



INTERRELATIONSHIP-BASED INFORMATION DELIVERY MANUAL DEVELOPMENT FOR SMART CITY INFRASTRUCTURE SYSTEMS

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Abstract

Smart cities are comprised of various infrastructure systems interacting with heterogeneous context information that frequently causes critical challenges in data sharing, exchange, and integration of infrastructure components. The complicated structure of the infrastructure 3D models and the unraveled relationships of their functional, operational features remain elusive, hindering their seamless interactions. To ameliorate this issue, this paper proposes an interrelationship-based model view definition approach using an urban-level ontology that improves consistent data interoperability at the urban scale. The study includes the modularization of each infrastructure data conducted based on their functionalities and the development of an ontological structure for a smart city that supports defining underlying connections between distinct functions of the infrastructure systems.

Introduction

Infrastructure systems of a smart city are composed of different, broad groups of interrelated elements that are imperative to provide comfort and well-being to citizens of an urban society. Their dependencies are exponentially increasing mainly because of the higher demands of efficiency in their performance as cities constantly become smarter throughout their infrastructure networks (Enayaty Ahangar et al., 2020). The interrelation among the infrastructure elements or entities is complex in a way that “a disruption to one entity can have a cascade effect to entities resulting in disruption to the entire network” (Lam & Tai, 2018). In a such condition, it is crucial to have an integrated and interoperable environment for BIM data exchange that allows a seamless information flow among the infrastructure entities, preventing any possible data loss or incompatibility among the system functions. However, a variety of infrastructure systems in heterogeneous domains has caused a BIM data exchange problem that hinders seamless data sharing, exchange, and integration.

Model View Definitions (MVD) are developed as a subset of the Industry Foundation Classes (IFC) schema to facilitate BIM data exchange and sharing. Information Delivery Manuals (IDM) are used for identifying tasks, processes, responsibilities, and information exchange requirements among various participants in a particular

domain, which is subject to be translated into MVD (Y. Lee et al., 2019). Developing IDM/MVD at an urban scale can provide an interoperable environment of 3D BIM models with seamless information sharing among different infrastructure systems (Shariatfar & Lee, 2020, 2023). IDMs are composed of exchange models (EM) that illustrate data exchange requirements, the phase, and the involved parties in an exchange process (Y. C. Lee et al., 2020). EMs in their general form can be used for illustrating data exchange between infrastructure elements.

For developing an urban-level MVD, however, there are three main issues related to EM and IDM development. The first one is a lack of a method for identifying critical connections and dependencies between infrastructure elements. This can become challenging especially at the urban level with a myriad of connections that are not necessary nor possible to create an EM for each of them. A streamlined mechanism is required to distinguish the critical connections for creating EMs and consequently an IDM for each urban level use case. The second issue is a lack of a consistent structure that illustrates a unified standard for defining and classifying infrastructure systems and their embedded elements. Different categorizations and definitions of infrastructure systems and functions can cause unexpected inconsistencies and redundancies in urban-scale EM development. The last, but not least, EMs are open for different interpretations and translations to develop MVD. This issue causes a primary obstacle in developing an automated data mapping process for MVD development that can reuse the previously developed concepts to create new model views (Shariatfar & Lee, 2021). A machine-readable format of IDM can be iteratively reused and disseminated for consistent data exchange and sharing with other urban-related schemas such as CityGML.

To tackle the identified challenges, this study proposes a new way to reveal underlying interrelationships and interdependencies of infrastructure systems and components by using the Design Structure Matrices (DSM) approach and an ontology. The proposed method modularizes the infrastructure systems based on the functions, elements, and their attributes in the four levels. As a next step, DSM is utilized for identifying the connections and their criticalities. The modularization levels are also used for defining the class hierarchies and

providing a unified ontological data structure for functional elements and properties. The provided ontology includes all necessary infrastructure systems while maintaining its structure in order to prevent inconsistencies. This proposed approach is expected to allow the development of formal and reusable EMs to facilitate MVD development at the urban scale and provide an integrated environment among the functions of different infrastructure systems.

Literature review

Both DSM and ontology have been previously used for improving urban infrastructures' efficiency and data modeling processes. DSM is usually designed for identifying system dependencies and decision-making purposes, and ontology is broadly adopted for modeling the dependencies and information sharing among the domains. DSM is used for decomposing complex systems into a set of subsystems including tasks/objects/phases (Nomaguchi et al., 2015). DSM-based models such as UrbWellth (Hoffmann et al., 2020) or the strategic structure matrix (Tang et al., 2013) were created to improve the infrastructure efficiency in urban planning and development. UrbWellth was developed to improve health-related urban well-being, and the strategic structure matrix was designed to identify the interactions in the wind energy infrastructure. DSMs in these studies were used for decomposing systems into smaller elements in order to reduce the complexities. Although DSMs can identify the interactions between different parts of systems, they are currently limited to be used for developing their data exchange standards.

Ontology is used in numerous studies as a shared knowledge model which allows defining and standardizing domain knowledge as a semantic relation between the elements of each infrastructure system (Pauwels et al., 2017; Xu & Cai, 2021). Previous studies such as El-Diraby et al. 2011 and Howell et al. 2018 utilize ontology for promoting interactions between infrastructure elements in a more homogeneous environment, rather than providing a global format that can be compatible with all urban systems in heterogeneous environments (El-Diraby & Osman, 2011; Howell et al., 2018). The reason is mainly due to the purpose of the studies which is using ontology as a tool for "providing data architecture and semantic formalizations" of different data sources, and the lack of a formal definition of inter-linked relationships (Le & David Jeong, 2016; Xu & Cai, 2021).

The literature shows that the previous DSM and the ontological models were mostly designed with domain-specific information. The gap in this area is the lack of a framework that provides a generalized data structure that is capable to include critical infrastructure systems and facilitate data interoperability at the urban scale. This study first uses DSM for modularizing the infrastructures and identifying their connections, and then, provides a unified ontological data structure for functional elements

and properties. The framework is expected to connect the functions, their elements, and their properties using the existing data exchange standards.

Methodology

The proposed methodology includes the following three steps: infrastructure modularization, DSM development, and ontology development. Figure 1 shows the steps and the overall process. In addition, the method was evaluated with the case study using one smart city model.

Interrelationship-based IDM development

The proposed method is designed to support consistent development of an urban scale MVD by classifying the infrastructure systems based on their functions and using the data exchange standard of all infrastructure systems for defining data and object properties in the ontology. This method offers a novel way of presenting data exchange, which is capable of representing the exchange of BIM data for various infrastructure systems at the urban scale.

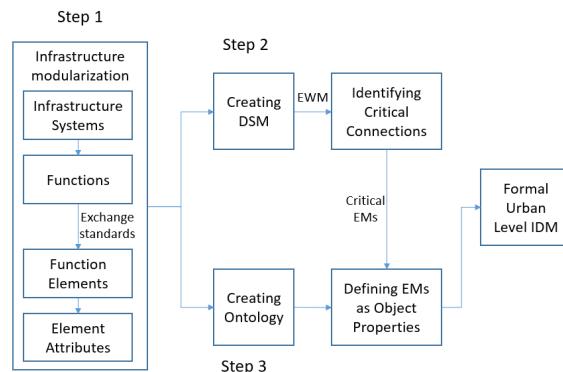


Figure 1: The overall process of the methodology

The first step is the modularization of the infrastructure systems that decomposes them into components based on their functions and elements. The objective of this step is to reduce the complexities of systems' relationships and identify the hidden connections for developing a DSM. Figure 2 is a schematic illustration of three modularization levels: the infrastructure systems; their functionalities; and the elements of each function.

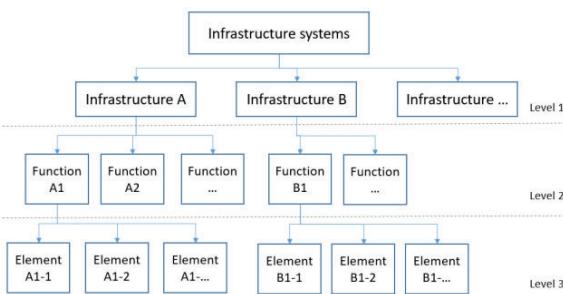


Figure 2: Schematic representation of the structure of the class hierarchy

The modularized systems are a fundamental structure for developing a DSM and identifying the connections. A

DSM designed for each level clearly illustrates the bi-directional interactions between infrastructures, functions, and elements. Figure 3 shows a schematic example of creating DSMs of levels 1 and 2, illustrating that each connection at a higher level represents an overall DSM at the lower level. This shows the variety of possible connections that can be defined between infrastructure systems and their functions. However, it is not possible, nor necessary to model every single connection. To resolve this possible issue, we have applied a weighting method to identify critical connections for future EM development. The entropy weight method (EWM) was also selected to measure the value of dispersion between different factors or elements in decision-making.

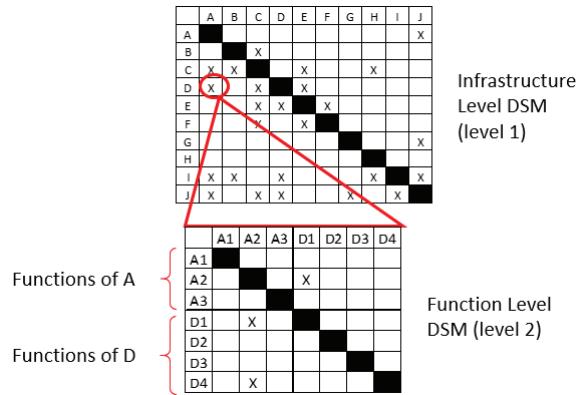


Figure 3. A schematic example of DSM hierarchy

The process of weighting a DSM consists of the two main steps. First, after identifying all DSMs at the lower level, a score is calculated for each connection based on the frequency of connections in each lower-level DSM. Figure 4 shows the process including the DSM at one level lower ($n-1$) and the scores of each of the DSMs are calculated using the following equation:

$$(1) \quad s_{ij} = \frac{\sum C_e}{\sum C_t} \quad (i \& j = 1, 2, 3, \dots m)$$

Where, C_e is the number of existing connections, C_t is the total number of potential connections, and m is the number of elements at the n^{th} level.

The second step involves the EWM formula that calculates the degree of dispersion between the connections. The greater the degree of dispersion indicates the greater degree of differentiation. The following equations are used to calculate the Entropy weights for the connections in the DSM:

$$(2) \quad e_j = -h \sum_{i=1}^m s_{ij} \ln s_{ij} \quad (i \& j = 1, 2, 3, \dots m)$$

$$h = \frac{1}{\ln m}$$

Where, m is the number of elements, and S is the scores attained from the lower DSM level ($n-1$). The left side of Figure 4 shows a schematic weighted DSM at a higher level (n) with entropy weights that show the criticality of connections between elements.

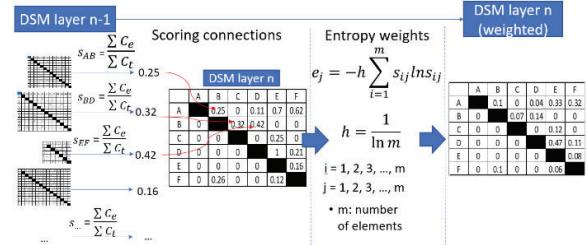


Figure 4: The DSM weighting method for identifying the critical connections

The third step is creating a base ontology that is composed of smart infrastructure systems that each contain a set of categories of functional properties similar to the modularization at the first step. Figure 5 shows the class hierarchies of the ontology developed based on the modularization shown in Figure 2. For example, a smart mobility infrastructure is composed of different functions that provide service to transportation infrastructure as shown in Figure 8. There are several documentations and standards for different infrastructure systems in which the function elements and their exchange requirements can be identified. For example, Work Zone Data exchange (WZDx) document was created by US Federal Highway Administration to facilitate data access on work zone activities (the next section describes this step in detail). The documents and standards can help identify the function elements, their properties, and possible interactions with the elements of other functions. The method in this study utilizes these documentations to define the hierarchies and the properties of the function elements at the third level.

In the next step, the connections among the infrastructure elements defined at the third level of the hierarchy are identified using EMs. Finally, the information in the EMs is defined with the ontological structure for providing computer-readable and assessable forms. Figure 6 shows the overall structure of the framework. The sample case study using smart city infrastructure systems and their smart functionalities shows the structure of the ontology and the advantages of the framework in detail.

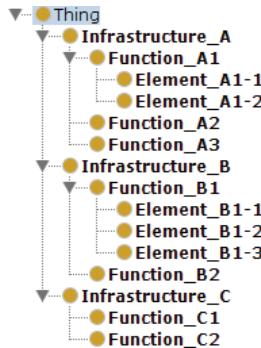


Figure 5: Class hierarchy based on the modularization in Figure 2

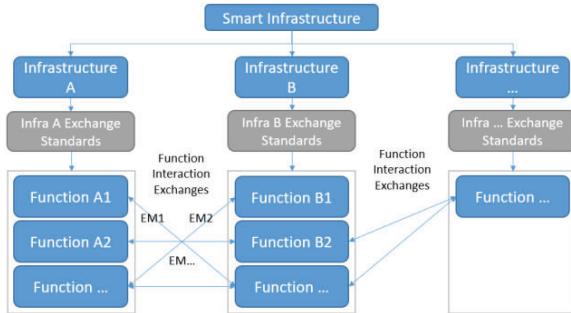


Figure 6: Interactions between the infrastructure functions through EMs defined in the ontology

Case Study and validation

The use case of roadway construction including BIM data exchange processes between Internet of Things (IoT) and smart mobility infrastructures was designed to evaluate the methodology and outcomes. The analysis and validation using this example aim to address the effect of construction work zone (roadway construction in this example) on roadway traffic by preparing the required information for the dynamic message sign function. The use case is supposed to provide information about any roadway construction to administration that controls dynamic message signs to post useful messages for drivers who are driving towards the work zone. Due to space limitations and clarity of the example, the IoT was decomposed into only three functions: Work Zone Event Detection, Hazard Detection, and Hazard Prediction, Hazard Detection, and Hazard Prediction functions. Work Zone Event Detection function was decomposed to Lane, Road Event, and Road Event Data Source elements. Similar decomposition was conducted for Smart Mobility.

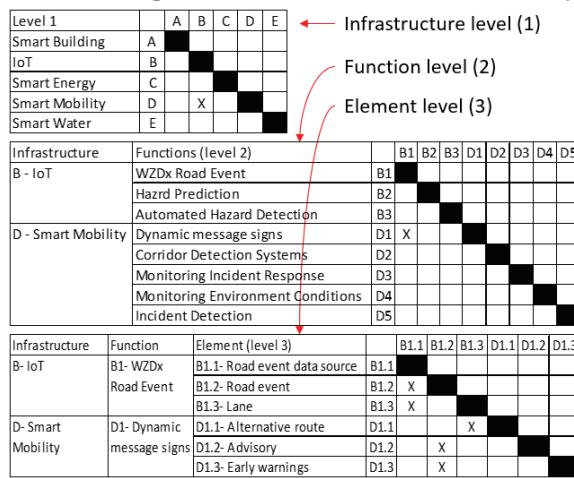


Figure 7: Levels 1, 2, and 3 of modularization and DSM development

Figure 7 shows the levels of modularization in DSM. Level 1 shows the connections between infrastructure systems, which in this example is the connection between IoT and Smart Mobility. Level 2 represents the connections between the Road Event function and

Dynamic Message Sign function, and level 3 shows the function elements which help develop the EMs in the end.

The roadway construction work zone data can be extracted from the roadway 3D BIM model. The EMs determine the information that require to be retrieved such as lane data, location data, etc. and sent to the administration that controls dynamic message signs. Figure 8 shows the functions and elements involved in this process (highlighted in the red boxes). In this case study, the smart function needs to inform the drivers about the construction project that is occurring ahead of an associated pathway. In addition, it should provide information about the available lanes and the lanes that are closed due to the construction process.

Work Zone Event Detection describes any alert or notification system regarding construction sites in public areas. This elements and properties of this function are defined based on WZDx (Work Zone Data Exchange) standard provided by US Federal Highway Administration (FHWA, 2018). This class should be able to show the lanes that are closed due to the construction process. The RoadEvent contains information that describes where, when, and what activity is taking place along a road segment. The data properties defined in the ontology are based on the RoadEvent, RoadEventDataSource, and Lane attributes in the WZDx standard shown in Figure 9. It must be noted that, several other class definitions can be considered for this use case, and there are several other subclasses, properties, and attributes that can be added to these functions. This type of classification for function elements is selected for simplifying the process.

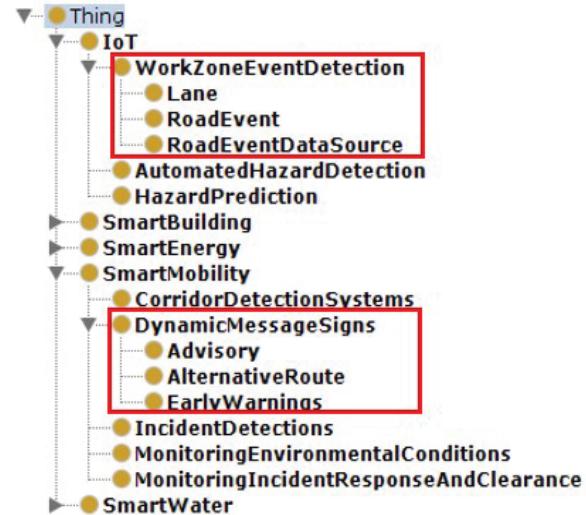


Figure 8: Involved functions for automated road event alert system case study

In this case study, we assume that the RoadEvent element extracts the construction information from the BIM model and provides them for the Dynamic Message Sign function. The Dynamic Message Sign function is composed of three categories of messaging according to

the VMS Guidelines provided by NYSDOT (New York State Department of Transportation) shown in Figure 10 (NYSDOT, 2018). In this framework each category can be defined as a functional element.

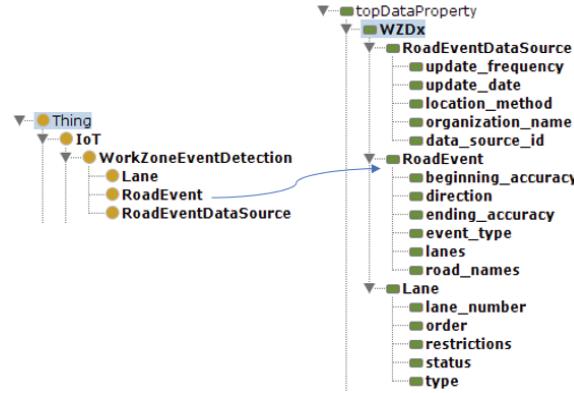


Figure 9: RoadEvent data properties

Each category can be defined as an element class under the Dynamic Message Sign function and the message types can be defined as the function elements (function subclasses) in the ontology. The messages are the attributes of each message type. For example, it can be stated that, Dynamic Message Signs is a function under Smart Mobility infrastructure which contains an element of type message named Early Warnings and one of its attributes is Slow Traffic. Figure 11 shows the function elements and attributes in the ontology structure. The data properties are in fact the attributes of the element class. Having these functions, the ontology allows to create an object property named isConnectedTo that connects Work Zone Event Detection function to Dynamic Message Signs function. The OntoGraph representation of this ontology is shown in Figure 14.

MESSAGE TYPE	USES – INFORMATION RELATED TO
Early Warning	Traffic Safety/End of Queue Protection Unexpected Traffic Slow Traffic Stopped Traffic
Advisory	Guidance Lanes Blocked (Temporary Duration) Lanes Closed (Long Duration) Highway/Highway/Ramp/Connector Closed Adverse Roadway Conditions Post-Event Congestion Advance Notice Major Closure Major Special Event Congestion Travel Times Expected Delays AMBER & Missing Person Alerts Adverse Weather Conditions
Alternative Route	Guidance Soft Detour (Optional Detour) Hard Detour (Required Detour)

Figure 10: Variable Message Sign (VMS) categories provided by NYSDOT

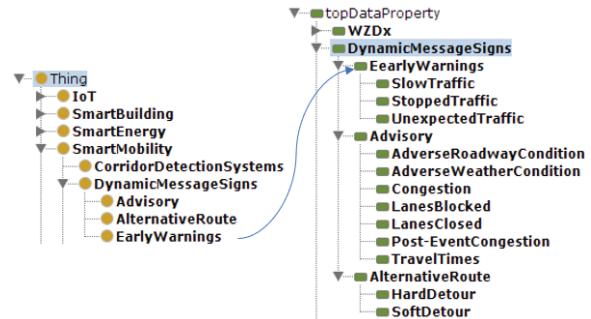


Figure 11: Dynamic Message Signs function and its attributes

A connection can be defined in form of an exchange model (EM) between the elements of each function. For example, let's assume that Work Zone Event Detection function identifies a construction event occurring in a roadway section. The detailed information about the roadway section can be extracted from the 3D BIM model shown in Figure 12. In this scenario, a part of this information needs to be sent for creating an alert message in the Dynamic Message Sign function. The tasks of each function should be the following:

- 1- Work Zone Event Detection function extracts the BIM data and sends the information about the construction ahead to the Dynamic message sign function
- 2- Dynamic message sign function receives the message about the roadway construction ahead and displays an advisory message.

Table 1 is an exchange model named EM1 that defines such data exchange between the tasks 1 and 2.

Table 1: Roadway construction message (EM1)

Stage	Construction
Exchange disciplines	Work Zone Event Detection, Dynamic Message Signs
Description	Information about the roadway construction such as event type, involved lanes, the directions of the involved (same direction or the opposite direction of the lane that the message sign is installed).

This process can be defined in ontology by connecting the elements of the two functions and assigning the required data types as their data properties. EM1 represents the connection between the elements of the functions by being defined in the ontology as object properties. Figure 13 highlights the involved elements and attributes of the proposed ontology in this scenario, showing that for the Dynamic Message Signs function, the Advisory element contains attributes such AdverseRoadwayCondition, Congestion, etc. In this use case, only the attribute LanesClosed is required to be exchanged. Similarly, for the Work Zone Event Detection function, attributes

required from the RoadEvent element are direction, event_type, and lanes (all highlighted in Figure 13).

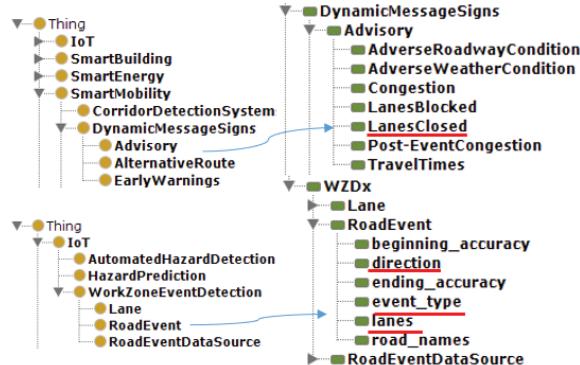


Figure 13: Involved function elements and their required attributes

Defining EM1 as an object property and assigning it to the classes defined in Figure 13, i.e., WorkZoneEventDetection → RoadEvent → DynamicMessageSigns – Advisory, shows the connection between these two function elements through its proper exchange model. In Figure 12 the yellow line represents EM1 which is the connection between the two function elements of WorkZoneEventDetection and DynamicMessageSigns.

We can apply the details of the case study by creating individuals in the ontology. The details are the data that is required to be transferred which were highlighted in Figure 13. In this case study event_type, direction, and lane attributes are required to be transferred into the Advisory class of DynamicMessageSign function, as a LaneClosed sign that contains the following information. Figure 14 shows the ontological representation of such scenario.

Message Sign Category: Lane Closed

- Message Details:
 - Construction (event_type data type)
 - Lane 1 (Lane data type)
 - Same direction (Direction data type)

Figure 14 shows that exchange models that are the fundamental parts of IDM/MVD development can be easily created in this ontological structure. This allows developers to create formal EMs and consequently, formal IDMs that can be automatically mapped with previously developed MVD concepts for developing new model views.

Discussion and result analysis

The purpose of this study was to create a novel structure that enables the development of interrelationship-focused IDM in the context of urban infrastructure. The outcome of this framework needs the following necessary characteristics to be used as a formalized procedure for urban-level IDM/MVD development.

The EM1 that was created in the Experiment section as a sample use case, can be used for other scenarios with similar data exchange requirements. This case shows the reusable characteristic of the developed EMs in this framework, which is necessary for urban-scale IDM/MVD development. Because of the numerous interactions between the infrastructure functions, it is highly possible that EMs become inconsistent and redundant. The reusable characteristic prevents redundancies in urban-scale EMs. Object properties can also be reused for different concepts. By referencing common properties to the same object property, there is no need to create a new property for each concept, which can lead to a large number of properties in the schema. Therefore, reusing object properties can help streamline the ontology and make it more manageable.

The ontological structure proposed in this study can be considered as a baseline that supports defining different smart functionalities for each functional category of all infrastructure systems. The purpose of creating this framework is to develop a unified ontological structure that can represent the complicated data exchange with modularized structures required for the interactions between the functions in different infrastructure systems. The structure should be able to contain all infrastructure systems at an urban scale with detailed information about its functions, elements, attributes, and relationships. The generality characteristic allows the development of a unified and agreed structure for different infrastructure systems with various domains.

The evolution of smart cities has a direct relation with improvements and evolution in infrastructure functionalities. The framework should have the capability to evolve along with new functions and elements that will be added to the infrastructure systems in the future. The flexible characteristic of the ontology allows adding new classes without changing the structure of the class hierarchy.

Conclusions

The proposed framework promotes a data exchange environment for integrating heterogeneous functionalities in various infrastructure systems. It addresses the heterogeneity issue of the domain standards that are separately created for every urban system by providing semantic modules for every functionality. Each infrastructure functionality contains the functional elements and attributes which are reusable for defining different connections with similar properties. The motive behind using the ontology is helping in standardizing and formalizing the interactions of infrastructure functions. The framework also helps create machine-readable exchange models and therefore accelerate developing formal IDMs. Future studies will be conducted to use this feature for creating an automated data mapping system between IDM components and previously developed MVD concepts in the MVD library developed in previous studies.

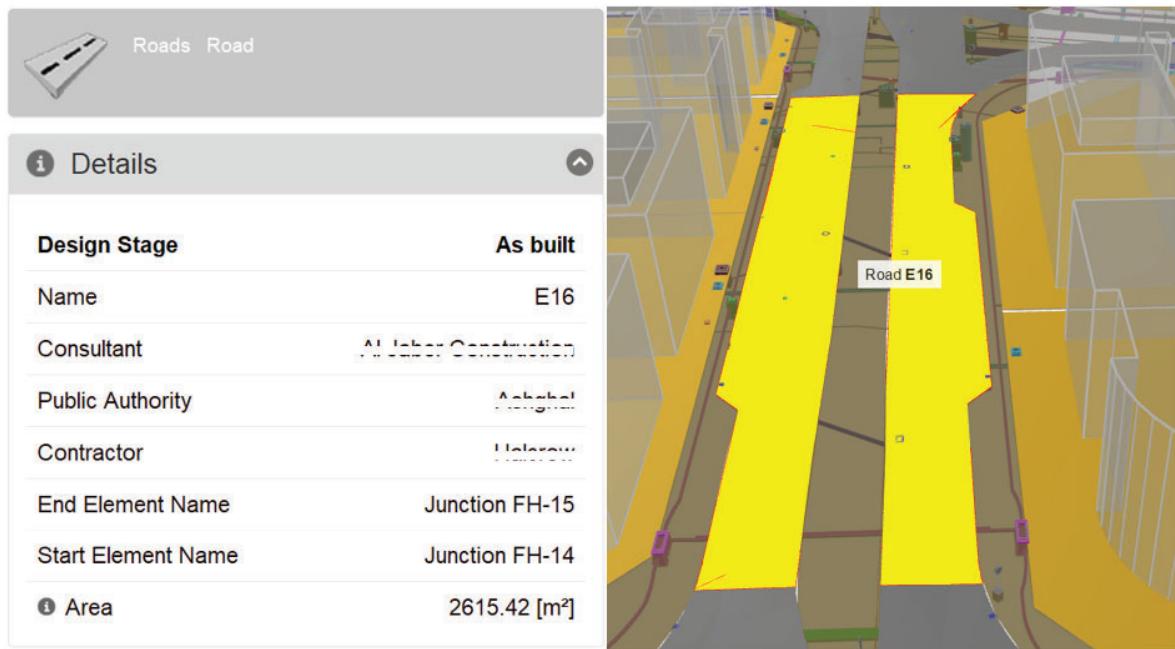


Figure 12: An example of detailed information about the roadway construction work zone extracted from a 3D BIM model

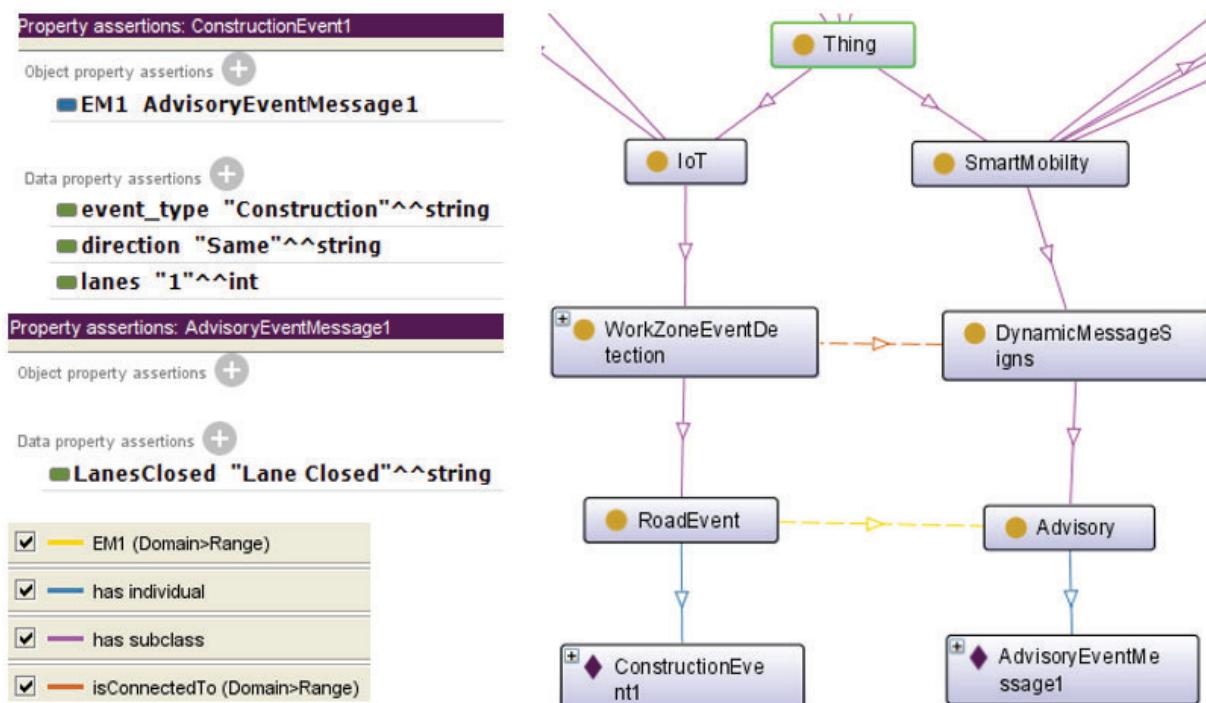


Figure 14: Creating individuals based on the defined EM and ontology

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