities and contractors. Hence, asset managers and technical managers need to be interviewed. Ideally, members from both asset management and engineering teams should be interviewed.

2. **Organisational Levels:** The research is focused on long-term decisions that managers of public space make in order to create value to their organisation. Thus, there is value in interviewing department heads and professionals at higher organisational levels. Given their position, they are the practitioners who decide the strategy for the assets of the public authorities and can offer valuable insights into the area of interest.

Undoubtedly, all practitioners like the engineers or designers of the contractor can offer valuable insights. However, the identified profiles can provide an adequate amount of data for this research given its limitations on time, purpose of the interviews and resources. After the crafting of the needed profiles, the potential participants will be approached through e-mail with a document which briefly introduces them to the research project, topic of discussion and estimated time of the interview. The brief introduction needs to be as concise as possible in order not to reveal extensive information and create bias to the potential interviewees.

CONDUCTING INTERVIEWS Due to the convenience of virtual meetings for the busy professionals, the interviews were conducted with the aid of Microsoft Teams software. The primary intention of the interviewer will be to follow the order of the interview protocol. However, the interviewer should be prepared to pursue unexpected topics when the interviewee diverges from the predefined area. Then, the interview has to return to the skipped questions and continue with its predefined sequence (Adams, 2015).

C.2 ANALYSIS OF THE INTERVIEWS' DATA – THEMATIC ANALYSIS

This section discusses the analysis of the interviews' data. To achieve that, thematic analysis will be used to analyse the aggregated qualitative data. Thematic analysis is a technique for detecting, analysing, and reporting patterns (themes) within the data (Braun and Clarke, 2006). Holloway and Todres (2003) suggested that thematic analysis should be regarded as a fundamental method for qualitative analysis. They further added that inexperienced researchers should firstly be familiarized with it, as it provides core competences for conducting many other methods of qualitative analysis. "Thematizing meanings" or creating themes is one of the common skills. Therefore, one of the main advantages of the thematic analysis is its flexibility. It is a technique that it does not need to follow a predefined theoretical framework and can be used in different approaches and within various frameworks (Braun and Clarke, 2006).

In this research, thematic analysis is used as a first step to identify themes or patterns for further analysis in the next phases of the research (Part III & Part IV see, Figure 2.1) (Saunders et al., 2003). Table C.1 cites some relevant advantages of the thematic analysis to this research as discussed by Braun and Clarke (2006) and Saunders et al. (2003).

Advantages of Thematic Analysis	Relevance to the Research
Easy and accessible qualitative method for inexperienced researchers	The methodology is suitable for the researcher's limited experience in qualitative research
Helpful in integrating and understanding extensive amounts of data and creating a thematic description	The research needs an approach to structuring interviews and document data and extract meaningful interpretations
Identify key concepts from a data set for further exploration	This complements the next phase of the research project as it can provide concepts to be used in the design phase

Table C.1: The advantages of thematic analysis and their relevance to the research

C.2.1 Research Set Up For Thematic Analysis

Several considerations must be taken prior starting the analysis. This section covers a collection of options established by Braun and Clarke (2006) which helped the researcher to tailor the analytical procedure.

A DETAILED DESCRIPTION OF THE DATA SET OR A THOROUGH EXPLANATION OF ONE SPECIFIC THEME One important consideration is whether the analysis will provide a thematic description of the entire data set or an in-depth analysis of one particular theme. The descriptive method offers the reader a sense of the critical themes. At the same time, the latter provides a thorough report of a specific area of interest within the data. For this research, the thematic analysis serves as a tool to identify key concepts which will be used as input for further exploration in the next phase. Moreover, the specific research questions were already formulated, which influenced the interview questions. Consequently, the approach of the thematic analysis can be characterised as descriptive.

INDUCTIVE VERSUS THEORETICAL There are two methods that can be followed for the identification of themes or patterns within the data. The first one is called inductive or "bottom-up" and it is a process of coding without a pre-existing a frame or relying to the analyst's prejudices. On the other hand, theoretical or deductive or "top-down" is based on the analyst's interest which is influenced by previous literature. It is a more detailed analysis of a particular area of the data. Taking into consideration the reasons mentioned in the previous section and because of its affinity with the descriptive approach, the inductive approach will be followed.

SEMANTIC VERSUS LATENT The last distinction is based on the level at which the themes are identified. In the semantic or explicit approach, the researcher does not go in further detail from what the interviewee has explicitly said. In the latent or interpretive approach, the analyst identify and interprets the underlying meanings and assumptions behind the semantic content of the data. The analysis will follow the semantic approach as its goal is to identify themes that will validate the findings of the literature review and provide key concepts for further exploration.

C.2.2 The Analytical Process

This section describes the procedure that an analyst should follow to conduct a thematic analysis. The process does not follow a linear progression and the analyst has to undertake an iterative process. The analysis involve the collection and analysis of data and going back over earlier to your analysis to revise your code and analytical themes as you collect new set of data. The following procedures are based on the guidelines of Braun and Clarke (2006) and Saunders et al. (2003).

STEP 1: BECOMING FAMILIAR WITH YOUR DATA The first step is to listen the interview recordings and transcribe them into a written form. Transcribing is considered an outstanding way to start familiarizing yourself with the content of your data. According to Bird (2005) it is "a key phase of data analysis within interpretative qualitative methodology". During this phase, the analyst should searching for meanings, taking notes and creating ideas for an initial version of a coding frame.

STEP 2: CREATING INITIAL CODES After the researcher has been familiarised with the data and generated an initial list of ideas, the creation of initial codes will take place in the second phase. Coding is the organisation of raw data into meaningful groups based on the area of researcher's interest. This activity can be performed manually or with the aid of a software. This research will use the computer program Atlas.ti to facilitate the coding process.

STEP 3: CREATING THEMES After the generation of codes, the analysis has to shift its focus in a broader level. During this phase of analysis the researcher examines the list of codes for patterns and correlations to get a brief list of themes relevant to the research question. Saunders et al. (2003) defined the term **theme** as: "a broad category incorporating several codes that appear to be related to one another and which indicates an idea that is important to your research question."

STEP 4: REFINING THE THEMES Step 4 involves the finalisation of the themes. The themes you develop must be part of a cohesive group in order to give you with a well-structured analytical framework to conduct your analysis. Therefore, there are two main reasons to undertake this step. First, data within themes is coherent and provide a clear meaning. Second, the themes are consisted of obvious and detectable divisions between them. The final step of this analysis is to remove, merge or broken down themes into more detailed ones depending the needs of the analysis.

STEP 4: REPORTING The final step of the process is to write down the analysis in a comprehensible and succinct way. The aim is to express an interesting story which convinces the reader for the validity of the analysis. The analyst should provide examples or extracts which prove the reason of the themes' creation. The report should not only provide data but needs also make explicit the relation to the research question.

D OVERVIEW OF CONNECTED STANDARDS

#	Standard	Domain of application	Domain	Mainly Coordinated with
1	IMBOR	The Netherlands	Public Space	- W3C standards: RDF/RDFS/OWL-2, Turtle, SPARQL and SHACL -NEN 2660-2 (Rules for information modelling of the built environment. The objective of the standard is to provide unambiguity about the (semantic) rules for data models that express the physical and spatial world of the built environment.) -NEN 3610:2011 (basic model for information models) -IMKL 2015 (Cadaster, Geonovum, A standardized data specification on a national level intended to communicate utility data in case of excavation works.) -BGT/IMGeo (Cadaster, Geonovum. It records how the government organisations digitally record the layout of outdoor public space in the Netherlands. -IMWV (CROW. It describes how, in addition to object-oriented data, traffic data for traffic engineering issues can be recorded in a uniform manner.) -BOR-MELD (CROW. Standard for recording reports about public space. It describes what information of a report is recorded, the problem reported by an organisation or a citizen and the underlying cause.) -Kor (CROW. It contains around 200 image-measuring rules for measuring the quality of the outdoor space.)
2	GWSW	The Netherlands	Urban Water & Sewer Management	- W3C standards: RDF/RDFS/OWL-2, Turtle, SPARQL and SHACL - NEN 3399:2015 (classification method for visual inspections of sewerage) -NEN NTA 8035:2020 (semantic modelling of the built environment) -NEN-EN 13508-2:2003+A1:2011 (coding system for visual inspection of sewerage) -NEN 3610:2011 (basic model for information models) -NLCS (CAD, BIM-loket. Uniform way of creation of digital 2D drawings for the civil engineering sector) -IMKL 2015 (Cadaster, Geonovum, A standardized data specification on a national level intended to communicate utility data in case of excavation works.) -BGT/IMGeo (Cadaster, Geonovum. It records how the government organisations digitally record the layout of outdoor public space in the Netherlands. -Aquo standard. (Informatiehuis Water. The backbone for exchanging information about water. It makes it possible to exchange data in a uniform manner between parties involved in water management.)

Table D.1: Standards connected with IMBOR and GWSW

E PROPERTY RESTRICTIONS

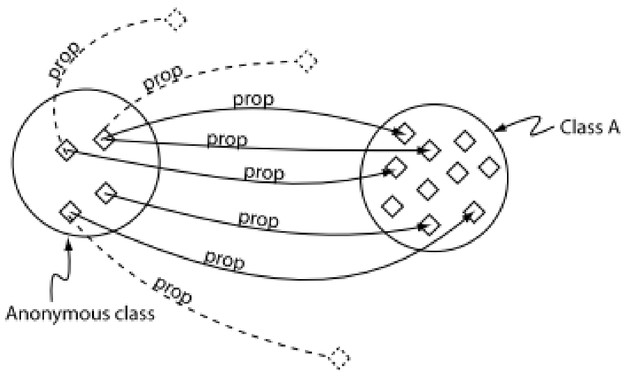

Figure E.1: Quantifier Restriction:Existential Restriction (Retrieved by Horridge and Brandt (2011))

As presented in Figure E.1, the set of individuals in the anonymous class have at least one specific relationship with the individuals in the class A. The dashed lined indicate that the individuals may have other relationships with individuals that they do not belong to the class A. Horridge and Brandt (2011) states for the exsitential restrictions that: "The existential restriction does not constrain the prop relationship to members of the class ClassA, it just states that every individual must have at least one prop relationship with a member of ClassA".

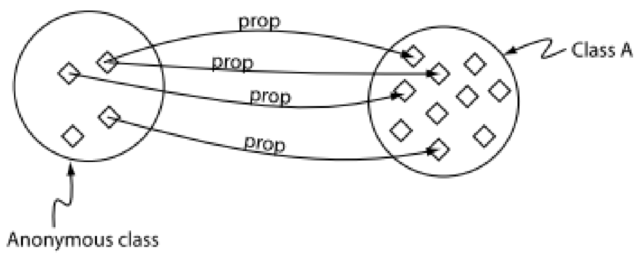

Figure E.2: Quantifier Restriction:Universal Restriction (Retrieved by Horridge and Brandt (2011))

Universal Restrictions or "allValuesFrom" or "only" restrictions, restrict the individuals of the anonymous class to be linked only with individuals of Class A for the given property.Moreover, an individual from the anonymous class can have multiple such relations with the individuals of Class A. This can be seen in Figure E.2. Note that, there is not necessary that all individuals of the anonymous class has relationship with an individual of Class A. However, according to Horridge and Brandt (2011): "if such a relationship for the given property exists, then it must be with an individual that is a member of a specified class."

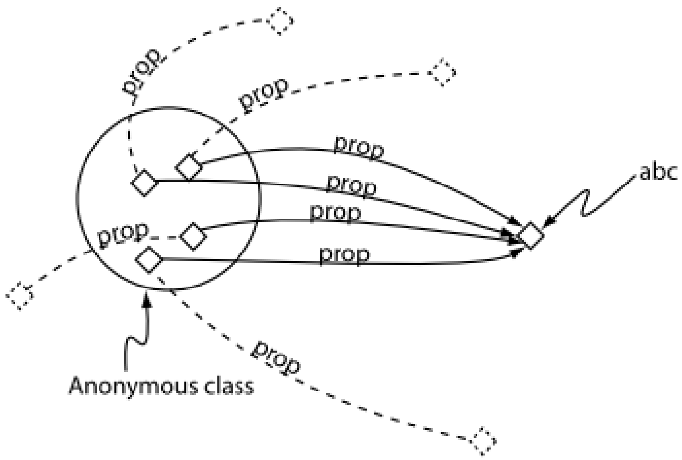

Figure E.3: hasValue Restriction (Retrieved by Horridge and Brandt (2011))

In contrast with the quantifier restrictions, hasValue restriction is not related to any individual of a specific class (e.g Class A) . The hasValue restriction describes an anonymous class of individuals which is related to a specific individual with the help of a specified property. This is presented in Figure E.3

F INDIVIDUALS

In this section the individuals created for the classes of the ontology can be seen. Note that the individuals of the sewer pipe can be seen in Table 5.5.

Sewerage System: R001

Note: The names, neighborhood, monetary values and dates are indicative.

#	Class of Individual	Individual	Relationship	Individual 2/ Value	Annotation
1	Sewerage System	R001	hasSystemID	R001	The unique identifiier of the sytem. It is applied in order to be distinguished from other assets in the portfolio
2	Sewerage System	R001	hasYearOfConstruction	1990-04-15	The year of construction of the sewerage system. ValueType: [yyyy-mm-dd] xsd:date
3	Sewerage System	R001	hasSubSystemPart	G7 (manhole)	
4	Sewerage System	R001	hasSubSystemPart	R001-001 (sewer pipe)	
5	Sewerage System	R001	hasLocation	LocationOf R001	
6	Sewerage System	R001	isDescribedBy	00-R-0010 (revision drawing)	
7	Sewerage System	R001	hasRelatedParty	Organisations	
8	Sewerage System	R001	hasRelatedParty	Individuals	

Table F.1: Individual of Sewerage System

Individuals connected to sewerage system R001:

- Location of R001
- Related Parties (Organisations & Individuals)
- Information Object - Revision Drawing 00R-0010

The sub-system parts manhole and sewer pipe will have their own table as they include most of the information attributes.

Note: The names, neighborhood, monetary values and dates are indicative.

#	Class of Individual	Individual	Relationship	Individual 2/ Value	Annotation
1	RelatedParty	Organisations	hasClientOrganisation Name	Municipality Of Rotterdam	ValueType: xsd:string
2	RelatedParty	Organisations	hasContractorOrganisation Name	ConstructionCompany1	ValueType: xsd:string
3	RelatedParty	Organisations	hasAdministrator Name	Wouter de Wie	ValueType: xsd:string
4	RelatedParty	Organisations	hasResponisbleContractor Name	Jonker De Vrij	ValueType: xsd:string
5	Revison Drawing	00-R-0010	hasObjectID	00-R-0010	ValueType: xsd:string
6	Revison Drawing	00-R-0010	hasDate	2018-12-15	ValueType: [yyyy-mm-dd] xsd:date

Table F.2: Individual Connected to Sewerage System R001

Manhole G7 subsystem part of R001: Note: The names, neighborhood, monetary values and dates are indicative.					
#	**Class of Individual**	**Individual**	**Relationship**	**Individual 2/ Value**	**Annotation**
1	Manhole	G7	executes	ProvideAccessToA SewerPipe	
2	Manhole	G7	executes	ProvideAccessToA SewerPipe	
3	Manhole	G7	isPartOfSystem	R001	
4	Manhole	G7	hasObjectID	G7	ValueType: xsd:string
5	Manhole	G7	hasDate	2020-03-03	The date that the object started to operate or the information object was created. ValueType: [yyyy-mm-dd] xsd:date
6	Manhole	G7	hasZcoordinate	-1.43	The Z coordinate in order asset manager know the depth of the manhole and the connected sewer pipe. By measuring the depth an indication for the soil subsidence can be derived. ValueType: [m] xsd:decimal: min=-20 max=300 [GWSW]Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
7	Manhole	G7	hasYcoordinate	444757.23	The Y coordinate in order asset manager know the position of the manhole and the connected sewer pipe. ValueType: [m] xsd:decimal place: min=289000 max=629000 [GWSW]Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
8	Manhole	G7	hasZcoordinate	100817.40	The X coordinate in order asset manager know the position of the manhole and the connected sewer pipe. ValueType: [m] xsd:decimal place: min=289000 max=629000 [GWSW]Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
9	Manhole	G7	hasManholeWidth	1250	ValueType: [mm] xsd:integer: min=300 max=4000 [GWSW] The internal width (horizontal, from the top view). If present, the width of the bottom tray.
10	Manhole	G7	hasManholeHeight	1250	ValueType: [mm] xsd:integer: min=500 max=4000 [GWSW] The internal height (vertical, from the side view). The distance from the inside bottom to the inside top of the manhole construction (including bottom box).
11	Manhole	G7	hasShape	Rectangular	ValueType: (Other, Rectangular, Round) [GWSW] The internal shape (horizontal, from the top view). If present, the shape of the bottom tray.
12	Manhole	G7	hasManholeMaterial	Concrete	ValueType: Asbesto cement, Concrete, Plastic, Clayware, Other) [EN13508-2+A1] The material of the fabric of the manhole or inspection chamber in accordance with Table C.4.
13	Manhole	G7	hasManholeType	Wastewater	ValueType: Asbesto cement, Concrete, Plastic, Clayware, Other) ValueTypes: (mixed,wastewater,rainwater,inflitration,press, drainage other).

Table F.3: Individual of Manhole

Individuals connected to Pipe R001-001:

Note: The names, neighborhood, monetary values and dates are indicative.

#	Class of Individual	Individual	Relationship	Individual 2/ Value	Annotation
1	FunctionalState	FunctionalState	isFunctionExecuted	False	Indication if the object executes the intended function. If not is an indication that the an operation & maintenance activity has to be applied. Value Type: xsd:boolean (Yes,No)
2	PhysicalState	PhysicalState	isInfluenceBy	Corrosion	
3	PhysicalState	PhysicalState	isRestoredBy	LastAdjustment	
4	PhysicalState	PhysicalState	isStateOf	R001-001	
5	PhysicalState	PhysicalState	hasDefect	True	Indication if there is a defect on the physical condition of the object. Value Type: xsd:boolean (Yes,No)
6	PhysicalState	PhysicalState	hasDefectSeverity	3	The inspector judges the severity of each individual defect by a one (no damage) to five (severe damage, replacement required) classification system, which is also described in the EN 13508-2. ValueType: xsd:inetger: min=0 ,max=5
7	Risk	Corrosion	hasInfluemceOn	PhysicalState	
8	Risk	Corrosion	hasRisk	True	The physical and functional condition can be influenced from vegetation, soil subsidence or corrosion. Values Boolean: Yes or No if there is a detected Risk.
9	Risk	Corrosion	hasCriticality	Medium	The criticaliity of risk. This will help to decide if the criticality is high, then the object has priority to be be treated by applying one of the activities of Operation & Maintenance. Value Type: xsd:string (Low,Medium,High)
10	Operation& Maintenance/ Activity/ Investigation	LastInvestigation	investigatesThe ConditionOf	R001-001	To collect, order, and process data in order to obtain information about the performance and the condition of the objects it includes.
11	Operation& Maintenance/ Activity/ Investigation	LastInvestigation	hasStatus	Executed	[GWSW} The realization status of the measure in the order: (Planned, In preparation, In progress, Executed, Cancelled).
12	Operation& Maintenance/ Activity/ Investigation	LastInvestigation	hasCost	1000.0f	Value Type: xsd:float
13	Operation& Maintenance/ Activity/ Investigation	LastInvestigation	hasMethod	Visual Inspection of sewer pipe	The method that has to be applied to the Object. Methods: (Visual Inspection of sewer pipes, Visual inspection of manhole, Pipe measurement, Other) https://data.gwsw.nl/1.5.2/Basis/index.html?menu_item=classes
14	Operation& Maintenance/ Activity/ Investigation	LastInvestigation	hasDateOfImplementation	2020-01-10	The most recent date that an operation & maintenance activity was applied to an object. Value type: [yyyymmdd] xsd:date
15	Operation& Maintenance/ Activity/ Investigation	LastInvestigation	hasAvailableBudget	120000.0f	The available budget that municipality can dispose for the appliance of management measures in its assets. ValueType: xsd:float
16	Operation& Maintenance/ Activity/ Maintenance	LastMaintenance	transforms	R001-001	
17	Operation& Maintenance/ Activity/ Maintenance	LastMaintenance	hasMethod	Cleaning sewer pipe	[GWSW} The realization status of the measure in the order: (Planned, In preparation, In progress, Executed, Cancelled). ValueType: xsd:string
18	Operation& Maintenance/ Activity/ Maintenance	LastMaintenance	hasCost	100.0f	xsd:float
19	Operation& Maintenance/ Activity/ Maintenance	LastMaintenance	hasStatus	Cancelled	[GWSW} The realization status of the measure in the order: (Planned, In preparation, In progress, Executed, Cancelled). ValueType: xsd:string
20	Operation& Maintenance/ Activity/ Maintenance	LastMaintenance	hasinterval	every 3 months	The Interval that the Activity has to be applied ValueType: xsd:string
21	Operation& Maintenance/ Activity/ Maintenance	LastMaintenance	hasDateOfImplementation	2021-11-10	The most recent date that an operation & maintenance activity was applied to an object. ValueType: [yyyymmdd] xsd:date
22	Operation& Maintenance/ Activity/ Investigation	LastMaintenance	hasAvailableBudget	120000.0f	The available budget that municipality can dispose for the appliance of management measures in its assets. ValueType: xsd:float
23	Operation& Maintenance/ Activity/ Investigation	LastAdjustment	restores	FunctionalState	
24	Operation& Maintenance/ Activity/ Investigation	LastAdjustment	restores	PhysicalState	
25	Operation& Maintenance/ Activity/ Maintenance	LastAdjustment	transforms	R001-001	
26	Operation& Maintenance/ Activity/ Maintenance	LastAdjustment	hasMethod	Repair	Methods: Repair: [NEN 3300:1996] restoration of the original functioning, whereby a limited change in state is implemented [NEN 3300:1996] restoration of the original functioning, whereby a limited change in state is implemented Improve: [NEN 3300:1996] Adjusting the original functioning. Renew: [EN ISO 11298-1:2018] work incorporating all or part of the original fabric of the pipeline, by means of which its current performance is improved. Replace: [NEN 3300:1996] restoration of the original functioning, whereby the existing object is removed and a new equivalent object is replaced . ValueType: xsd:string
27	Operation& Maintenance/ Activity/ Maintenance	LastAdjustment	hasCost	10000	xsd:float
28	Operation& Maintenance/ Activity/ Maintenance	LastAdjustment	hasStatus	Cancelled	[GWSW} The realization status of the measure in the order: (Planned, In preparation, In progress, Executed, Cancelled). ValueType: xsd:string
29	Operation& Maintenance/ Activity/ Maintenance	LastAdjustment	hasinterval	-	
30	Operation& Maintenance/ Activity/ Maintenance	LastAdjustment	hasDateOfImplementation	2020-03-03	The most recent date that an operation & maintenance activity was applied to an object. ValueType: [yyyymmdd] xsd:date
31	Operation& Maintenance/ Activity/ Investigation	LastAdjustment	hasAvailableBudget	120000.0f	The available budget that municipality can dispose for the appliance of management measures in its assets. ValueType: xsd:float

Table F.4: Individuals connected to Sewer pipe

ConnectionOfRG52 subsystem part of R001:					
#	Class of Individual	Individual	Relationship	Individual 2/ Value	Annotation
1	Connection	ConnectionOfRG52	executes	SupplyOfWasteWater	
2	Connection	ConnectionOfRG52	isPartOfSystem	R001	
3	Connection	ConnectionOfRG52	hasComponentPart	RG52	
4	Connection	ConnectionOfRG52	hasTotalNumber OfConnections	30	Value Type: xsd: integer: min=0 max =9999
5	Connection	ConnectionOfRG52	hasConnectionType	HouseConnection	Vaue Type: xsd:string (House Connection, Gully Connection)

Table F.5: Individual of Connection

Connection Pipe RG52 component part of Connection:					
#	Class of Individual	Individual	Relationship	Individual 2/ Value	Annotation
1	ConnectionPipe	RG52	executes	SupplyOfWastewater	
2	ConnectionPipe	RG52	isPartOfSubSystem	ConnectionOfRG52	
3	ConnectionPipe	RG52	hasPipeDiameter	160	ValueType : [mm] xsd:integer: min=63 max=4000
4	ConnectionPipe	RG52	hasPipeType	Combined	ValueTypes: xsd:string (Combined, Wastewater, Rainwater, Drainage, other)
5	ConnectionPipe	RG52	hasPipeMaterial	PVC	ValueType: xsd:string (Asbestos cement, Cement mortar, Concrete, Epoxy, Glass fibre reinforced plastic, Reinforced concrete, Cast iron,Steel, other)
6	ConnectionPipe	RG52	hasPipeShape	Round	ValueType: (Other, Rectangular, Round) [GWSW] The internal shape (horizontal, from the top view). If present, the shape of the bottom tray.
7	ConnectionPipe	RG52	hasZEndcoordinate	-5.25	The Z coordinate of the connection pipe at the point of connection with the sewerage system. ValueType: [m] xsd:decimal: min=-20 max=300 [GWSW]Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
8	ConnectionPipe	RG52	hasYStartCoordinate	444638.62	The Y coordinate of the connection pipe at the source of the connection (house or gully road). ValueType: [m] xsd:decimal place: min=289000 max=629000 [GWSW]Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
9	ConnectionPipe	RG52	hasYEndCoordinate	444635.00	The Y coordinate of the connection pipe at the point of connection with the sewerage system. ValueType: [m] xsd:decimal place: min=289000 max=629000 [GWSW]Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
10	ConnectionPipe	RG52	hasXStartCoordinate	100694.06	The X coordinate of the connection pipe at the source of the connection (house or gully road). ValueType: [m] xsd: decimal: min=-7000 max=300000 [GWSW] Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
11	ConnectionPipe	RG52	hasXEndCoordinate	100695.83	The X coordinate of the connection pipe at end of the connection. The point where it connects with the sewerage system. ValueType: [m] xsd: decimal: min=-7000 max=300000 [GWSW] Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).

Table F.6: Individual of Connection Pipe

G QUERYING THE ONTOLOGY

The information that the ontology intends to capture and structure aims to facilitate asset managers. Therefore, the information that should be derived has to enable strategic decisions and be within the scope of the ontology. The scope of the ontology has been defined by the competency questions.Thus, these are the questions/queries that the ontology should be able to answer. The following competency questions were answered with a query that returns the preferred data:

1. **Identification of the sewerage system.**
    - What is the ID of the sewerage system and/or its components?
    - What is the year of construction of the sewerage system?

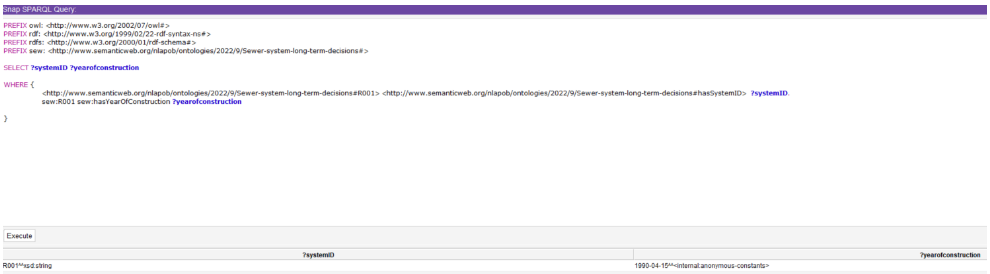

Figure G.1: Competency question 1 query

2. **Identification of the related parties of the sewerage system?**
    - What is the name of the client organisation of the sewerage system?
    - What is the name of contractor organisation of the sewerage system?
    - What is the name of the administrator of the sewerage system?
    - What is the name of the responsible person of the contractor organisation for the sewerage system?

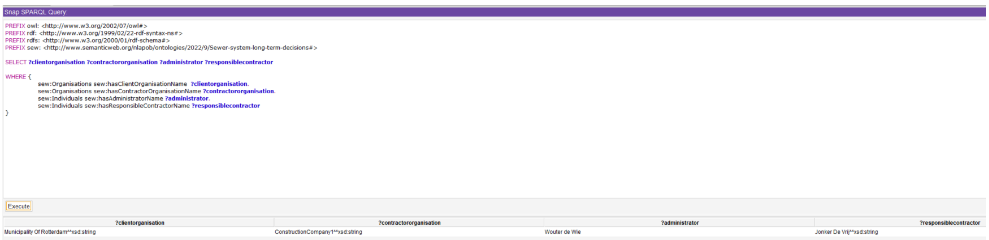

Figure G.2: Competency question 2 query

3. **Identification of the location of the sewerage system**
    - What is the municipality that the sewerage system is located?
    - What is the city of the sewerage system ?
    - What is the neighborhood of the sewerage system ?

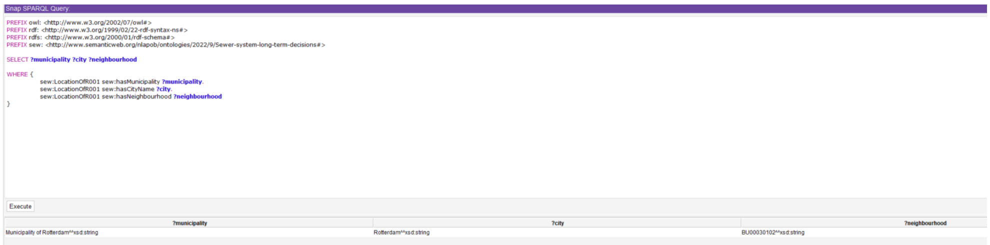

Figure G.3: Competency question 3 query

4. **Assessment of the dependencies between (1) the sewerage system and its components (2) components.**
   - How the sewerage system and its components relate to each other?
   - How the components of the sewerage system are related to each other?

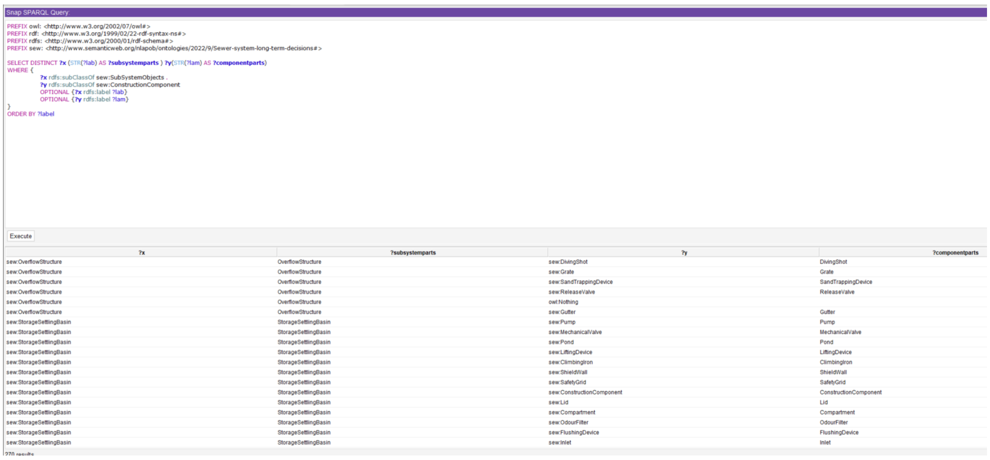

Figure G.4: Competency question 4 query

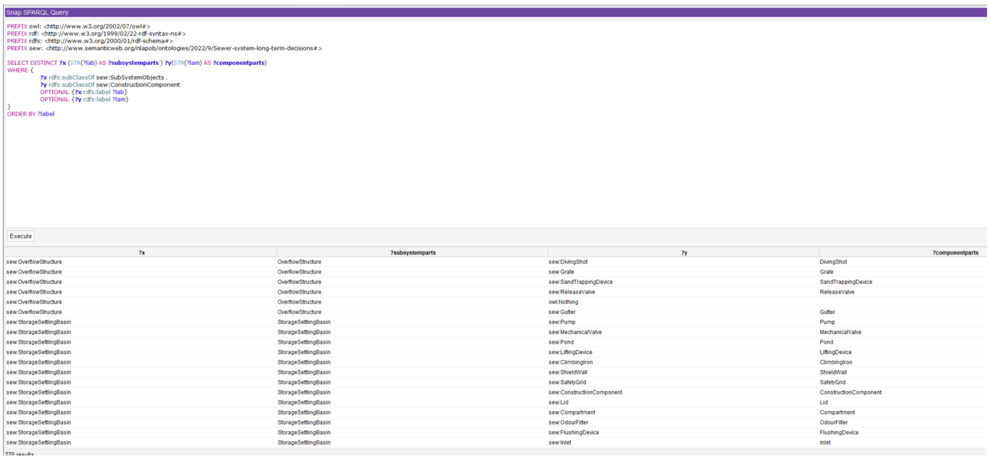

Figure G.5: Competency question 4 query 2

5. **Assessment of the functioning and usage of the sewerage system and/or its components.**
   - What is the function of the component?
   - What is the functional state of the component? Is the function performs according to the designed specification?
   - What is the physical condition/state of operation of the system and/or its critical components? Is there any defect?

- What is the severity of the defect to the physical condition?

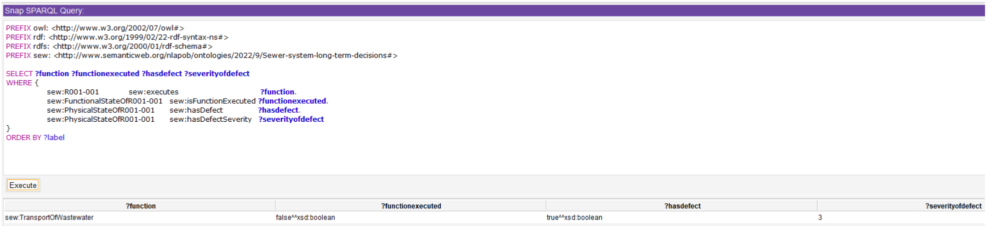

Figure G.6: Competency question 5 query

6. **Mapping the risks that might cause deterioration of the state or performance of the sewerage system and its components.**
   - Is there any risk to the state of the sewerage system due to soil subsidence?
   - Is there any risk to the state of the sewerage system due to vegetation?
   - Is there any risk to the state of the sewerage system due to corrosion?
   - Is the sewerage system or a component in high risk?

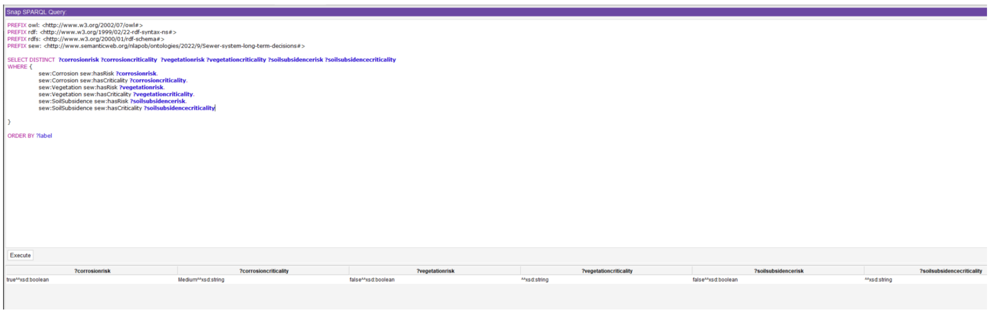

Figure G.7: Competency question 6 query

7. **Identification of the sewerage system's and/or its components' characteristics which influence its state**
   - What is the maximum capacity of the system or its components?
   - How many years the system or the component is in operation?
   - Which is the position in the (1) x-, (2) y- or (3) z-coordinate of the sewerage system and/or its critical components (manhole, sewer pipe?)
   - What is the shape of the sewerage system component?
   - What is the type of the material of the critical components (sewer pipes, manholes) of the sewerage system?
   - What are the dimensions of the critical components of the sewerage system?
   - What is the soil type of the sewerage system?

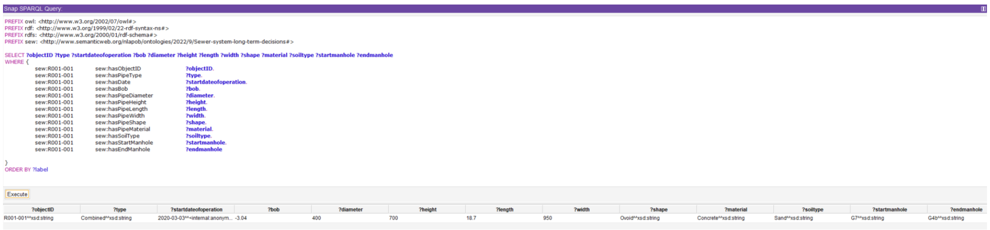

Figure G.8: Competency question 7 query 1

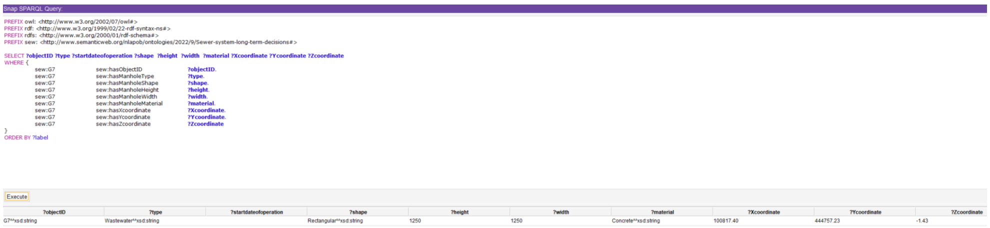

Figure G.9: Competency question 7 query 2

The sewer line capacity needs the dimensions of the sewer pipeline to be calculated. This is why asset managers need to know the dimension of the pipes. They need to know the estimated flow and see if the system operates according to designed specifications. The Continuity equation and the Manning equation for steady-state flow is used to calculate flow in a sewer pipe. Continuity Equation Q = V*A, where:

- Q = the volumetric flow rate,
- V= the mean velocity,
- A= the cross sectional area of the pipe.

8. **Planning of operation & maintenance activities.**
   - What is the available budget for the execution of operation & maintenance activities?
   - When was the last inspection performed?
   - When was the last maintenance performed?
   - What was the last maintenance or inspection method?
   - What is the status of the activity?
   - What is the cost of the activity?

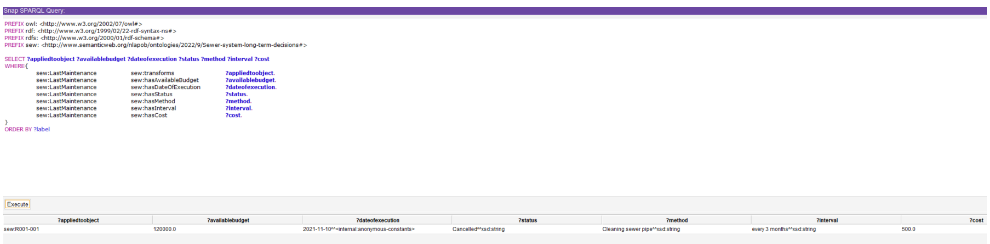

Figure G.10: Competency question 8 query 1

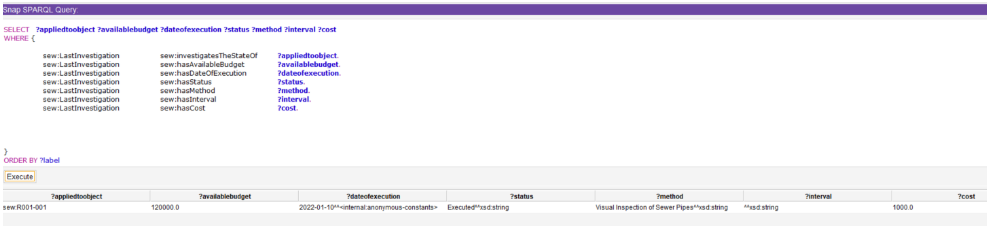

Figure G.11: Competency question 8 query 2

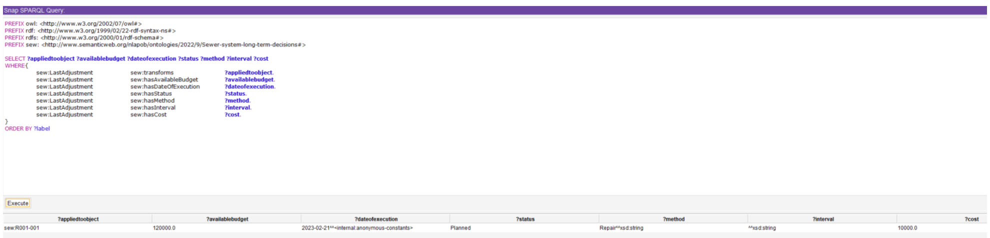

Figure G.12: Competency question 8 query 3

H FINAL VERSION OF THE ONTOLOGY

H.1 TAXONOMY

#	Top Level	2nd Level	3rd Level	4th LEvel	5th Level
1	Sewerage System				
2	Related Party	Organisation			
		Individual			
3	Location				
3	Object	InformationObject	DigitalDrawings ListOfMaterials ListOfMeasurements RevisionDrawing SewerInspection		
		PhysicalObject	SubSystemObject	Connection SewerPipe Manhole	
				Structure	StorageSettlingBasin OverflowStructure PumpingStation
			Construction Component	Compartment FlushingDevice Gutter ConnectionPipe FlowProfileDevice MeasuringInstrument Valve Pump MechanicalValve AirVent ClimbingIron ConnectingPiece DivingShot Foundation Grate Inlet Lid LiftingDevice OdourFilter OdourTrap OverflowSill PipeUnit Pond ReleaseValve SafetyGrid SandTrappingDevice SewerVakve ShieldWall	
5	Function				
6	State	PhysicalState			
		FunctionalState			
7	Risk	CorrosionRisk SoilSubsidenceRisk VegetationRisk			
8	Operation& Maintenance	Activity	Adjustment		
			Maintenance		
			Investigate		

Table H.1: Final Class Hierarchy/Taxonomy

H.2 OBJECT PROPERTIES OF THE ONTOLOGY

#	Domain	Property Name	Range	Characteristic	Explanation
1	Sewerage System	hasSubSystemPart	SubSystemObject		It is similar with hasPart relation.
2	SewerageSystem	hasLocation	Location	Functional	-
3	SewerageSystem	hasRelatedParty	RelatedParty		
4	SewerageSystem	hasPart	PhysicalObject		
5	SewerageSystem	isDescribedBy	InformationObject		
6	PhysicalObject	isPartOf	SewerageSystem	Functional	
7	SubSytemObject	isPartOfSystem	SewerageSystem		
8	Location	isLocationOf	SewerageSystem	Functional	
9	RelatedParty	isRelatedPartyOf	SewerageSystem		
10	SubSytemObject	hasComponentPart	ConstructionComponent		It is similar with hasPart relation. -
11	ConstructionComponent	isPartOfSubSytem	SubSytemObject		
12	PhysicalObject	executes	Function	Irreflexive	-
13	Functions	isExecutedBy	PhysicalObject		
14	PhysicalObject	hasState	State	Functional	
15	PhysicalObject	hasFunctionalState	FuntionalState	Functional	-
16	PhysicalObject	isTransformedBy	Operation&Maintenance		
17	State	isStateOf	PhysicalObject	Functional	
18	InformationObject	isDescriptionOf	SewerageSystem		
19	Operation&Maintenance	transforms	PhysicalObject	Functional	
20	Operation&Maintenance	restores	State		
21	State	isRestoreBy	Operation&Maintenance		
22	Risk	hasInfluenceOn	State		-
23	State	isInfluencedBy	Risk		
24	FunctionalState	isFunctionalStateOf	PhysicalObject		
25	Investigation	investigatesTheStateOf	PhysicalObject		
26	PhysicalObject	isInvestigatedBy	Investigation		

Table H.2: Object Properties and their Characteristics

H.3 DATA PROPERTIES

#	Domain	Property Name	Range	Characteristic	Annotations
1	Sewerage System	hasSystemID	xsd:string	Functional	
2	Sewerage System	hasYearOfConstruction	xsd:string	Functional	ValueType: [yyyymmdd] xsd:dateTime
3	Organisation	hasClientOrganisationName	xsd:string	Functional	
4	Organisation	hasContractorOrganisation Name	xsd:string	Functional	
5	Individual	hasAdministratorName	xsd:string	Functional	
6	Individual	hasResponsibleContractor Name	xsd:string	Functional	
7	Location	hasCityName	xsd:string	Functional	
8	Location	hasMunicipality	xsd:string	Functional	
9	Location	hasNeighbourhood	xsd:string	Functional	The name of the neighbourhood where the sewerage system is located. The name conforms with CSB format. E.g BU00030102
10	Object	hasDate	xsd:date	Functional	The date the object started to operate or the information object was created. ValueType: [yyyy-mm-dd] xsd:date
11	Object	hasObjectId	xsd:string	Functional	
12	ConnectionPipe or SewerPipe	hasBob	xsd:decimal		Altitude relative to NAP of the inner bottom of the tube of the pipe. It is the lower point of the pipe and its Z coordinate.
13	ConnectionPipe or SewerPipe	hasPipeDiameter	xsd:integer	Functional	ValueType: [mm] xsd:integer: min=63 max=4000
14	ConnectionPipe or SewerPipe	hasPipeHeight	xsd:integer	Functional	ValueType: [mm] xsd:integer: min=63 max=4000
15	ConnectionPipe or SewerPipe	hasPipeLength	xsd:decimal	Functional	ValueType: [m] xsd:decimal: min=1 max=75
16	ConnectionPipe or SewerPipe	hasPipeWidth	xsd:integer	Functional	Value Type: [mm] xsd:integer: min=63 max=4000 seeAlso: [EN13508-2+A1]The width of the section in millimeters. (Not required where both dimensions are the same-eg.circle)
17	ConnectionPipe or SewerPipe	hasPipeShape	xsd:string	Functional	ValueType: xsd:string [Other,Ovoid,Ovoid inverted, Parabolic, Horse shoe section, semi-eliptic section, semi-circular section, U-shaped section, rectangular section)
18	ConnectionPipe or SewerPipe	hasPipeType	xsd:string	Functional	ValueType: xsd:string (Combined, Wastewater, Rainwater, Drainage, other)
19	ConnectionPipe or SewerPipe	hasPipeMaterial	xsd:string	Functional	ValueType: xsd:string (Asbestos cement, Cement mortar, Concrete, Epoxy, Glass fibre reinforced plastic, Reinforced concrete, Cast iron,Steel)
20	ConnectionPipe or SewerPipe	hasSoilType	xsd:string	Functional	ValueType: (Gravel,Clay,Clay+sand,Heavy clay, Sand, Sand+Gravel, Other)
21	SewerPipe	hasStartManhole	xsd:string	Functional	Municipalities assign to every manhole a unique number as identifier. e.g. G01 G= manhole for combined sewer V= manhole for wastewater sewer H= manhole for rainwater sewer S=manhole for connection sewer I= manhole for infiltration sewer P = manhole for press sewer D= manhole for drain sewer
22	SewerPipe	hasEndManhole	xsd:string	Functional	-//-
23	Manhole	hasManholeHeight	xsd:integer	Functional	ValuueType: [mm] xsd:integer min=500 max=4000 [GWSW] The internal height (vertical, from the side view). The distance from the inside bottom to the inside top of the pit construction (including bottom box)
24	Manhole	hasManholeMaterial	xsd:string	Functional	ValueType: xsd:string Asbesto cement, Concrete, Plastic, Clayware, Other)
25	Manhole	hasManholeWidth	xsd:integer	Functional	ValueType: [mm] xsd:integer: min=300 max=4000
26	Manhole	hasShape	xsd:string	Functional	ValueType: xsd:string (Other, Rectangular, Round)
27	Manhole	hasXcoordinate	xsd:decimal	Functional	ValueType: [m] xsd: decimal: min=-7000 max=300000 [GWSW] Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
28	Manhole	hasYcoordinate	xsd:decimal	Functional	ValueType: [m] xsd:decimal: min=289000 max=629000 [GWSW] Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
29	Manhole	hasZcoordinate	xsd:decimal	Functional	ValueType: [m] xsd:decimal: min=-20 max=300 [GWSW] Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
30	PhysicalState	hasDefect	xsd:boolean		Value Type xsd:boolean (Yes,No)
31	PhysicalState	hasDefectSeverity	xsd:integer		ValueType: xsd:inetger: min=0 ,max=5
32	FunctionalState	isFunctionExecuted	xsd:boolean		Value Type xsd:boolean (Yes,No)
33	Operation& Maintenance	hasAvailableBudget	xsd:float	Functional	
34	Activity	hasCost	xsd:float		
35	Activity	hasInterval	xsd:string		
36	Activity	hasLastDateOfExecution	xsd:date		value type: [yyyymmdd] xsd:date
37	Activity	hasMethod	xsd:string		
38	Activity	hasStatus	hasStatus		[GWSW} The realization status of the measure in the order: (Planned, In preparation, In progress, Executed, Cancelled)
39	Risk	hasRisk	xsd:boolean		Values Boolean: Yes or No if there is a detected Risk
40	Risk	hasCriticality	xsd:string	Functional	Value Type: xsd:string (Low,Medium,High)

Table H.3: Data Properties and Restrictions

#	Domain	Property Name	Range	Characteristic	Annotations
41	Connection	hasConnectionPipe	xsd:string		
42	Connection	hasConnectionType	xsd:string	Functional	Vaue Type: xsd:string (House Connection, Gully Connection)
43	Connection	hasTotalNumberOf Connections	xsd:integer		The total number of connected housing units or gullies in the sewerage system. Independs on the type of connection.
44	ConnectionPipe	hasXStartCoordinate	xsd:decimal	Functional	The X coordinate of the connection pipe at the source of the connection (house or gully road). ValueType: [m] xsd: decimal: min=-7000 max=300000 [GWSW] Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
45	ConnectionPipe	hasXEndCoordinate	xsd:decimal	Functional	The X coordinate of the connection pipe at end of the connection. The point where it connects with the sewerage system. ValueType: [m] xsd: decimal: min=-7000 max=300000 [GWSW] Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
46	ConnectionPipe	hasYStartCoordinate	xsd:decimal	Functional	The Y coordinate of the connection pipe at the source of the connection (house or gully road). ValueType: [m] xsd:decimal place: min=289000 max=629000 [GWSW] Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
47	ConnectionPipe	hasYEndCoordinate	xsd:decimal	Functional	The Y coordinate of the connection pipe at the source of the connection (house or gully road). ValueType: [m] xsd:decimal place: min=289000 max=629000 [GWSW] Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
48	ConnectionPipe	hasZEndCoordinate	xsd:decimal	Functional	The Z coordinate of the connection pipe at the point of connection with the sewerage system. ValueType: [m] xsd:decimal: min=-20 max=300 Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).
49	Manhole	hasGroundLevel	xsd:decimal		The Z coordinate of the ground/road level. Conform to coordinate system EPSG:7415 (x/y according to EPSG:28992 (=RD), z conform EPSG:5709 (=NAP).

Table H.4: Data Properties and their Restrictions of Added Terms After Validation

COLOPHON

This document was typeset using LaTeX. The document layout was generated using the arsclassica package by Lorenzo Pantieri, which is an adaption of the original classicthesis package from André Miede.

TU Delft

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