

# UNIVERSITY OF TWENTE.

Faculty of Engineering and Technology

Master thesis

**Construction Management and Engineering**

**Conceptual Modeling of Lifecycle Digital Twin Architecture  
for Bridges; A Data Structure Approach**

Inga Maria Giorgadze

3 of November 2020

**Supervisors:**

Dr. J.T. Voordijk

Dr.ir. F. Vahdatikhaki

Faculty of Engineering and technology

University of Twente

7522 NB Enschede

The Netherlands

# Conceptual Modeling of Lifecycle Digital Twin Architecture for Bridges; A Data Structure Approach

Inga Maria Giorgadze  
University of Twente  
Faculty of Engineering Technology  
Drienerlolaan 5, 7522 NB, Enschede, The Netherlands  
i.giorgadze@student.utwente.nl

## ABSTRACT

While the concept of BIM encourages the use of digital semantic models for communication and decision making across the entire lifecycle of assets, in the current practice, the use of BIM is predominantly limited to the design phase. The major issue with the use of BIM in the post-design phases is mainly the integration of non-design data (i.e., safety, productivity, and structural health, etc.) in the model, because in the current process this is done manually and therefore it is time-consuming and error prone. To address this gap, the concept of Digital Twin (DT) has emerged in recent years. In DT concept, cyber-physical system theory is utilized to use a wide array of sensory data to collect condition data about an existing asset and then integrate this data into the digital model. While a few pilot projects indicate the potentials of DT, the major limitation is that the current scope of DT is limited to operation and maintenance phase. This research argues that the DT concept can be extended to the entire lifecycle of the asset by trying to incorporate relevant sensory and non-sensory data into the digital model in an automated and systematic way. However, in the current literature there is no clear insight about such a holistic and life-cycle DT concept for infrastructure projects. Especially, there is very little understanding about how various sensory and non-sensory data from construction and operation phases can be seamlessly integrated into the 3D BIM models. Therefore, this research aims to develop a conceptual model for the architecture of Lifecycle DT (LDT) focusing on bridges. To this end, an ontological modeling approach was adopted to develop an overview of bridge LDT. Since this conceptual model would provide an insight into how to make conventional BIM models LDT-ready, it can be used as the basis for the transition towards the implementation of LDT for bridges. The developed conceptual model was validated through a set of

interviews with experts. The findings of the research indicate a set of lifecycle information needs that the model should be equipped with, to cover the needs of different disciplines. These information pieces can be represented by a set of required fields in the BIM model. This way the sensory data are pre-allocated in the model at its early creation upgrading it into DT-ready. Apart from the sensory data a set of interlinked data pieces was identified among different databases of different disciplines. It is proposed that the LDT-ready BIM model serves also for linking these databases to enable a seamless information flow from one lifecycle phase to another. The allocation of all these data pieces occurred in an ontological model representing the data structure of the LDT-ready BIM model, as well as the relationships between different entities of the model. This ontological model offers an insight of a lifecycle modeling practice as well as an automated data incorporation in the model, confronting respective gaps in literature. Overall, the proposed solution enables a smooth transition towards an upgraded and more automated modeling practice as indicated by the concept of DT.

*Index Terms* – Lifecycle Digital Twin, Digital Twin-ready BIM model, data structure requirements, ontology creation

## 1 INTRODUCTION

Integrating the lifecycle information of a construction project in a modeling practice has received much attention lately, as fragmented information deriving from different sources gain added value when combined. Building Information Modeling (BIM) attempts to include all the relevant information of a project for its whole lifecycle, for both the product and the processes in an object-oriented 3D model. However, the shortcoming of the current BIM practices is that a considerable amount of manual work is required to generate, maintain, and update the information.

This manual process is not only time-consuming but also error-prone. Therefore, an effort is being put towards a shift to more automated acquisition and integration of information in BIM to serve an asset's whole lifecycle.

Digital Twin (DT) is an upcoming concept, gradually gaining ground in the construction sector, which can serve the needs for automatic acquisition and integration of information. In this concept, the digital replica goes beyond object-centric data models like BIM which serve as simple data repositories. In object-centric data models, properties and relationships between components are manually distributed and assigned to the different parts visualized in a 3D model. On the other hand, DT is a multi-physics model, fed with meaningful data about the asset and the environment around it, acquired by its physical twin. As far as the construction industry is concerned, DT can be described as an extension of BIM, with the step taken forward regarding the automatic update of the digital model from its physical counterpart itself. This extension improves the dynamic and reactive abilities of the current BIM practices, through the use of sensors, IoT, and cyber-physical system. Such technologies make the physical asset smart and enable it to communicate with its digital counterpart about its health and condition.

The possibilities deriving from DT may serve a large spectrum of construction activities, however, proposed applications mostly focus on Operation and Maintenance (O&M) activities involved in asset management. To assist the integration of the lifecycle information concerning a construction project, the application of DT should consider the entire lifecycle of the asset. In Lifecycle DT (LDT), the digital and physical counterparts evolve in parallel from the design phase until the final demolition of the asset. In this concept, BIM is a platform that can host the collected data, and therefore its application should be expanded to serve the demands of real-time, automated data acquisition, and model evolution. However, the transition towards that concept demands several modifications in the designing approach and the BIM practices.

To enable a smooth and gradual transition towards the new modeling practices posed by the concept of LDT, it is suggested to align the current practices towards that direction. More specifically, since LDT is described as an extension of BIM for the construction sector, the BIM models should be created in accordance with the needs regarding the implementation of the LDT concept. All the necessary lifecycle information and the respective sensors should be predefined and the expected data pieces should be distributed and related to the relevant components of the asset. The different elements and properties that are assigned to host these data pieces should be considered in the development of the initial BIM model. In this way, a DT-ready BIM model, which is created in the design phase, can function as a LDT once the sensors and data acquiring

technologies are in place. In other words, future BIM models should be prepared from the design phase already in view of a full-scale LDT model.

### 1.1 Problem Statement and Research Objective

Several applications of the DT have been proposed for construction projects, with the majority of them focusing on the O&M phase and ignoring the importance of the information generated in the early phases of a project. Additionally, these attempts are conducted in a fragmented and independent way, lacking the consideration of an integrated lifecycle approach. It can be hence observed that a framework regarding the application of a LDT is absent.

Given that LDT supports seamless flow of information from one phase to another and allows for the optimization of different tasks in a more holistic way, it is important to move in the direction of transition from the current practices to LDT. As Brink & Weishut, (2020) also mention about the application of DT, "Data is at its most powerful when combined with other data". Furthermore, Gervasio & Dimova, (2018) highlighted the importance of decisions made and information generated during the design phase for the performance and the maintenance of a project. Therefore, apart from linking the different phases to integrate the scattered cases of implementing the DT concept, the inclusion of the design phase in the digital counterpart of the DT is considered crucial for the rest of the lifecycle, even if the physical counterpart is not yet present during that phase.

This research proposes the application of a LDT, where the digital and physical counterparts evolve in parallel from the design phase until the final demolition of the asset. To achieve the alignment in the evolution of these two across their entire lifecycle, it is necessary to predefine all the aspects that should be included in the model from its early creation to upgrade it to a DT-ready model. To summarize, current modeling practices lack the DT-readiness consideration and are conducted in isolation from the future needs regarding the lifecycle information flows and the links with sensor data.

This research aims to confront that absence and offer a conceptual model for the architecture of the LDT focusing on bridges. The conceptual ontological model outlines the requirements a conventional BIM mode should meet to be upgraded into DT-ready. The consideration of the models' readiness to incorporate new modelling practices serves as a basis for a smooth transition towards the implementation of the LDT for bridges. Briefly summarized, the objective of the research can be formulated as follows:

*"To identify the data structure requirements of a DT-ready BIM model for a bridge project during the design phase."*

To pursue the objective of this research, the following research questions need to be answered:

1. What is the current data structure of a typical BIM model of a bridge?
2. What information is needed during the whole lifecycle of the bridge vis-à-vis the current model's data structure?
3. What are the relevant data acquisition technologies that can be used for capturing the desired lifecycle information?
4. How can lifecycle data needs be coherently structured in the BIM model?
5. How can the proposed manuscript for the data structure be validated?

## 2 RESEARCH BACKGROUND

### 2.1 Building Information Modeling Deficiencies

BIM is a modeling practice currently used for the majority of construction projects. BIM can be described as a set of technologies that aim to serve the product and process needs of the lifecycle of an engineering project. All the relevant information is stored in a common platform, shared among the involved parties, and is represented visually in a 3D object-oriented digital model, which adds to the simplicity and common comprehension. However, even though in theory BIM is supposed to facilitate the whole lifecycle of a project, in practice there are some impedances in fully implementing BIM. According to Baumgartner & Schöggel, (2016) regardless of the progress made in the tools used in BIM practices, these tools still have shortcomings. The reason behind it is that usually these tools are being held separately from the manufacturing company's mainstream operations and therefore they cannot address the need for collaborative activities throughout the entire product lifecycle. Furthermore, each tool focuses on specific activities and processes within an enterprise, which further weakens the link among different activities involved in the project's lifecycle. This shortcoming is also discussed by Lu et al., (2019) who pose the information capture, exchange, use, and management throughout an asset's whole lifecycle as a key challenge to implementing BIM within asset management. The issue about information capture and management is further highlighted by Stojanovic et al., (2019), who underline that the generation and maintenance of BIM data requires a considerable amount of manual work and domain expertise to make use of the full potential of the digitization practices offered by BIM.

An effort is being put towards a shift to more automated acquisition and integration of information for the

enrichment of BIM. Isikdag, (2015) explains that initially, BIM evolved from a shared warehouse of information to an information management strategy, and thereafter will evolve to a construction management method. This new emerging dimension refers to enabling an integrated environment, distributed, up-to-date and open information and derivation of new ones, where sensor networks and IoT are technologies needed for this evolution. The integration of information acquired from sensors will add value to the building information by transforming it into meaningful, full state, and up to date. It is therefore widely agreed that the current BIM practices are inadequate to cover the lifecycle needs of an asset, and attention is given to advance these practices into more automated ones, bringing this way BIM closer to the concept of DT.

### 2.2 The concept of Digital Twin

The concept of DT was first introduced in 2012 for the verification and validation of aerospace vehicle models, in order to identify and quantify the limit states of the aerospace vehicles, since the last ones are likely to encounter unforeseen conditions. A general definition of DT which has been recognized and used by most people till now was given by Glaessgen & Stargel, (2012). According to this definition, "DT is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin".

Compared to what is already known from object-oriented modeling, Stojanovic et al., (2019) use the metaphor of an additional information layer to the digital model, which fuses as-designed and as-is physical representations when describing DT. Similarly, Haag & Anderl, (2018) describe DT as a system consisting of a physical twin, a digital twin, and a communication interface that connects the two. Among the characteristics of DT Tao et al., (2018) lists the real-time reflection of the physical space to the virtual one as distinguishing for the concept. Other characteristics of the concept are interaction and convergence. These mean that data generated in various phases in physical space can connect, that historical data and real-time data can be deeply mined, and that smooth connection channels between the two spaces allow an easy interaction. Finally, DT is characterized by self-evolution, meaning the continuous improvements that the virtual model undergoes through the comparison of virtual space with physical space in parallel. Based on the above, DT can be considered as an extension of BIM with the step taken forward regarding the automated acquisition of data from the physical asset itself, and the dynamic change of the model based on this data.

Several applications of the DT have been proposed for different lifecycle phases of a construction project. Regarding the construction phase, the CoSMoS Project proposes the integration of wireless sensor data with a BIM

model to enhance worker safety against hazardous situations (Riaz, et al., 2014). Furthermore, regarding the operation phase, project Dasher is an attempt of Autodesk to trace and optimise the energy consumption of buildings using a large number of motion, light, power usage and CO2 sensors to identify the occupancy, adjust heating and humidify and air ventilation systems, with an ultimate goal to minimize the anthropogenic greenhouse gases (Azam & Hornbæk, 2011). A similar approach referring to the maintenance phase is adopted by Valinejadshoubi, et al., (2017), who proposed the integration of accelerometer, thermometer, and strain gauge measurements in a BIM model to monitor the structural health of a four-story building.

### 2.3 Literature gap

It is widely identified by the scientific community that current BIM models are inadequate to cover the lifecycle needs of an asset and that a shift towards an automated acquisition and integration of reliable data is required (Baumgartner & Schöggel, 2016; Becerik-Gerber et al., 2012; Chen et al., 2014; Stojanovic et al., 2019). The cases found in literature offer a variety of possible applications of sensing technologies in both buildings and infrastructure projects. There are many proposed technical frameworks of how to link real-time sensing data to a BIM model and how this could enhance different activities of a project's lifecycle. However, an overall lifecycle approach considering all the phases of an asset, from the design to its demolition is missing and this hampers the implementation of the LDT.

To be able to satisfy the needs of the LDT concept, it is necessary to adopt a new approach regarding the management of the involved data in an asset's lifecycle and the way this data should be stored and managed from the early modeling phase. Becerik-Gerber et al., (2012) indicate the importance of including non-geometric data in the model such as manufacturing data, operational instructions and procedures, spare parts and maintenance specifications, warranty information, sensor data, and maintenance history. Besides, Chen et al., (2014) describe that embedding sensors to BIM by modeling them in the design phase and then later using them for infrastructure monitoring has not been explored yet. Therefore, it can be observed that an approach that considers a structured set of all the predefined relevant data of an asset's whole lifecycle is missing in the current design practices. This absence considers the early identification and inclusion of all the necessary information regarding the design, construction, operation, maintenance, and demolition of the asset, and hence the harmonization of this information across the entire lifecycle of the asset.

## 3 RESEARCH METHODOLOGY

### 3.1 Scope and context of the research

BAM Infraconsult BV is the company that provides the context for the research. The company is part of Royal

BAM Group NV, striving for smart, safe, and sustainable solutions in its distinctive way. BAM Infraconsult BV occupies itself with different kinds of infrastructure projects including roundabouts and traffic tunnels, bicycle bridges, multi-story car parks, sea locks, dike improvements, doubling railway tracks, drinking water mains, and super-fast fiber-optic connections. Furthermore, technologies and digitization constitute an important part of the company's agenda. The company provides access to the modeling practices and standards that are going to be used as a reference for this research.

Since the scope of infrastructure projects is large and each type of asset has its own specific needs that cannot be generalized and extrapolated to other projects, it is needed to focus on a specific type of infrastructure project. For this research, the model of a bridge is studied to identify the requirements that it should meet to be LDT-ready.

### 3.2 Research design

To answer the questions that serve in reaching the objective of the research, several steps were required. The research design includes the actions associated with the different research phases and as can be seen in Figure 1, the methodology consists of five phases, each aiming to answer one of the research questions. The first three phases are preparatory ones and explore different aspects relevant to the implementation of the LDT, and in the next two phases, the results of the preparatory ones are synthesized in a proposed solution and finally validated. The different steps are following described in more detail:

#### 3.2.1 Phase 1 – Current practices

The first phase of the research plan aimed to provide an insight into the way data is currently structured in a typical bridge BIM model. A practical investigation was conducted to explore the decomposition and classification of parts, the nature, and distribution of the properties of the model. To this end, an actual BIM model of a bridge from a contractor was thoroughly scrutinized. The findings of this investigation were then presented to a BIM specialist who was involved in the development of the model to verify and validate the observations. More specifically, an in-person semi-structured open-ended interview aimed to clarify potential issues regarding the object breakdown structure, the reasons behind the chosen decomposition approach, the inclusion of metadata, and the use of other platforms and formats associated with BIM practices. Finally, the first phase ended with the first preparatory product for the synthesis, namely a class diagram mapping the current ontology of the typical bridge model, answering this way the first research question of *what is the current data structure of a typical BIM model of a bridge*.

### 3.2.2 Phase 2 - Exploration of lifecycle information needs

In this phase, the necessary lifecycle information that the DT-ready BIM model should cover was explored. More specifically, all the relevant information that should be included, regarding different disciplines from different lifecycle phases of the bridge was identified. To achieve that, multidisciplinary input was needed and therefore a set of interviews was conducted to cover that need. A round of six in-person semi-structured open-ended interviews took place to identify the interest of different parties regarding the data that they desire to retrieve from the model to optimize their activities.

The criterion for the selection of the interviewees was to cover the whole lifecycle of the project and identify the information needs of each phase, as well as the information flow needs among the phases and disciplines. The lifecycle coverage by the interviewees and the relevance of each regarding the different lifecycle phases is depicted in Figure 2. Furthermore, another criterion for the interviewee selection was their position in the corporate hierarchy, meaning that people with practical experience over the activities of the department were preferred compared to higher-level decision-makers. The practitioners of each discipline were chosen because they were expected to have a clearer overview about their everyday needs and hence a more specific picture about the desired situation. More specifically, a Systems Engineer and a Design Leader were expected to give their insights about the information generated in the design phase and should be included in the lifecycle model, a Site Engineer was asked to outline the desired information that would enhance the construction activities during the construction phase, a Maintenance Engineer was called to describe what should be included in the model to optimize the maintenance activities during the O&M phase, a Safety Specialist was chosen to list the information needed to maximize the occupational safety planning for the different lifecycle phases, and finally, a Sustainability Specialist was selected to define the necessary information to maximize the sustainability performance of a project across its lifecycle.

Each interview ended with some specific Requests For Information (RFI) that the interviewees would like to be able to retrieve from the model. Finally, the missing data pieces were extracted from the RFIs and were classified according to their content. The missing data pieces were summarised in the second preparatory for the synthesis product, the RFI Taxonomy which covered the second research question of *what information is needed during the whole lifecycle of the bridge vis-à-vis the current model's data structure*.

### 3.2.3 Phase 3 – Exploration of relevant technologies

This phase of the research identified relevant technologies able to cover the needs that emerged from the previous

phase. A literature review explored appropriate data collecting systems for each RFI of the respective taxonomy, that required a sensor retrieved measurement. Finally, a set of specific technologies was selected to address the needs of sensor-retrieved missing data pieces. This phase ended with the third required product to synthesize the desired ontology, namely the Information Collecting Systems Taxonomy. This taxonomy listed the proposed technology solutions to address the RFIs deriving from the previous phase, clarifying this way *what are the relevant data acquisition technologies that can be used for capturing the desired lifecycle information*.

### 3.2.4 Phase 4 – Synthesis

At this stage, the products of the previous preparatory phases were synthesized in a common data mapping scheme. More specifically the identified missing data pieces of the second phase and the proposed solutions of the third were added to the ontology scheme describing the current data structure from Phase 1, enriching this way the current ontology scheme. This enrichment considered the additional classes and property fields that needed to be modeled to transform the model into LDT-ready. The incorporation of the missing data pieces in the current ontology introduced a set of requirements for the model's data structure, which answered the fourth research question of *how can lifecycle data be coherently structured in the BIM model*.

### 3.2.5 Phase 5 – Validation

To assess the result of the research a validation plan was needed. Several approaches were found in the literature for evaluating different kinds of ontologies. As reviewed by Brank, et al., (2005), Raad & Cruz, (2015), and Delir Haghighi, et al., (2013), the main evaluating approaches include comparing the ontology with a “golden standard”, application-based evaluation, comparison with a corpus of documents and finally human-based evaluation. This research considered a theoretical framework that connected different parts that are not incorporated yet in an existing ontology. Therefore, a comparison with a “golden standard” would not be possible since there was no reference ontology as a benchmark. Furthermore, since the ontology is at a theoretical level, and therefore not yet implemented, an application-based approach would also not be applicable. Therefore, a human-based evaluation from domain experts was adopted in this research.

The need for domain expertise was covered by the interviewees participating in Phase 2, namely the exploration of lifecycle information needs. These domain experts were considered to be the most suitable candidates to assess the research results, firstly because they are going to be the actual users of the proposed framework, and secondly, because they were more able to assess to what extent the RFIs that they have addressed are covered by the ontology.

Regarding the evaluation criteria, the ones that could be used to assess the ontology via human expertise were correctness, completeness, conciseness, and adaptability (Raad & Cruz, 2015; Delir Haghighi, et al., 2013). The criterion of correctness indicates whether the ontology represents correctly the real-world concept of the lifecycle of a viaduct. Completeness measures whether the domain of interest is appropriately covered, while conciseness indicates that an ontology should not include unnecessary concepts or redundancies. The last criterion, adaptability or extendibility designates whether an ontology is easily adaptable in the case of adding new definitions and new knowledge to existing ones.

For the execution of the validation, the domain experts were firstly presented the ontology alongside with examples of how it can be used to cover some RFIs, and then asked to fill in a questionnaire. The questionnaire considered whether the ontology satisfied the set of predefined assessment criteria. These criteria characterized the ontology qualitatively, however, to retrieve a more measurable assessment a 1-5 scale was used to indicate to what extent does the ontology satisfy each criterion. The lower score of the scale nominated that the criterion is not satisfied while the higher score indicated that the criterion is absolutely met. Apart from grading the ontology according to the scale, the questionnaire respondents were also asked to justify their answers and recommend improvements and additions. As approved by candidates from all the disciplines, the proposed solution was valid, the research was successful and the final research question *of how can the proposed manuscript for the data structure be validated* was answered.

## 4 RESULTS

### 4.1 Current modeling practices

The current ontology, as emerged from the exploration of the BIM models, is represented by a class diagram that can be seen in Figure 3. It can be seen that the model consists of two main parts, the topographic view and the viaduct model itself. The topographic view represents the environment surrounding the viaduct, including geometric information about the ground surface. Regarding the viaduct itself, the different construction entities from the software's library like floors, walls, columns, and beams are being used to represent the different components of the viaduct.

More specifically, regarding the foundation of the viaduct, the piles that are the slender members helping the weight applied by the viaduct to be transmitted evenly through the ground are represented by foundation piles. The pile caps that are placed right on top of the piles and provide them additional load transferring capacity are represented in the BIM model by a foundation slab. As far as the substructure is concerned, the abutments that are used at the ends of a

bridge span for the superstructure to rests, are represented by a basic wall. The same element type is also used to represent the wing walls of the viaduct, which are the structures located adjacent to the abutments and act as retaining walls. The road buffers used at the connection of the deck with the roads on the land are represented by buffer plates. Columns are the construction entity used to model the piers of the viaduct, which are the parts providing intermediate support between two bridge spans. The last parts of the substructure, the headstocks that provide sufficient seating for the girders and distribute the loads from the bearings to the piers are represented by wall entity types in the model. Regarding the superstructure of the viaduct, the deck which is the functional area that allows vehicles and pedestrians to cross is represented by a concrete floor. A combination of different kinds of beams like edge beam and ZIP profile beam is used to model the girder which is the load-bearing member supporting the deck. The bearings that are the parts providing a resting surface between the piers and the deck are represented by pedestal support. Finally, an asphalt floor is used to model the top asphalt layer of the deck, and sheet walls are used to model temporary separating objects used in the construction processes.

As far as the properties of the different elements of the model are concerned, apart from some instance-specific properties, all the elements share a set of common attributes. More specifically, all the elements of the model include information about their dimensions, area, volume material, and construction methods. Apart from these technical and geometrical properties, all the elements are characterized by a set of distinguishing codes, the assembly code, and the *codings*. The assembly code is a property included by default in the model. For the definition of this unformat code, the standard of NL-SfB is used. According to this standard, the classification of elements uses a hierarchical discretisation and the digits of the code characterise the element according to their functionality, the construction methods used, the materials and preparation processes, and their environmental and space characteristics. The *codings* is a locally developed standard by the members of the company to further distinguish elements unambiguously. *Coding* is an instance property that is not included by default and must be manually added by the modelers.

The process for defining the *coding* for each element consists of two steps and combines two decomposition approaches. This process holds for any kind of project and a template for the respective decomposition is present for each project type. The first step of decomposing the model takes place based on the locations of the objects. The viaduct is segmented into different locations with different objects belonging to each segment. The definition of segments is not standardized, but it takes place according to the specific needs of each project in a way that best assists the different tasks associated with the model. The designers

define the boundaries of each segment manually based on the specific needs and geometric characteristics of the project. Regarding the case of the viaduct, the decomposition may occur either based on the orientation of the viaduct or predefined x, y, z axes. The decomposition of the viaduct model in locations can be seen in Figure 4. The second decomposition step distinguishes sublocations of the objects and matches the commonly agreed decomposition of bridges in rough objects, namely foundations, substructure, and superstructure. The decomposition of the model in sublocations can be seen in Figure 5.

These two approaches for the asset's breakdown are both necessary for the naming protocol of the elements. With the combination of the prescribed digits that derive from each step, it is possible to unambiguously define all the elements in the model. Four levels of *codering* are needed to reach the desired unambiguous level of distinction:

*Codering 1:* Defines the object itself among a set of projects e.g. VI02 for the second viaduct of a larger construction project.

*Codering 2:* Adds the definition of the sub-object based on the sublocation of the object e.g. OB (Onderbouw) for the substructure of the viaduct.

*Codering 3:* Adds the definition of the segment of the sub-object e.g. 02 for the location marked accordingly.

*Codering 4:* The deepest level of *codering* defining the specific element based on the use of abbreviations as described in the company's standard element library e.g. CL (Column) for the pier of the substructure.

Therefore, the digits of *codering* 1,2,3 and 4 are used to ultimately define each instance of each project, which in this example is the *codering* VI02.OB.02.CL defining the column located in the location 02 of the substructure of the viaduct VI02. The steps of this process are depicted in Figure 6.

As far as the model's data enrichment is concerned, this occurs in an as automated way as possible. In other words, metadata is pulled in the model with the help of different add-ins. These add-ins are created in-house by different companies, and each tool may enhance different activities. For example, there is a tool that extracts specific non-visible background information from the model and registers them in the main visible properties of the elements. Such information may be the Globally Unique Identifier (GUID) for each element, the bounding box of the shapes, the area of different faces of a shape etc. Another tool calculates the area of different faces of a shape and registers it in the properties of the elements, which is very useful for calculating the surface of a construction's shell. Another example is a tool, that based on the concrete type of each element, assigns properties like the environmental class, the strength, the minimum cover etc.

These tools serve as an example of the possible extent of activities that can be executed with the assistance of a suitable algorithm. An important prerequisite to apply such tools is to have an unambiguous naming policy for the different parts of the model to enable an accurate filtering, selecting, and logic applying among the elements. At this point, the important role of the *codering* definition practice is highlighted. Furthermore, the more data is registered in the properties of an element, the larger the variety of logic rules that can be applied, which increases the potential of automated activities.

By projecting this phase's findings to the research goal of creating a DT-ready BIM model it can be observed that an initial effort of automation is already in place in the industry. The different tools created by the company's members allow different linkage possibilities with different databases, which is very useful regarding the automatic feeding of the model with sensor retrieved data. Also, apart from the existing tools, the unambiguous naming policy followed in the projects is a prerequisite that allows the development of any kind of tool that demands filtering, selecting, and allocating properties and values to some elements of the model. The application of logic rules may also enable the clearance and processing of raw sensor retrieved data before storing the information in the model. Therefore, it can be concluded that the company's efforts to introduce a local standard for the naming policy are in favor of the automated data feeding of the model which empowers the concept of LDT.

On the other hand, regarding the evolution of the model, it was observed that the models are no longer updated after the design phase. Some minor changes may occur in the construction phase, but the model is left on side afterwards. Therefore, the modeling practices fail to follow the lifecycle of the assets, and hence there is no clear picture of the as-is situation of the assets post-construction, and this hinders the activities conducted in the following lifecycle phases. Concluding, it is necessary to identify the lifecycle information needs and align the modeling practices according to them.

## 4.2 Exploration of lifecycle information needs

To investigate the information pieces missing from the current ontology and to upgrade it to LDT-ready, six domain experts were interviewed. The selected domain experts cover different disciplines of the asset's whole lifecycle and provided their insight about what they would like the model to include. The derived RFIs from the multidisciplinary interviews and the respective missing data pieces are summarised in a taxonomy that can be found in Table I.

For the classification of the RFIs, the missing data pieces needed to satisfy the requests are first listed. One or more



missing data pieces may derive from each RFI. Each data piece is further characterised according to the lifecycle phase that it is generated and is relevant for. Following, part of the missing data pieces is linked with an existing class of the current ontology of the model. The rest of the data pieces that remain unlinked indicate the need for enriching the ontology with the appropriate classes, suitable to host the respective data piece. Then, each data piece is characterised according to whether the relevant information exists in another discipline, or whether the information needs to be generated via the assistance of some information collecting technology. In the case that the missing data piece exists in another discipline or another platform, the source of the information is listed as well in the table. For the missing data pieces signed with a “\*”, the data piece needs a combination of sensor retrieved information with some information generated in another discipline to be satisfied. The derived RFIs are further classified according to the lifecycle phase they are generated from.

#### 4.2.1 RFIs deriving from the Design Phase

Regarding the Design Phase, different RFI emerged from different disciplines and are presented as follows:

*Q1. To select and filter the elements in the model to highlight the ones that satisfy a requirement, while distinguishing between own and client’s requirement.*

Compared to the elements included in the current ontology it can be observed that the missing data pieces from this RFI are the conformance with the requirement and the requirement owner.

*Q2. To retrieve the value of the end of the lifespan for each element separately.*

The missing data piece that derives from this RFI is the end of the lifespan of the different elements. This information is generated during the design phase however, it is most relevant during the O&M and Demolition phase, where the maintenance schedule can be optimized based on this information.

*Q3. To include the environmental impact value in the model for each element and for different scenarios to assist decision making.*

The missing data piece in this case is the environmental impact value, which is calculated at the Design Phase and stored in other platforms. The inclusion of that information in the BIM model combined with visualization potential provided by the respective software is expected to assist the decision making. This information may be generated during

the Design Phase, however it can assist decision making during the whole lifecycle of the asset.

*Q4. To retrieve the Material Passport (MP) of each element from the model.*

The missing piece, in this case, is a link with the existing documentation of the MP. This linkage occurs during the Design Phase at the creation of the model however, similarly to the environmental impact value it is relevant during the whole lifecycle of the project.

#### 4.2.2 RFIs deriving from the Construction Phase

As far as the Construction phase is concerned, the RFI that emerged from the interviews are as follows:

*Q5. To include the executed quality checks in the model for the different objects and register possible non-conformances*

The desired data pieces missing from the current ontology, in this case, are the link with the existing *Quality checks* documentation and the *conformance or not with the model*. This information is further relevant in the O&M Phase, where an accurate as-built documentation is crucial for planning the maintenance activities.

*Q6. To retrieve an estimation of the duration and cost of the execution for the different work sets and objects separately.*

The information piece that this RFI demands to be satisfied is the duration and cost of execution of the different tasks and objects. This information offers more accurate estimations for the following tenders, hence it enhances the Design Phase as well.

#### 4.2.3 RFIs deriving from the O&M Phase

The RFIs associated with the O&M Phase are formulated as follows:

*Q7. To be informed when the usage of the deck receives a value close to the designed one, to trigger attention for scheduling maintenance activities.*

The request demands the inclusion of the loading cycles that derive from the O&M Phase and the as-designed load capacity of the deck that derives from the Design Phase.

*Q8. To raise attention to the objects of the bridge that demand more frequent maintenance tasks compared to the planned activities.*

To satisfy this RFI it is needed to include in the ontology the record of planned maintenance activities as well as the record of the implemented activities.

#### 4.2.4 RFI's deriving from the Demolition Phase

The RFI that is associated with the demolition activities at the end of the asset's lifecycle is formulated as follows:

*Q9. To raise attention once the concentration of dangerous substances during drilling reaches a specific threshold.*

It is required, therefore, to include the data piece of the concentration of dangerous substances in drilling activities to satisfy this RFI.

#### 4.2.5 RFI's deriving from the entire lifecycle

Finally, some of the RFI's that derived from the interviews are not being generated during a specific lifecycle phase, on the other hand, they are relevant during the whole lifecycle of the asset. More specifically these requests are formulated as follows:

*Q10. To monitor whether a piece of equipment is still on-site and trace its location.*

This information may be generated during any lifecycle phase that equipment is used, hence during the Construction, Maintenance, and Demolition Phase. The missing data piece that this RFI indicates for the enrichment of the ontology is the location of the equipment.

*Q11. To retrieve an accurate estimation of the duration and cost of rented equipment as a verification to the received bills.*

Similarly, as the construction equipment may be used during different lifecycle phases, this RFI is also relevant for all these phases. The missing data pieces, in this case, are the duration and cost of the rental.

*Q12. To retrieve the deviation between actual and designed environmental variables.*

The relevant environmental variables for a construction project are the humidity and the temperature. The missing data pieces needed to satisfy this RFI are the as-designed temperature and humidity which are determined during the Design Phase, and the implemented environmental temperature and humidity, that are being measured during the entire lifecycle of the asset.

*Q13. To raise attention when the temperature falls beneath the threshold that allows the formulation of ice on the asphalt surface.*

The missing data piece that satisfies this RFI is again the implemented environmental temperature and humidity, that are being measured during the entire lifecycle of the asset.

*Q14. To raise attention once the workers are close to some identified danger which can be either a slope, a height, a moving vehicle, or dangerous materials.*

This RFI demands the definition of the location of the workers and risks. Some of the identified risks may be predefined during the Design Phase, and some others may be dynamically defined during the execution of some activity. For the second case, the respective activity may refer to either the Construction, Maintenance, or Demolition Phase.

*Q15. To raise attention when a moving vehicle approaches an area with unstable or humid ground.*

The missing data pieces that derive from these RFI's are the location of the moving vehicles and the location of unstable ground. Similarly, these locations may be either predefined during the Design Phase, or dynamically defined during some task of the asset's lifecycle.

### 4.3 Exploration of relevant data-collecting technologies

From the missing data pieces identified in the previous phase, the ones that are satisfied via the assistance of some kind of information retrieving technology are treated separately in this part. As can be seen in Table II, the respective missing data pieces are isolated from the overall RFI Taxonomy to assist the purpose of this phase, which is the creation of the Data Collecting Taxonomy. In this Table, each missing data piece is characterized by an information retrieving system able to cover that need, and a specific technology solution is proposed for each. The solutions are further elaborated in the following section.

#### 4.3.1 Real-Time Localization Systems

The most commonly used technologies that have been proposed in the construction sector for real-time localization are Ultra-Wide Bands (UWB), Radio Frequency Identification Tags (RFID), and Global Positioning Systems (GPS). RFID tags are the most reviewed and preferred ones for their simplicity of use and affordability. RFID is a technology using radio waves of different frequencies for identifying objects. A typical RFID system comprises of a RFID tag, which is formulated by a microchip that stores data and an integrated antenna serving as a transmitter, and an RFID reader (Lu, et al., 2011). According to Nasr, et al., (2013) RFID tags are applied in three different fields in the

construction sector, and these are tracking assets, people, and monitoring productivity.

As far as tracking assets are concerned RFID tags may assist activities referring to waste management, proper source management, and storing information about the manufacturer. Furthermore, regarding the equipment rental record-keeping, RFID tags can store the log of borrowing and return thus help to track the machines and tools, preventing loss, misplacement, or burglar (Lu, et al., 2011). Therefore, apart from enhancing the awareness of the equipment's location, this technology enables the calculation of renting duration, which already satisfies two of the missing data pieces of the RFI Taxonomy, the location of the equipment (Nr 14) and the duration of the rental (Nr 15).

Regarding the people tracing in the construction sector, this activity aims in enhancing safety on the construction site. As Awolusi, et al., (2018) described the use of real-time tracking systems during construction increases the situational awareness of the workers, by continuously collecting data from the job site, detecting environmental conditions and the proximity of workers to the danger zones. These zones can either be static and predefined in the model or dynamically identified with the use of the same technology. Furthermore, Teizer & Cheng, (2014) added to these preventive actions the use of sensing technology to detect the unauthorized intrusion to access-controlled or restricted spaces. The possibilities that this technology provides for assisting safety issues can satisfy another three missing data pieces in the RFI Taxonomy. These data pieces are the location of the workers (Nr21), the location of the hazards (Nr 22), and the location of the moving vehicles (Nr 23).

Finally, RFID technology may be used to monitor the productivity of both people and machinery. More specifically the technology assists the labour attendance record system, and this can also be linked with the log of rented machines and tools (Lu, et al., 2011). This possibility offers a clear picture of the time spent on the construction site and if also linked with specific tasks and work sets then it covers the missing data piece of the duration for the execution of different tasks (Nr7) from the RFI Taxonomy.

#### 4.3.2 *Laser Scanning Systems*

Photogrammetry, laser scanning, videogrammetry, and range images are technologies used to derive three-dimensional information from the physical environment and depict this information in a 3D digital model. Laser scanning is preferred to enhance different construction activities despite its higher cost. The advantage that this technology offers compared to the rest alternatives is the lower processing time for raw data. The LiDAR technique, which stands for Light Detection And Ranging, utilises the emission and return time of highly collimated

electromagnetic radiation to calculate the distance from the instrument optical centre to a reflecting target surface (Abellán, et al., 2014). The two main activities that a laser scan may assist regarding the research topic is the terrestrial scanning of the topography before the asset construction and the as-built documentation post the construction.

As far as the Terrestrial Laser Scanner (TLS) is concerned it may be either aerial, which is commonly used in large-scale terrain mapping, or ground-based which enables a more suitable view of steep slopes. The point cloud deriving from a TLS provides high-resolution topographic surveying with details about the orientation and steepness of inclinations and the diffuse of erosion. This information set can cover two missing data pieces from the RFI Taxonomy, namely the location of hazards and more specifically the location of steep slopes (Nr 22) and the location of unstable eroded ground (Nr 24).

Regarding the post-construction processes, laser scanning is a precise reality capturing technique that can be integrated into the as-built documentation processes, to significantly reduce the amount of labor and manual process of on-site data collection and measurements (Usmani, et al., 2019). Transforming a 3D spatial surface into an object-oriented model involves several steps. Firstly, the spatial on-site data must be collected through the assistance of laser scanning, and this process ends up with a point cloud describing the desired surface. Then, this point cloud must be broken down in elements in accordance with the modeling software used. This may occur either by recognizing and manually modeling the elements that constitute the point cloud or in an automated way through the assistance of some add-in. Revit offers a variety of add-ins that can create simplified depictions of building components by fitting geometric primitives, identify the walls' thicknesses, heights, and component's textures. The potential provided by such technology offers detailed documentation of the as-built situation which satisfies the missing data piece of conformance with the model (Nr 6) from the RFI Taxonomy.

#### 4.3.3 *Structural Health Monitoring Systems*

Regarding the structural health monitoring of a bridge, the use of Weigh-In-Motion (WIM) sensors is the most common practice to assess the condition of the bridges deck. WIM systems comprehend a wide range of technologies that allow estimating wheel weights and axle spacing of road vehicles moving at full speed and can be categorized as pavement-based or bridge-based technologies. Bridge-based WIM systems record the deformation of the bridge (typical strains) while the vehicle of interest is traversing the structure and use this information to estimate the vehicle's weight distribution (Cantero & Gonzalez, 2014). The use of this technology has assisted several applications including pavement and bridge design, assessment, and monitoring, monitoring the loads for fatigue calculations, management

of road infrastructure, and traffic planning. Therefore, such technology allows the measurement of the loading cycles of the bridge's deck covering the respective missing data piece (Nr 9) from the RFI Taxonomy.

#### 4.3.4 *Environmental Variables Measuring Systems*

These systems are used to measure the variables applied in the physical environment around the asset. The first sensor proposed for this reason is a hygrometer which is an instrument used in meteorological science to measure the humidity, or amount of water vapour in the air, in soil, or in confined spaces. Several major types of hygrometers are used to measure humidity. Hygrometers may be mechanical, electrical hygrometers, or indirectly measure humidity by sensing changes in weight, volume, or transparency of various substances that react to humidity (Britannica, 2019). A hygrometer can, therefore, cover the information needs of the environmental humidity (Nr 18) and the location of unstable humid ground (Nr 24) from the RFI Taxonomy. Similarly, the need for the environmental temperature (Nr 20) can be covered by the conventional air temperature measuring device.

#### 4.3.5 *Real-Time Respirable Dust Monitoring System*

To monitor the concentration of dangerous substances included in concrete during drilling activities, the use of wearable real-time respirable dust monitoring devices is proposed. These instruments use light scattering photometric technology to measure the amount of total respirable dust in the air. When properly calibrated, the instrument can determine the amount of crystalline silica contained within that aerosol sample. Then the level of respirable silica exposure is displayed on the device to inform the workers (TSI, 2020). This device satisfies the last missing data piece in the RFI Taxonomy, namely the concentration of dangerous substances in the air (Nr 13).

The different technologies chosen to satisfy the RFIs that demand sensor-retrieved information, may assist activities belonging in different lifecycle phases. The association of the selected technologies with the different lifecycle phases is depicted in a matrix that can be seen in Figure 7.

## 4.4 **Synthesis**

The synthesis concerns the integration of the results from the previous research phases. More specifically, the current ontology scheme is enriched to cover the lifecycle information needs and the respective data-collecting technologies covering these needs. The incorporation of these entities in the current ontology occurs in different ways. Some entities are being added as supplementary properties in existing classes of the ontology while some others require the introduction of new classes or even new sections of classes to allow a meaningful incorporation of the new entities. After the addition of these entities in the current ontology, the latter one is enriched as can be seen in Figure 8.

The enriched ontology consists of three main sections: the physical asset, the digital model, and the lifecycle which is the main addition compared to the current ontology. The physical asset has a lifecycle that is proposed to be represented in the digital model, which in turn communicates bilaterally with the physical asset, as the concept of DT implies. This relationship between the three main sections is depicted in Figure 9.

Regarding each section separately the way they are developed to include all the emerged entities can be seen in Figures 10, 11, and 12, respectively. More specifically, the lifecycle section includes apart from the different lifecycle phases, the different lifecycle aspects as well. These aspects that have not been represented in the model before are the different resources, processes, and involved risks. The resources include the different human agents involved in the design, construction and maintenance processes, the equipment, software, and material. The processes include construction, maintenance, logistics as well as designing actions. Finally, the risks refer to both safety hazards during some construction and maintenance tasks, as well as designing risks of failing to meet some requirement or budget restriction.

As far as the physical asset section is concerned, the data collecting technologies are added in the scheme as physical entities either embedded or remotely assisting the asset. The set of information collecting technologies is included in the data collection unit category, which is further divided into embedded sensors and remote sensing technologies. More specifically, the first category includes the LiDAR and TLS systems, and the latter one includes the hygrometer, thermometer, RFID tags, WIM sensors and real-time respirable dust monitoring devices.

Regarding the digital model section, the main addition in this section compared to the current ontology is the consideration of an agent and process model apart from the object one. DT has been characterised as a multiphysics and multiscale modelling practice, hence solely an object-oriented model is not adequate to cover the needs posed from the DT concept. The agent model represents the behaviour of the different resources while the process model concerns predictive, safety or productivity simulations. The three model types, namely the agent, process and element model are representations of different aspects of a common reality comprising a single digital model.

Apart from the introduction of new classes in the ontology, some data pieces can be distributed as additional properties to existing classes of the element model to increase its DT-readiness. This distribution may either concern the whole of the elements, the model in total or specific parts of the model. A first set of shared parameters is added to all the elements of the model. Each element is characterised by this

set of parameters and each element has a different value. As derived from the research the shared parameters that are added as properties to all the elements of the model are the requirement ID, the quality check ID, the conformance with the model, the end of the lifespan, the location, the as-scheduled and implemented maintenance record, the as-designed and environmental temperature and humidity resistance, the environmental impact value and the Material Passport.

Another set of parameters that characterise the model in total and hence there is no meaning in distributing them are the global parameters. The global properties host the same value for the different elements and therefore are assigned to the surrounding environment which is represented by the topographic view in the object model. The global values as identified in the research are the air humidity and temperature, the water diffusion of the ground and the soil erosion.

A final set of properties are project specific ones. Contrary to the shared and global parameters that can be repeated in different projects, the project specific parameters depend on the nature of the projects and the specific client's requirements. The only project specific parameter concerning the viaduct is the "loading cycles" of the deck.

As far as the relationships of the ontology are concerned, a set of new relationships has emerged from the incorporation of the new entities in the enriched ontology. Different classes from different sections are related to each other, and new relationships emerged within the individual sections as well. More specifically, the introduction of the data collecting technologies in the physical asset section introduced links between embedded sensors and different construction components of the physical asset section, equipment pieces and working agents from the lifecycle section. Furthermore, new linkages emerged also between data-collecting technologies of the physical asset section and the different model types of the digital model section, which is fed from these technologies. Another example, denoting the multiple emerged interrelations within individual sections, derives from the introduction of the risks in the lifecycle section. The lifecycle risks are associated with some construction processes, which in turn consume resources. Different data-collecting technologies monitor the progress of the processes and the productivity rate of the resources and then feed this information to the different sub-models of the digital model.

Regarding the way the limitations of the current modelling practice are being addressed from the proposed ontological model this occurs in different ways. Firstly, the combination of different model types, namely the agent, process and element model offers a multiscale modelling practice and a holistic modelling approach. Such a global modelling perception is in favour of managing and incorporating

diverse lifecycle data generated through the lifespan of a construction project. Furthermore, the predefinition and pre-inclusion of the different properties as well as the information flow channels increases the DT-readiness of the element model. The information paths and hosting fields are predefined at the creation of the DT-ready BIM model, and once the asset and data collecting technologies will be in place the concept of DT will be implemented and the model will be automatically updated by valid information. Moreover, the new emerged relationships between the new introduced classes offer a thick net of interrelated data which in turn offers a larger variety of application of logic rules based on this dataset. With the assistance of some algorithms and the application of logic rules it is possible to deeply mine data and identify patterns, apply correlation analyses, and identify emerged and latent phenomena. These applications serve as basis for machine learning and artificial intelligence, which are concepts closely related to the DT.

At this point, it should be clarified that the ontology is not an exhaustive representation of all the lifecycle aspects that the DT model can enhance, nor all the potential data collection variety that can assist such a model. This ontology serves as a comprehensive example of a lifecycle approach for a viaduct's DT modeling practice. Partial coverage has been conducted regarding the different instances included in the ontology, with the focus mostly given in covering the possible relations between the chosen instances.

#### 4.5 Validation

The validation sessions were executed in three rounds with candidates grouped according to their expertise backgrounds. The first session considered domain experts with background in coding and different programming languages, the second session considered an asset management background, and the third session considered a sustainability management background. The presentation of the ontology took place similarly in the three sessions, however the examples given and the RFIs tackled were adjusted to each domain expertise in order to assist the comprehension of the ontology for different backgrounds. Finally, the seven validation candidates from the three sessions were assigned to fill the same questionnaire from their perspective each.

For the criterion of correctness, six out of seven domain experts stated that the ontology constitutes a largely true description of the lifecycle of a viaduct, while one candidate stated that the representation is somewhat true. Regarding this criterion, the domain expert who has a coding and programming languages background, proposed a more structured classification of the element model's instances between libraries, object types, and instances. More specifically, the proposed ontology consists of only one tier of object decomposition, which compared to the Revit

software is respective to the instances tier. The domain expert hence proposed to add the tiers of libraries and families before reaching the instance level, to align the ontology structure with Revit's element structure. For example, the viaduct's girder is represented by ZIP profile beams that constitute a single instance from the Beams Family, which is not included in the proposed ontology. Furthermore, it was proposed from the same domain background in coding to investigate in more depth the possible data types for each attribute in the ontology's classes. Overall, the ontology scored high in all the three validation sessions with an average of 3.8 out of 5 in the correctness criterion.

As far as the completeness criterion is concerned, the majority of the respondents gave positive feedback. One out of seven domain experts found that the ontology covers the lifecycle of a viaduct to an absolute extent, five respondents found that the lifecycle is covered to a large extent and one respondent found that this occurs to a moderate extent. In order to complement the ontology, the respondents recommended the addition of some elements with a shorter lifespan, with examples given the architectural finishes, water drainage, and expansion joints. Additionally, a domain expert proposed the inclusion of the pre-design phase in the lifecycle, to consider the tendering processes and risks as well. Altogether, this criterion scored 4 out of 5.

Regarding the conciseness of the ontology, the general view of the respondents indicates that there are no redundancies. More specifically, five respondents found no redundancies in the ontology, one respondent identified some redundant representations, and one other many redundancies. The sharp deviation in the respondent's answers in this criterion can be justified by the fact that each validation candidate is assigned specific tasks for a specific lifecycle phase. More specifically, the lowest score given to this criterion derived from the sustainability specialists, and an interesting observation is that they do not use BIM for their tasks but their own native software. Moreover, the native software used in the Sustainability Department does not offer a 3D viewer and hence no geometric details, and this may further explain the reason the respondents found many redundancies in the ontology. In general, the ontology scored 4.2 out of 5 in the criterion of conciseness.

Concerning the adaptability and extendibility, this criterion was assessed through two potential scenarios. The first scenario concerns the extent to which the ontology is adaptable to include other aspects of a viaducts lifecycle, and the second scenario concerns the extent to which the ontology can be adjusted to represent the lifecycle of some other infrastructure asset. Regarding the first scenario, it was mostly agreed that the ontology is relatively easily adaptable. One respondent stated that it is very easy to add new aspects of a viaducts lifecycle in the ontology, four respondents stated that this can occur quite easily, one stated

that this is somewhat possible and finally the last respondent found this impossible. Overall, the ontology scored 3.5 out of 5 for the first scenario of this criterion. As far as the adjustment of the ontology to another infrastructure asset is concerned, three respondents stated that this may happen easily, two stated that it is somewhat possible and the rest believe that it is either hard or impossible to do so. To improve the level of the ontology's adaptability it was recommended to keep it at a higher level and develop it in detail only at a specific project level. Furthermore, it was proposed to integrate into the ontology information standards like COBIE, NEN 2767, and align the ontology with the company's object type library to reach a higher level of standardization. Again, in this criterion the lowest scores were given from the representatives of the Sustainability Department. The lack of a 3D modeling experience of the sustainability specialists may justify the poor assessment of the ontology's adaptability as well. Altogether, the ontology scored 3 out of 5 in the second scenario of the adaptability and extendibility criterion. The scores for each criterion as well as the proposed improvements for each are summarized in Table III.

Comparing the different backgrounds of the respondents, the ontology scored the highest from participants of the Asset Management background, with an average of 4,6 out of 5. Following, the participants with a programming background assessed the ontology with an average of 3,7 out of 5, while the lowest scores derived from respondents of the Sustainability Department who assessed the ontology with an average of 3,2 out of 5. As mentioned before, the Sustainability Departments not only does not use BIM for their tasks, but also their native software does not use a 3D viewer. This fact may explain the sharp deviation in the scoring results compared to the results of the rest background fields.

Apart from grading the specific criteria of the questionnaire some more interesting points emerged through the discussion of the validation sessions as well. Firstly, as far as the data collection technologies selected are concerned, it was assured that technology-wise the proposed sensing technologies can be immediately applied. The data-collecting technologies have already a sufficient level of maturity and the computational power poses no restrictions in linking data retrieved from them. Furthermore, it was also identified from some of the participants that a big part of the information needs exists within the company's different departments but flows insufficiently to the departments that it is more relevant for. As a mitigating solution, the participants agreed that it is necessary to clearly communicate and predefine a set of information needs and standardize the process of information exchange between departments. This set of predefined information needs should be communicated to the modelers at the early creation of the model to assure that all the property fields are being included in the model for the different lifecycle

phases. Finally, it was commonly agreed by all the participants in the validation sessions that the major challenge in adopting the proposed modeling practice is changing the people's routines to adjust them to a new one. More specifically, people involved in a project's lifecycle occupy themselves in small pieces of the lifecycle each, and are ignorant of the larger picture, which hinders the alignment of their tasks with a lifecycle approach.

Overall, the ontology scored from a medium to a good grade in the different criteria and the proposed improvements consider specific departments and tasks, which can be adjusted to a project level. Therefore, the ontology is considered valid as a general lifecycle framework for implementing the concept of DT for a viaduct in a BIM model.

## 5 DISCUSSION

As identified in the literature gap, on the one hand BIM practices lack the automated data integration which contributes to models being left aside after the design phase, and on the other hand DT applications in the construction sector that offer automated data integration, are mainly focused in the O&M phase. Regarding the scientific contribution of this study, the proposed ontology incorporates and allocates sensory data to the elements of the BIM model, which confronts the first part of the literature gap, and proposes a lifecycle implementation of the DT, which aims to cover the second part of the literature gap. More specifically, this study introduces the LDT which is an attempt to offer a lifecycle framework for the application of the DT rather than focusing on the O&M phase. Moreover, the research introduces the concept of DT-readiness that offers upgraded BIM models hosting sensor data, linking different databases, and increasing the automation potential of the BIM models. This attempt of upgrading BIM models into DT-ready adds value to the application of LDT as it provokes consideration of the lifecycle needs and offers a smooth transition towards the implementation of the concept. Therefore, as far as the current state art is concerned, this study offers an approach of gradual transition from current modeling practices.

The results of the study indicate that the DT does not necessarily concern a sophisticated technological application, but mostly a structured data incorporation. More specifically, the developed ontology highlights the fact that the DT concept does not solely consider sensory data, but the actual value of the concept is the incorporation and linkage of various data and its continuous flow across the lifecycle. The lifecycle application of the concept reveals the importance of information generated at the Design Phase and hence the relevance of the inclusion of that phase in the LDT. The ability of LDT to seamlessly incorporate versatile information and allow it to flow from one lifecycle phase to another, constitutes it an appropriate tool for lifecycle management. In other words, LDT is a

very useful tool for sustainability and circularity approaches in the construction sector, which evinces the social and environmental contribution of the research as well.

Regarding the research methodology, the participation of actual domain experts as input for the conduction of the ontology is considered a strength of the study. The data pieces used to enrich the ontology derive from actual practitioners and reflect the real modeling needs. Furthermore, the domain experts validated the research results from a practical point of view as well, and this fact adds to the implantability potential of the ontology. On the other hand, the fact that the information needs emerged from actual practitioners also poses some limitations to the study. The research considers the satisfaction of a restricted set of information needs that emerged through the interviews. However, the data collecting technologies selected for the satisfaction of the information needs may play a multifunctional role. As identified in the review of the data collecting systems [4.2], some sensors and data collecting technologies may provide different input and serve different lifecycle phases. The full potential off the selected technologies through the lifecycle was not exploited in this research. For example the Weigh-In-Motion sensors may provide an insight about the traffic of the road apart from the loads applied on the deck, and laser scanning may also be applied to identify and monitor the evolution of cracks for structural health monitoring apart from recording the as-built situation. To address this limitation, further work should explore the full potential offered by the selected technologies to further enrich the ontology and provide a larger spectrum of possible applications on the basis of a richer database. Furthermore, another limitation of the research is the consideration of a specific asset. The ontology was conducted according to the needs of a viaduct and therefore it cannot be directly applied to another asset. At a higher level, the ontology can still serve other types of assets, however the different needs of other assets may introduce different object breakdown structures, sensor needs, processes and risks and hence the ontology should be developed accordingly. Future work may consider which parts of the ontology can be kept as universal and how the rest of the ontology can be developed for other asset types.

As far as the application of the ontology is concerned, there are some prerequisites that need to be met to adopt the proposed ontology. From a technical point of view, the different platforms, databases, and data collecting technologies should be interoperable to apply the recommended data structure. By interoperability, not only the data format is meant but also the data granularity. In other words, the decomposition of objects, worksets and the naming policy should follow the same standardized approach among the different disciplines. In the case interoperability is not directly possible, intermediate format transforming platforms, or data processing algorithm should

adjust the data to link everything in the BIM model. Regarding the working routines, they will also need to undergo some changes. New collaborations, roles and tasks will emerge, and people should be persuaded to embrace them in view of a greater lifecycle picture. Closer collaborations and more intense interdisciplinary communication are needed to communicate the information needs and find the best path for the information to flow, and this process needs to be coordinated and monitored, which introduces new roles as well. Furthermore, people should be adequately informed about the added value of the new modeling practice to avoid resistance for changing working routines. As far as administrative and legal issues are concerned, the application of the ontology is relevant for a lifecycle approach, hence a DBFMO contract type is needed to adopt the ontology for a project.

Once the prerequisites are met and the ontology is adopted there are many ways it can contribute to a corporate level as well. The proposed ontology offers a thick data net that has summarised a list of lifecycle information that can serve as a basis for different applications for the companies. The proposed dataset offers a variety of logical rules that can be applied to identify patterns, expose latent errors, apply correlation analyses, and develop machine learning algorithms, which in turn enable multifactor lifecycle optimisations. The different factors that can be optimized may be costs, time and sustainability, and the optimisation may occur in different fields as logistics, resources consumption, design for disassembly, maintenance planning and circular management after the demolition. Finally, apart from the efficient lifecycle management the proposed ontological model may trigger a development in a company's digitization status and technological maturity.

## 6 CONCLUSION

To summarize, this research aimed to bring the current state of art one step closer to the application of DT by identifying the requirements a BIM model should meet to allow a gradual transition. To address the research objective, which was the registration of the data structure of a DT-ready BIM model for a viaduct, an ontological model was developed mapping the distribution of various data pieces among the elements of the model. This ontology describes what are the additional information that need to be included in the BIM model, what are the needed data collecting technologies, how are the sensor measurements distributed in the model and what are the relationships between the different entities. Overall, the proposed data structure indicates how the models should be created in consideration of the LDT offering a smooth transition for the application of the concept.

## ACKNOWLEDGMENT

This work was supported by BAM Infraconsult BV, which offered access to the company's files, modeling practices, standardization documents, and knowledge exchange meetings. The research was hosted in the BIM Services Department with close collaboration with the BIM Specialists Team.

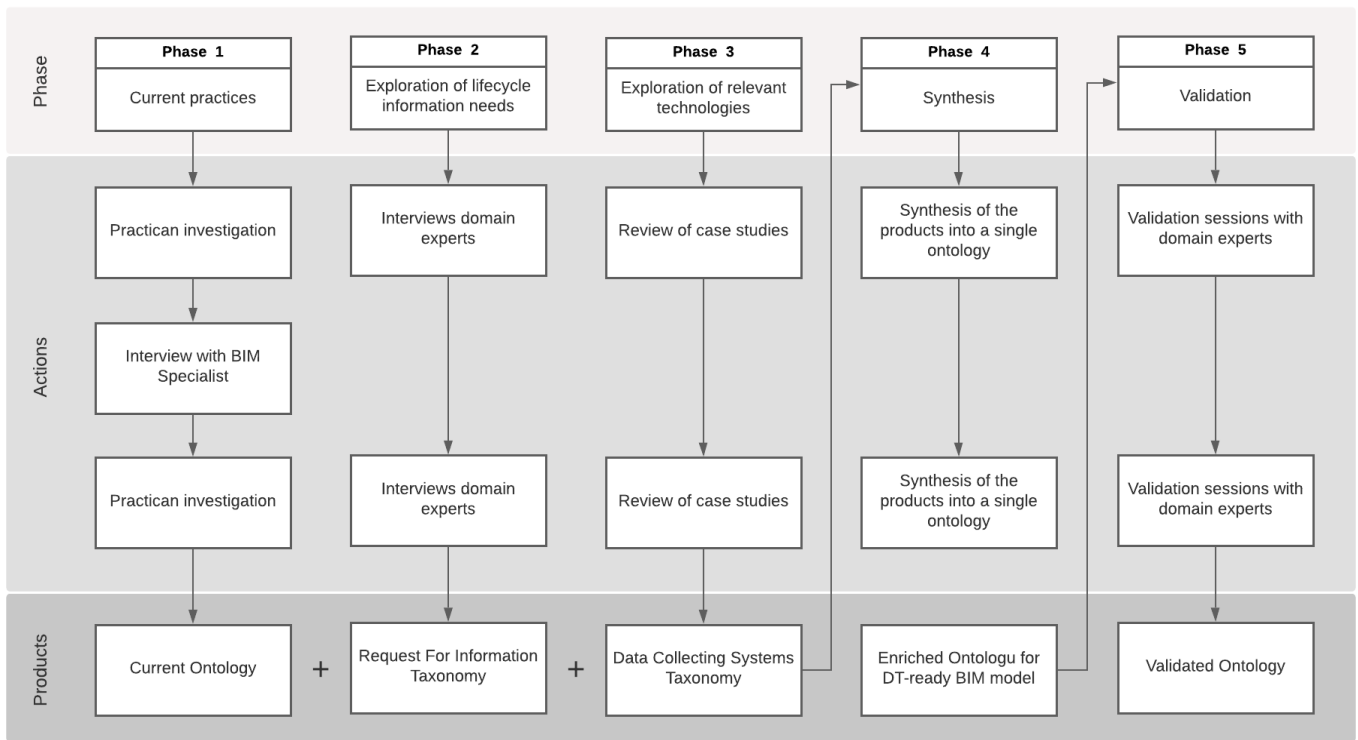
## REFERENCES

- Abellán, A., Oppikofer, T., Jaboyedoff, M., Rosser, N., Lim, M., & Lato, M. (2014, January). Terrestrial laser scanning of rock slope instabilities. *Earth Surface Processes and Landforms*, 39(1), pp. 80-97. doi:<https://doi.org/10.1002/esp.3493>
- Awolusi, I., Marks, E., & Hallowell, M. (2018, January). Wearable technology for personalized construction safety monitoring and. *Automation in Construction*, pp. 96-106. doi:<https://doi.org/10.1016/j.autcon.2017.10.010>
- Azam, K., & Hornbæk, K. (2011). Big data from the built environment. *Ubicomp '11: The 2011 ACM Conference on Ubiquitous Computing* (pp. 23-32). Beijing China: Association for Computing Machinery.
- Baumgartner, R., & Schöggel, J.-P. (2016). Sustainable product management - Combining physical and digital product lifecycles to enable a circular economy. *Interdisziplinäre Konferenz zur Zukunft der Wertschöpfung*. Hamburg.
- Becerik-Gerber, B., Jazizadeh, F., Li, N., & Calis, G. (2012). Application Areas and Data Requirements for BIM-Enabled Facilities Management. *Journal of Construction Engineering and Management*, 138(3). doi:10.1061/(ASCE)CO.1943-7862.0000433
- Brank, J., Grobelnik, M., & Mladenčić, D. (2005). A SURVEY OF ONTOLOGY EVALUATION TECHNIQUES.
- Brink, B., & Weishut, J. (2020, July 2). *Bits & Pieces : Uniting the physical and digital world for a more sustainable Europe – a Dutch perspective*. Retrieved from [White Paper]: <https://www.royalhaskoningdhv.com/en-gb/specials/universal-digital-twin>
- Britannica, T. E. (2019, December 18). Retrieved from Encyclopædia Britannica : <https://www.britannica.com/science/hygrometer>
- Cantero, D., & Gonzalez, A. (2014, July). Bridge Damage Detection Using Weigh-In-Motion Technology. *Journal of Bridge Engineering*. doi:10.1061/(ASCE)BE.1943-5592.0000674
- Chen, J., Bulbul, T., Taylor, J., & Olgun, G. (2014). A Case Study of Embedding Real-time Infrastructure Sensor Data to BIM. *Construction Research Congress 2014*. Atlanta, Georgia: © 2014 American Society of Civil Engineers. doi:10.1061/9780784413517.028
- Delir Haghighi, P., Burstein, F., Zaslavsky, A., & Arbon, P. (2013). Development and evaluation of ontology for intelligent decision support in medical emergency management for mass gatherings. *Decision Support Systems*, 54(2), 1192-1204.
- Gervasio, H., & Dimova, S. (2018). *Model for Life Cycle Assessment (LCA) of buildings*. JRC Technical Reports.



- Glaessgen, E., & Stargel, D. (2012). The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. Honolulu, Hawaii. doi:<https://doi.org/10.2514/6.2012-1818>
- Haag, S., & Anderl, R. (2018). Digital Twin – Proof of Concept. *Manufacturing Letters*, *15*, 64-66. doi:[10.1016/j.mfglet.2018.02.006](https://doi.org/10.1016/j.mfglet.2018.02.006)
- Isikdag, U. (2015). *Enhanced Building Information Models Using IoT Services and Integration Patterns*. Springer. doi:[10.1007/978-3-319-21825-0](https://doi.org/10.1007/978-3-319-21825-0)
- Lu, Q., Xie, X., Heaton, J., Parlikad, A., & Schooling, J. (2019). From BIM towards Digital Twin: Strategy and Future Development for Smart Asset Management. *9th Workshop on Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future*. doi:[10.17863/CAM.40565](https://doi.org/10.17863/CAM.40565)
- Lu, W., Huang, G. Q., & Li, H. (2011, March). Scenarios for applying RFID technology in construction project management. *Automation in Construction*, pp. 101-106. doi:<https://doi.org/10.1016/j.autcon.2010.09.007>
- Nasr, E., Shehab, T., & Vlad, A. (2013). Tracking Systems in Construction: Applications and Comparisons. *49th ASC Annual International Conference Proceedings*. Long Beach California.
- Raad, J., & Cruz, C. (2015). A survey on ontology evaluation methods. *IC3K 2015 - Proceedings of the 7th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management*, (pp. 179-186). Lisbonne, Portugal.
- Riaz, Z., Arslan, M., Kiani, A., & Azhar, S. (2014, September). CoSMoS: A BIM and wireless sensor based integrated solution for worker safety in confined spaces. *Automation in Construction*, 96-106.
- Stojanovic, V., Trapp, M., Richter, R., & Hagedorn, B. (2019). Semantic Enrichment of Indoor Point Clouds: An Overview of Progress towards Digital Twinning. *37th eCAADe Conference*, (pp. 809-818). Porto. doi:[10.5151/proceedings-ecaadesigradi2019\\_051](https://doi.org/10.5151/proceedings-ecaadesigradi2019_051)
- Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. *International Journal of Advanced Manufacturing Technology*, *94*, 3563–3576. doi:[10.1007/s00170-017-0233-1](https://doi.org/10.1007/s00170-017-0233-1)
- Teizer, J., & Cheng, T. (2014, December). Proximity hazard indicator for workers-on-foot near miss interactions with construction equipment and geo-referenced hazard areas. *Automation in Construction*, pp. 58-73. doi:<https://doi.org/10.1016/j.autcon.2015.09.003>
- TSI. (2020, July 10). Retrieved from [https://www.tsi.com/silica/?utm\\_source=ishn&utm\\_medium=news-%20%20wkly&utm\\_content=expmn-silica&utm\\_campaign=expmn](https://www.tsi.com/silica/?utm_source=ishn&utm_medium=news-%20%20wkly&utm_content=expmn-silica&utm_campaign=expmn)
- Usmani, A., Elshafey, A., Gheisari, M., Chai, C., Aminudin, E., Tan, & Tan, C. (2019, December 5). A scan to as-built building information modeling workflow: a case study in Malaysia. *Journal of Engineering, Design and Technology*, *18*(4), 923-940. doi:<https://doi.org/10.1108/JEDT-07-2019-0182>
- Valinejadshoubi, M., Moselhi, O., & Bagchi, A. (2017). Managing Structural Health Monitoring Data Using Building Information Modelling. *SMAR*. Zurich Switzerland.
- Wong, G., & Breheny, M. (2018). Narrative analysis in health psychology: a guide for analysis. *Health Psychology and Behavioral Medicine*, 245-261.

**FIGURES**



**FIGURE 1**  
RESEARCH DESIGN

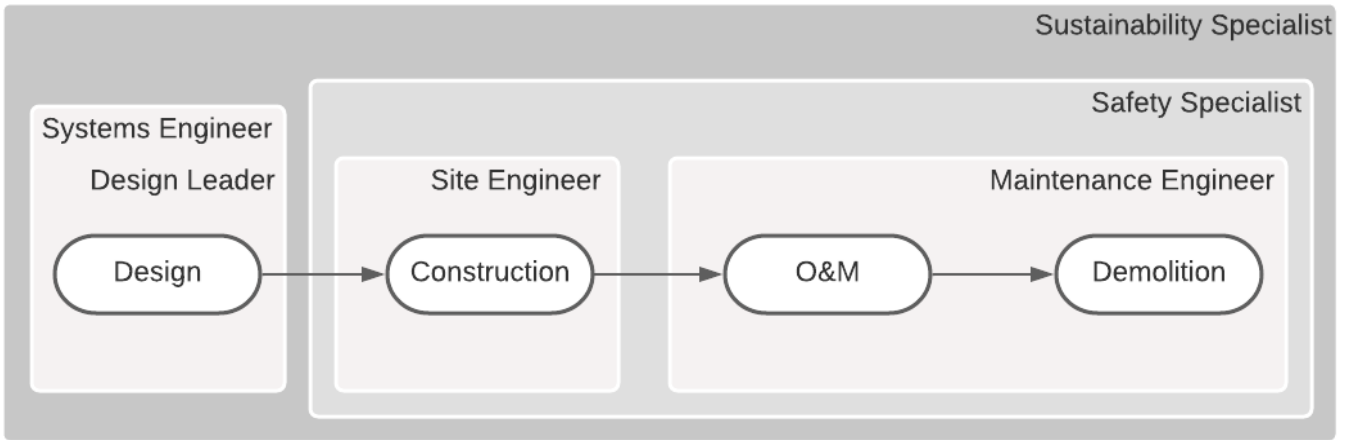


FIGURE 2  
LIFECYCLE COVERAGE BY THE INTERVIEWEES

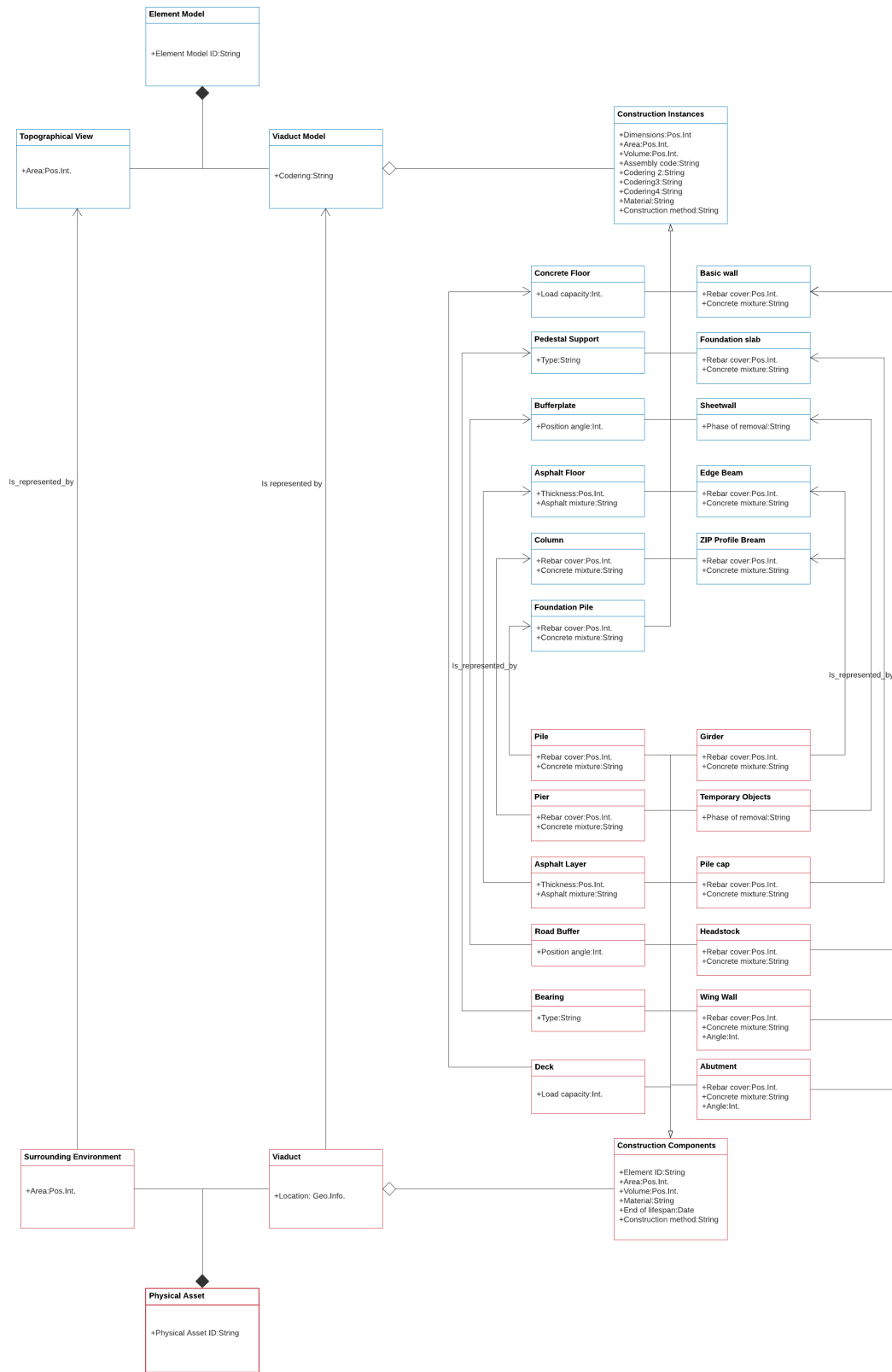


FIGURE 3  
UML CLASS DIAGRAM OF THE CURRENT ONTOLOGY

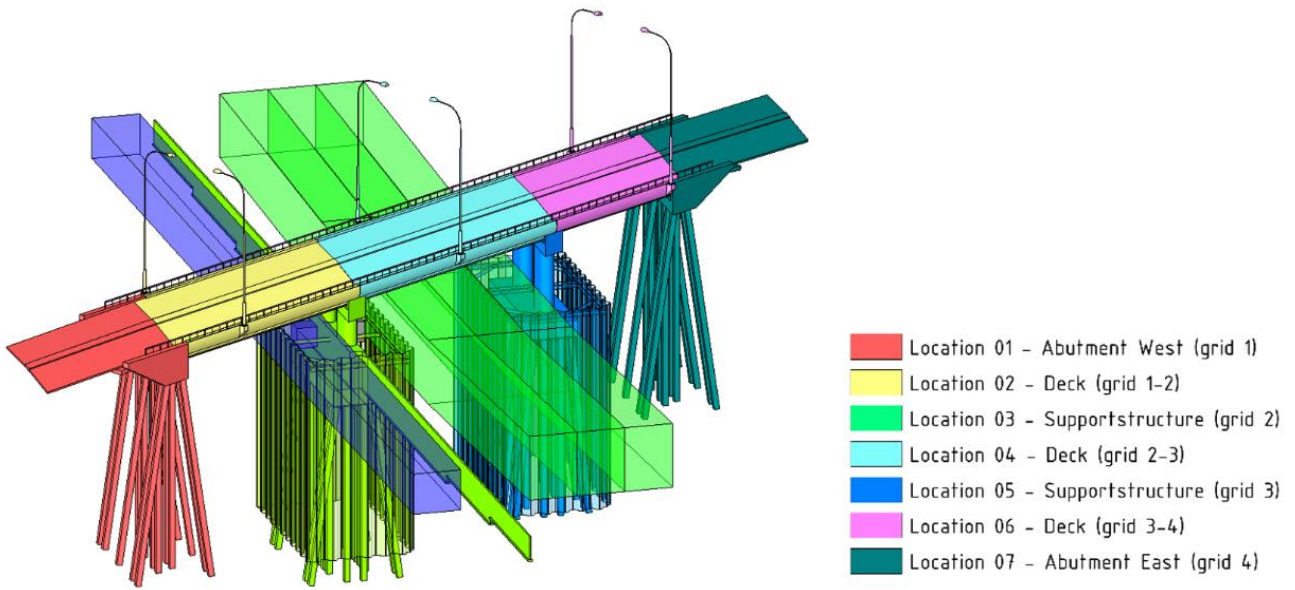


FIGURE 4  
DECOMPOSITION OF THE MODEL IN LOCATIONS

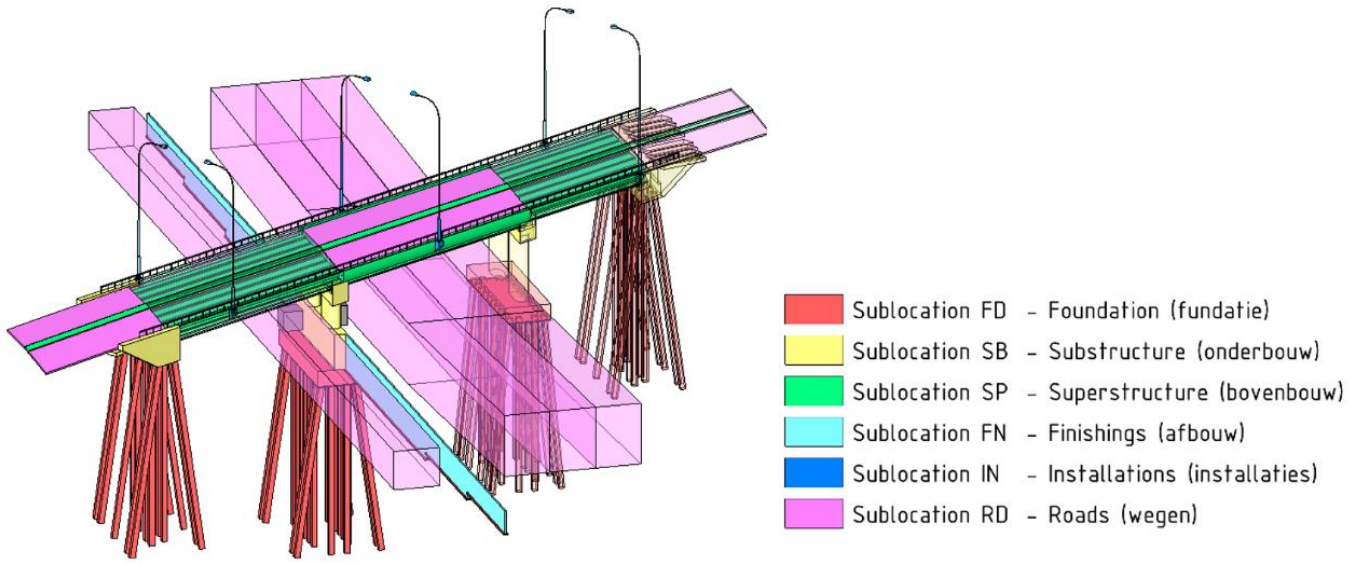


FIGURE 5  
DECOMPOSITION OF THE MODEL IN SUBLOCATIONS

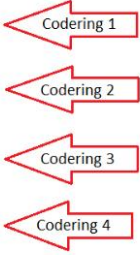
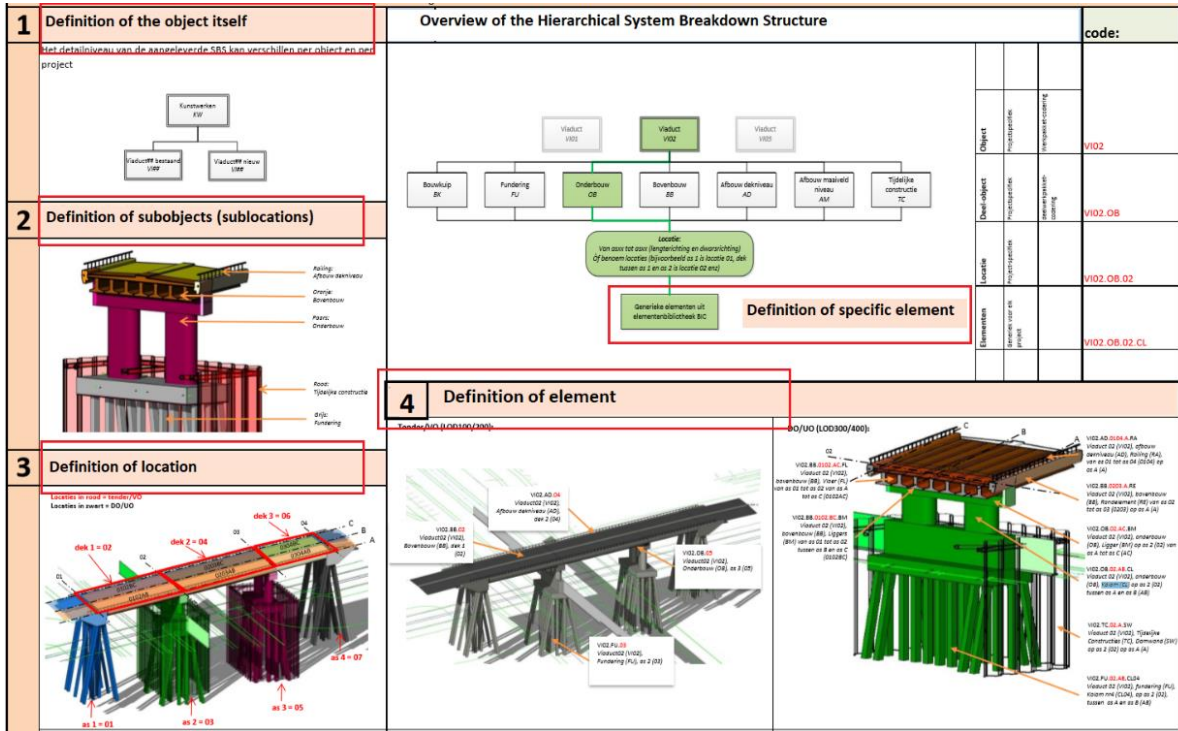


FIGURE 6  
GUIDELINE FOR CONSTRUCTING THE CODERINGS FOR A VIADUCT

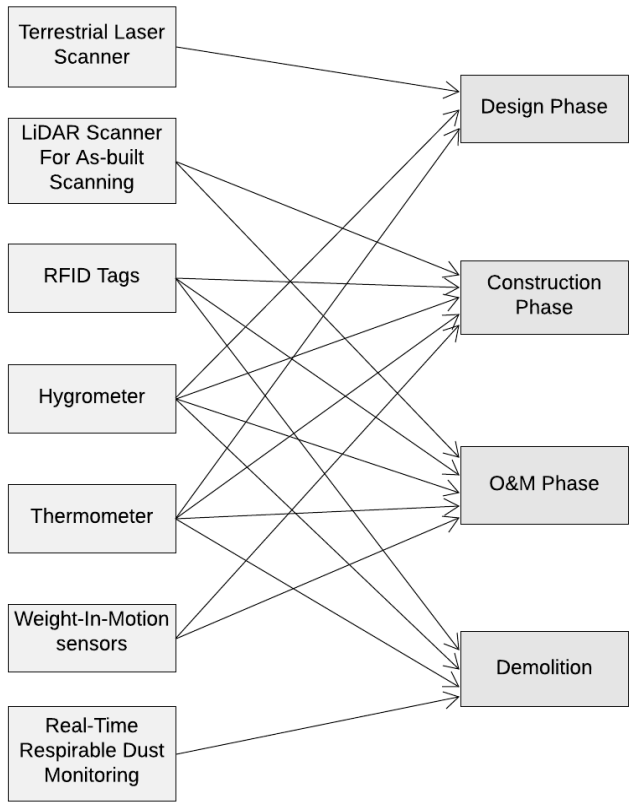


FIGURE 7  
LIFECYCLE COVERAGE FROM THE DATA-COLLECTING TECHNOLOGIES



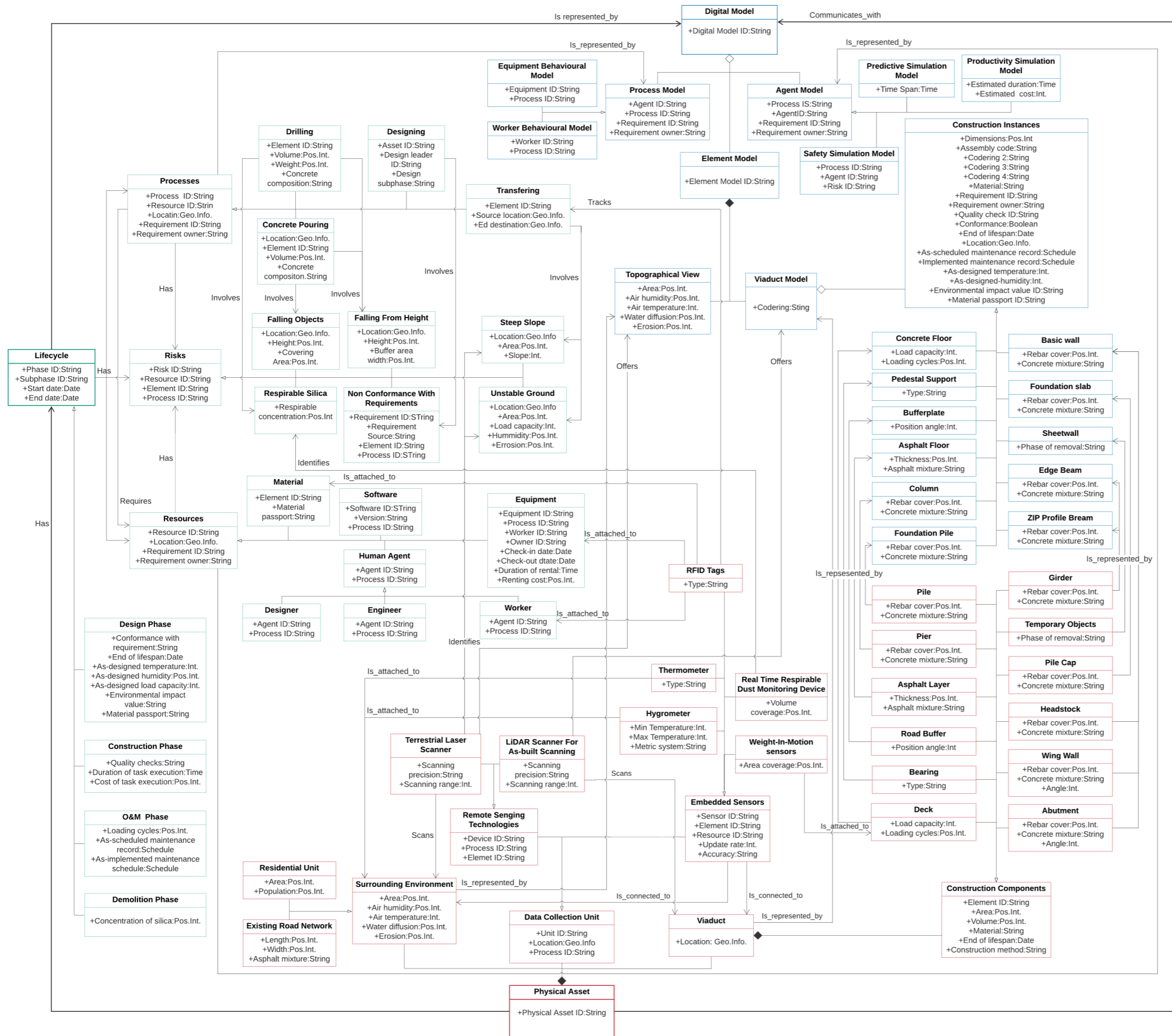


FIGURE 8  
ENRICHED ONTOLOGY

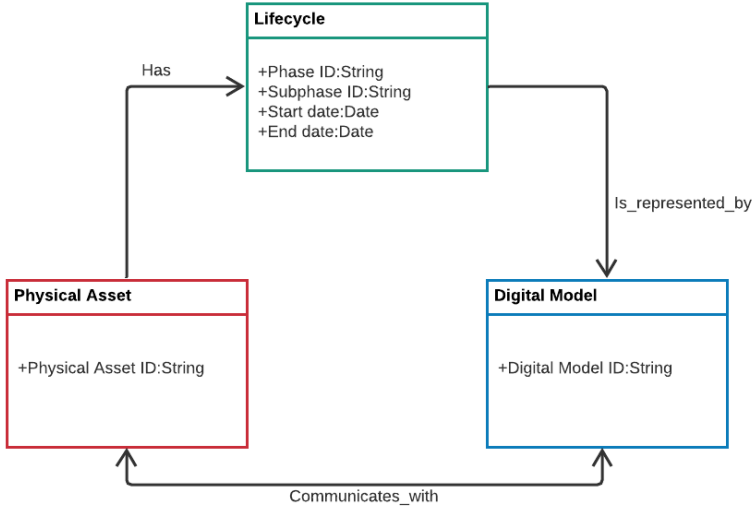


FIGURE 9  
RELATIONSHIP OF THE THREE MAIN SECTIONS

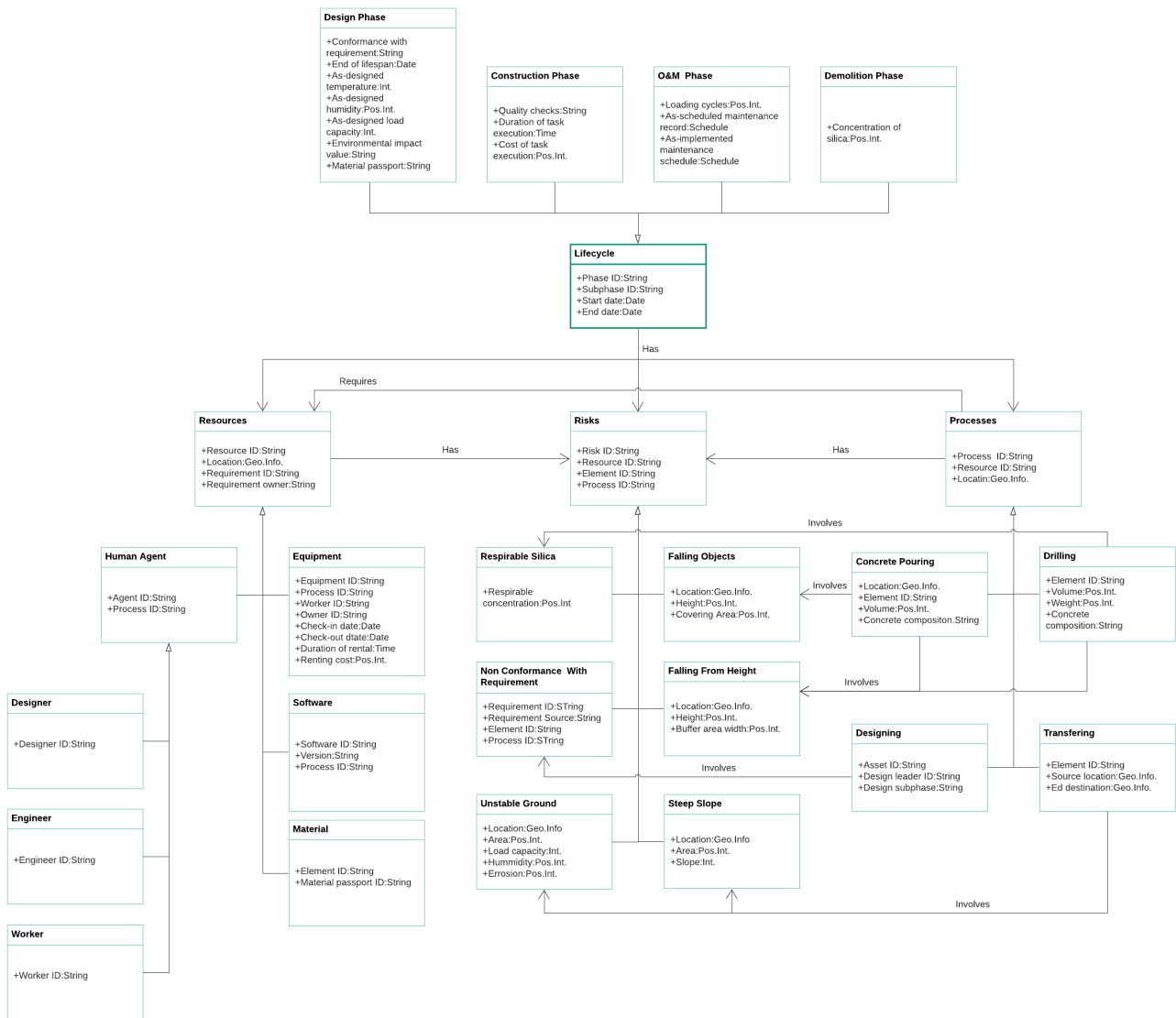


FIGURE 10  
LIFECYCLE REPRESENTATION OF A VIADUCT

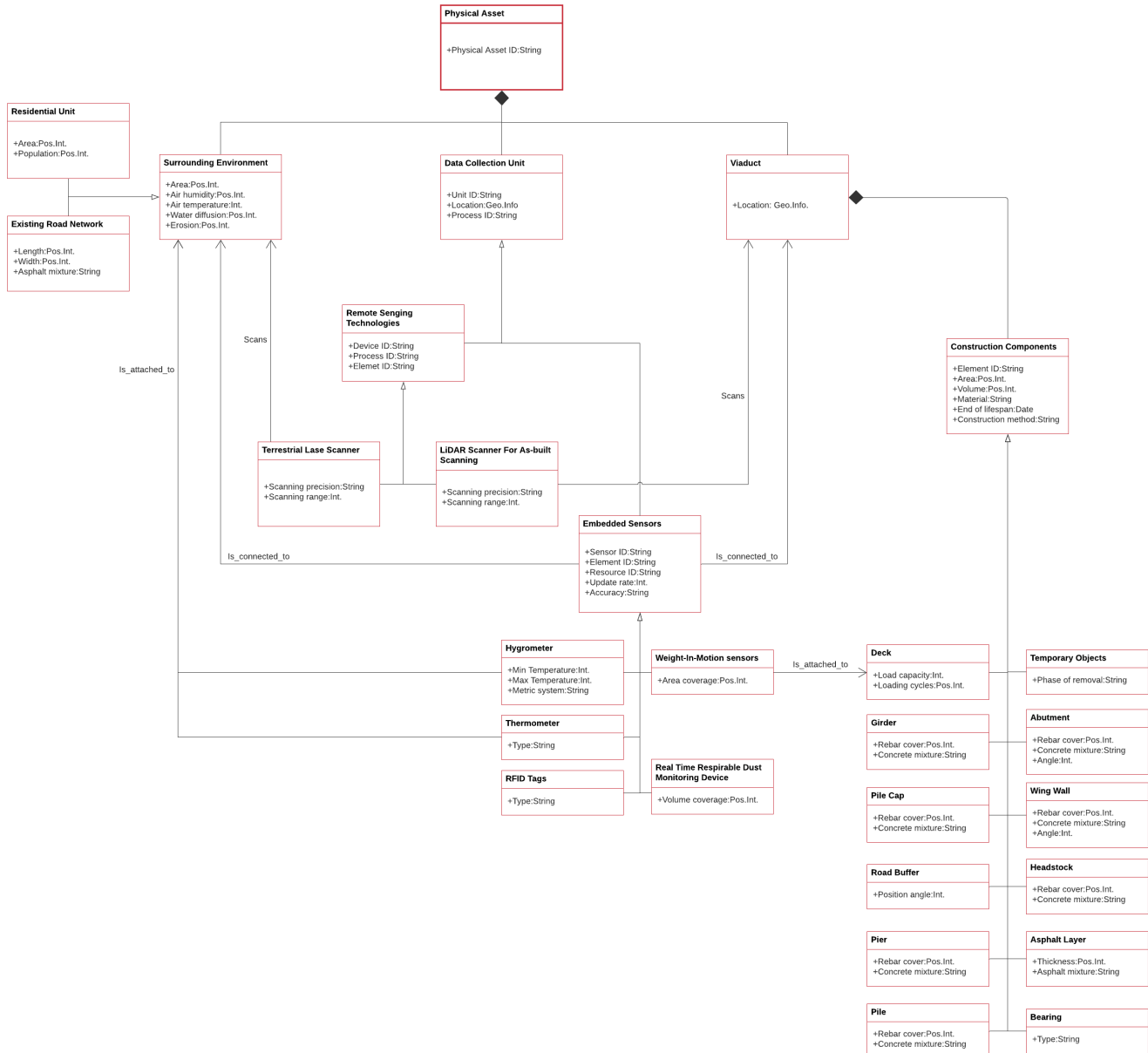
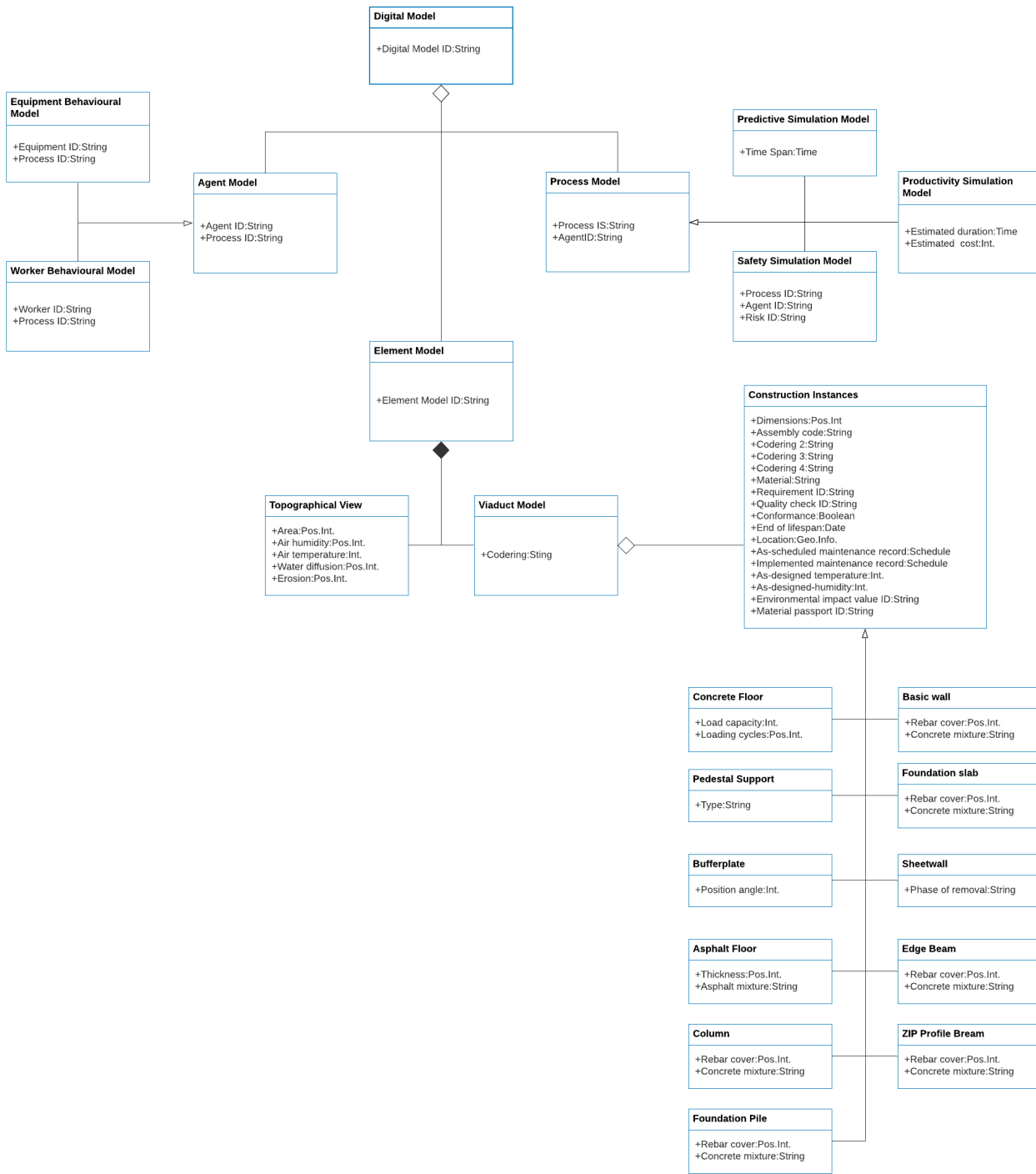


FIGURE 11  
PHYSICAL ASSET REPRESENTATION

FIGURE 12  
DIGITAL MODEL REPRESENTATION



## TABLES

TABLE I  
RFI TAXONOMY

Nr Information Need	Nr RFI	Data piece required	Linkage with class	Linkage with existing information	Source of existing information	Sensor retrieved information
1	1	Conformance with requirements	All elements, All activities	X	Relatics	-
2	2	Quality checks	All elements, All activities	X	Relatics	-
3	2	Conformance with model	All elements	-	-	X
4	3	Location of equipment	Equipment elements	-	-	X
5	4	Duration of rental	Equipment elements	-	-	X
6	4	Cost of rental	Equipment elements	X	Cost Excel Sheets for renting equipment	-
7	5	Duration for execution	All activities	-	-	X
8	5	Cost of execution	All activities	X	Cost Excel Sheets for execution of tasks	-
9	6	End of lifespan	All elements	X	Suppliers, Designers	-
10	7	Loading cycles	Deck	-	-	X
11	7	As designed load	Deck	X	Designers	-
12	8	Implemented maintenance frequency	All elements	X	Asset Management	-
13	8	As-scheduled maintenance frequency	All elements	X	Asset Management	-
14	9	As designed humidity	All elements	X	Suppliers, Designers	-
15	9	Environmental humidity	Global measurement	-	-	X
16	9, 10	As designed temperature	All elements	X	Suppliers, Designers	-
17	9, 10	Environmental temperature	Global measurement	-	-	X
18	11	Location of workers	Crew members	-	-	X
19	11	Location of hazards *	Elements, activities, and areas characterised as dangerous	X	Site Management, Modellers	X
20	12	Location of moving vehicles	Moving vehicles	-	-	X
21	12	Location of unstable ground *	Topographical view	X	Site Management, Modellers	X
22	13	Concentration of dangerous substances in the air	Areas characterised as dangerous	-	-	X
23	14	Environmental impact value	All elements, All activities	X	Sustainability Department	-
24	15	MP	All elements	X	Sustainability Department	-

TABLE II  
INFORMATION COLLECTING SYSTEMS TAXONOMY

Nr Information Need	Nr RFI	Data piece required	Linkage with class	Real time location systems	Laser scanning systems	Structural health monitoring	Environmental variables monitoring systems	Real Time Respirable Dust Monitoring System	Specific information retrieving technology
3	2	Conformance with model	All elements		X				LiDAR for as-built scanning
4	3	Location of equipment	Equipment elements		X				RFID for asset tracking
5	4	Duration of rental	Equipment elements	X					RFID for asset tracking
7	5	Duration for execution	All activities						RFID for productivity monitoring
10	7	Loading cycles	Deck			X			Weight-In-Motion sensors
15	9	Environmental humidity	Global measurement				X		Hygrometer
17	9, 10	Environmental temperature	Global measurement				X		Thermometer
18	11	Location of workers	Crew members	X					RFID for people tracking
19	11	Location of hazards *	Elements, activities, and areas characterised as dangerous	X	X				RFID for asset tracking
20	12	Location of moving vehicles	Moving vehicles	X					RFID for asset tracking
21	12	Location of unstable ground *	Topographical view	X	X		X		RFID for asset tracking, LiDAR for terrestrial laser scanning, Hygrometer
22	13	Concentration of substances in the air	Areas characterised as dangerous					X	Real time respirable dust monitoring devices

TABLE III  
EVALUATION CRITERIA SCORES

Criterion	Score	Characterization	Improvements
Correctness	3.8 / 5	Largely true description	More structured classification of libraries, object types, and instances.
			Explore possible data types for attributes.
Completeness	4.0 / 5	Lifecycle coverage to a large extent	Addition of elements with a shorter lifespan.
			Inclusion of pre-design phase.
Conciseness	4.2 / 5	Single representations can be omitted	-
Adaptability & Extendibility Scenario 1	3.5 / 5	Somewhat possible – easily extended to add other lifecycle aspects of a viaduct	-
Adaptability & Extendibility Scenario 2	3.0 / 5	Somewhat possible to adjust the ontology to some other infrastructure asset	Keep it at a higher level and develop it at a project level.
			Align with the company's object type library.
			Integrate information standards like COBIE, NEN 2767.