An ontology design enhancing the information transfer between project delivery and asset management

A design science research project within the municipality of Rotterdam

Master thesis

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by

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Executive summary

As digitization moves on, more data is produced and the value of this data increases. However, data is still transferred manually between different digital systems. Reason to manually transfer information is lacking interoperability between these systems. Huge costs are related to this lacking interoperability as they cause high data losses. Issues with interoperability and information losses are present as well in the field of asset lifecycle information management. Especially in the transition of project delivery to asset management.

This research investigated the stated problem within the Engineering office of the municipality of Rotterdam. The research followed a design science research approach consisting of five steps. First the scientific knowledge base was defined, second the local practice is researched. Third design requirements were listed based on the pre-taken steps. Fourth an ontology was designed based on these requirements. Fifth, based on the investigated scientific literature into the topic the following objective was constructed:

"Design an ontology linking assets and their related information to BIM data-schemes and domain ontologies in a general way."

The reasoning for this objective was based on the following conclusions resulting from analysing the scientific knowledge base. Two main perspectives exist regarding the transfer of information, a technological and an information perspective. It is found that the systems of project delivery and asset management have issues in mapping objects of Building Information models based on BIM data-schemes such as IFC and NLCS. Additionally, regarding to the information perspective it is concluded that an important aspect in the information transfer process is the alignment of information available and information need. Literature advised to design an ontology to overcome these issues. As the stated issues were handled several times on a case-by-case basis, this research aimed to do it for multiple cases.

The second step included research on the local practice. Therefore, two cases were researched more in-depth. One unique case: the renovation of the escalators at the Maastunnel, and one standard cases: the sewer replacement of the Saftlevenstraat. Within these cases the information transfer process, the information availability, and the information need were analysed. The main conclusions are that information is mainly available about assets or objects and that this information is mainly stored in documents not understandable by computers. In addition, the information transfer process for the sewer replacement was already established quite well. Regarding the escalator renovation case, a limited idea of how to transfer the available information in a valuable way was present.

Based on the analyses of the scientific knowledge base and the in-depth research cases a list of design requirements was established. To optimize the value of the ontology additional requirements from the FAIR principles were derived. Based on the derived requirements an ontology was designed with the main features as showed below. A main limitation of the research is that the design is limitedly tested or evaluated.

- Objects are central in the design, meaning, all information should be linked, eventually indirectly, to an object.
- Information type is included as a specific entity to provide structure in the information.
- Information related to an information type can be expressed in attributes, documents, and activities.
- The information inside a document can be made explicit in attributes and activities.

- The modelling references can refer to a specific object in a specific BIM-model or to meta-object of a specific BIM data-scheme.
- The domain ontologies refer always to a specific instance within such an ontology.
- Findability and accessibility are incorporated by the means of a separate regulation entity to provide flexibility on the abstraction level of regulation.

The research has some clear contribution to as well the scientific knowledge base as the local practice. Scientific contributions of this research are the designed ontology and the analysing made of the FAIR principles in relation to their application on an ontology for governmental data instead of scientific data. It should be mentioned that no extensive literature research is performed into an earlier application of this kind. Regarding the local practice, the main recommendation, next to the designed ontology, is to state explicit what information is in what documentation. This makes it easier to align the information available and needed and thereby enhances an early consideration on the information transfer process.

To conclude some recommendations for future research are presented. Future research could validate the findings of this research by investigating the information transfer withing the engineering of Rotterdam or strengthen the generalizability by doing the investigation within other major Dutch municipalities or other organizations dealing with the same problem. In addition, the ontology design could be tested and validated. Finally, it is recommended to do research in the application of software analysing documentation and able to extract explicit attributes and activities within these documents. The current developments regarding artificial intelligence and language models may offer opportunities to derive explicit knowledge from documents and transfer it in an explicit way solving a part of the problem at hand.

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Introduction

As digitalization moves on, more data is produced and the combined value of this data increases (Loebbecke & Picot., 2015). However, manual transfer of documentation is still common (Kassem et al., 2014). According to Kassem et al (2014) documentation is transferred manually since the source and target system are not interoperable. This lacking interoperability incurs significant costs (Keady., 2013 in Kassem et al., 2014), associated to activities that recreate lost information and by inefficiencies resulting from the loss of information (Kassem, 2014). Minimizing information loss not only reduces costs but can also extend the lifetime of assets and increase their reuse and recycling rates (ISO, 2018).

While this research project focus on information interoperability by local governments/ municipalities in the context of transferring asset information, the phenomenon is studied in-depth via an embedded case study within the municipality of Rotterdam. As illustrated by figure 1, a decline in the value of information between the completion of project development and the commencement of asset management is experienced within the municipality of Rotterdam. Interoperability issues are present as digital information is transferred manually between the departments related to this transfer (personal meeting, file manager 23-03-06). An elaboration on the research context, and these departments is given in section 1.4.

This chapter introduces the research project. Section 1.1 elaborates on the problem at hand, followed by the scientific relevance (section 1.2) and the research objective (section 1.3). The context of the research is presented in section 1.4, while section 1.5 discusses the scope. The COSEM and societal relevance are addressed in sections 1.6 and 1.7, respectively. Finally, section 1.8 outlines the structure of the thesis.

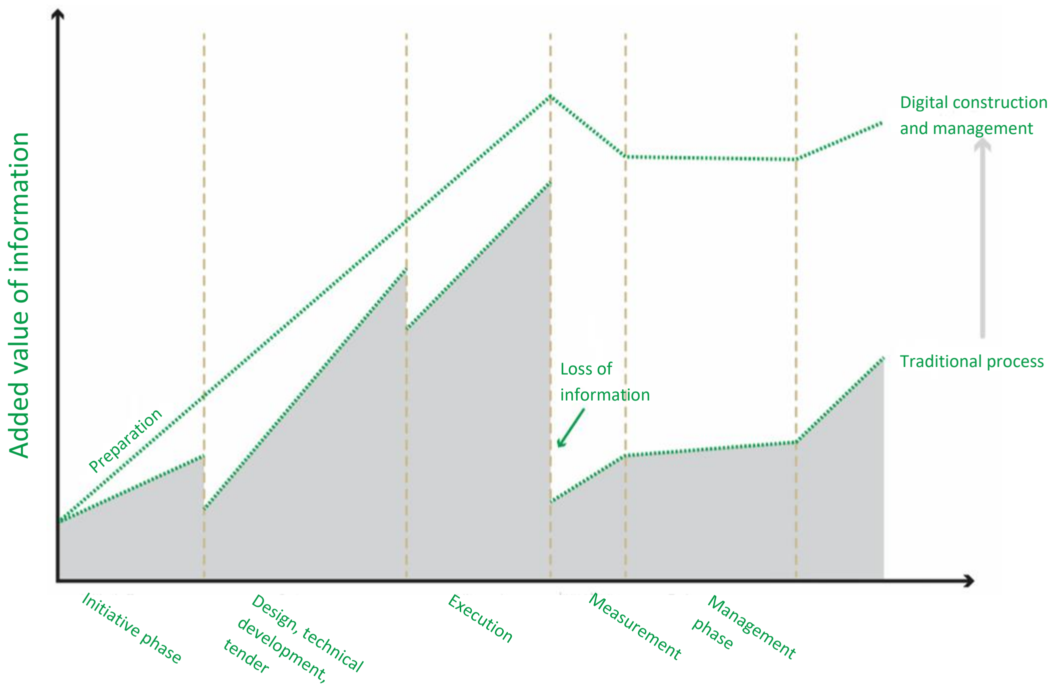

Figure 1: information value during an assets life-cycle (R. Jonker, 2022)

1.1 Problem statement

Figure 1 illustrates a significant decline in the added value of information between the conclusion of project development and the initiation of asset management. As the process of digitalization progresses, a larger volume of data is generated, resulting in an increased combined value of this data (Loebbecke & Picot, 2015). Decision-making processes are increasingly reliant on data, emphasizing the importance of having accurate and appropriate information. However, the abundance of data can make it challenging to identify the right and correct information, especially when a multitude of documents are transferred without a structured framework and without providing insight into the contained information (Witte, 2017). Conversely, providing less data than available represents a missed opportunity and results in a loss of data value. Hence, it is not only important to consider which information should be transferred but also how it should be transferred. The way information is presented, such as orally during a meeting, in printed form, as a PDF or Word document, or in a structured file format like XML, has implications for the value of the conveyed information. The chosen format imposes restrictions on the usability and actions that can be performed on the information provided. To illustrate the problem, let's consider an example:

During the design and construction process of a new sewer, Building Information Modelling (BIM) is used to create digital 2D and / or 3D models. These models contain pertinent asset information such as dimensions and materials used. The modelling software structures asset information according to specific BIM data-schemes. BIM data-schemes, such as IFC (Industry foundation classes) and NLCS (Dutch CAD Standard), define how data within BIM-models is stored. However, the asset management software does not support these schemes. The information stored in the BIM-models cannot be mapped onto the asset management data automatically. Therefore, it is transferred via PDF files to City asset management and entered manually into the asset management system. In other words, the lack of interoperability between BIM-models and the asset management software requires the manual transfer of asset information.

By entering, for example, the material and year of installation of a new sewer into the asset management system, the digital analysis of the sewer system becomes effortless. Insight into the age or material of a sewer in a specific area can be obtained with just a few mouse clicks. Without entering the information into the asset management system, analysing the same overview would require sifting through numerous PDF files, ranging from a few to thousands, depending on the size of the area. Transferring the information from the 2D and 3D models in a format that is readable by the asset management system would eliminate the need for manual input. Consequently, more information can be transferred, creating opportunities to enhance asset lifecycle management, thereby increasing asset lifetimes, material reuse and recycling rates, and reducing costs.

1.2 Scientific relevance and knowledge gap

In chapter 3, a comprehensive discussion is provided as the foundation for this research. A concise summary of the key points is outlined below. The transfer of information from project development to Asset management is hindered by lacking interoperability, which serves as the main reason for information loss. To address this issue, a literature study was conducted to investigate the transfer of asset information and interoperability. The study identified two primary reasons for lacking interoperability:

1. Misalignment between the availability of information and the information needs of Asset management (Bosch et al., 2015; Cavka et al., 2017; Farghaly et al., 2019; Toyin & Mewomo, 2022; Tsay et al., 2022).
2. Inadequate mapping of objects, information, or data from Building Information Modelling (BIM) software to asset management systems (Dinis et al., 2022, p. 887; Jiang et al., 2019, pp. 21-22; Rogage & Greenwood, 2020; Toyin & Mewomo, 2022).

To overcome these issues, the suggestion is made to develop an ontology (Jiang et al., 2019). Previous studies by Farghaly et al. (2019), Le et al. (2018), and Rogage & Greenwood (2020) have utilized ontologies on a case-by-case basis to address similar challenges. However, a comprehensive ontology that links BIM data-schemes with asset management systems in a general manner, specifically focusing on the transfer of information, is not found in the existing literature.

Several domain-specific ontologies, such as CB-NL, IMBOR, and GWSW, exist for the Dutch context, describing assets and their related information. These ontologies aim to provide shared descriptions and definitions of assets to avoid miscommunications (digiGO BIM Loket - CB-NL, n.d.). However, their utility is limited due to their varying scopes and functions. To cover the information available for the Rotterdam sewer system, for example, a combination of these ontologies is required (Format Areaalgegevens Objectgroep Riolering Gemeente Rotterdam, internal documentation, 06-07-2022). Additionally, no ontology that links these domain-specific ontologies has been identified. Therefore, it is aimed to contribute to the scientific knowledge base by creating an ontology linking assets and their related information to BIM data-schemes and domain ontologies in a general way. Meaning, assets and their related information, transferred between two systems, should be linkable to multiple BIM data-schemes and domain ontologies.

1.3 Research objective

The objective of this research is to design an ontology linking assets and their related information to BIM data-schemes and domain ontologies in a general way. (Computational) Ontology is defined by Guarino et al. (2009., p.2) as "means to formally model the structure of a system, i.e., the relevant entities and relations that emerge from its observation, and which are useful to our purposes." To achieve this objective, it is essential to gain a thorough understanding of the information availability and information needs within City development and City asset management. The available and needed information should be known to identify the relevant entities and relations. Creating an ontology integrating the information availability of City development and information need of City asset management and link this information to BIM data-schemes and domain ontologies could result in a better mapping of objects, information, and data. This results in increased interoperability between BIM-models and the asset management system and a decrease in the loss of information value. In addition, an improved mapping of objects, information and data allows for a better alignment of information.

1.4 Context

This research, including the embedded case study, is conducted within the Engineering office of the municipality of Rotterdam in response to their expressed challenges regarding information loss during the information transfer process. The engineering office operates under the department of City development (Stadsontwikkeling), which is responsible for overseeing all development activities within the city. One notable ongoing project managed by City development is the annual replacement of 40 kilometers of sewer infrastructure.

In contrast, the department of City asset management (Stadsbeheer) focuses on the management and maintenance of assets throughout the municipality. It is important to highlight that although both departments are part of the same municipality, they function as separate organizations. Additionally, an external asset management company is involved in the organizational framework. The asset management of one of the researched cases is tendered to this external partner. It should be noted that City development and City asset management are public entities, while the external asset management company is a private entity. Consequently, differences in requirements regarding the extent and quality of information to be transferred are expected to exist between the public – public transfer and the public – private transfer.

1.5 Scope

Due to the vast number of assets in the public space and the limited timeframe of 25 weeks for this research, two specific cases are selected as units of analyses within the embedded case study. This limits the number of assets of interest. The first unit of analysis is the renovation project of the monumental escalators at the Maastunnel. This is a very specific and unique project. The second unit of analysis, a more standard project, is the sewer replacement project at the Saftlevenstraaat. An elaboration on the case selection is given in chapter 2 as part of the research approach, however, interoperability issues and information losses are observed in both projects. The cases are discussed in detail in chapter 4 and 5.

As described in figure 2 asset lifecycle information management have multiple information flows. This research focuses on the information flow from City development to City asset management or the external asset management company. Nevertheless, the information availability at the end of a development project and the information needs within asset management are relevant to determine the specific information to be transferred. The research did not impose a predefined scope regarding which information should or should not be transferred; this was discovered during the research. The transfer of information from Asset management to City development is not explored in this research. Nonetheless, information transferred to City development and therefore part of the in-depth researched projects is considered. This information is, after all, available within the internal information flow of those projects.

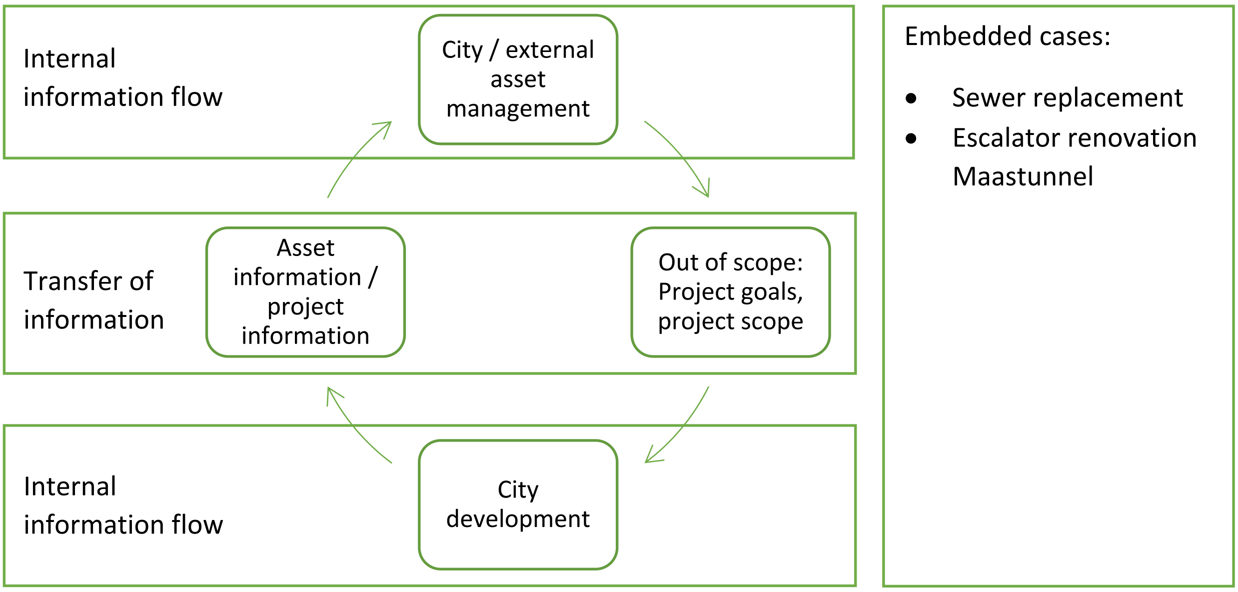

Figure 2: Scope description

1.6 Link to COSEM-programme

The COSEM-programme is about exploring innovations in complex socio-technical environments (TU Delft, n.d.). Making a design to improve the transfer of information between asset engineering & construction parties and asset management entities using information technology while taking the complex socio-technical environment into account links to this programme quite well. Courses relevant for this research are Cosem Research Challenges (SEN131A), Complex system engineering (SEN112), and the Design project (SEN116). In the Cosem Research Challenges course the execution of a literature review was taught. The course Complex system engineering provided diverse methods, such as a systems decomposition, to break-down a complex system in smaller pieces. The design project made explicit that a system is a combination of rules, processes and (technical) objects, and that they influence each other. Therefore, not only the information availability and need regarding the transfer of information are analysed, but the followed process as well.

1.7 Societal relevance

The research is conducted within the engineering office of the municipality of Rotterdam, which enhances the societal relevance of the study. By addressing an issue identified by a public body, the research aims to provide valuable insights. The analysis of the current information transfer process is carried out through a comprehensive case study, enabling the formulation of concrete recommendations concerning both the procedural and technological aspects. These recommendations can be implemented in the short term or be seen as long-term objectives. While the engineering office and the municipality of Rotterdam directly benefit from these recommendations, other stakeholders can also apply the findings. The need for efficient information transfer extends beyond the boundaries of the municipality. By implementing the suggested recommendations and utilizing the developed ontology, the level of information loss can be significantly reduced. This, in turn, creates opportunities for improved asset lifecycle management. Enhancing asset lifecycle management can result in prolonged asset lifetimes, cost savings in asset management, and increased opportunities for asset reuse and recycling (ISO, 2018).

1.8 Thesis outline

In conclusion of this chapter, an overview of the thesis structure is presented. Chapter2 proceeds with outlining the research approach, including the identification of sub-questions necessary to attain the research objective, and an explanation of the methods employed to address these sub-questions. In chapter 3 the scientific knowledge base is researched and discussed. Subsequently, an in-depth analysis of the two cases is provided. Chapter 4 presents the analysis of the escalator renovation project, while chapter 5 addresses the sewer replacement project of the Saftlevenstraat. The design requirements for the developed ontology are discussed in chapter 6. Chapter 7 presents the designed ontology including a reflection on the design in relation to the design requirements. The main findings, scientific and local contribution, and limitations of the research are discussed in chapter 8. Finally, the thesis concludes with recommendations for further research.

2. Research approach

This chapter presents the research approach used to attain the main research objective. Following the research approach, sub questions are introduced and methods to answer these sub-questions are discussed.

2.1 Design science research

The objective of this research is to design an ontology linking assets and their related information to BIM data-schemes and domain specific ontologies in order to enhance interoperability between project development and asset management. Since a design is made within a scientific research project and within the local practice of the municipality of Rotterdam an approach is needed that allows for the combination of empirical local practice data and scientific data. The design science research (DSR) approach as presented by Johannesson & Perjons (2021, p. 9) is specifically developed for this. Therefore, this approach is followed during this research project. According to Johannesson & Perjons (2021, p. 9), the main attributes of design science research are 1) the usage of strict research methods to create new knowledge of general interest; 2) A relation of this new knowledge to an already existing knowledge base in order to ensure that proposed results are well founded and original; and 3) communication of results to both practitioners and researchers. Figure 3 presents the context and relations of a design science research project.

Having a closer look at figure 3, the box of the design science project represents this research: investigate the process of information transfer and information loss in the transfer of information between project development and asset management. It also represents the design of an ontology to link standards to asset and asset information to enhance interoperability between project development and asset management. The design science project is embedded in a research community. The community embedding this project is interested in Building Information Modelling (BIM), Asset lifecycle (information) management and interoperability. Inputs for the design science project are the scientific body of knowledge, feeding the research community, and findings within the local practice. The scientific body of knowledge provides a scientific basis and serves as the foundation for this research. Insights from the local practice contribute, in the form of empirical data, as building blocks for the design. As a result of the design science project, contributions to the local practice and the scientific knowledge base are realised.

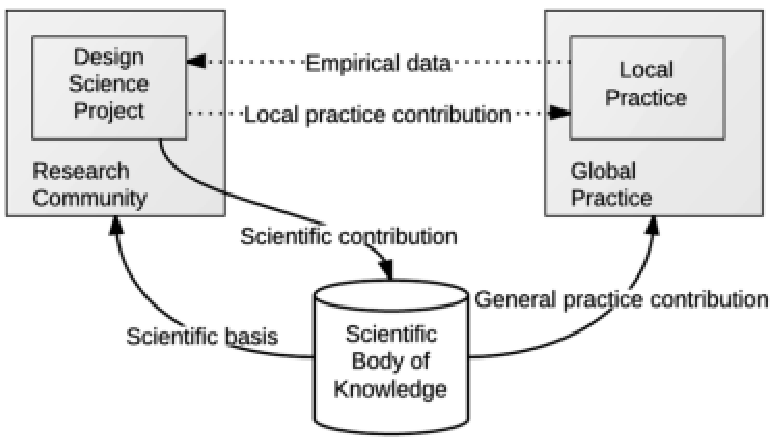

Figure 3: Context of design scieence research projects (Johannesson & Perjons (2021, p. 10)

2.2 Limitations of design science research

As the main research approach is described, it is important to acknowledge the limitations of the selected approach. By discussing the limitations of the research approach, potential challenges regarding the research execution are addressed. Upfront the research, control measures are taken to prevent major impact of the limitations on the research. During the research, the control measures are evaluated and updated. Afterwards, reflection on the research regarding the limitations helps to evaluate the research and can provide insights for future research. First, the limitations of design science research and a case-study are presented. This is followed by an overview of the control measures applied.

The limitations of Design Science Research are discussed by Livary (2015). Related to figure 3, Livary (2015) identified two design research strategies depending on the research context. The first one is designing a meta-artefact focused on the global practice. The second strategy deals with designing a specific artefact that can be applied in a specific local practice. Since the design is made within the local practice of the municipality of Rotterdam and based on two real-word projects, it can be argued that the second strategy should be followed. Strategy two as identified by Livary (2015) has the following main difficulties, pitfalls, and uncertainties:

- The general problem (the DSR problem) is to be figured out during the DSR project
- There is uncertainty about the specific solution to be designed
- There is uncertainty about the possible DSR contribution to the scientific body of knowledge
- The research is easily (too much) focused on the client's actual problem
- The client may be reluctant to use the latest available knowledge

To address the limitations presented above several control measures were taken. Measures taken upfront are the writing of a research proposal and creation of a research planning. The research proposal demands upfront thinking about the research approach, the research objective and research methods used, while the planning sketches a timeframe for the different research activities. The research proposal and planning are discussed and reviewed prior to the research. Regular progress reviews and updates to the planning were conducted throughout the research process. Close communication was maintained with the supervisor from the municipality of Rotterdam, with nearly daily contact and weekly meetings to discuss progress in-depth. These meetings were instrumental in ensuring adherence to the research plan and preventing an excessive focus on the client's immediate problem. Additional meetings were scheduled with the daily supervisor and a field expert to find guidance on identifying the actual DSR problem, determining the specific solution to be designed, and assessing the contribution to the scientific body of knowledge. Feedback from the graduation committee was given during a kick-off, mid-term, green-light meeting. This feedback focussed on satisfying the scientific standards and being rigorous enough in describing the performed research activities.

2.3 Research questions and research methods

Based on the framework provided by Johannesson & Perjons (figure 3) four sub-questions and one sub-activity have been derived. Answering the sub-questions and performing the sub-activity results in attaining the research objective. Each sub-question and the sub-activity is related to a part of the framework.

2.3.1 Sub-question 1: Scientific basis and background

To start the research, the scientific basis of the research is defined. Doing so, places the research in the research community and ensures that the research build upon existing knowledge, instead of reinventing the wheel. The current state of literature is examined by performing a literature review. Based on the literature review, issues in the transfer of information in the lifecycle of assets are identified. Furthermore, a direction for the design research is extracted. The literature review is presented and discussed in chapter 3. Section 2.4.1 addresses the literature selection process. The literature review provides an answer to sub-question one:

RQ1: What is the current state of the literature concerning information transfer and loss of information between asset lifecycle phases?

2.3.2 Sub-question 2: Findings from local practice

The second phase of the research involves analysing the local practice, which acts as the second source of input for the design science project. To gather comprehensive empirical data, two units of analysis are investigated within the embedded case study conducted at the municipality of Rotterdam. For each case under study, the available data during the project delivery phase and the data required for asset management are identified. Additionally, the processes of information transfer are outlined and analysed. Various research methods, such as interviews and desk research, are employed within the embedded case study and the selected cases. A detailed description of the embedded case study method and other employed methods can be found in Section 2.4. The analysis of the local practice provides an answer to sub-question two:

RQ2: What is, within the municipality of Rotterdam, the availability of information at the end of project development and the information need at the start of asset management

2.3.3 Sub-question 3: Define the design requirements

To ensure that the designed ontology is useful and is of added value to the scientific knowledge base and local practice, design requirements are defined and discussed. The design requirements are a specification of findings from the scientific basis and local practice. To enhance the value of the ontology, additional requirements are derived from the FAIR principles (Wilkinson et al., 2016). The FAIR principles are findable, accessible, interoperable, and reusable. They originate from the idea that the value of research output should be maximized (Jacobsen et al., 2020). Although the FAIR principles focus on scientific data, compliance to the FAIR principles may optimize the value of governmental data also since transparency and openness is becoming more important (Ministry of General Affairs, n.d.; VNG Realisatie, 2022). Therefore, incorporating these principles in the ontology design enhances the added value of the design. Limitations imposed by using governmental data, instead of scientific data, in relation to the FAIR principles, are also discussed. Stating explicit requirements for the design provides insight into the exact required functioning of the design. Having this insight before the design process leads to a more efficient and effective design process. Testing the created design against the requirements helps in evaluating the ontology. Defining the design requirements is related to the design science project box of the framework of Johannesson & Perjons and answers sub question three:

RQ3: What are the requirements for an ontology as stated in the research objective?

2.3.4 Sub-question 4: Design and evaluate the ontology

After listing the design requirements, the ontology is designed. This activity is like the requirements defining phase part of the design science project box. The design should meet the design requirements. Although, the design requirements can provide a starting point for the design, it is not possible to come up with a perfect design at once. Therefore, an iterative process (figure 4) of designing, testing, and evaluating is followed. During each cycle of this process small improvements in the design are made (Hevner et al., 2004; Peffers et al., 2007). After several cycles, an optimum is reached. No further improvements are found unless the design is disimproved in another part. The design is evaluated by testing the design against the design requirements of sub-question four. No extensive testing and evaluation sessions are performed due to time limitations. Chapter 6 provides an answer to research question four:

RQ4: What is a feasible design meeting the design requirements?

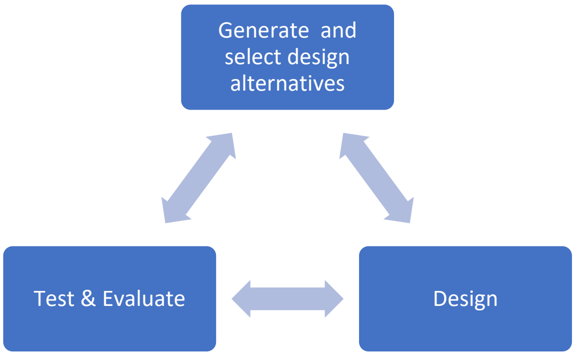

Figure 4: A minimalized design cycle

2.3.5 Sub-activity 1: Scientific and local practice contribution

The final part of the research is presenting a conclusion and discuss the research findings and implications. Main findings of the research are presented and their contribution to as well the scientific knowledge base as the local practice are discussed. Furthermore, the generalizability of the case study results is considered. Limitations of the research with respect to the scientific and local contribution are discussed as well. To conclude, recommendations for further research are presented.

2.4 Methodology per research question

The research questions presented in section 2.3 relate to different parts of the framework as shown in figure 3. Different methods are used to answer the sub-questions related to the identified research parts. In this section an overview of the methods used to answer each sub-question is given. This overview is presented in table 1. Each method is discussed below.

Research part	**Used method**
part 1: Scientific basis and background	Literature review and expert consulting
part 2: Local practice	Embedded case study, -> Interviews, desk research, fly on wall research
part 3: Requirement elicitation	Desk research and expert consulting
part 4: Design	Schematic drawing, desk research

Table 1: overview of research methods

2.4.1 Literature review

As described, a literature review is performed to define the scientific basis for the design science project. According to Snyder (2019., p. 333) "building research on and relating it to existing scientific knowledge is the building block for all scientific research activities, regardless of discipline and should therefore be priority for all academics.". Performing a literature review and relate the results to this research project gives notion to this statement. Since it is not possible to review all papers that could be relevant in the time span of this research a semi-systematic literature review strategy is selected (Snyder., 2019). The aim of this semi-systematic literature review is to provide an overview of the existing literature regarding asset lifecycle information management and interoperability. These concepts cover the topic of information transfer between project teams designing and constructing assets and Asset management maintaining and operating assets. A second goal is the identification of common issues within this field of research. A semi-systematic literature review can be used to attain both objectives (Snyder., 2019; Wee & Banister., 2016). As prescribed by Snyder (2019) and Wee & Banister (2016) the procedure followed in conducting the literature review is described explicitly. The literature review process to answer research question one, has followed the following two steps.

First, a common language is created by discussing the concepts of asset, asset lifecycle information management and interoperability. Creating this common language does scope the research project and thereby the research community of interest as well. Scoping the research helps in selecting the right and relevant literature for the research.

Second, the current literature is investigated in a structured way using Scopus. The results of this structured review are evaluated with a field expert. Based on this evaluation, additional research focussing on Building Information Modelling (BIM) is added. For the initial literature review, the core concepts are constructed into the search string:

"(TITLE-ABS-KEY (asset AND lifecycle AND information AND management)) AND (interoperab*)"

This resulted in a list of 82 documents. Since the research is conducted in a limited period it is not possible to review such an extended cross-section of the literature. Because the research is focussed on fixed and tangible assets the search results are additionally limited to the subject area "Engineering". To further limit the number of results, a filter on the document type "Article" is applied. After setting the filters, 24 documents are found. Based on abstracts eight papers focussing on information flows across lifecycle phases are finally selected for the initial literature review. If an abstract did not lead to a clear inclusion or exclusion the whole paper was scanned. In chapter 3 an overview of the included literature with accompanying analysis is presented.

Since only a minor cross-section of the literature was reviewed, a field expert is asked to review and verify the results and conclusions drawn. Based on the field expert's review additional literature related to Building Information Modelling is searched and found. The additional literature is found by searching on "BIM definitions" on Google Scholar and with Scopus by searching with the keyword "BIM" combined with terms like "asset management", "Interop*" and, "review" in different combinations. To review the literature efficiently there is searched for existing literature reviews explicitly. In that way a broad overview of the existing literature was covered. Resulting in a solid basis for the design science project.

2.4.2 Embedded case study

As described, in-depth knowledge of the local practice is required for this research project. More specific, in-depth knowledge about the information transfer process from the end of project development to the start of asset management is needed. According to Yin (2018., p. 45) a case study is “an empirical method investigating a contemporary phenomenon in depth and within its real-world context.” This definition does match with the input required from the local practice; the studied phenomenon is the transfer of information from project teams to Asset management within the context the municipality of Rotterdam. According to its definition, a case study can provide the knowledge required for the design science project. Therefore, it is considered a suitable method for answering sub-question two.

The case study is structured as a single-case embedded case study, a type two case study according to Yin (2018). It’s a single case design since the studied phenomenon of information transfer is only investigated within the municipality of Rotterdam. No other, independent cases are researched. Furthermore, it is embedded since two units of analysis are investigated to gain in-depth knowledge of the phenomenon research within the main case. These units of analysis are a sewer replacement project and an escalator renovation project. A schematic representation is provided in figure 5.

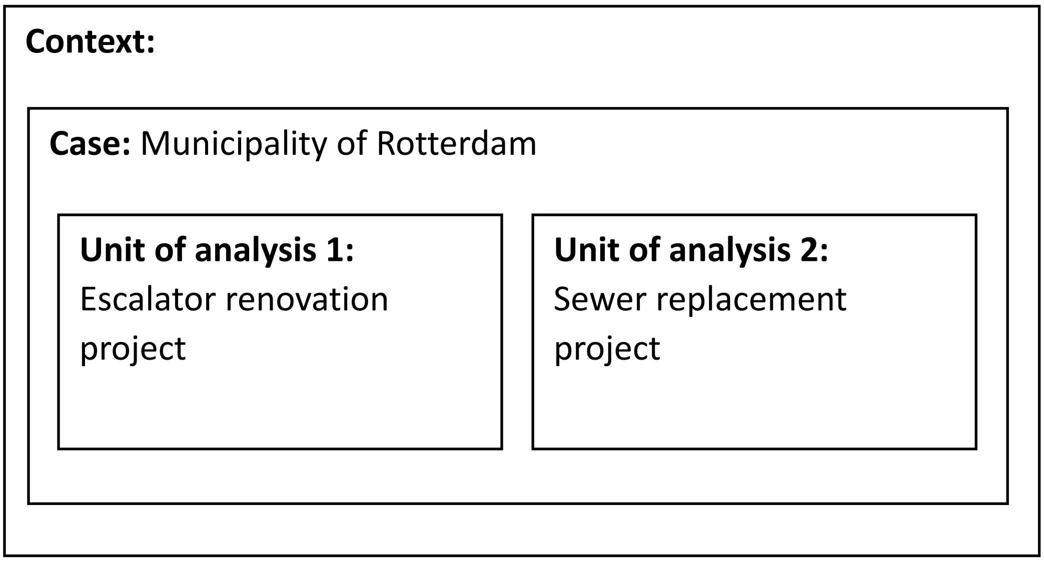

Figure 5: Context of embedded case-study

2.4.2.1 Unit of analyses, selection

The municipality of Rotterdam is responsible for numerous assets and asset types. These assets vary from sewers to playing grounds to public lighting and many more asset types. Based on meetings with employees from the engineering office and City asset management in the first weeks of the research it became clear that there was no clear picture of the kind of information that was lost in the information transfer. It seemed that only drawings and revision drawings are actively transferred. The remaining project information is archived at the end of a project. There was no clear alignment in the information availability and the information need. To gain further knowledge about the information needs from City asset management and information availability from the engineering office and to scope the research it was decided to select two projects to study the transfer of information between project teams and Asset management more in-depth.

During the meeting with the project manager of the escalator renovation project it was mentioned that the project was facing issues with the information transfer. Taking part in this project offered the chance to view the information transfer process from nearby. Furthermore, it provided access to a clear bounded set of asset information. A limitation of the escalator project was the uniqueness of the project. Investigating only such a unique asset would probably not lead to a design widely usable. Therefore, it was decided to select a second, more standard, project, the sewer replacement of the Saftlevenstraat. Multiple sewer replacement projects are executed per year given the task of 40-kilometre sewer replacement per year.

Selecting a unique and a standard project is analogue to the two-tail selection rational for a multiple-case design provided by Yin (2018., p. 96). By selecting one 'standard' project and one 'unique' project a broad area of projects is covered. Similarities and differences in information availability and need for both type of assets can therefore be distinguished. Inside the selected projects three sub-units are analysed; the information transfer process, the information available within the project team and the information need of Asset management.

2.4.2.2 Case study limitations

Limitations of case-study research are divided into two categories, limitations of case-study research in general and limitations of an embedded single-case study. Yin (2018) state five common concerns regarding case-study research:

- Rigorous enough
- Confusion with "non-research" case-studies (such as case-studies in a newspaper or magazine)
- Generalizing from case studies
- Unmanageable level of effort
- Comparative advantage

The first two concerns relate to the fact that a scientific case study should satisfy the scientific standards. The research should follow a systematic research approach and report on the research activities and results in an open and transparent way (Yin, 2018). Concern three state that the conclusions resulting from the case study should not only be about the case itself but should provide knowledge about more abstract concepts. These concepts can be theoretical propositions or a generalization of the case-situation (Yin, 2018). An unmanageable level of effort is the fourth concern. The case study should not take too long and should not result in too extended documentation. The final concern states that a case study is not per definition the best research method. The control measures mentioned in section 2.2 apply to dealing with the limitations of case study research too.

Additional research methods are used within the case study method: desk research, interviews and fly on the wall / fly in the soup research.

2.4.3 Desk research

Desk research is used widely in this research. First, it is an important source for the case study and for researching both units of analysis. Documentation about the information transfer process within the municipality and project documentation of both the investigated projects are analysed. Second, desk research is used within the block of the design science project. Literature is reviewed regarding the FAIR principles as requirements for the design. Furthermore, multiple NEN-norms, documents and websites regarding linked data and domain ontologies including their documentation are read and analysed to gain feeling for the subject and as input for the design.

2.4.4 Interviews

A second method applied within the embedded case study are semi-structured interviews. Semi-structured interviews can be used to gather elaborate responses in a systemic way without fully restricting the interviewee (Qu & Dumay, 2011). By having an interview protocol guidance is given to the interview. It gives direction into the knowledge that is required from the interviewee. However, by having it semi-structured, there is room to dive deeper into topics brought up by the interviewee and eventually relevant for the research. In this way, information which existence was not known by the researcher can be identified. The selection of interviewees was done through snowballing. The starting point for people to speak with was given by the daily supervisor**.** In appendix A, an overview of the performed interviews and meetings is presented. In this overview the functions of the interviewee or attendances are used instead of their names. Three different types are distinguished. 1) Interviews related to the general case and getting the actual design science research problem clear.2) Interviews regarding the escalator renovation project. 3) Interviews regarding the sewer replacement of the Saftlevenstraat. To document the results of these interviews a short report is made of each interview.

2.4.5 Fly on the wall / Fly in the soup

In analysing the escalator renovation project, a mix between the fly on the wall and fly in the soup method is applied. Where the fly on the wall method implicates no interference with the situation analysed, the fly in the soup method is known for being part of the situation (Simon Thomas, 2019). In analysing the escalator renovation project, the weekly meetings were attended to gain further knowledge about the escalators, the renovation process, and the information transfer process. During the main part of research project, the meetings were attended as ‘fly on the wall’. The meetings were merely observed. Towards the end of the research project, the escalator renovation project team wanted to use the gained knowledge, and a transition towards the fly in the soup method was made. According to DeWalt & DeWalt (2002, p. 23; in Simon Thomas, 2019) this shift is not considered problematic as long as the researcher is aware of his role. In Appendix A, an overview of the main attended meetings is given.

2.4.6 Schematic drawing

Schematic drawing is used as representation method for the designed ontology. Visualising the ontology in a schematic way does make it easy to read. An additional benefit is that changes to the design can be implemented without any technical difficulties. In this way, fast incremental improvements can be made. The tool used to create the schematic drawings is Miro. Furthermore, sketches are made on paper. To create visual more appealing figures of the design, the schematic drawings are recreated in Visio.

3. Scientific knowledge base

As stated in the research approach, a design science project needs foundation from the scientific knowledge base. To establish this foundation, the scientific knowledge base is analysed through a literature review (section 3.4). Resulting from this literature review, conclusions are drawn on the current state of literature within the research community that embeds the design science project and is interested in the field of interoperability and asset lifecycle information management (section 3.5). Prior to conducting the literature review, a common language is established by discussing the core concepts of asset, asset lifecycle information management, and interoperability in section 3.1 to 3.3. Establishing this common language helps define the scope of the research project and the targeted research community. Defining the scope of the research facilitates the identification and selection of relevant literature.

3.1 Asset

The concept 'asset' is very broad. Ouretani et al. (2008, p. 362) present the following definition: "An asset is defined as any core, acquired elements of significant value for this organisation, which provides and requests services for this organisation." To gain further understanding of what assets are, the concept is decomposed (Ouretani et al, 2008, pp. 361-362). A main distinction is made between tangible and intangible assets (Snitkin, 2003, p. 6). Tangible assets can be further broken down into fixed or capital assets, such as buildings, and liquid assets like cash and inventory items. Examples of intangible assets are knowledge, business culture and processes. In this research, an asset is described by tangible and fixed. Tangible because the assets are designed and built. Furthermore, they must be maintained. This makes them fixed or long-term assets.

Within the Dutch context there are several norms and standards related to assets. The IMBOR (informatiemodel beheer openbare ruimte / information model management public space) and GWSW (Gegevenswoordenboek stedelijk water / Urban Water Data Dictionary) are two well-known standards. The CB-NL (Conceptenbibliotheek Nederland / Conceptlibrary Netherlands) is also widely used. The IMBOR is an open standard that contains naming of all object types present in the public space. Datatypes relevant for the management of those assets are part of the model as well (Crow.nl, z.d.). The GWSW is an ontology describing the systems and processes relevant for the management of urban water (Stichting RIONED, n.d.). The CB-NL (Conceptenbibliotheek-Nederland) or Concept library- Netherlands is a third standard. The CB-NL aims to define concepts used in the different existing standards in a uniform way (*digiGO BIM Loket - CB-NL*, n.d.). It describes generic and reusable concepts used within the Dutch building sector. By placing itself between other used standards as a thesaurus, it can function as linkage between those standards. Other standards can link to the CB-NL, and thereby to each other. Linking via the CB-NL ensures they use the same definition of a concept or object. Having such ontologies, it becomes easier to share object data. However, the ontologies do focus on describing assets in an isolated way. The interaction with other objects, not being a sub or supertype of the described object, is not considered.

3.2 Asset lifecycle information management

Asset lifecycle information management combines the concepts of asset lifecycle management and information management. By defining these concepts, a definition of asset lifecycle information management is derived.

Asset lifecycle management can be defined as 'performing coordinated activities in order to optimize the value of an asset during its lifecycle in an effective and efficient way' (Nastasie et al., 2010; Ouretani et al., 2008; Somia Alfatih et al., 2015). An assets lifecycle refers to the phases an asset goes through during its life. Two divisions are used often: the simpler 'beginning, middle, and end-of-life cycle’ has three phases, while the more detailed division has five phases: acquire, deploy, operate, maintain, and retire. Note that the operate and maintain phase run parallel (Nastasie et al., 2010; Ouretani et al., 2008). Performing asset lifecycle management requires an integral look on activities performed on an asset during its life. When an asset is owned by multiple organizations during its life this demands coordination between its owners. By doing so, assets might be designed to be easier to maintain, reuse, etcetera.

Analogue to asset lifecycle management, information management can be described by performing coordinated activities in order to optimize the value of information in an effective and efficient way. It should be noted that the value of information can vary along stakeholders and in time. Combining the definitions of asset lifecycle management and information management, asset lifecycle information management can be defined as ‘performing coordinated activities in order to optimize the value of information during an assets lifecycle to enable effective and efficient asset lifecycle management’.

3.3 Interoperability

Compared to the concept of asset lifecycle information management, interoperability is a more straightforward term. The ISO-norm, ISO/IEC 33001:2015, defines it as “*the ability of two or more systems or components to exchange information and to use the information that has been exchanged.*" (Shehzad et al., 2021, p. 3). Shehzad et al. (2021) states that this not only demands interoperability on a technical level, but on an organizational, semantic, and legal level as well. This means that systems not only should be able to exchange information technically, but that organizational processes and a legal foundation should support this information exchange as well. The semantic level refers to the meaning of data and concepts. Agreement on that is also required.

Both discussed concepts are related to each other because interoperability is necessary for effective asset lifecycle (information) management. Without interoperability the information available, during the lifecycle of an asset, will lack quality and thereby lead to suboptimal asset lifecycle management. That finally results in assets adding less value to society than possible.

3.4 Literature overview

To investigate the current literature and find knowledge gaps the core concepts of asset lifecycle information management and interoperability are constructed into the following search string:

“(TITLE-ABS-KEY (asset AND lifecycle AND information AND management)) AND (interoperab*)”

Additional information about the literature selection process is presented in section 2.4.1. The results of this initial literature review were evaluated with a field expert. Based on this evaluation, additional research is added focussing on Building information modelling (BIM).

In table 2, the selected papers are presented. The first column presents the authors and year of publication of the paper. This is followed by the domain of focus of the paper, the product delivered and the main findings relevant to this research.

Table 2: Overview of reviewed literature

Author(s) (year)	Domain of focus	Product / Method	Findings
Aziz et al. (2017)	Lifecycle management of highways by integrating big data with a building information model (BIM)	A system architecture design translated to a proof of concept	Data from the design and construction phase can be useful for assets managers and can be integrated with other data sources
Bosch et al. (2015)	Building information modelling in the operations stage	A structured approach for alignment between supply of and demand for information	A lack of alignment between the supply of and demand for information is the main reason for marginal added value of BIM in the operational stage
Cavka et al. (2017)	The process of developing and formulating BIM requirements to support the lifecycle of assets	A methodology to support a rigorous and detailed analysis of BIM requirements	Clearly specified Information requirements can save stakeholders significant amounts of time in performing tasks across an asset's lifecycle
Farghaly et al. (2019)	Information transfer between asset management platforms using Linked Data	A process map for Linked Data generation for building assets to improve asset management	Linked Data enables interoperability between systems. But right information should be available to support use cases
Le et al. (2018)	Information handover between Design & Construction (D&C) data to asset management in transportation projects	A handover data model compiled into an ontology in the Ontology Web Language (OWL) format	An ontology model can successfully extract required asset data from project documents.
Nastasie et al. (2010)	Information standards relevant to the integration of asset management systems	An overview of standards in the domains of Engineering, business and information management	1) The intersection of domains are characterized by the creation of standards. 2) There is a tendency towards the XML format 3) universal architectures are the way to go in the information management domain (p. 252)

Rogage & Greenwood (2020)	Challenges in the transfer of information between the D&C phase and the Operate & Maintain (O&M) phase and overcoming the technological challenge	The use of industry foundation classes schema to automatically transfer information from a building model to a facility model	Three types of barriers for the incorporation of BIM into the O&M phase; communication, experience, and technology. Technical interoperability between D&C and O&M systems will not become standard in a short time, but problems can be overcome on a case-by-case basis. (p. 469)
Succar & Poirier (2020).	Information flows during a project lifecycle	A framework that describes and aims to predict information flows across an asset's lifecycle.	The framework sets the foundation for an open access digital platform to deal with project and asset lifecycle information.

Analysing the domain of focus, the products delivered and the main findings relevant to this research four observations can be made. First, the alignment of information between the 'design & construct' (D&C) and the 'operate & maintain' (O&M) phase is important to take advantage of interoperability (Bosch et al., 2015; Cavka et al., 2017; Farghaly et al., 2019). Second, working with ontologies is the most recent way to overcome interoperability issues (Farghaly et al., 2019; Le et al., 2018; Rogage & Greenwood, 2020). Third, multiple projects tried and did overcome the problem of interoperability. However, as stated by Rogage & Greenwood (2020 p. 469), this only happens on a case-by-case basis. Finally, most of the projects found using the research string focus on highways or buildings. None of the projects dealt with asset management in the outside public space. Based on the evaluation of this literature review by a field expert, additional research into BIM and BIM interoperability is performed.

3.4.1 Building information modelling (BIM)

Before focussing on interoperability and BIM it is useful to define BIM since there is not a clear and uniform description of BIM. Matejka & Tomek (2017) identified three main perspectives of BIM. BIM can be seen as a product, a method, or a methodology. The product refers to a model itself, the method to the modelling process, and the methodology to using BIM as a way of working. Taking the methodology perspective BIM can be described as creating and using digital 2d or 3d models, eventually linked with other digital programmes to increase effectivity and efficiency of a building project (Aryani et al., (2014). BIM models are designed in specific programmes and make use of specific file-formats. Different programmes exist for different specialisms (Auotdesk, n.d.). Currently, BIM is often used within the design and construction phase, application within the operation and maintenance phase stays behind (Azhar., 2011; Durdyev et al., 2022; Gu & London., 2010). Additional literature is found by searching on BIM definitions on Google Scholar and with Scopus by searching on BIM combined with terms like asset management, Interop* and, review in different combinations. To review the literature efficiently there is searched for existing literature reviews explicitly.

As stated, BIM models are designed in specific programmes and make use of specific file-formats. The different programmes and file-formats resulted in interoperability issues. This prevented efficient collaboration between stakeholders. If stakeholders use different software, they cannot open each other's files. To overcome this issue, BuildingSMART developed openBIM. BuildingSMART is an international branch organisation that stimulates digitalization within the building and construction sector (BuildingSMART., n.d.). OpenBIM is "a universal approach for collaborative design, construction, and operation of buildings based" (Jiang et al., 2019., p.9). Part of openBIM is the IFC (industrial foundation classes) standard which is a vendor-neutral file-format and one of the most used file-formats for information exchange (Di Biccari., 2022., p. 16).

While IFC has greatly supported the collaboration within the D&C phase by enhancing interoperability between BIM programmes and laying the basis for other developments, such as integration with geometric information systems (GIS) (Jiang et al., 2022 pp. 19-20), it has not solved the entire problem of interoperability. An ongoing issue is the mapping of IFC-objects with other standards (Dinis et al., 2022 p.887; Jiang et al., 2019 p.21-22). Even with the BIM-GIS integrations this is still a problem. The mapping of objects relates to the issue that an object within IFC is not directly equal to objects within other standards. The objects and relations within IFC must be translated to the objects and relations of other standards to enable or strengthen interoperability. Jiang et al., (2022 pp. 21-22) states that the generic level of the IFC-scheme is at the basis of this issue. They propose further research into ontologies focussed on: "1) the development and (re-)use of inter-connected ontologies including upper- and domain-level ontologies; (2) a library of modelling alternatives to satisfy different representational needs; and (3) more effective software environments which can support different phases in the ontology-based software lifecycle."

Focussing on the interoperability between the D&C and O&M phases lack of BIM adoption in the O&M phase should be acknowledged. Toyin & Mewomo (2022) and Tsay et al. (2022) provide an overview of barriers and challenges for this adoption. Where Toyin & Mewomo (2022) present a classification of hindering barriers, Tsay et al (2022) has scored the limiting factors on their rate of influence. Although both papers present the limiting factors differently, there are overarching factors. First, both organizational and technical factors do limit the adoption of BIM. Related to the technical factor, the compatibility between BIM software and asset management programmes. It is remarkable that the influence of this incompatibility for BIM adoption is only rated two out of five (Tsay et al., 2022 p 28). This rating is explained by other factors, such as lacking data quality and non-alignment of information required. A third broad overarching factor is the lack of involvement of stakeholders. There is reluctance to adapt process flows, which prevents the adoption of BIM.

3.5 Conclusion – Answer to sub question 1: scientific basis and background

To answer sub-question one, a semi-systematic literature review was performed. First, the concepts asset, asset lifecycle information management, and interoperability were defined. Thereafter, the literature concerning asset lifecycle information management and interoperability was investigated. Based on the review of a field expert the review was extended with an analysis of the scientific knowledge base regarding BIM and BIM interoperability.

As answer to the sub question several conclusions can be drawn. First, there are different perspectives to the transfer of information between asset lifecycle phases. The main perspectives identified are the technology and the information perspective. The technology perspective refers to the technological ability to transfer information while the information perspective refers to the alignment of information between projects and asset management.

Regarding the technology perspective it can be concluded that it is possible to extract relevant data from project documents. However, the mapping of this information to asset management systems remains an issue. The application of specific BIM applications not interoperable with asset management systems prevents the direct transfer of project data into asset management systems. The use of specific data-schemes, such as IFC and NLCS, is thereby a main factor. The development and (re-)use of interconnected ontologies including upper- and domain-level ontologies is proposed as part of the solution to solve these issues. However, information and process issues are not solved by the design of an ontology.

Issues related to the information and process perspective are the lack of data-quality, misalignment of information availability and need between projects and asset management, and the non-involvement of stakeholders concerned with the transfer of information. Regarding the data-quality and the misalignment of information a coupling with domain ontologies such as the CB-NL and IMBOR could be interesting because these standards explicitly describe what assets are and which information is related to these assets. However, their utility is limited as each of them has a different scope and functions. A combination of the ontologies is needed to cover the information available for, for example, the Rotterdam sewer system (Format Areaalgegevens Objectgroep Riolering Gemeente Rotterdam, internal documentation, 06-07-2022).

It is aimed to contribute to the scientific knowledge base by developing an ontology linking assets and their related information to BIM data-schemes and domain ontologies in a general way. Meaning, assets and their related information, transferred between two systems, should be linkable to multiple BIM data-schemes and domain ontologies. This should enable an improved mapping of objects, information, and data and raise opportunities for a better alignment of information availability and information need.

4. Embedded case 1: Monumental escalators Maastunnel

The first unit of analysis to discuss is the renovation of the monumental escalators at the Maastunnel. First a description of the case is given in section 4.1. This is followed by a description of the information transfer process in section 4.2. Section 4.3 respectively 4.4 discusses the information availability of the project team and the information need of Asset management. Finally, a conclusion is drawn in section 4.5. In chapter 6 the findings are translated into requirements for an ontology design dealing with the types of information identified in both test cases.

4.1 Case description

Eight monumental wooden escalators mark the entrances of the cycling and pedestrian tubes of the Maastunnel. The Maastunnel is an 80-year-old monumental tunnel located in Rotterdam. It connects the north and south side of the Maas and is thereby an important traffic link within Rotterdam. The escalators are alike the whole Maastunnel 80 years old and quite unique. Not many escalators of the type installed in the Maastunnel exist anymore (Keunen, 2021). The length of 43 meters, the second longest in the Netherlands, and height difference of 17 meter are impressive as well (Meder, 2021; Post, 2023). Increased failure rates and noisy operation were signs of wear and indicated the need for renovation. However, due to the monumental status and the unique characteristics, it is not a regular renovation project (project manager, personal communication, 12-01-23). The monumental status requires that the exterior is restored to originality. In opposite, safety regulations and innovation in material, mechanical, and electrical systems requires the update of components. For example, Bakelite was originally used for the wheels of the stair steps. Due to the innovation within synthetic plastics Bakelite is not available anymore. Let alone Bakelite wheels for escalator steps.

After completing the renovation project, responsibility for the maintenance is transferred from the project team to an external asset management company (Vialis). The project team does exist among others out of mechanics and engineers who maintained the escalators for many years. These mechanics have gained a lot of implicit knowledge regarding these unique escalators and their working. Vialis will be responsible for the whole Maastunnelcomplex as result of a 15-year integral maintenance agreement (Vialis B.V., 2022). To ensure effective and efficient maintenance of the escalators, relevant, sometimes implicit, knowledge from the project team should be made available and usable for Vialis.

4.2 Information transfer process

The information transfer process between the project team renovating the escalators and the external asset management company was not discussed elaborately upfront the project execution. However, it was agreed that the transfer would be a so-called ‘warme overdracht’ (warm transfer) (project manager, personal communication, 20-04-23). This means that the transfer of responsibility for the escalators would happen in cooperation. However, no clear substance was given to the exact meaning of a ‘warme overdracht’.

To enhance the warm transfer, process mechanics from the external asset manager and its sub-contractor were able to join and view renovation activities performed on the escalators by the project team. In this way, they could learn from the experienced mechanics of the project team and their implicit knowledge. Additional they could gain feeling for the working of the monumental escalators.

As not all escalators were renovated at the same time, the responsibility for the escalators is transferred one by one. Once an escalator is fully renovated, responsibility for the maintenance is transferred to the external asset management company. As the project team's mechanics are still present to renovate the remaining escalators, help in this maintenance could be asked easily.

In practice, the transfer of implicit knowledge is not as optimal as hoped for. Main reason seems the misalignment in the presence of the mechanics of the project team and the external asset management company. While the mechanics of the project team are present at the escalators each day, the mechanics of the external asset management company are mainly present in cases of malfunction. It succeeds insufficiently to be present during renovation activities and regular maintenance on the escalators under renovation. As consequence, the implicit knowledge of the project team's mechanics is transferred insufficiently to mechanics of the external asset management company. As the implicit knowledge is not transferred mouth to mouth, it should be made explicit to prevent information losses.

Besides the transfer of implicit information, explicit information should be transferred as well. Although, the principle of a warm transfer is valid for this information as well, no explicit process was agreed upon upfront the project. As the project continues and comes to an end, the need for the transfer of information is felt more. However, day to day business and work pressure does make it difficult to transfer information systematically and in a meaningful way. A meaningful way means that the information has value to the asset management company, it cannot be just a pile of documents.

4.3 Information availability escalators Maastunnel

The available information regarding the renovated escalators at the Maastunnel is split up in explicit and implicit information. The explicit information refers to all available documentation, while the implicit information refers to the knowledge of the project team's mechanics. First, the explicit information is discussed, second the implicit knowledge.

4.3.1 Explicit information

Insight into the components of an escalator is required to analyse the available object information. To determine which components are present and relevant, the maintenance history of the year 2022 is analysed. For each week, the performed checks, maintenance and remarks are reviewed. Components and installations are identified based on these reviews, reports of the weekly project team meetings, and a tour along the escalators. To keep track of the identification source of the components both the maintenance history as the documentation were imported into Relatics and explicitly linked to the components. Components identified based on the weekly meetings and the tour along the escalators were marked as well. To structure the identified installations and components these are placed in a decomposition (figure 6) and a taxonomy (figure 7). In a decomposition the 'is part of' relation is graphed, while a taxonomy shows the 'is an' relation. The relations are bottom to top. The concept below has a 'is part of' or 'is an' relation relative to the concept above. Both figures are reviewed by a constructor of the escalator renovation project team.

Having analysed the escalators components and their sources linked within Relatics, an overview of the available documented information is available. Nevertheless, the information within the linked documentation is not made explicit. However, the type of information in the documentation is analysed by opening all available documents. It is not made explicit what information was available per document. Nevertheless, the type of documents and type of information available in those documents are identified.

The document types and information identified are quite diverse. For different components different types of documents are identified. The main type of document found are technical drawings. These drawings show the exact measures, including eventual deviations, of components placed within the escalator. In some drawings the weight and material of the component are mentioned as well. Beside the technical drawings other documents are available. Such as documents containing calculations and test results related to the lifetime and degradation of the escalator wheels. Other documents are related to the procurement and warranty of components. Furthermore, documentation concerning the installation and adjustment of components exist. While the escalator is a heavy machine, the adjustment of some parts should be very precise to prevent excessive degradation or damage (Post, 2023). The above-mentioned documents are mainly about mechanical components of the escalator, but there is also documentation related to the electrical installations. These are wiring diagrams of the control cabinets and safety mechanisms.

A lot of documentation is available about the escalator and its components. However, in analysing the documentation it was noticed that it was difficult to distinguish documentation, especially drawings, of the old and new situation. It was not always clear if documents were applicable to the new situation, the old situation, or to both situations. Second, it was noticed that the naming of the documentation was not always clear about the content of a file. Related to this, some files were specific about one escalator while others were not. Sometimes it was clear that these files, not specific for one escalator, were valid for the escalators in general. However, files specific for one escalator did not always exists for all escalators. Leaving the question, could the content of this file be generalized to all escalators or not? Without providing context or further explanation to the full list of documentation this could lead to indistinctness by Asset management not familiar with the documentation. Providing this context for the documentation should be part of the created design.

4.3.2 Implicit information

No full insight in the implicit knowledge of the mechanics is available. However, there are some main types identified. These types are how to control the escalators functioning, how to perform certain maintenance activities, and how to tune components. Regarding the control activities, each Monday the working of the escalators is checked. It is not clear what activities are performed to fulfil these checks. Information available, but not explicit yet, contains what components are checked, how are these components checked and when is the check considered successful. Maintenance activities are not described explicitly as well. For example: how should the chains be lubricated and with what oil. This is closely related to the tuning of components. How tight should chains and handrails be adjusted, what tolerances are acceptable in the movement of those parts? It should be noted that this knowledge is professional knowledge and therefore not always easy to make explicit. Sometimes it depends on a mechanic's professional judgement whether a tolerance is acceptable or not. Nevertheless, guidelines of these checking, maintenance and adjustment activities based on the years of experience of the mechanics would be a way to make the available implicit knowledge more explicit. Based on these guidelines, new mechanics could execute the maintenance on the escalators and gain experience while doing so.

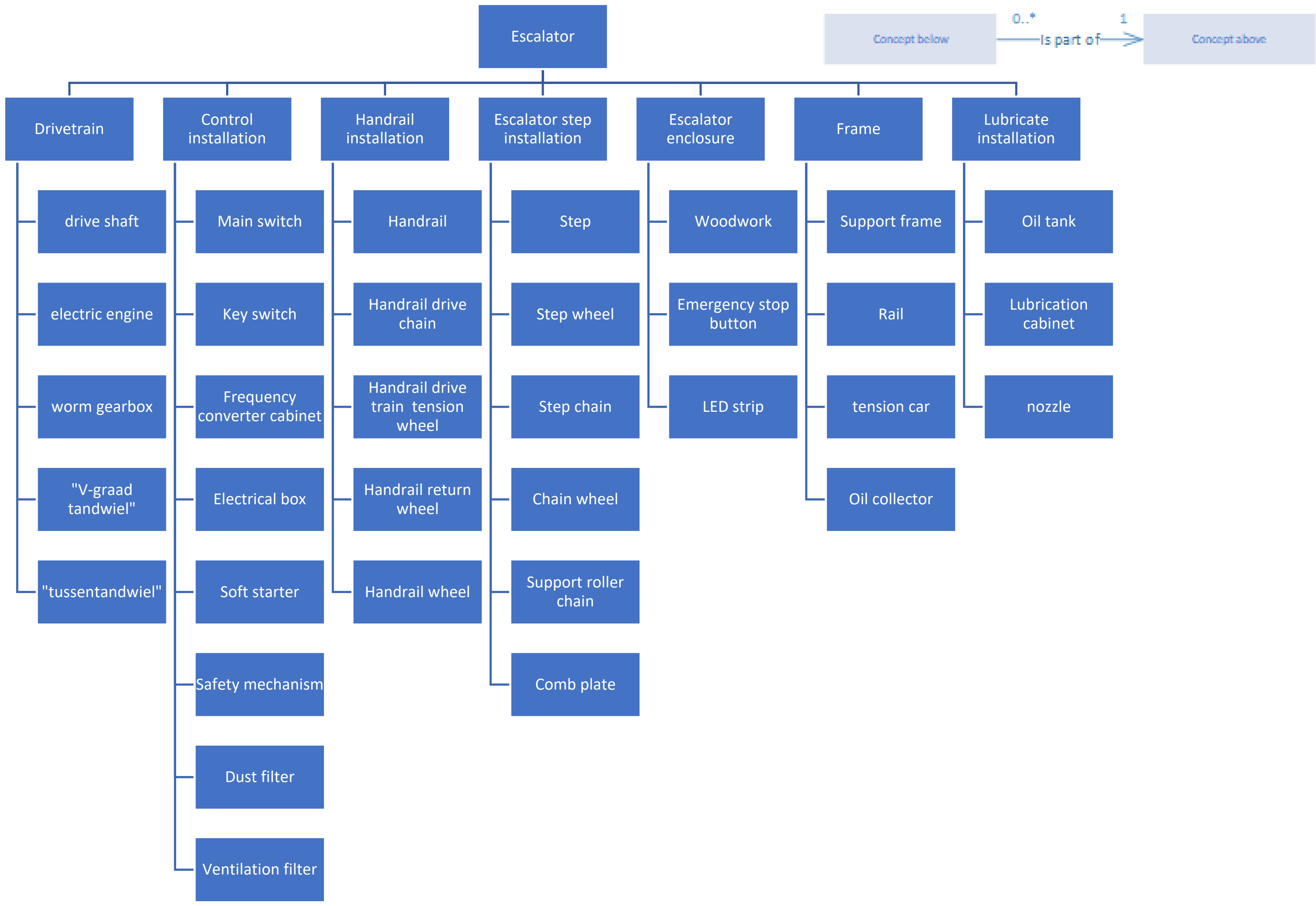

Figure 6: Escalator decomposition

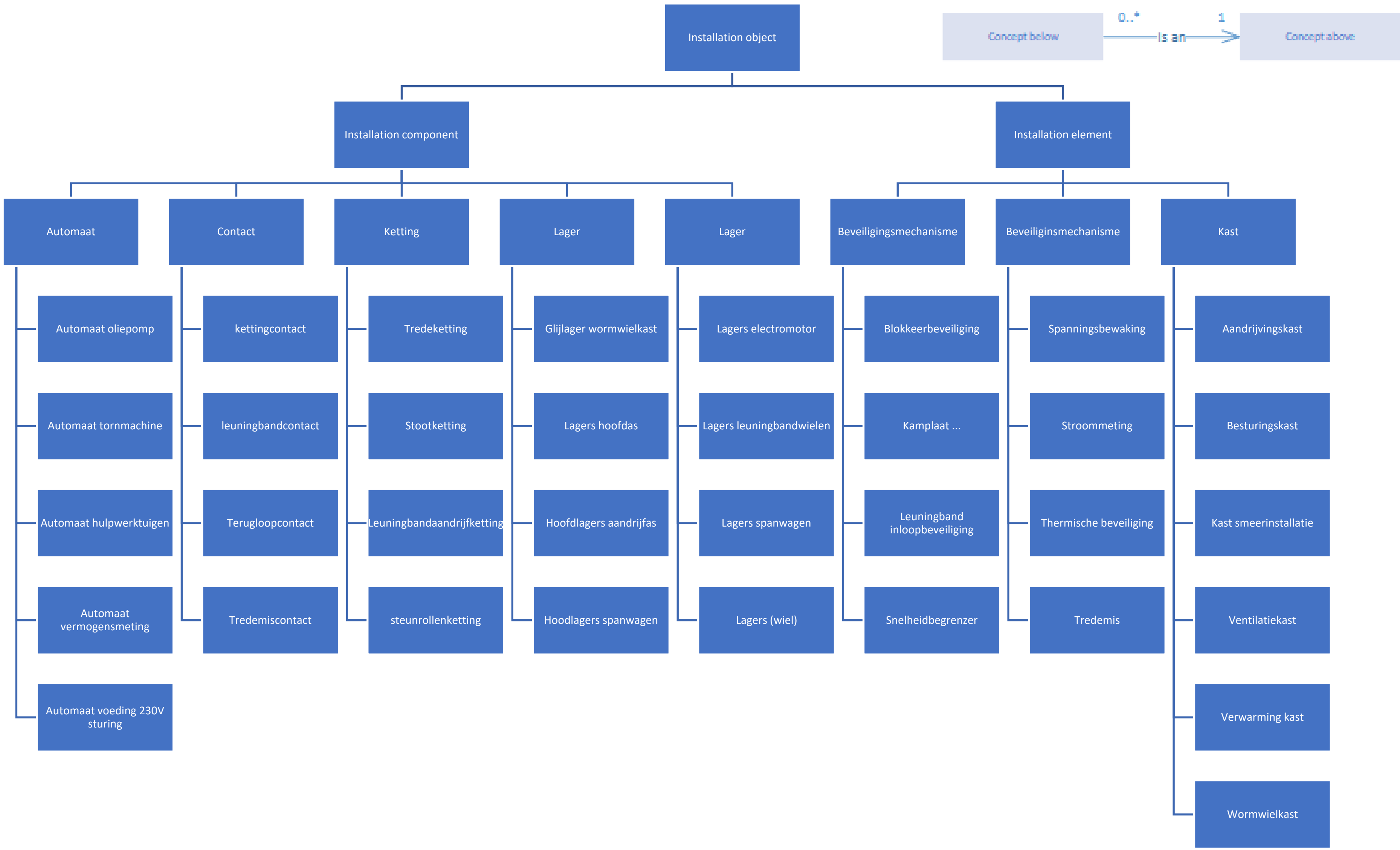

Figure 7: Escalator taxonomy

4.4 Information need escalators Maastunnel

After completion of the renovation the external asset management company is responsible for the escalators. This company outsources the maintenance of the escalators again to a company specialised in elevators and escalators. The information need for asset management is discussed with the main asset manager of the Maastunnelcomplex and the asset manager responsible for the escalators.

Discussing asset management with the main asset manager of the Maastunnelcomplex (12-01-2023, personal meeting), it became clear that asset management, related to the Maastunnelcomplex, can be divided into two streams: maintenance and depreciation. Maintenance can be divided into the goal of extending an assets lifetime while keeping the assets performance within the stated boundary conditions. The branch of replacement / depreciation is divided into the factors of costs and time. A schematic representation is given by figure 8. Besides dividing asset management in a maintenance and depreciation branch two support legs are shown. Insight in design choices and object characteristics helps optimizing choices in managing assets (Main asset manager, personal communication, 12-01-2023).

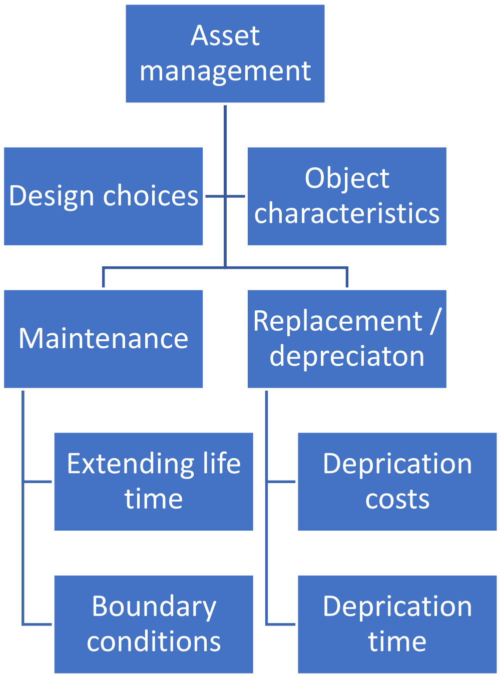

Figure 8: Asset management break-down

Aside from general information needs for asset management, specific needs with respect to the escalators was discussed as well. This resulted in only a short, but broad, description: “The information to be transferred must be of such a level, that the external asset management company could take its responsibility. (Main asset manager, personal communication, 12-01-2023). So, Asset management should have detailed enough information to take concrete actions in executing their responsibilities. Reason for this general description of information need is that the main asset manager does not have in-depth knowledge about the escalators. Furthermore, the asset management system includes the escalators as one object only. No further decomposition of the escalators is made. This does limit the information that can be transferred without making the information overwhelming and unreadable. Additionally, it limits the view of possible knowledge needed.

Prior to the meeting with the asset manager responsible for the escalators an overview of (a part of) the required transfer information was provided (internal communication, 16-02-2023). This overview consisted of four items. No specific parts or components were mentioned. It was stated that the transfer file should contain the following information:

- List of suppliers
- List and location of spare parts
- Stock of spare parts
- Stock advises on spare parts

This matches partly with the description given by the main asset manager of the Maastunnelcomplex. The four requested information items are related to maintenance information. Spare parts are needed to replace broken items and the supplier of these parts should be known to order new ones. Remarkable is that it is not requested to specify which components are ordered by a supplier. Perhaps providing this information is perceived as logic. Nevertheless, that specific kind of information is not requested. Other information regarding maintenance was not requested by this overview. However, in a meeting with the escalator asset manager (13-04-2023) further information concerning this topic was requested.

The asset manager responsible for the escalators mentioned three aspects concerning the information required from the project team. First, the translation of maintenance needs to job plans. Second, an as-built file. And third, knowledge transfer of mechanics regarding controlling and inspection. A translation of the maintenance needs to job plans requires insight in the maintenance need. Thereafter, this insight can be translated into concrete jobs. The maintenance needs and job plans are about the specific tasks required to keep the escalators in good condition. What tasks should be done and in what frequency. It is related to the implicit knowledge held by the mechanics of the project team. This relates the first aspect strongly to the third aspect of transferring the knowledge of the mechanics. Making this knowledge more explicit is necessary to translate the maintenance needs to job plans. The as-built file is a set of documents and drawings describing how the escalators are constructed and what components are exactly used. As-built data are complementary to design data as deviations of the design can happen in the construction or renovation process. Having as-built data instead of design documentation can prevent errors in the process of asset management. For example, by ordering the wrong parts, or by having to examine the actual connections of cables because the actual connections are different than showed in the design documentation. Additional to job plans and the as-built data information specific for certain objects should be transferred. This relates for example to the reusability of handrails and the substantiation of the escalator chain selection.

4.5 Conclusion – Answer to sub-question 2, 1st case

Three aspects regarding the information transfer of the escalator renovation project are analysed. The information transfer process, the information availability, and the information need. It is concluded that, although a so-called ‘warme overdracht’ was agreed upon, no specific process for the information transfer was established. As consequence, the transfer of the project team’s implicit knowledge is limited. With respect to the available documentation, it is concluded that, although a lot of documentation exists, it is hard to derive exact information needed. Regarding the information need, information about maintenance activities, object specificities, as-built documentation, object suppliers, and spare parts is required.

The transfer of information could be enhanced by providing a structure for the information availability and need. Having this structure would enhance insight in the information available, ready to transfer, and the information still implicitly held by the project team mechanics. Based on this insight, a process to transfer this information could be established. A beginning on the structure is made by creating a decomposition and a taxonomy of the escalator objects and linking the available documentation to the components identified. However, the content of these documents is, based on the document's naming, not always directly clear. The ontology design should increase insight in this content by providing additional context.

5. Embedded case 2: Sewer replacement Saftlevenstraat

The second unit of analysis is the sewer replacement project within the Saftlevenstraat. Section 5.1 provides a description of this project. This section is followed by discussing the information transfer process in section 5.2. The information availability is presented in section 5.3, while the information need is discussed in section 5.4. Conclusions with respect to the analysis of the sewer replacement project and sub-question 2 are drawn in section 5.5.

5.1 Case description

The sewer replacement project of the Saftlevenstraat is the second unit of analysis. The Saftlevenstraat is located in the centre of Rotterdam between the Nieuwe Binnenweg and the Rochussenstraat near the Erasmus medical centre. Since the sewer in the project area is circa 70 years old, it was decided to replace it (Internal communication, functional advice). During this replacement project not only the sewer is replaced, but gas and waterpipes are replaced as well. Furthermore, the public space is renewed. Cooperation with Stedin and Evides was required for the replacement of the gas and waterpipes. Stedin is the network operator of the gas network, while Evides operates the network for water supply. Related to the public space, input of citizens was gained. In this research only the replacement of the sewer is considered. The replacement project preparation started early 2020 (Intranet municipality of Rotterdam). The execution of the project started in January 2022 and was finished early 2023.

5.2 Information transfer process

Since sewer replacement projects are executed more often within the municipality of Rotterdam, the information transfer process is described and prescribed in a procedure. Additional to the established transfer procedure, an improved pilot procedure exists . Both procedures are visualised in figure 9 (File manager, personal communication, 06-03-2023; Efficientie in de revisieprocedure, internal documentation; Systems engineer BIM 3, internal presentation, 17-05-2023). While in the Saftlevenstraat replacement project the standard procedure is followed, the pilot procedure is discussed as well. This provides insight in current developments within the transfer process.

As visualised in figure 9, two sources deliver information towards Asset management. The first source is a revision drawing, which is delivered by the contractor and approved by the project team. Source two is the LVZK (Leidingverzamelkaart, Pipe collection map). The LVZK is a map containing all geometric and administrative pipe and cable attributes of all network operators owning a network in the municipality of Rotterdam. The map shows where which pipes, or cable are laid in the public underground (Overheid.nl., 2022). The input for the LVZK comes from position measurements of the new placed sewer.

Related to the first source, a standard and pilot version exists. The data requirements for both procedures are described in the “Format Areaalgegevens Objectgroep Riolering Gemeente Rotterdam” (Internal documentation, 06-07-2022). The standard way to deliver the revision drawing to the contract manager for approval is via a PDF. This PDF is a digital drawing without any additional digital processable information. Any information on the revision that needs digital processing, needs to be entered manually. The pilot procedure accommodates for delivering digital processable data. By providing the relevant data in a prescribed file-format, a revision drawing can be automatically produced from this data. In other words, the data can be represented as a drawing. By having regular data stored in a database, and thereby in a computer-readable way, many more options than only represent it as a drawing are possible. After approving the revision, independent of the followed procedure, a PDF is provided to Asset management. This means that the digital processable information available within the pilot procedure is still lost within the process.

As stated, the second source of information is the LVZK. After measuring the sewage position and creating a skeletal based on the x and y values, the skeletal is distributed automatically to a software package wherein the LVZK data can be checked. The check includes a comparison with the provided revision. If the skeletal from the LVZK and the revision are identical, the skeletal is imported into the WMO-database. WMO stands for water, means, and objects and is the database for the asset management system. After importing the skeletal, additional attributes are manually added from the revision.

A final step in the process of information transfer for sewer replacement is transferring the z value of the new sewer assets from the WMO-database to the LVZK. This action is performed by running a script. The z value refers in this case to the topside of the sewer assets.

A current flaw in the process, besides the needed manual actions, is that in case of an incomplete or incorrect revision, a revised revision is needed. Getting the revised revision delays registering the new sewer assets. This delay can take up to multiple months and sometimes no revised revision is sent at all. In those cases, the old sewer data is not updated and remains in the asset management database (Personal meeting, Asset manager water - Djurre Schouten). No information is transferred into the WMO-database of City asset management and a discrepancy arises between the WMO-database and the LVZK-database. Based on this inconsistency and the asset manager's personal knowledge, it is evident that the sewer has been replaced, indicating that the data in the asset management system is outdated.

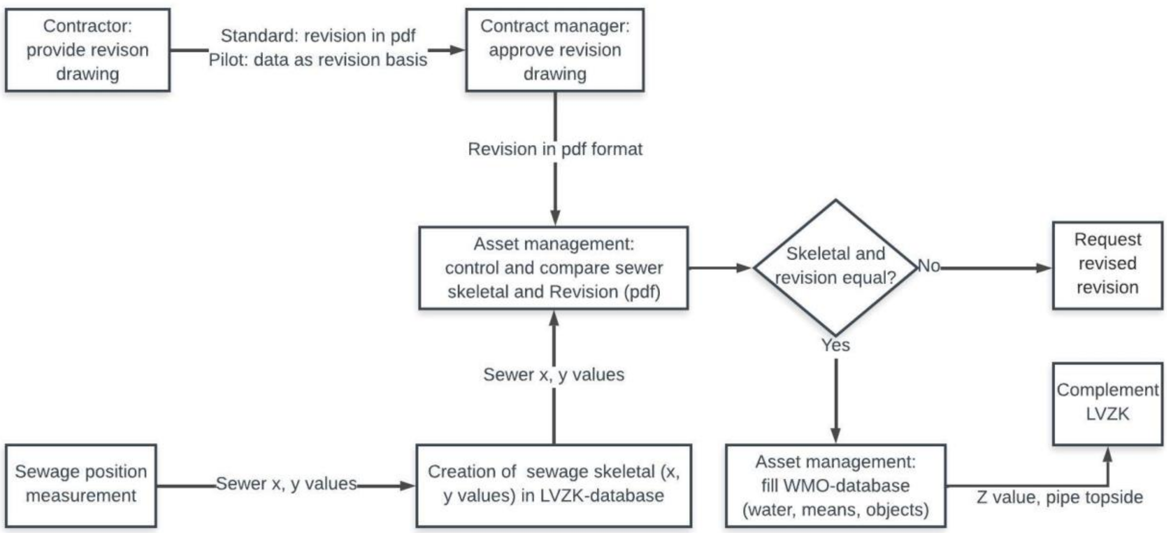

Figure 9: Sewer revision process

5.3 Information availability sewer replacement Saftlevenstraat

To get insight in the available information relevant to the sewer replacement project of the Saftlevenstraaat the following steps are taken. First, the available documentation is introduced by the project manager of the project (Personal meeting, 20-03-2023). Second, this documentation was analysed. This section will follow the same structure. First the available documentation is presented. Thereafter, the content of this documentation is discussed and a conclusion regarding the available information is drawn.

A sewer replacement project is typically split up in two parts. Part one is the preparation of the project, part two is the execution of the project. In preparing the project all the plans are made, designed, analysed and discussed with stakeholders. In addition, all necessary documentation is prepared. In the execution phase, the actual execution of the project is done. Documentation regarding this execution is stored separately.

As stated in figure 9 the current information transfer process only incorporates the transfer of revision drawings. Visualised information entails the start & end point, length, diameter, material, type, and construction month of the sewer pipes. Furthermore, information is provided about the housing connections and manholes. For the housing connections, this is the same information as for the sewer pipes. For the manholes, information is given on the connection of pipes to the manhole. On what side are which pipes connected, and on what height is the connection made. Additionally, some extra characteristics of the manhole are given. For example, if a check valve is used.

Additionally, in analysing the documentation of the preparation and execution phase other, eventual valuable, documentation was found. Regarding the preparation phase, valuable documentation is the 'Functioneel advies (Functional advice, FA)'. Additional relevant documentation of the execution phase consists of an overview of the used materials & products, deviation reports concerning the sewer replacement activities and inspection videos of the new placed sewer.

The functional advice is considered as the start documentation for a sewer replacement project. It is an analysis of the current system and its shortcomings given the environmental developments. Given the more intense rainfall and drought periods new challenges regarding water management have come up. Advice is given by what kind of sewer system the old sewer should be replaced and why certain choices in the new design are made regarding these new challenges. This entails for example why is chosen for separating rain -and wastewater drainage, and how this separation is planned.

The overview of used materials & products provide information of what exact materials are used in the new placed sewer. Additional information regarding the supplier of these articles can be provided. Difficulty in transferring this information is that it is not registered currently where each article is placed. So, it is not clear what sewer pipe is placed where. Only the attributes such as material and diameter are registered.

Deviation reports concerning the sewer replacement activities provide information about deviations of the as-built situation from the designed sewer system. It does not only provide information about what is changed but can provide information about why these changes are made as well. Insight in the deviations made from the design are already provided via the revision drawings. However, insight in the why is not transferred yet. Transferring the why would complete the reasoning behind the sewer system started from the functional advice until the complete sewer.

A video inspection of the sewer is made to review the quality of the new placed sewer. Based on these videos scores are assigned to specific parts of the sewer on predetermined factors. Additional remarks about specialties are made as well. Insight in the quality of the new-placed sewer can help in estimating the deterioration of the sewer during its lifetime.

5.4 information need sewer replacement Saftlevenstraat

After finishing the sewer replacement project, City asset management becomes responsible for the sewer. More precise, the department of Water and sewer Management of City asset management. The asset manager provided an inventory of the attributes and information wished to be linked with sewer assets in their asset management system (Internal documentation, 12-04-2023). This list is used as main source to identify the information need regarding sewer replacement.

The input for the list of needed information was given by three sewer asset managers and one specialist. The list contains 52 items but is not a full overview of the information need because sentences like 'et cetera' are used. For this research this is not an issue since the focus is on information types instead of the exact information values. To identify these information types, all the list items are categorized. This results in a list of 6 types of information. The distinguished information types are objects, attributes, supporting documents, data, thematic views, and maintenance information. As the thematic views are about the representation of information within the asset management system, this information type is considered out of scope for this research. The maintenance information needed is about explicitly linking planned replacement activities to assets. As newly replaced sewers typically do not have to be replaced within a few decades, the replacement is not planned. Therefore, the needed maintenance information is considered not relevant as well.

Most of the objects and attributes mentioned are expected. This entails for the general sewer objects, such as manholes, pipes, and connections. Nevertheless, some additional objects are needed. Two types of additional needed objects can be distinguished. First, more specific sewer objects within the system, such as swirl valves and air-vents. Second, objects not directly related to the sewer system, and therefore primary based in external databases. Such as trees and objects, not being sewer objects, within the LVZK.

Three links to supporting documents are mentioned. The documents referred to are drawings related to certain objects, a document describing the sewer system, and a document specifying object's particularities. This means that documentation should be linked explicitly to certain objects. A difficulty therein is the documentation describing the whole sewer system of interest. As the system is not a specific installed object but consists of a collection of objects. To link the document an overarching (system) object should be created, or the document should be linked to each object within the system separately. Creating an overarching system object is alike a decomposition with the top-object sewer system and part of relations directed from sewer pipes, manholes, and other objects part of the system. Linking each object with the system separately can be easier in the transfer process but has the difficulty that all objects within the system are not explicitly part of that specific system.

The third information type to discuss are measuring data. Measuring data is collected via monitoring wells and by sewer inspections. Monitoring wells are used to measure the groundwater level (Stichting RIONED, n.d.). Sewer inspections are performed via video recordings whereafter the images are scored based on the quality of the inspected pipes and manholes (Asset manager water, personal communication, 12-04-2023). Special of such measuring data is that multiple data points can exists in time. Each time a measurement is repeated a new data point is created. Consequently, a history of these measurements can be created. This history can provide extra insight in the development of the measured items. To create this history, it is needed to store each measurement and related data point. An example of information that should be transferred are the groundwater level measurements performed by the project team to review the level prior, during, and after the sewer replacement activities.

5.5 Conclusion – Answer to sub-question 2, 2nd case

Several conclusions can be drawn by analysing the information transfer process, information availability, and information needs related to the sewer replacement of Saftlevenstraat, and sewer replacements in general. First, the transfer process is established, so it is known what information should be transferred and how. Second, information is transferred within documents and drawings and is only made digitally processable by entering it manually into the asset management system. Third, first steps into further digitalizing the transfer of information are made. However, the information transfer from the project team to City asset management remains, for now, dependent on revision drawings in a PDF file.

With regards to the information availability and need it is concluded that the information transfer could be improved on the following aspects. The substantiation of the sewer design should be transferred and / or linked to the sewer within the asset management system. Furthermore, more detailed as-built data could be provided by transferring deviation information and the results of the video inspections. A further specification of the used products and object types is considered valuable as well. Finally, it is noticed that in the current standard procedure no reference is made to domain ontologies. In the pilot procedure references are made to the IMBOR and a Rotterdam specific object type library.

6. Design Requirements

As stated in section 2.3.3, design requirements should be defined to ensure that the designed ontology is useful and adds value to the scientific and local practice. Furthermore, well-defined design requirements allow for an evaluation of the design against these requirements. Section 6.1 and 6.2 present and discuss the requirements derived from the scientific knowledge base and case-analysis. To optimize the value of information further, additional requirements are based on the FAIR principles. The FAIR principles stand for findable, accessible, interoperable, and reusable. Although these principles are primarily developed for research data, their applicability to governmental data is discussed in section 6.3. Thereby the specific considerations and implications for their application in this context are taken into account. Finally, an overview of these requirements is given in section 6.4.

6.1 Requirements from initial literature research

The literature presented in chapter 3 provide requirements for the design. The first one, basis for this research, is the need for an ontology. An ontology should enable easier mapping of objects, information, and data of different standards onto each other. This implicates the following requirements. The design should be an ontology and the ontology should include the linking of standards to objects, information, and data. The standards that should be linked are the standards used for the 2d and 3d modelling, such as IFC and NLCS, and standards describing assets and their relations to other assets such as the CB-NL, IMBOR and GWSW. Since it can differ between the type of asset which standard should be linked, it is chosen to make no distinction in which standards should be linked and which one should not.

6.2 Requirement based on embedded case study.

The performed case studies are elaborately discussed in chapter 5 and 6. the main findings followed by an overview of the derived requirements are listed below:

Assets stand central in the provided information as well as in the required information by Asset management. Information available and needed is most of the times related to certain specific assets. Sometimes, as in a functional advice, information is provided on a system level. However, as for most documentation in the escalator renovation project and for the main information transferred in the Saftlevenstraat sewer replacement project, information is about specific attributes of specific assets.

Information is currently provided mainly in documents and 2d PDF drawings. Though, it should be noted that for sewer replacement projects first steps to transfer information in a computer understandable way are taken. However, the transfer of information from the project team to Asset management still requires the manual input of information into the asset management system. Concerning the escalator renovation project, the transferred information consists of a bulk transfer of files and drawings and the transfer of implicit information via mouth-to-mouth communication of mechanics. Providing structure in this documentation and implicit knowledge is a prerequisite for the ontology design.

For the escalator renovation project, the required information by Asset management was related to maintenance needs and jobs to plan and execute that maintenance. Further required information relates to the existing stock of components. Which components are in stock, where are these components located, how many components are available, which amount of stock for which component should be available, and who are suppliers of components. Additional needed information concerned the implicit knowledge on asset specific attributes regarding adjustment settings and reusability.

The analysis of the sewer replacement project of the Saftlevenstraat shows that the following information types are relevant for the designed ontology: objects, attributes, supporting documents, and measuring data. Related to the objects, a distinction is made between sewer objects, and objects part of other systems, such as trees. Furthermore, documentation substantiating the sewer design and data regarding inspections are required by Sewer asset management.

The abovementioned findings are translated into the following design requirements:

- Assets should be central in the design.
- Documents and drawings that describe the assets or its related information should be incorporated in the design.
- The ontology should provide structure for the available and needed information.
- Multiple information types such as object characteristics, maintenance activities, stock information, and measuring data should be part of the design.

6.3 FAIR principles

To further optimize the value of information, compliance to the FAIR principles should be enhanced by the designed ontology. As stated, the FAIR principles stand for findable, accessible, interoperable, and reusable. In this section, the considerations and implications related to the differences between research and governmental projects are discussed. Each principle is discussed separately, and per principle a requirement is derived. As the FAIR principles are already discussed extensively by Wilkinson et al (2016) and Jacobsen et al (2020), no extensive description of the FAIR principles themselves is given.

Regarding the findable principle, it is considered that while governmental data is becoming more open and transparent not all data acquired during a project can be published. This for various reasons such as privacy or for competitive considerations. Furthermore, some stakeholders should be able to find specific data, while others should not. Hereby can be thought of security measures; only some stakeholders should have insight in these measures. In other words, depending on someone's role or organization data should be findable or not. This implies that it should be possible to take this difference in findability into account. Besides the consideration of who can find certain data, it is also relevant when this data can be found. Some data is published on a specific time or after a specific event, such as an approval. In conclusion, findability should be incorporated within the design considering the role or organization of someone and the status of the information at a certain moment.

Close related to the principle of findability is the principle of accessibility. This principle state that information not only should be findable but be accessible as well. This means that the actual information and values available should be visible and readable. To make it clear an example is given: with respect to sewer replacement project of the Saftlevenstraat video recordings are made to analyse the quality of the new-placed sewer. Taking the findable principle into account, the existence of the videos should be findable. Related to accessible, the videos should be watchable. As both principles are close related, the same considerations can be made. Not everyone should be able to access all information and this access can depend on certain attributes or statuses. Therefore, the implications stated for the findable principle are valid for the accessible principle as well. Dependent on someone's role or organizations and the status of that information, information should be accessible.

The principle of interoperability substantiates the need for an ontology linking assets and their related information to BIM-references and domain ontologies. In discussing this principle, Jacobsen et al. (2020) state that knowledge should be represented in an understandable way for humans and computers. Furthermore, it is stressed that (meta)data is described by other vocabularies that follow the FAIR principles and that these descriptions are qualified. This implies that the meaning of the relation between a concept and another vocabulary is described as well. Since an ontology models the structure of a system with its concepts and their relations Guarino et al. (2009., p.2) the description of relations between these entities is part of the ontology design. Nevertheless, these descriptions should be explicit enough to provide a human -and machine understandable relation between two concepts. This means that the relations themselves can be seen as concepts with certain attributes and eventually can be described by providing context from other vocabularies. Modelling relations as concepts in the ontology has impact for the human and the machine understandability. Since this research does communicate to humans, the ontology design should in first place be understandable for humans. However, the machine-understandability should not be ignored totally. It should be noted that the principle of interoperability relates only to the semantic and technological level of interoperability as identified by Shezhad (2020) and discussed in section 3.3.

The reusable principle does mention the legal aspect. It requires the release of data with a clear and accessible data usage license (Wilkinson et al., 2016 p. 4) Furthermore, the principle implies that the data is described in such a way that the quality of the data is clear enough to decide on reusage of the data. Other attributes relevant for eventual reuse of the data should be available as well. Concepts providing this information should be part of the ontology design.

6.4 Overview of design requirements – answer to sub-question 3

To give a straightforward answer sub-question 3 an overview of the design requirements is provided below. To offer traceability the requirements are sorted by their source.

Scientific knowledge base

- The design should be an ontology.
- Relevant concepts within the ontology design should link to modelling standards and domain ontologies.

Embedded case study

- Assets should be central in the design.
- Documents and drawings that describe the assets or its related information should be incorporated in the design.
- The ontology should provide structure for the available and needed information.
- Multiple information types such as object characteristics, maintenance activities, stock information, and measuring data should be part of the design.

FAIR principles

- Findability of concepts should be made explicit in the ontology design.
- Accessibility of concepts should be made explicit in the ontology design.
- All relations between concepts should be described explicit.
- Insight in the quality of the data is provided.
- Other attributes relevant for the reusage of data are provided.

7. Design

Having the design requirements defined, the next steps in the design science research process are creating, presenting, and discussing the design. This chapter is structured as follows: section 7.1 presents the designed ontology. The entities and relations within this ontology are described and discussed, including the links to the modelling references and the domain ontologies. Section 7.2 concludes with an evaluation of the design against the requirements stated in chapter 6 and by providing the key message resulting from two limited evaluation discussions.

7.1 Designed ontology

The designed ontology (Figure 18, complete design overview) aims to link an object and its related data to each other and to modelling standards and domain ontologies. In this section the ontology is discussed part by part. As an ontology is defined by Guarino et al. (2009., p.2) as "means to formally model the structure of a system, i.e., the relevant entities and relations that emerge from its observation, and which are useful to our purposes." design choices are made about which entities and relations are relevant for the design and which are not. Entities can, analogue to a system of systems, exist out of sub-entities and relations. Identifying the correct level of detail can be difficult. To keep the amount of information in each figure limited, not all concepts, attributes, and relations are presented at once. First, a short overview of the elements present in the design is given. Second, the relations related to the entity 'object' are discussed. Third, the relations between the concepts of 'information type', 'attribute', 'document', and 'activity'. Fourth, the findability and accessibility, and fifth, the metadata relevant to all or main concepts.

Figure 10 shows what elements are present in the ontology design. The rectangles represent the identified concepts, the arrow between those concepts indicate a relevant relation between these concepts. The relation is described by the indication on the arrow. The multiplicity of both concepts is displayed at the ends of the arrow. The multiplicity specifies the lower and upper bound of the allowed cardinality. For example, in the presented design, a modelling-reference models always one object, while an object can have none to many modelling references.

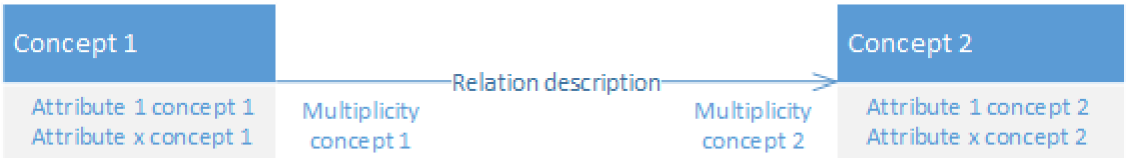

Figure 10: Elements of an ontology

7.1.1 Object

As illustrated by figure 11, the central entity within the design is 'Object'. The entity 'Object' has four self-relations ('is part-of', 'is an', 'is connected to', and 'is located in'), and four outgoing relations to other entities within the design. The outgoing relations link to the entities of 'BIM-reference', 'Domain ontology reference', 'information type', and 'findable / accessible'. The self-relations and the relation to 'Modelling reference' are discussed below. The entities of 'Information type', 'Domain ontology reference' and 'Regulation' (of findability / accessibility) and the relations to these entities are discussed in section 7.1.2 respectively 7.1.3. Section 7.1.4 discusses the need for additional metadata related to the identified entities.

The 'is part-of' relation is derived from the escalator renovation project and supports the creation of a decomposition. The 'is an' relation is used for the creation of a taxonomy. Domain ontologies use this relation often (CROW, n.d.; digiGO BIM Loket - CB-NL, n.d.; Stichting RIONED, n.d.). The 'connected to' relation is explicitly used in the sewer replacement project. Pipes and manholes are connected to each other. For sewer pipes this connection is explicitly mentioned. Nevertheless, for other objects this relation can be valuable as well. For example, within the construction of the escalators, which components are connected to each other. It provides an additional view on the whole construction. The 'connected to' relation can be split in a mechanical connection or an electrical connection. The electrical connection can, for example, be used to give insight in the electrical control of the escalator installation and how the safety mechanisms are incorporated in the system. Finally, the 'is located within' relation provide information about the location of the object. Additional location information can be provided via an information type.

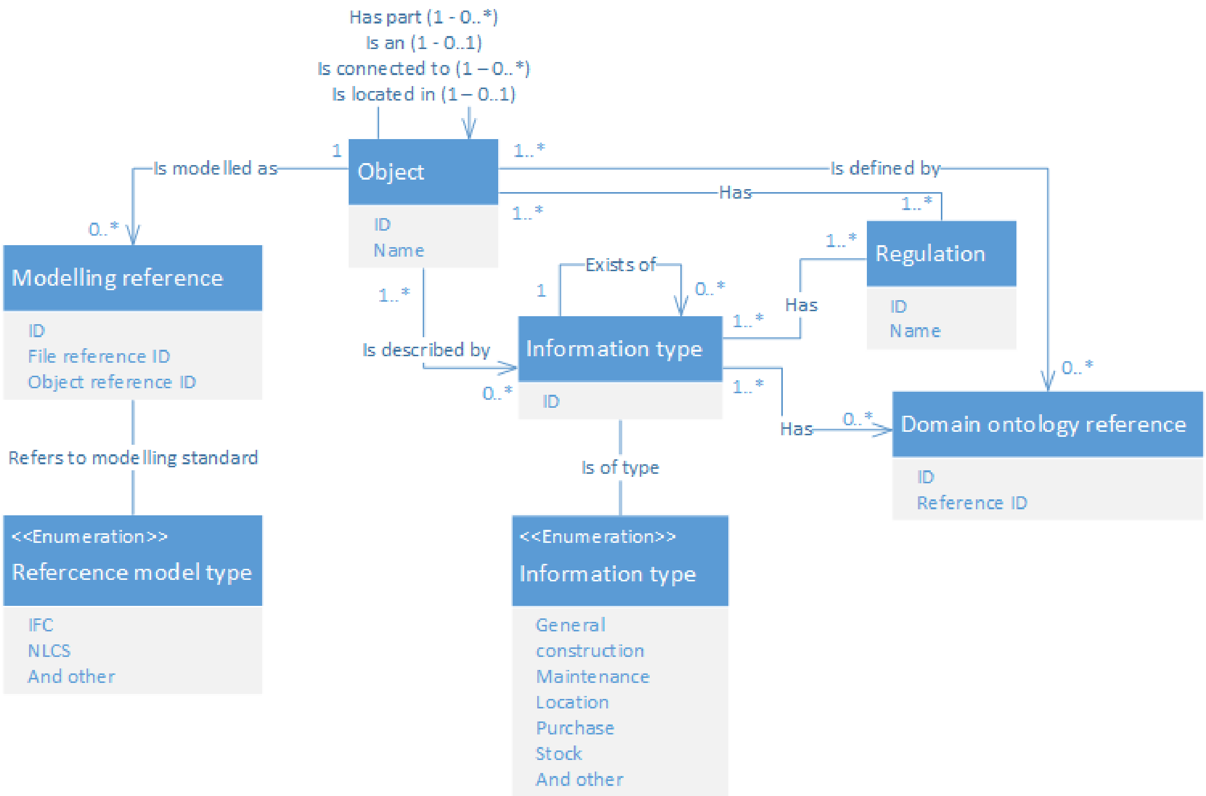

Figure 11: sub-model of object

As stated, there are four outgoing relations to other entities. Two of them link to modelling standards and domain ontologies. Since the modelling standards provide information about the representation in a BIM-model and the domain ontology provide information about the definition, functions and attributes of an object, the links are designed as two separate relations. The link to the BIM-model can be explicit to an object within a certain model or to a meta-object of a specific modelling standard.

The link to a domain ontology is instantiated by using the unique resource identifier of a specific domain ontology. Ideally this data is visualised via linking to the domain ontology. Nevertheless, it is an option to add data, such as the type's name, to the project or asset database hardcoded.

7.1.2 Information type

The entity 'Information type' is the third entity with a relation starting from 'Object'. An object is described by one-to-many types of information. As presented in figure 12, the entity functions as a collection for attributes, documents, and activities providing information about that information type. Having such a collection offers the opportunity to gain quick access to certain needed information related to an object.

To enable an increased structure of information, a self-relation is added to the design. An ‘information type’ can exist of none-to-many instances of ‘information type’. Additionally, a reference to domain ontology is added to ensure a well-defined definition of the ‘information type’. It should be reviewed critically if a selected definition of a domain ontology is in line with the actual type of information provided.

As analysed in the embedded case-study, information is available and needed in three kinds of entities: Attributes, Documents, and Activities. All these entities can be linked to ‘information type’ directly. However, the entity ‘document’ is a special one, as documents in the current process are used to transfer object information. Commonly, attributes, and activities related to one or multiple objects are described in these documents. To provide information about these documents it is valuable to make explicit which attributes and activities are described by what document. Having this information explicit, it becomes easier to select or open the right document in the search for information. Eventually, the need to transfer documentation may decline as all the information is already explicitly available. These entities should consequently be transferred or accessible digitally.

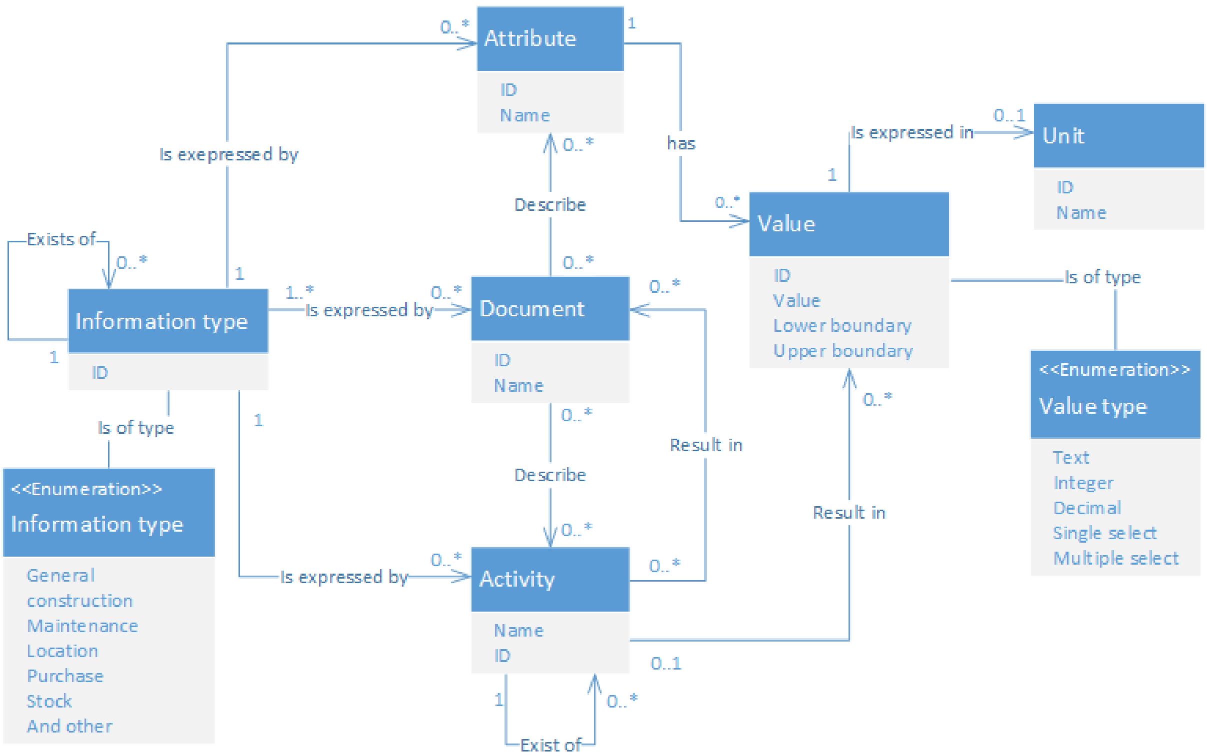

Figure 12: sub-model of information type, attribute, document, and activity

For ‘Attribute’ and ‘Activity’’, the relations to other concepts seems quite similar. While the in-going relations are exactly equal, there are some differences in the outgoing relations. First, an ‘Activity’ can result in none-to-many documents. Additionally, an activity, for example a measurement, can result in one or more values. Each value is associated with exactly one attribute. So, while both entities, attribute, and activity, have a relation to ‘value’, the meaning of this relation is different. It should also be noticed that an ‘Attribute’ can have none-to-many values. None, as it is known that the attribute is relevant, but no value is known yet, multiple as the value has changed over time, and this history is relevant to transfer. A final difference is the presence of a self-relation for ‘Activity’. An activity can always be decomposed into simpler sub-activities. While this decomposition is not necessary in most cases, it can be valuable for complex, non-straightforward, activities. It could be argued that some attributes can be decomposed as well. However, this relation is not considered relevant as no examples of such a decomposition are identified during this research.

In addition to the relations discussed above, the entities 'information type', 'attribute', document, and 'activity' can have a reference to a domain ontology (figure 13). While most domain ontologies mainly focus on objects and attributes, other concepts, such as activities and documents are defined as well. Regarding the reference of an activity to a domain ontology, the relation describes the type of the activity. The other reference relations are an 'is equal' to or 'is defined as' relation.

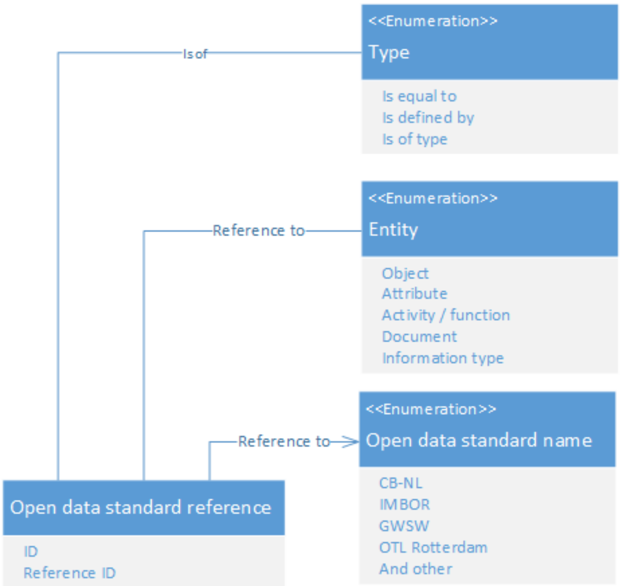

Figure 13: submodel of domain ontology reference

7.1.3 Findable / accessible

Based on the FAIR principles discussed in chapter 6 the ability to regulate the findability and accessibility of information should be part of the design. Therefore, entities for findability and accessibility are added. A remaining question is to what "information" entities these "regulatory" entities should be linked. Regulation can be applied on different levels of abstraction. Dependent on the trade-off between efficiency and precision in the regulation, a different detail level is selected. Regulating transparency on the 'object' level is quick but not precise. In opposite, regulation at the level of 'attributes', 'documents', and 'activities' is very precise, but a lot of work. To offer freedom in the level of regulation both high- and low-level regulation are designed for. By linking the entities of findability and accessibility to both abstraction levels, the user can decide on which level findability and accessibility are regulated. There is always, at least, one organization, person or role that has access to the information. The relation between a regulated entity and the findability and accessibility is shown in figure 14.

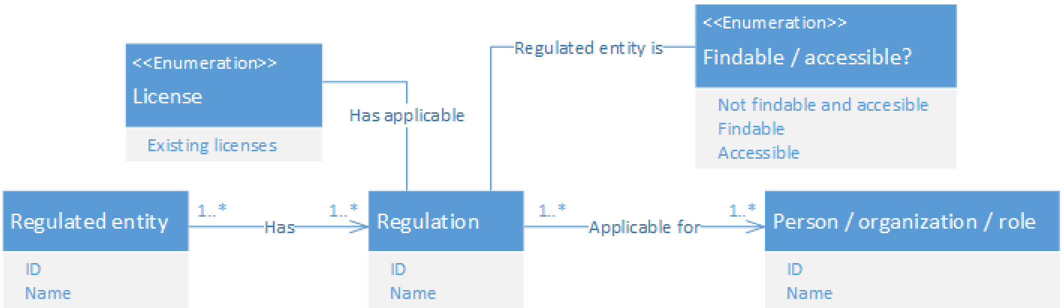

Figure 14: Sub-model of regulation of findability and accessibility

7.1.4 Meta-information

To ensure that the provided information is findable and if allowed, reusable, some predefined metadata should be provided for all concepts identified. Not for all entities the same metadata is required. Especially for the main entities object, information type, attribute, document, and activity more data should be provided. Nevertheless, first the required metadata for all entities is discussed.

For all entities, at least the attributes as shown in figure 15 should be provided or created automatically. By having these attributes each instance is uniquely identifiable and the registrar of the instance is known. Furthermore, the registration date / time provides some historical context; is an instance created recently and is not it updated yet or is it an older instance that was created accidentally perhaps. Finally, each instance has per definition a name or value. By demanding a name or value it is aimed that a human understandable identification is provided directly. This is beside the (auto-generated) unique ID.

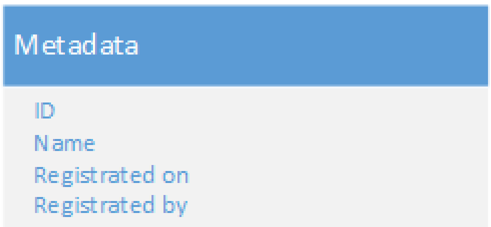

Figure 15: overview of standard metadata

Next to the standard metadata, some entities require extra metadata to provide additional information regarding the data quality and the reusability. This applies to the entities of document and activity. The additional metadata for ‘document’ is shown in figure 16. The fields of requested by and authorised by are the least standard. Nevertheless, both datatypes can provide information about the quality of a document. As a document is created on the request of someone, and / or it is authorized by someone as well, it can be expected that the quality of the content is higher than a document created to quickly store some information. Providing information about the creator of the document enables the option to ask eventual questions relevant to the reusability of a document. The same substantiation can be given for the relation between ‘activity’ and ‘person / organization’ (figure 17). In addition, a description of an activity and the method used should be provided. Especially the method used may provide information regarding the quality of, for example, a measurement.

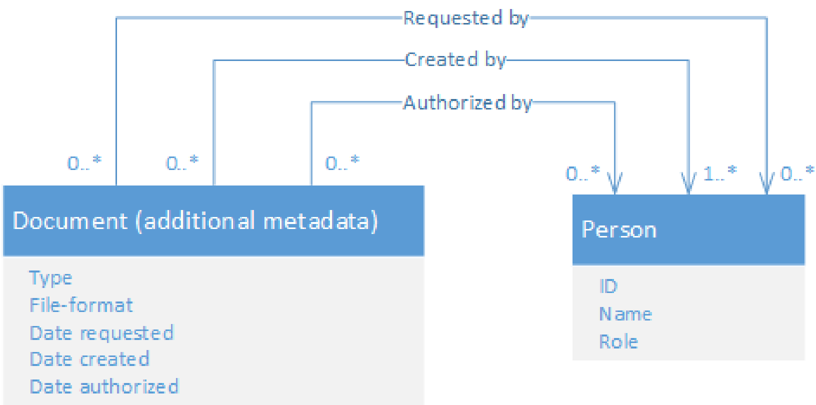

Figure 16: (additional) Metadata of document

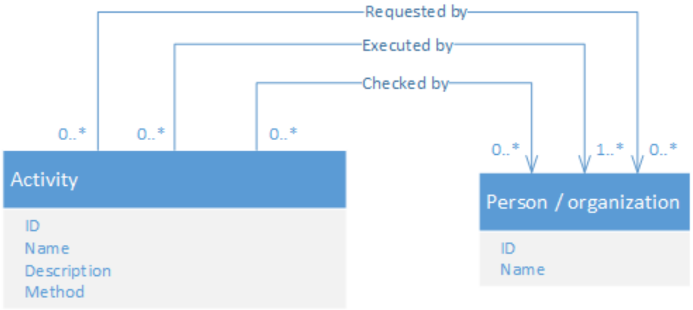

Figure 17: (additional) Metadata of activity

7.2 Evaluation of the design

The design presented above is evaluated against the requirements identified in chapter 6. For each of the requirements it is evaluated if, and to what extend the requirement is met (table 3). It can be concluded that most of the requirements are fulfilled. In addition, the design is very limited discussed within the escalator renovation project (16-05-2023) and in a preliminary phase with a field expert (21-03-223). Based on the evaluations, it is not possible to make strong claims regarding the exact relevance of the concepts and relations identified and about the practical contribution and usability of the design. Nevertheless, the design provides a structure for the information to be transferred, and thereby facilitates the alignment of information availability and need.

The minor evaluation discussions highlighted the importance of determining the appropriate level of detail. Breaking down each asset into its smallest components could lead to an overwhelming amount of data, which would be challenging for both humans and computers to manage. While it could be argued that additional investments in the IT infrastructure could address the issue of managing large data volumes for computers, this does not apply to humans. However, it is also not desirable to have all information directly linked to the top asset, as information should be provided in a structured way. The designed ontology allows for a flexible degree of decomposition and does not dictate what information should be transferred, leaving the decision on the level of detail to the ontology users. However, a structure to decide on a clear level of detailed is offered by the design.

REQUIREMENT	EVALUATION
The design is an ontology	The definition of an ontology is defined by Guarino et al. (2009., p.2) as “means to formally model the structure of a system, i.e., the relevant entities and relations that emerge from its observation, and which are useful to our purposes.” The presented design complies to this definition. As the concepts and relations are based on the performed case-study into the ‘system’ of information transfer, they are considered relevant. Nevertheless, the design is not tested or evaluated by experts. Therefore, it cannot be claimed that all concepts and relations are relevant. It could also be that relevant concepts and relations are missing.
Relevant concepts within the ontology design link to modelling standards and domain ontologies	For this requirement, the question is again, what are the relevant requirements? To be as complete as possible, multiple domain ontologies have been browsed through. The concepts part of these ontologies and part of the design are linked. Most concepts part of the designed ontology can be linked to a domain ontology or a modelling standard.

Objects are central in the design	The design process started with the entity ‘object’. As consequence, ‘object’ is the only entity without any in-going relations. Therefore, it is concluded that objects or assets are central in the design. Nevertheless, it should be mentioned that the absence of in-going relations is not a prerequisite for being central in the design. It could be argued that the total number of relations is a better measure, or the number of relations with unique concepts.
Documents and drawings describing assets and their information are incorporated in the design.	Within the presented design, ‘document’ has an important place. The choice is made to model the concepts of document and drawing as one entity. However, the type of document could be indicated. Explicit relations to attributes and activities described in documents or drawings are added to the design. The relation between objects and documents is made via the entity ‘information type’.
Structure is provided for available and needed information	The ontology provides structure for the available and needed information by multiple means. The self-relations of ‘object’ are a first option to create structure. By creating a decomposition or taxonomy, quick insight in the composition and objects / components of an asset is provided. A second means is provided by ‘information type’ and the self-relation of this entity. This construction allows to create comprehensible collections of information regarding a specific aspect of an asset.
Multiple information types are part of the design.	To include the information types identified as mentioned in chapter 6, three choices are made. First, the concept information type is, as stated above, explicitly incorporated in the design. Second, a distinction is made between the concepts attribute and activity. Third, an attribute can have multiple values. This provides for the creation of a value history, and thereby accommodate measurement data. The value’s registration date and the in-going ‘has result’ relation from activity provide additional context to a value’s history.
The concepts of findability and accessibility are explicit part of the design	Regarding the findability and accessibility, a specific regulation entity is included in the design. This entity has relations with ‘object’, ‘information type’, ‘attribute’, ‘document’, and ‘activity’ to allow for regulation on a high -or low abstraction level.
Insight in data quality and reusage	Insight in the data quality is provided by requiring additional metadata for the entities of document and activity. In addition, most of the identified concepts can be linked to a domain ontology providing extra context to reuse information. The ontology itself provides already the most important context to eventually reuse certain information. Furthermore, an upper -and lower bound are added as attribute types for ‘value’. With these attributes extra certainty is given about the value of an ‘attribute’.

Table 3: Design evaluation

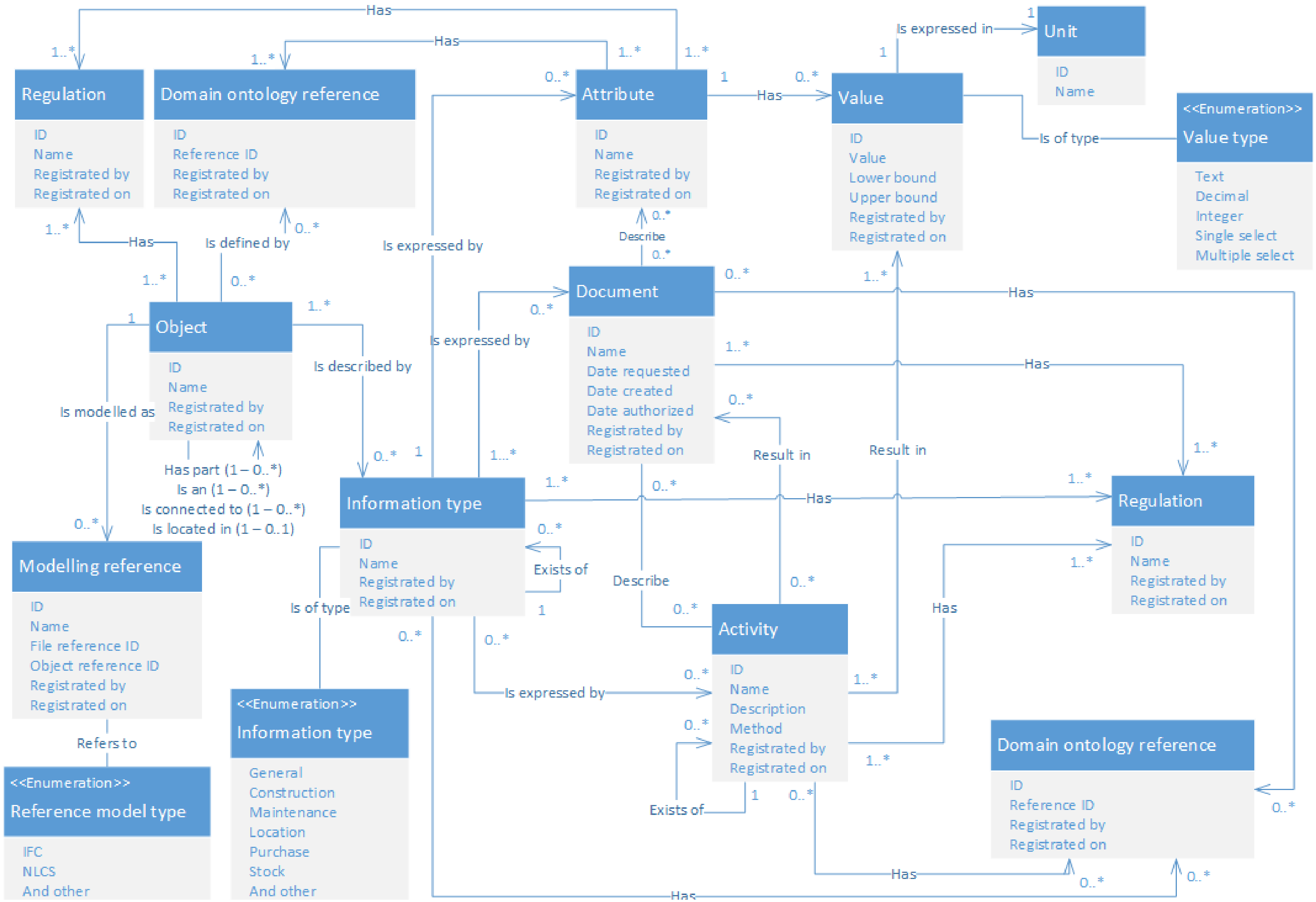

Figure 18: Ontology design (complete)

8. Conclusion and discussion

The final step of the presented design science research approach is to discuss the contributions of the presented research and design to the scientific knowledge base and local practice related to the problem and objective presented in chapter 1. The objective of this research was to design an ontology linking assets and their related information to BIM data-schemes and domain ontologies in a general way. Such an ontology should increase the interoperability between asset development and asset management information systems, and thereby reduce the loss of information.

In this chapter an answer to each sub-question is presented in section 8.1. Sections 8.2 and 8.3 follow with the scientific and practical contributions derived from these answers. The limitations of the research that may impact these contributions are discussed in section 8.4, and finally, recommendations for future research are presented and discussed in section 8.5.

8.1 Main findings

In this section the main findings of the research are presented. For each of the four sub-questions, a short description of the research approach is followed by an answer to the sub-question.

8.1.1 Sub-question 1: scientific basis and background

To provide the scientific background and define the scientific basis for the research project a literature study into the current state of the literature regarding asset lifecycle information management and interoperability is performed. Additional literature focussed on Building information modelling (BIM) was analysed after a review of the initial literature review by a field expert.

As result of the literature study, it is concluded that there are two main reasons for the lacking interoperability between project development and Asset management:

1. Misalignment between the availability of information and the information needs of Asset management (Bosch et al., 2015; Cavka et al., 2017; Farghaly et al., 2019; Toyin & Mewomo, 2022; Tsay et al., 2022).
2. Inadequate mapping of objects, information, or data from Building Information Modelling (BIM) software to asset management systems (Dinis et al., 2022, p. 887; Jiang et al., 2019, pp. 21-22; Rogage & Greenwood, 2020; Toyin & Mewomo, 2022).

In addition, it is suggested by Jiang et al. (2019) to use an ontology to overcome these issues. While ontologies are used several times on a case-by-case basis (Farghaly et al., 2019; Le et al., 2018; Rogage & Greenwood, 2020) and specific domain ontologies, such as the CB-NL, IMBOR, and GWSE, exist to limit ambiguity and miscommunications related to asset information, no ontology was found that links multiple modelling standards and domain ontologies. Designing such an ontology was therefore taken as objective for this research.

8.1.2 Sub-question 2: findings from local practice

Analysing the local practice facilitated the identification of entities and relations relevant for the ontology. Two cases within the municipality of Rotterdam are analysed in-depth as part of the embedded case study. The two cases are the renovation of the monumental escalators at the Maastunnel and the sewer replacement of the Saftlevenstraat. The analyses focussed on the information transfer process, the information availability, and the information need. The following conclusions regarding the findings within this local practice are drawn.

The information transfer process is established for the regular sewer replacement and as consequence, it is known what information should be transferred how. In opposite, such a process did not exist for the escalator renovation project. Although, it was agreed that the transfer of the responsibility for the escalators would happen in cooperation between the project team and the external asset management company, the transfer of information remained limited. Especially since a lot of information exists implicitly by the project team mechanics. This due to their years of experience. For both cases, it was found that a lot of information was stored in documentation not readable by the asset management information systems. Therefore, the manual transfer of information inside those documents is needed to fill the asset management information system with the relevant data. To enhance the interoperability between project development and Asset management the information inside the documents should be made more explicit so the information becomes readable by the asset management information system. Additionally, multiple information types and documents relevant to transfer are identified:

- Object information like the object type, attributes, specificities, the supplier and the existence and location of spare parts.
- Maintenance activities required to extend the lifetime of the asset and keep the working conditions within the stated boundary conditions. This is mainly relevant for specific assets where such knowledge is not available within the team of Asset management.
- Asset documentation including as-build documentation and supporting documentation containing substantiation for design choices, additional drawings, or specifications of objects.

8.1.3 Sub-question 3: Design requirements

Based on the conclusion of the scientific knowledge base, the findings from the local practice and additional research into the FAIR principles (Wilkinson et al., 2016) a list of design requirements was established in chapter 6. The FAIR principles stand for findable, accessible, interoperable, and reusable. Below the requirement list is presented. The requirements are sorted by their source.

Scientific knowledge base

- The design should be an ontology.
- Relevant concepts within the ontology design should link to modelling standards and domain ontologies.

Embedded case study

- Assets should be central in the design.
- Documents and drawings that describe the assets or its related information should be incorporated in the design.
- The ontology should provide structure for the available and needed information.
- Multiple information types such as object characteristics, maintenance activities, stock information, and measuring data should be part of the design.

FAIR principles

- Findability of concepts should be made explicit in the ontology design.
- Accessibility of concepts should be made explicit in the ontology design.
- All relations between concepts should be described explicit.
- Insight in the quality of the data is provided.
- Other attributes relevant for the reusage of data are provided.

8.1.4 Sub-question 4: Ontology design and evaluation

The whole ontology, linking assets and their related information to BIM data-schemes and domain ontologies in a general way is presented in figure 18 (page 49). The design is discussed piece by piece in chapter 7, here an overview of the main features of the design is given. These features relate to the list of requirements. Besides an extended evaluation against the design requirements limited evaluation discussions with the escalator renovation project (16-05-2023) and, in a preliminary phase, with a field expert (21-03-2023) were held.

Based on these discussions it is concluded that the application of the ontology could lead to practical issues if an asset is decomposed into too much detail. This due to an overwhelming amount of (unnecessary) data. In opposite, some decomposition is needed to provide structure for the information that should be transferred. Deciding on the level of detail of the transferred information is up to the ontology users. Nevertheless, the design provides a structure for the information to be transferred, and thereby facilitates the alignment of information availability and need.

Design features

- Objects are central in the design, meaning, all information should be linked, eventually indirectly, to an object.
- Information type is included as a specific entity to provide structure in the information.
- Information related to an information type can be expressed in attributes, documents, and activities.
- The information inside a document can be made explicit in attributes and activities.
- The modelling references can refer to a specific object in a specific BIM-model or to meta-object of a specific BIM data-scheme.
- The domain references always refer to a specific instance within a domain ontology.
- Findability and accessibility are incorporated by the means of a separate regulation entity to provide flexibility on the abstraction level of regulation.
- Metadata provide additional information related to the reusability of information.

8.2 Contribution to scientific knowledge base

The contribution of this research to the scientific knowledge base has three aspects. First, the research contributes to the scientific knowledge base by addressing the knowledge gap identified in the literature review. An ontology is designed that enable the linking of assets and their related information to BIM data-schemes and domain ontologies. Thereby, the research add knowledge to both the information and technology perspective regarding the transfer of information between asset lifecycle phases. To the technology perspective as it is proposed to store information in a structure that simplifies the transfer of information into asset management systems. To the information perspective as concepts and relations between these concepts relevant for the transfer of information are derived from the analyses of two real-world cases. As result of these cases an insight is gained in the current way of transferring information within the municipality or Rotterdam as well

The second aspect relates to the FAIR principles. While the FAIR principles are designed for the openness and transparency of scientific data, this research has considered the implications of applying the principles on governmental (asset) data. In addition, the principles considered relevant, eventually adapted, are included in the ontology design. It should be mentioned that no extensive literature research is performed into the application of the FAIR principals on governmental data and within an ontology. Nevertheless, this research may provide new insights in the application of the FAIR principles.

8.3 Practical contributions and recommendations

The main contribution of this research is, of course, the designed ontology. However, it is not yet tested and implemented. Therefore, the direct practicality can be questioned. Nevertheless, some other practical contributions and recommendations are made. First, the contributions generalizable to the general practice are mentioned. Second, some direct contributions to the local practice are stated.

Regarding the municipality of Rotterdam, it is noticed that the department of City development and City asset management are two separated organizations on paper and in practice. It is recommended to cooperate on a closer level to improve the information transfer process. Especially regarding the pilot procedure of the sewer information transfer process. Although, besides the sewer replacement project no other standard information transfer procedures are analysed, it is valuable to align the provided and required information for all standard assets. It offers the opportunity to standardize and thereby digitalize and eventually automatize the information transfer process. As result, the information loss will decline.

Another recommendation is to make explicit what information is stored in which documents. It should be clear what information of what object or activity is described in a document. This increases the understanding of the available information. Having insight in the information available, insight in the information lost is obtained easier. Insight in the information lost offers opportunities to take concrete action to reduce this loss.

While it is stated by a numerous amount of literature, a final recommendation is to start as early as possible to think about the transfer of information to Asset management. Once a project is started, day-to-day business takes priority over other subjects. Defining the information transfer process and aligning the information availability and need as early as possible prevents additional work later in the project.

With respect to the generalizability of these recommendations it is assumed that the municipality of Rotterdam is not much different as the three other major municipalities within the Netherlands. Therefore, the findings of this research may be generalized to at least these municipalities. In addition, the transfer of information at the end of asset development is not limited to municipalities. Beside other governmental organizations such as ‘Rijkswaterstaat’ and the regional water authorities, major private compagnies with their own asset management systems will have the same issues. These organizations can provide from the findings presented as well.

As stated, in addition to the generalizable contributions, the research execution had some direction contributions related to the escalator renovation project. Analysing the information transfer of the escalator renovation project prioritised this subject within the project. Due to the interviews and by being a fly on the wall / in the soup, unintentionally focus is brought to the relevance of information transfer by as well the project team as the asset management team responsible for the escalators after the renovation. In addition, the decomposition, created to structure the information available, is considered useful and will be imported into the asset management system.

8.4 Research limitations

To provide insight in the quality and generalizability of the results, limitations of the presented research are discussed. First, limitations regarding the research contributions and generalizability are discussed. Second, limitations regarding the reproducibility are discussed.

A main limitation of the research is that the presented design is only limitedly evaluated and not tested extensively. This is needed to validate the scientific and practical value of ontology. Due to the limited time available for the research project, extensive evaluation and testing of the ontology was not possible. A second limitation is the limited number of projects analysed as basis for the design. While it was and deliberated choice to analyse only two projects within the main case, it limits the research' generalizability. Having considered one unique project and one standard project both limits as strengths the generalizability. It's a limitation of the research as differences between standard projects and unique projects themselves are not considered. In opposite, it is a strength as a broad range of projects is reviewed. A final limitation is the probable non-exhaustive description of the literature connected to the research problem. As the DSR problem had to be find out during the research project, it was difficult to search for the relevant literature right from the start. By having evaluated the initial literature review additional literature was added. However, additional literature into the field of ontologies regarding the transfer of information could have been search for more thoroughly.

Regarding the reproducibility the main limitation is that a lot of the documentation used is internal documentation. As this documentation is not publicly available, an exact reproduction of the research is difficult. Nevertheless, by being transparent in the methods and procedures used within the research project, it is aimed to address this limitation. Related to this, the analysis of the internal documentation is, due to the use of Relatics, documented extensively. The documentation of the performed interviews and the findings within the fly on the wall / in the soup is more scattered and less extensively. However, an overview of all official meetings held is provided.

8.5 Recommendations for future research

To conclude, several recommendations for future research are provided.

A straightforward recommendation is to investigate more cases and projects regarding the transfer of information. Two options for researching additional cases exist. 1) Additional projects within the municipality of Rotterdam. 2) Research the transfer of information within other organizations. Researching more projects within the municipality of Rotterdam can provide direct substantiation to the findings of this research as the context is the same. Conducting the same research in another case lead to higher generalizability of the results as the context is different, but the phenomenon research remains the same.

Future research could also focus on evaluating and testing the designed ontology. By testing the ontology, eventual flaws in the design could be improved and additional knowledge is gained about the implementation and usage of the ontology. Using linked-data methods could be promising to create a valuable implementation with respect to the FAIR principles. However, the transfer of information from these models into other software applications should be considered.

A final recommendation is to do research into the application of software automatically analysing documentation regarding the attributes and activities insight this documentation. Additional these attributes and activities could be placed in a predefined structure. The current developments regarding artificial intelligence and language models may offer opportunities to derive explicit knowledge from documents in an 'easy' way.

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Appendix A – List of interviews

List of interviews to identify the design research problem

Date	Subject	Attendees (except the researcher)
2022-12-13	Information transfer SO/SB in general	Systems engineer BIM 2
2022-12-13	Information transfer SO/SB in general	Project manager escalators Maastunnel 1
2022-12-19	Information transfer SO/SB in general	Advisor Public Space and Asset Management
2022-12-19	Research inspiration and guidance	Field expert - Advisor BIM & GWW
2022-12-22	Information transfer SO/SB in general	Advisor GIS 1
		Advisor GIS 2
		Advisor GIS 3

Interviews, conversations, and presentations for analysing the Saftlevenstraat sewer replacement project.

Date	Subject	Attendees (except the researcher)
2023-01-31	Conversation: Sewer replacement and data transfer	Systems engineer BIM 3
2023-02-14	Sewer system in general	Accountmanager water
2023-03-06	Sewer information transfer proces	File manager
2023-03-20	Information availabilty sewer replacement Saftlevenstraat	Project engineer
2023-04-12	Information need sewer system	Asset manager Water
2023-05-17	Presentation: Efficiency in the revision procedure	Systems engineer BIM 3

List of main meetings related to escalator renovation project

Date	Subject	Attendees (except the researcher)
2023-01-12	Introduction to the escalator renovation project team including a tour alongside the escalators.	Mechanics escalators Maastunnel
		Project manager escalators Maastunnel 1
		Project manager escalators Maastunnel 2
2023-01-12	Asset management in general	General Asset manager Maastunnelcomplex
		Projectmanager escalators Maastunnel 1
2023-04-13	Information transfer process and information need	Asset manager escalators maastunnel
		Maintenance manager Maastunnel complex
		Service coordinator tunnel technical installations Maastunnel
2023-05-16	Escalator decomposition and information need / level of detail	Projectmanager escalators Maastunnel 1
		Asset manager escalators maastunnel
		Maintenance manager Maastunnel complex
		Service coordinator tunnel technical installations Maastunnel
		Advisor City asset management
		Maintenance Engineer

Appendix B – Relatics model escalator analysis

The model provided below is used to identify the relevant components within an escalator.