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City infrastructure ontologies

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ABSTRACT

Sustainable urban infrastructure planning and maintenance require an integrated approach that considers various infrastructure assets (e.g., the ground, roads, and buried pipes) and their inter-linkages as a holistic system. To facilitate the usage of this integrated approach, we propose a model of city infrastructure assets and their interdependencies, providing details on how asset properties and processes affect each other. This model is represented as ontologies in OWL 2 Web Ontology Language Manchester Syntax, which can be read and interpreted by machines automatically. These ontologies cover the classifications, properties and processes of the ground, roads and buried water pipes, as well as some related human activities and natural phenomena (e.g., precipitation). The ontologies not only provide a foundation for integrating various types of infrastructure and environmental data, but also for understanding the potential knock-on effects of asset failures. The ontologies have been utilised in a decision support system for integrated urban inter-asset management.

1. Introduction

A city is a system of systems, which includes land-use, transport, waste, water, energy, infrastructure and social, economic and environmental processes (Walport & Wilson, 2016; Javed et al., 2022). Infrastructure refer to the basic physical and organizational structures and facilities that a country, a city or an organization needs and uses in order to work effectively. Infrastructure is usually categorised based on the provided services, such as transport (e.g., road, rail, air), energy (e.g., electricity, gas, solar, wind), water and waste treatment or disposal (e.g., drinking water, wastewater, solid waste), information and communication technologies, cultural and social services (e.g., schools, hospitals, museums), etc. (HM Treasury, 2016), which support almost all aspects of daily life. It is important to manage city infrastructure effectively and in a sustainable way which minimises the potential impact of infrastructure failures or disorders on the societal, economic and natural environment.

One of the main challenges in managing city infrastructure is the increasing *complexity* and *interdependencies* of infrastructure (Rinaldi, Peerenboom, & Kelly, 2001; Buldyrev, Parshani, Paul, Stanley, & Havlin, 2010). As the infrastructure system is highly interconnected, a failure in one infrastructure component may lead to a series of linked impact or failures, which are referred to as *cascading failures* (Buldyrev et al., 2010). Due to such interdependencies, even a small temporary defect or failure may result in significant losses. For example, in October 2011, a power failure at a major exchange in Birmingham, UK, caused

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the temporary loss of broadband services for hundreds of thousands of BT Broadband customers across the UK, and many business users reported considerable lost revenue as a result (BBC, October 2011). In addition, climate change can cause unprecedented extreme weather events and amplify the effects of interdependency among infrastructure (IPCC, 2012). The impact of weather extremes include major destruction of assets, disruption to services, injury and loss of life, loss and impact on plants and animals. Transportation, energy and water infrastructure are all sensitive to climate extremes. For example, extremes in temperature, precipitation, flood and drought can result in damage to roads, rails and ports; extreme storm events can affect electricity transmission infrastructure.

Though the complexity and interdependencies of infrastructure may bring challenges and risks, they can represent opportunities to increase organizational resilience and sustainability as well (Carhart & Rosenberg, 2016; Grafius, Varga, & Jude, 2020). Among them, *simple interdependency-based opportunities* refer to those based on information sharing and knowledge exchange. *Geographic opportunities* refer to those for cost-saving and increasing system efficiency in the case where multiple infrastructure systems are physically close or share the same footprint. *Integrative opportunities* refer to those where there exists a synergy and extensive functional interconnection between multiple infrastructure systems at multiple points. In order to tackle the challenges and grasp the opportunities brought by the complexity and interdependencies of infrastructure, it is essential to establish a model to describe the interdependencies of infrastructure systems at a detailed level to facilitate information sharing and knowledge exchange.

Despite the fact that the interdependencies of infrastructure have been described in the literature, infrastructure systems are typically managed by single government departments, local agencies, companies and organisations, without much collaboration and information sharing (Wei et al., 2020; Araya & Vasquez, 2022), which has resulted in many social, environmental and economic problems and losses. Due to the lack of usable information about buried utility infrastructure, a large number of street excavations are adversely affected every year around the world (Open Geospatial Consortium, 2017). For example, a work crew replacing a pipe line strikes a gas main unknowingly, which leads to a gas leak with the threat of an explosion.

Data describing the locations and conditions of different kinds of infrastructure, as well as the knowledge of their interdependencies, can provide indispensable information for supporting decision making in infrastructure planning and maintenance. Due to the large size and increasing complexities of infrastructure data and the complicated interdependencies between them, it is difficult for humans to understand or interpret them all together. Therefore, it is necessary to represent infrastructure assets, as well as their properties and processes, in a model such that both humans and computers can process, integrate, analyse and reason with all sorts of related data to gain a better understanding of the whole infrastructure system.

In computer science, an ontology refers to an explicit specification of a shared conceptualization and plays an important role in establishing a common vocabulary for people who need to share information (Gruber, 1993). In an ontology, concepts (i.e., types or classes) and their relationships are specified in a formal knowledge representation language (Hitzler, 2021), and hence can be read and interpreted by machines automatically. In the context of the semantic web, ontologies present increasing importance in data sharing and integration. An ontology can help overcome the problem of semantic heterogeneity and facilitate communication between different systems (Bittner & Donnelly, 2005). Since different kinds of urban infrastructure components are usually seen as different systems, interacting with each other and forming a *system of systems*, it is appropriate to build a model of infrastructure systems in the form of ontologies.

In this work, we propose a model of city infrastructure and their interdependencies following the *system of systems* approach, providing details on how properties and processes of different infrastructure affect each other. Whereas it is clear that buried assets such as pipes, cables and sewers are critical infrastructure assets, the *ground* deserves equal status as an asset of interest. The ground and buried infrastructure have an interdependent relationship with each other, i.e., the ground supports the buried infrastructure (and indeed the road above), while the buried infrastructure (or operations on it) can also affect the ground (Rogers et al., 2012). A suite of ontologies representing the proposed model are developed to describe the ground, roads, buried water pipes, as well as related human activities and natural phenomena. The ontologies are utilised in a decision support system for integrated urban inter-asset management.

The rest of the paper is structured as follows. Section 2 reviews existing interdependency models of infrastructure, as well as existing ontologies which describe the ground, roads and buried utilities. Section 3 describes an example motivating the development of the city infrastructure model. Section 4 presents the proposed model of city infrastructure. Section 5 presents the ontologies representing the knowledge within this model. Section 6 describes the use of description logic reasoners and SPARQL to query the ontologies. Section 7 describes the application of the ontologies in a decision support system. Section 8 discusses the spatial information handling within the proposed ontology framework first, then the advantages, limitations and implementations of the ontologies. Section 9 summarises the main contributions of this paper and directions for future work.

2. Related work

This section presents existing interdependency models of infrastructure systems and existing ontologies describing the ground, roads and buried assets.

2.1. Existing interdependency models

Several attempts have been made to model the interdependencies among different individual infrastructure systems (Rinaldi et al., 2001; Rinaldi, 2004; Ouyang, 2014; Hasan & Foliente, 2015; Sun, Bocchini, & Davison, 2022). Among them, Hasan and Foliente (2015) provided a review of different approaches to assessing infrastructure interdependences and analysed their strengths and limitations. The main approaches are: empirical, agent-based simulation, system dynamics, economic theory-based, and network-based. Among all these approaches, the network-based one is the most similar to the approach taken in our work. In the network-based approach, infrastructure systems are represented as networks, different components of a system are represented as vertices, and the relationships between components are represented as edges. In contrast, here we build a 'semantic' (in the sense of semantic web described by Berners-Lee, Hendler, & Lassila, 2001; Hitzler, 2021) network, where the classifications, properties and processes of infrastructure assets (e.g., the ground, roads and buried water pipes), as well as their relationships, are represented.

Recently, Sun et al. (2022) provided an overview of interdependency models of infrastructure, which are classified into the following three main categories based on the implementation method: dependency tables, interaction rules, and data-driven approaches. The implementation method employed in our work is closest to qualitative dependency tables described by Sun et al. (2022), where descriptive terms are used to summarise interdependent relations between two infrastructure systems. In constrast, we made an attempt to model the interdependences in a more detailed level by building 'qualitative dependency tables' between *properties and processes* of infrastructure systems and representing them as ontology axioms to facilitate automated reasoning.

2.2. Existing related ontologies

The concept of *Ground* or *Soil* was defined in several existing ontologies. Some of them are general environmental ontologies or thesauri, such as the Semantic Web for Earth and Environment Terminology (SWEET) ontology (Raskin & Pan, 2005), the environment ontology (ENVO) (Buttigieg, Morrison, Smith, Mungall, & Lewis, 2013), the General Multilingual Environmental Thesaurus (GEMET) (GEMET, 2021), the AGROVOC Multilingual Thesaurus (Food & Agriculture Organization of the United Nations, 2022). These general environmental ontologies or thesauri cover the term ground or soil, some soil classifications, as well as some properties and processes of soil. Besides these general environmental ontologies or thesauri, several ontologies are specialized for describing soil (dos Santos Aparício, de Farias, & dos Santos, 2006; Zhao, Zhao, Tian, Qian, & Zhang, 2009; Heeptaisong & Srivihok, 2010; Das, 2010; Shivananda & Kumar, 2013; Du, Dimitrova, Magee, Stirling, & Curioni, 2016; Helfer, Costa, Bavaresco, & Barbosa, 2021; Elumalai & Anouncia, 2021). The majority of these ontologies describe the classifications or types of soil from the perspective of soil or agricultural sciences. Differing from the existing soil classification ontologies, we focus on defining properties and processes of the ground, as well as their relationships, from the perspective of geotechnical engineering, such that they can be used to assess the condition of urban infrastructure systems.

The concept of *Road* has been defined in several transportation ontologies as part of the transportation network (Lorenz, Ohlbach, & Yang, 2005; Corsar, Markovic, Edwards, & Nelson, 2015; Katsumi & Fox, 2018), or defined in ontologies for urban development or smart cities (Berdier & Roussey, 2007; Berdier, 2011; Katsumi & Fox, 2019; Varga et al., 2022). It has also been defined in general ontologies or vocabularies covering various domains, such as the environment ontology (ENVO) (Buttigieg et al., 2013), the DBpedia ontology (DBpedia Association, 2023), and the Linked Open Vocabularies (LOV) (Vandenbussche, Atemezing, Poveda-Villalón, & Vatant, 2017). Buried assets, such as *pipes* and *cables*, have been defined in several infrastructure management ontologies or utility ontologies (Fu & Cohn, 2008; Osman & El-Diraby, 2006; Zeb & Froese, 2014). These ontologies or thesauri define different types of utilities or infrastructure products, as well as their attributes. Differing from the existing works described above, we focus on defining properties and processes of roads and buried water pipes, as well as how they affect each other.

3. A motivating example

Deterioration of an infrastructure asset (e.g., a pipe, road or cable) refers to a process or change that leads to a loss of performance with respect to an expectation (e.g., level of services, cost of ownership, etc.). Such a change is often driven by one or more mechanisms or processes. To understand the deterioration processes of infrastructure assets, it is necessary to consider different properties and processes of infrastructure, as well as their interdependencies.

Consider the deterioration process of a buried iron water pipe under a road. Firstly, this process is affected by properties and processes of the pipe, as well as those of other pipes or cables which are close or connected to it. For example, the length, diameter, material and wall thickness of a pipe are all related to pipe cracking. In addition, soil acts as the intermediary between buried assets and pavements, hence soil properties and processes also affect the deterioration process, and roads affect buried pipes via soil. For example, the pipe corrosion process is affected by soil water content, soil biology, soil chemistry, as well as pipe material, pipe water biology, pipe water chemistry, etc. Pipe corrosion can lead to pipe cracking. Soil deformation is another contributing factor to pipe cracking. Soil deformation process affects and is affected by soil stiffness and soil strength, which are affected by soil water content and soil plasticity. Furthermore, soil, roads and buried assets are all affected by the environment and human activities. For example, railfall affects soil water content and road water content; hence rainfall indirectly influences other properties and processes which are affected by soil water content and road water content as well. Another example is air temperature, which affects soil temperature and road temperature; hence air temperature indirectly influences other properties and processes affected by soil temperature and road temperature. In addition, human excavation and construction affect soil permeability which in turn affects and is affected by soil water content.

As illustrated by the example, the deterioration processes of infrastructure assets are complicated and inter-related, involving properties and processes of city infrastructure (e.g., pipes), the ground or soil, the natural environment and human activities. When the number of deterioration parameters is small, it may be still feasible to draw all the parameters as well as their relationships in a figure to allow domain experts to examine and analyse the situation.

However, as the number of parameters increases, it becomes more and more difficult to visualize the overall picture or even part of such a deterioration model, not to mention understanding or analysing it. In order to tackle this problem, it is important and necessary to develop a model of infrastructure and their interdependencies which is capable of representing and reasoning with the infrastructure assets' deterioration processes, their causes and consequences.

Based on the motivating example, the following requirements were identified for developing the city infrastructure model.

1. The model should provide a vocabulary covering various properties and processes of different infrastructure assets (e.g., the ground, roads and water pipes), as well as some terminologies for describing the natural environment and human activities which have close relationships with infrastructure assets.
2. For an individual infrastructure asset, the model should represent relationships between its properties and processes. For example, soil water content affects soil strength.
3. The model should represent relationships between properties and processes of *different* infrastructure assets. For example, pipe cracking is affected by soil deformation.
4. The model should represent how properties and processes of infrastructure assets affect and are affected by the natural environment and human activities. For example, soil water content is affected by evapotranspiration, and traffic affects soil deformation.

4. A model of city infrastructure

This section presents the proposed model of city infrastructure. The high-level representation of the model is shown in Fig. 1, consisting of the ground, roads, buried assets, the natural environment, and human activities, as well as their relationships and interdependencies. The ground affects and is affected by roads and buried assets; roads and buried assets affect each other via the ground; the natural environment and human activities affect and are affected by the ground, roads and buried assets.

The model of city infrastructure were developed by a team of

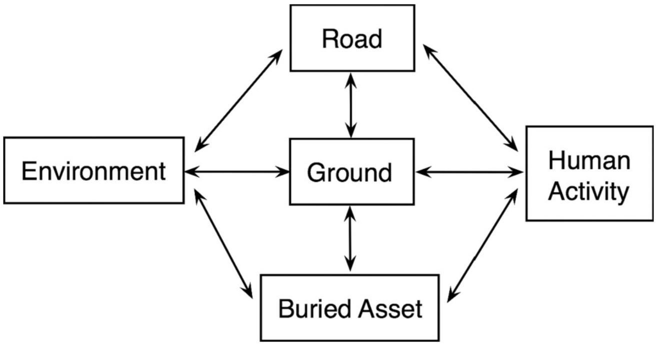

Fig. 1. A high-level representation of the model of city infrastructure. The double-ended arrow means 'affecting and being affected by directly'.

computer scientists and domain experts in geotechnical engineering, water engineering, infrastructure asset management, geography, earth and environmental sciences. We took a system of systems approach to developing this model, covering different *infrastructure assets*. The classification of infrastructure assets is shown in Fig. 2, which comes from discussions with domain experts in several workshops.

The proposed model consists of five sub-models: (1) the ground, (2) roads, (3) water pipes, (4) human activities and (5) the natural environment, as well as relationships and interdependencies between these sub-models. For each infrastructure asset, the model defines its classification, properties, processes, as well as relationships among properties and processes. The models of the ground, roads and water pipes are the main focus of the model development. The current model does not include sewer pipes, cables nor other buried assets, whose related properties and processes are different from those of water pipes, but a model of each of them could be developed using a similar methodology described in this paper. Note that we did *not* aim to develop a comprehensive model of human activities nor the natural environment. For human activities, the model defines the activities which affect or are affected by the ground, roads or buried utilities. For the natural environment, the model defines natural phenomena which affect or are affected by the ground, roads or buried utilities.

Since the ground plays the key role of a medium in many interactions between roads and buried utilities and is located in the centre of the model, we started by developing a model of the ground. The development of models for roads and water pipes was then followed using a similar methodology.

In the rest of this section, we first describe the modelling process using the ground as an example, then present the content of the ground, road and water pipe models, finally describe the relationships and interdependencies across different models.

4.1. The modelling process

In this work, a model of the ground was developed from the perspective of geotechnical engineering to suit the requirement of urban infrastructure management, on the basis of a model of soil (Du et al., 2016). The model of soil defines two main high-level classes: *SoilProperty* and *SoilProcess*. It defines two main relations: *hasImpactOn* and its inverse *influencedBy*, which mean 'affects or changes' and 'is affected or changed by', respectively. More specifically, a process q *hasImpactOn* a property p, if q causes a change in p; a property p *hasImpactOn* a process q, if a change in p changes how the process q occurs; a property p_1 *hasImpactOn* a property p_2, if a change in p_1 causes a change in p_2; a process q_1 *hasImpactOn* a process q_2, if q_1 changes how the process q_2 occurs. The model of soil was presented to domain experts as an example before developing the city infrastructure asset models.

An iterative procedure of developing a model of the ground. The development of the model of the ground was an *iterative* process over the following Steps 1–4.

Step 1: define high-level categories. A top-down approach was taken to developing concept hierarchies. The concept hierarchies of *Ground*, *GroundProperty* and *GroundProcess* were defined, through a series of workshops and discussions with experts in geotechnical engineering.

Step 2: select property and process concepts. The properties and processes defined in the model of soil were listed as candidate concepts to be included in the model of the ground. The ground specialists checked the listed properties and assigned a priority number to each property regarding its relevance and importance to the integrated management of infrastructure systems (see Table 1). Some candidate properties were deleted during this process, as they were deemed to be not relevant or were covered by other properties (the ground specialists are interested in coming up with a list of independent parameters first), whilst several new properties were added and included. For example, the concept *SoilMoistureContent* was deleted,[1] since it has the same meaning of *SoilWaterContent*; the concept *SoilAvailableWaterCapacity* was deleted, since it is more relevant to plants than the assessments of roads or buried utilities; whilst the concepts *SoilDryDensity* and *SoilConsistencyLimits* were added to describe the state and the classification of soil, respectively. This resulted in a new list of ground properties ranked by their priorities. Similarly, a new list of ground processes was obtained.

Step 3: classify property and process concepts. The new lists of prioritised ground properties and processes were classified into the high-level categories defined in **Step 1**. An example classification of ground properties is presented in Table 1.

Step 4: define relationships among properties and processes. In order to collect information about how the ground properties and processes affect each other, spreadsheets were designed and distributed to the ground specialists. For example, in a table to collect the information of how ground properties affect each other, all the properties are listed in the same order vertically and horizontally, forming an m*m matrix, as shown in Table 2. For every property p_1 listed vertically in the first column, it was checked against every *other* property p_2 whether p_1 *hasImpactOn* p_2. If yes, a letter *Y* was written in the corresponding cell; otherwise, a letter *N* was written or the cell was left empty. Similarly, the tables of how processes affect each other, how processes affect properties and how properties affect processes were designed in the same fashion and sent to ground specialists.

As the existence of *hasImpactOn* relationship between every pair of properties and processes needs to be considered separately, it required a large amount of time and effort to fill in such tables. Therefore, the first row of each of these tables were filled in together by a group of ground specialists during a workshop to gain common understanding; then, the tables were sent to each ground specialist to work on afterwards.

In total, 256 *hasImpactOn* relation statements were proposed or voted 'Y' by at least one expert. Among them, 91 relation statements were agreed by all the four experts; 39 statements were agreed by three experts; 62 statements were agreed by two; and the remaining 64 relation statements were voted 'Y' by one expert only.

Due to the existence of many differences or disagreements on relation statements and the complexity of this information capturing process, the above process was iterated and led by a senior expert in geotechnical engineering to gain an agreement between different experts. Based on the work in the first iteration, a new categorization of the ground properties and processes was proposed to take into account how the properties and processes were used for different purposes or in different contexts, as well as how to facilitate the process of defining relationships among properties and processes using tables. With the new classification, the existence of many *hasImpactOn* relationships can be considered together at a category level, which reduced the effort required to fill in the relationship tables. New spreadsheets were designed and successfully employed for collecting information on property and process relationships and interdependencies.

Developing other sub-models. The models of roads and water pipes were developed following the similar iterative process as detailed above. Their initial models were built by specifying and extending the high-level classes of the SWEET ontology (Raskin & Pan, 2005) based on the UK standards for highways, Design Manual for Roads and Bridges (DMRB) (Standards for Highways, 2023), and a research article on data structures of water pipes (Clair & Sinha, 2014), respectively. Then iterations of Steps 1–4 were followed to produce the final models.

The model of human activities was constructed by extracting relevant concepts from the SWEET ontology (Raskin & Pan, 2005), and

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[1] After defining *GroundWaterContent* following Steps 3 and 4, an equivalent axiom *GroundMoistureContent* ≡ *GroundWaterContent* was added directly.

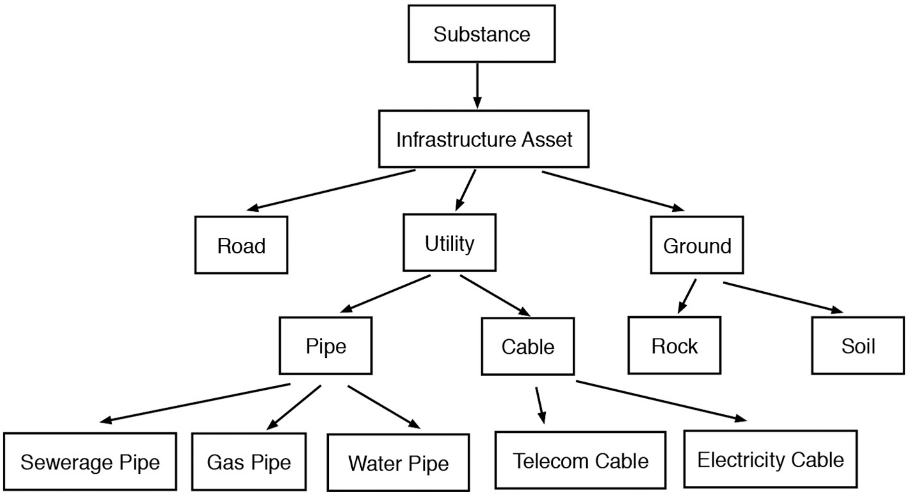


Fig. 2. A classification of infrastructure assets. An arrow from A to B means B is a $SubClassOf A$.

Table 1
Categories and priorities of ground properties. The letters P, C, M, K stand for *Physical*, *Compositional*, *Mechanical*, *Chemical*, respectively, referring to the corresponding categories defined in the concept hierarchy of *GroundProperty*. Properties with lower numbers in the column ‘Priority’ have higher priorities, e.g., 1 means the highest priority.

	Ground Property	Priority	Category
1	GroundWaterContent	1	P
2	GroundPorosity	1	P
3	GroundClayMineralogy	1	C
…	…	…	…
40	GroundFabric	2	C
41	GroundOrganicMatterContent	2	C
42	GroundThermalConductivity	2	M
…	…	…	…
56	GroundAirContent	3	C
57	GroundOxygenConcentration	3	K
58	GroundBufferingCapacity	3	K
…	…	…	…

specifying the high-level concept *HumanActivity* for roads and water pipes through the development of models of roads and water pipes.

The model of the natural environment was developed by extracting classes and hierarchies from the SWEET ontology (Raskin & Pan, 2005). Most of the classes defined in this model came from the *Phenomena* category defined in the SWEET terminology, and were verified by domain experts. The model of the natural environment can be seen as a sub-model of SWEET.

4.2. The content of the ground, road and water pipe models

This section presents the models of the ground, roads and water pipes. The model of the ground consists of the concept hierarchies of *Ground*, *GroundProperty* and *GroundProcess*, as well as the relationships among ground properties and processes. The concept hierarchy of *Ground* is shown in Fig. 3.

The direct subclasses of *GroundProperty* and their definitions are provided below. Each of the subclasses contains further subclasses. Fig. 4 provides a partial illustration of the conceptual hierarchy of *GroundProperty*. It shows all the direct subclasses of *GroundProperty*. Among them, only the direct subclasses of *GroundMechanicalProperty* are presented, due to limited space.

1. *GroundDescriptionProperty*: a ground description property provides a visual description of the composition, structure and fabric of the ground, including the position of the ground water table. For example, *GroundDensity* is a *GroundDescriptionProperty*.
2. *GroundStateVariable*: a ground state variable describes the current state of the ground which helps predict its future behaviour subject to external or internal processes. For example, *GroundTemperature* is a kind of *GroundStateVariable*.
3. *GroundClassificationProperty*: ground classification properties refer to the physical characteristics of the ground used in engineering classification schemes. For example, *GroundPlasticity* is a kind of *GroundClassificationProperty*.
4. *GroundConstructionProperty*: ground construction properties refer to engineering properties that are relevant when soil is used as a construction material. For example, *GroundAirContent* is a kind of *GroundConstructionProperty*.
5. *GroundMechanicalProperty*: ground mechanical properties refer to engineering properties of soil that influence their behaviour subject to a change in load (external loads such as traffic, and internal loads such as water pressure) or ground deformation. For example, *GroundStiffness* is a kind of *GroundMechanicalProperty*.
6. *GroundThermalProperty*: ground thermal properties refer to the properties relevant to sensors that measure temperature, and those can influence ground processes and their impact on buried structures. For example, *GroundThermalConductivity* is a kind of *GroundThermalProperty*.
7. *GroundChemicalProperty*: ground chemical properties refer to the pH and redox potential of the soil, and the organic content of the soil

Table 2
A table used to collect information about how ground properties affect each other.

property p_1	property p_2			
	GroundWaterContent	GroundPorosity	GroundClayMineralogy	…
GroundWaterContent	–	Y		…
GroundPorosity	Y	–		…
GroundClayMineralogy			–	…
…	…	…	…	…

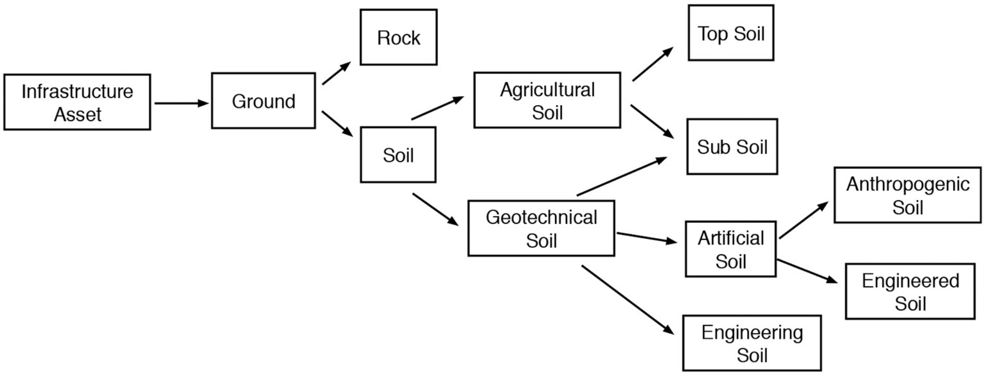


Fig. 3. The concept hierarchy of *Ground*.

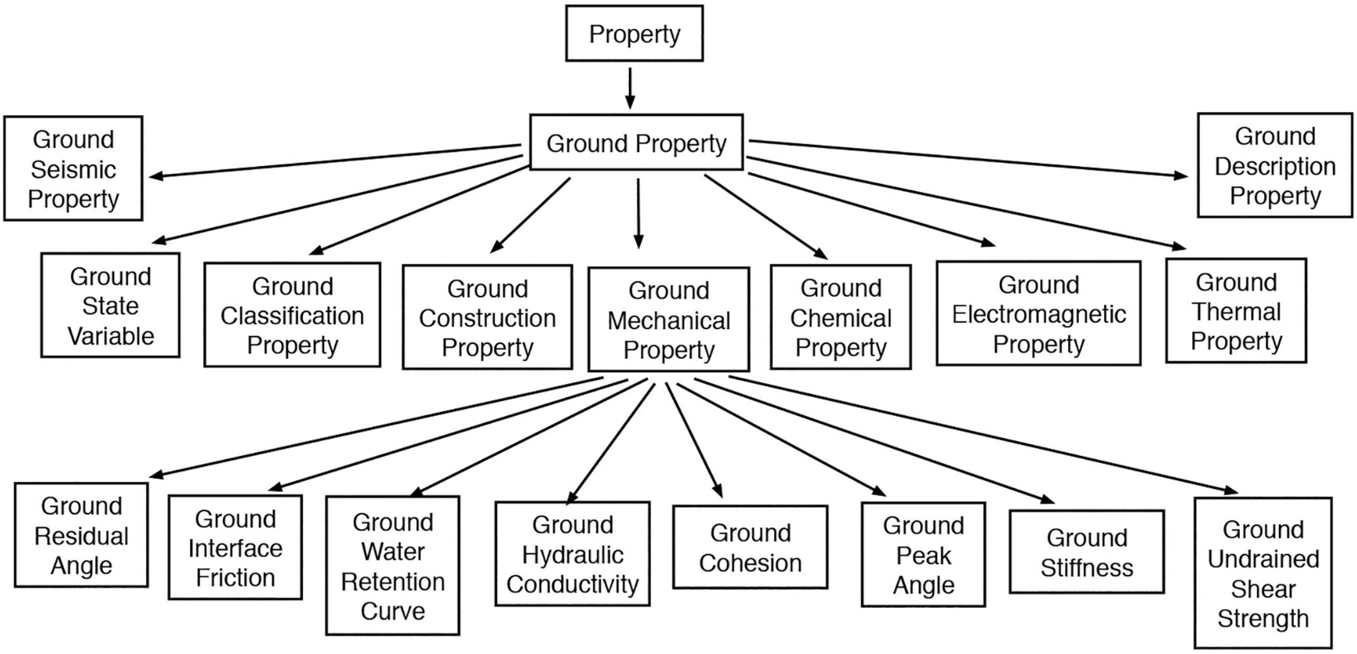


Fig. 4. A *partial* illustration of the concept hierarchy of *GroundProperty*.

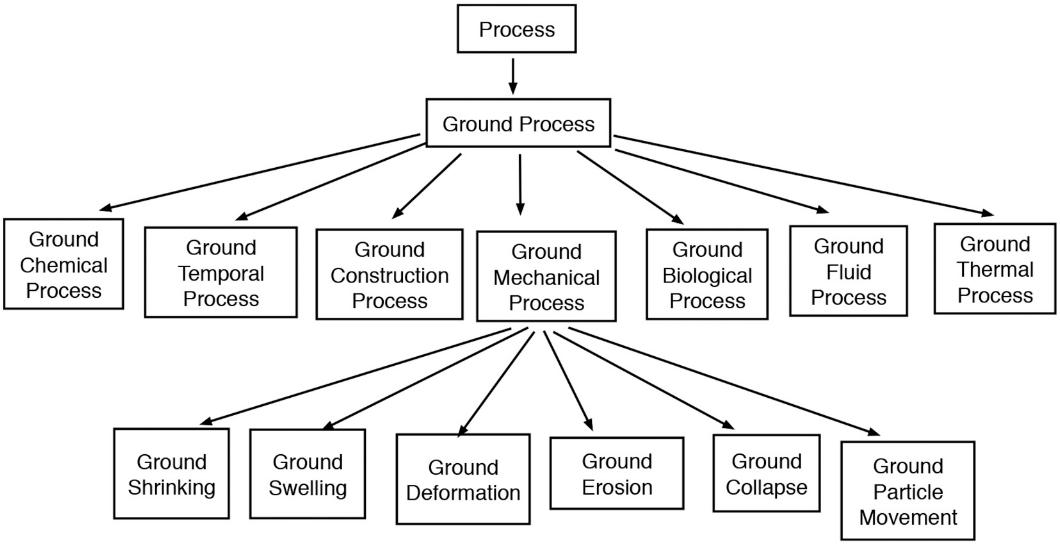


Fig. 5. A *partial* illustration of the concept hierarchy of *GroundProcess*.

which can be relevant to potential degradation of buried utilities. For example, *GroundpH* is a *GroundChemicalProperty*.

8. *GroundElectromagneticProperty*: ground electromagnetic properties refer to the properties relevant to electrical sensors, and those can influence soil properties which may affect construction and utility materials. For example, *GroundElectricalConductivity* is a kind of *GroundElectromagneticProperty*.
9. *GroundSeismicProperty*: ground seismic properties refer to the properties relevant to sensors that measure ground motion, and those can influence the transfer of vibrations through the soil. For example, *GroundP-WaveVelocity* is a *GroundSeismicProperty*.

The direct subclasses of *GroundProcess* and their definitions are listed below. The subclasses are classified into further levels. Fig. 5 presents all the direct subclasses of *GroundProcess*. Due to limited space, in the next level, only the direct subclasses of *GroundMechanicalProcess* are presented.

1. *GroundConstructionProcess*: ground construction processes refer to anthropogenic processes such as excavation, dewatering, applying engineered fill and building ground structures (e.g., foundations, retaining walls, tunnels). For example, *GroundCompaction* is a kind of *GroundConstructionProcess*.
2. *GroundFluidProcess*: ground fluid processes refer to the processes that involve the movement of water in the ground due to infiltration, evapotranspiration, and differences in potential because of external load and groundwater levels. For example, *GroundWaterFlow* is a kind of *GroundFluidProcess*.
3. *GroundMechanicalProcess*: ground mechanical processes refer to the processes that lead to volume changes, including erosion and changes in loading. For example, *GroundDeformation* is a kind of *GroundMechanicalProcess*.
4. *GroundTemporalProcess*: ground temporal processes refer to the processes that lead to ground movement and ground deterioration over a period of time. For example, *GroundSubsidence* is a kind of *GroundTemporalProcess*.
5. *GroundThermalProcess*: ground thermal processes refer to the processes that cause ground movement due to temperature changes. For example, *GroundFreezing* is a kind of *GroundThermalProcess*.
6. *GroundBiologicalProcess*: ground biological processes refer to the processes involving organic material that lead to chemical changes to the ground. For example, *GroundMineralization* is a kind of *GroundBiologicalProcess*.
7. *GroundChemicalProcess*: ground chemical processes refer to the processes (other than biological processes) that lead to chemical changes in the ground. For example, *GroundChemicalReaction* is a kind of *GroundChemicalProcess*.

In addition, the model of the ground defines how ground properties and processes affect each other. Such definitions are specified in spreadsheets. As an example, Fig. 6 shows part of the spreadsheet on how ground properties affect each other.

The model of roads defines the concept hierarchies of *Road*, *RoadProperty* and *RoadProcess*, as well as relationships among road properties and processes. Fig. 7 presents a classification of roads from the perspective of pavement design, construction and maintenance.

As Fig. 8 shows, the class *RoadProperty* is classified into *RoadStructuralProperty*, *RoadFunctionalProperty*, *RoadEnvironmentalProperty* and *RoadFinancialProperty*, which refer to inherent or acquired features of a road associated with its structure, functionality, environment, financial values and costs, respectively. Based on the structure of pavements, the class *RoadStructuralProperty* is classified further into subcategories.

The direct subclasses of *RoadProcess* and their definitions are listed below. Fig. 9 presents all the direct subclasses of *RoadProcess*. Due to limited space, only the direct subclasses of *RoadThermalProcess* and *RoadMechanicalProcess* are presented in the next level.

1. *RoadConstructionProcess*: road construction processes refer to the processes that are constructed or result from road construction operations. For example, *RoadTrenchFilling* is a kind of *RoadConstructionProcess*.
2. *RoadFluidProcess*: road fluid processes refer to a systematic series of mechanized or chemical activities that are triggered by fluid causing roads to deteriorate. For example, *RoadWaterInfiltration* is a kind of *RoadFluidProcess*.
3. *RoadMechanicalProcess*: road mechanical processes refer to a systematic series of mechanized activities causing road to deteriorate. For example, *RoadDeformation* is a kind of *RoadMechanicalProcess*.
4. *RoadTemporalProcess*: road temporal processes refer to a systematic series of mechanized or chemical activities relating to time causing road to deteriorate. For example, *RoadFunctionalDecline* is a kind of *RoadTemporalProcess*.
5. *RoadThermalProcess*: road thermal processes refer to a systematic series of mechanized or chemical activities that are triggered by changes in temperature causing road to deteriorate. For example, *RoadFreezing* is a kind of *RoadThermalProcess*.

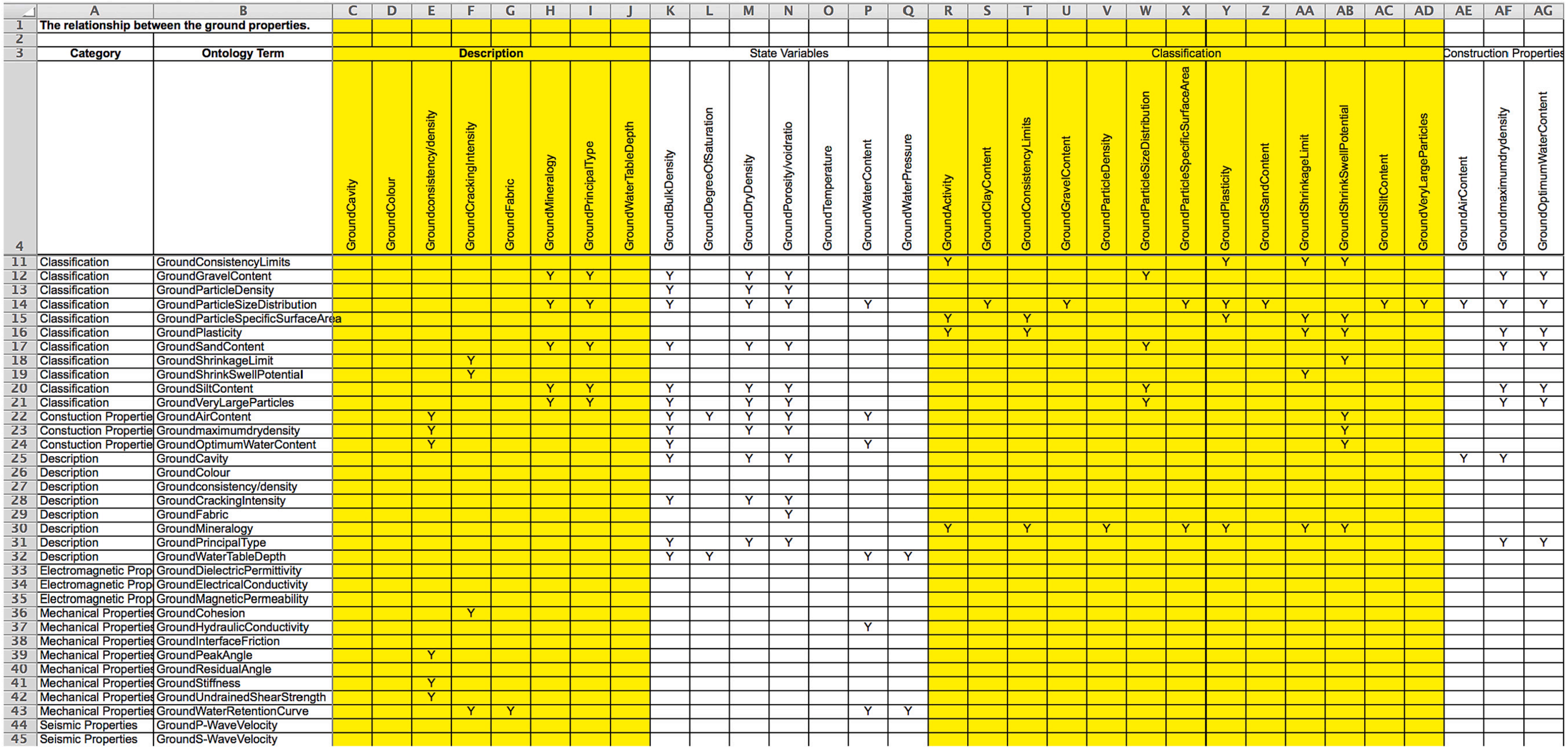
The model of roads also defines how road properties and processes affect each other. An example spreadsheet of such definitions is presented in Fig. 10.

The model of water pipes defines the concept hierarchies of *WaterPipe*, *WaterPipeProperty* and *WaterPipeProcess*, as well as relationships among water pipe properties and processes. A classification of *WaterPipe* is presented in Fig. 11, based on the materials of water pipes.

The direct subclasses of *WaterPipeProperty* and their definitions are provided below. Fig. 12 presents them, as well as the direct subclasses of *WaterPipeMaterialProperty*.

1. *WaterPipeTrenchDimension*: water pipe trench dimension refers to the properties about installation of a water pipe in a trench. For example, *WaterPipeTrenchWidth* is a kind of *WaterPipeTrenchDimension*.
2. *WaterPipeGeometryProperty*: water pipe geometry properties cover the length between connections, length of pipe sections, depth and elevation, and pipe cross sections. For example, *WaterPipeDepth* is a kind of *WaterPipeGeometryProperty*.
3. *WaterPipeMaterialProperty*: water pipe material properties cover the material, joints and valves. For example, *WaterPipeExternalCoating* is a *WaterPipeMaterialProperty*.
4. *WaterPipeNetworkProperty*: water pipe network properties refer to those about a pipe within a network, e.g., the number of connections in a network. For example, *WaterPipeConnectionDensity* is a kind of *WaterPipeNetworkProperty*.
5. *WaterPipeFluidProperty*: water pipe fluid properties cover the properties of the fluid. For example, *WaterPipeWaterCorrosivity* is a kind of *WaterPipeFluidProperty*.
6. *WaterPipeConditionProperty*: water pipe condition properties are those used to describe the conditions of a water pipe, including any indirect indicators. For example, *WaterPipeWallRoughness* is a kind of *WaterPipeConditionProperty*.
7. *WaterPipeRecord*: water pipe records cover the records of the water pipe performance and any changes to the pipe. For example, *WaterPipeFailureRecord* is a kind of *WaterPipeRecord*.
8. *WaterPipeFinancialProperty*: water pipe financial properties cover the cost of installing, maintaining and replacing the pipe. For example, *WaterPipeInstallationCost* is a kind of *WaterPipeFinancialProperty*.
9. *WaterPipeLocation* and *WaterPipeOwner* refer to the position and the owner of a pipe, respectively.

The direct subclasses of *WaterPipeProcess* (see Fig. 13) and their definitions are listed below.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
1	**The relationship between the ground properties.**																																
2																																	
3	**Category**	**Ontology Term**	**Description**								State Variables							Classification													Construction Properties		
4			GroundCavity	GroundColour	Groundconsistency/density	GroundCrackingIntensity	GroundFabric	GroundMineralogy	GroundPrincipalType	GroundWaterTableDepth	GroundBulkDensity	GroundDegreeOfSaturation	GroundDryDensity	GroundPorosity/voidratio	GroundTemperature	GroundWaterContent	GroundWaterPressure	GroundActivity	GroundClayContent	GroundConsistencyLimits	GroundGravelContent	GroundParticleDensity	GroundParticleSizeDistribution	GroundParticleSpecificSurfaceArea	GroundPlasticity	GroundSandContent	GroundShrinkageLimit	GroundShrinkSwellPotential	GroundSiltContent	GroundVeryLargeParticles	GroundAirContent	Groundmaximumdrydensity	GroundOptimumWaterContent
11	Classification	GroundConsistencyLimits																Y							Y		Y	Y					
12	Classification	GroundGravelContent						Y	Y		Y		Y	Y									Y									Y	Y
13	Classification	GroundParticleDensity									Y		Y	Y																			
14	Classification	GroundParticleSizeDistribution						Y	Y		Y		Y	Y		Y			Y		Y			Y	Y	Y			Y	Y	Y	Y	Y
15	Classification	GroundParticleSpecificSurfaceArea																Y		Y					Y		Y	Y					
16	Classification	GroundPlasticity																Y		Y							Y	Y				Y	Y
17	Classification	GroundSandContent						Y	Y		Y		Y	Y									Y									Y	Y
18	Classification	GroundShrinkageLimit				Y																						Y					
19	Classification	GroundShrinkSwellPotential				Y																					Y						
20	Classification	GroundSiltContent						Y	Y		Y		Y	Y									Y									Y	Y
21	Classification	GroundVeryLargeParticles						Y	Y		Y		Y	Y									Y									Y	Y
22	Constuction Propertie	GroundAirContent			Y						Y	Y	Y	Y		Y												Y					
23	Constuction Propertie	Groundmaximumdrydensity			Y						Y		Y	Y														Y					
24	Constuction Propertie	GroundOptimumWaterContent			Y						Y					Y												Y					
25	Description	GroundCavity									Y		Y	Y																	Y	Y	
26	Description	GroundColour																															
27	Description	Groundconsistency/density																															
28	Description	GroundCrackingIntensity									Y		Y	Y																			
29	Description	GroundFabric												Y																			
30	Description	GroundMineralogy																Y		Y		Y		Y	Y		Y	Y					
31	Description	GroundPrincipalType									Y		Y	Y																		Y	Y
32	Description	GroundWaterTableDepth									Y	Y				Y	Y																
33	Electromagnetic Prop	GroundDielectricPermittivity																															
34	Electromagnetic Prop	GroundElectricalConductivity																															
35	Electromagnetic Prop	GroundMagneticPermeability																															
36	Mechanical Properties	GroundCohesion				Y																											
37	Mechanical Properties	GroundHydraulicConductivity														Y																	
38	Mechanical Properties	GroundInterfaceFriction																															
39	Mechanical Properties	GroundPeakAngle			Y																												
40	Mechanical Properties	GroundResidualAngle																															
41	Mechanical Properties	GroundStiffness			Y																												
42	Mechanical Properties	GroundUndrainedShearStrength			Y																												
43	Mechanical Properties	GroundWaterRetentionCurve				Y	Y									Y	Y																
44	Seismic Properties	GroundP-WaveVelocity																															
45	Seismic Properties	GroundS-WaveVelocity																															

Fig. 6. A screenshot of part of the spreadsheet of how ground properties affect each other.

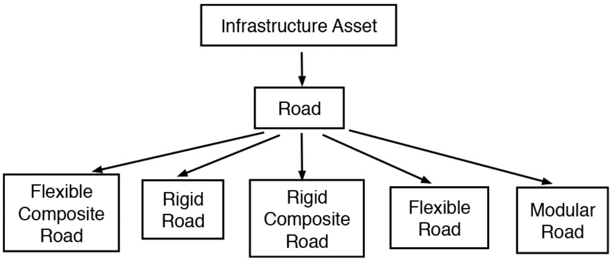


Fig. 7. The concept hierarchy of *Road*.

1. *WaterPipeCracking*: water pipe cracking refers to the action of a pathway appearing in a pipe allowing water from inside the pipe to flow outside.
2. *WaterPipeCorrosion*: water pipe corrosion refers to the chemical action of decreasing the structural material of a pipe available for transporting water.
3. *WaterPipeJointFatigue*: water pipe joint fatigue refers to the action of stressing a joint which, if repeated, could cause a joint to fail.
4. *WaterPipeValveLeaking*: water pipe valve leaking refers to the action of water coming out of the pipe due to a pathway through a valve.

The model of water pipe also defines how water pipe properties and processes affect each other. An example spreadsheet of these definitions is shown in Fig. 14.

4.3. Relationships and interdependencies across models

Based on the work by Clarke et al. (2017) on designing a decision support system for proactive management of subsurface utilities, the following main types of relationships and interdependencies between the aforementioned sub-models of city infrastructure are defined.

1. Human activities (e.g., traffic load) and the natural environment (e.g., air temperature, rainfall and flooding) have impact on roads.
2. A road transmits actions to the ground. For example, a road will transmit a force (e.g., traffic load) to the ground. If a road is damaged, it can also transmit water and chemicals through infiltration.
3. The ground transmits actions to its underlying utilities. For example, any ground movement could lead to the deformation of its underlying utilities.
4. Utilities, when damaged, transmit actions to the ground. For example, a water pipe leakage will affect the ground, as the leaking

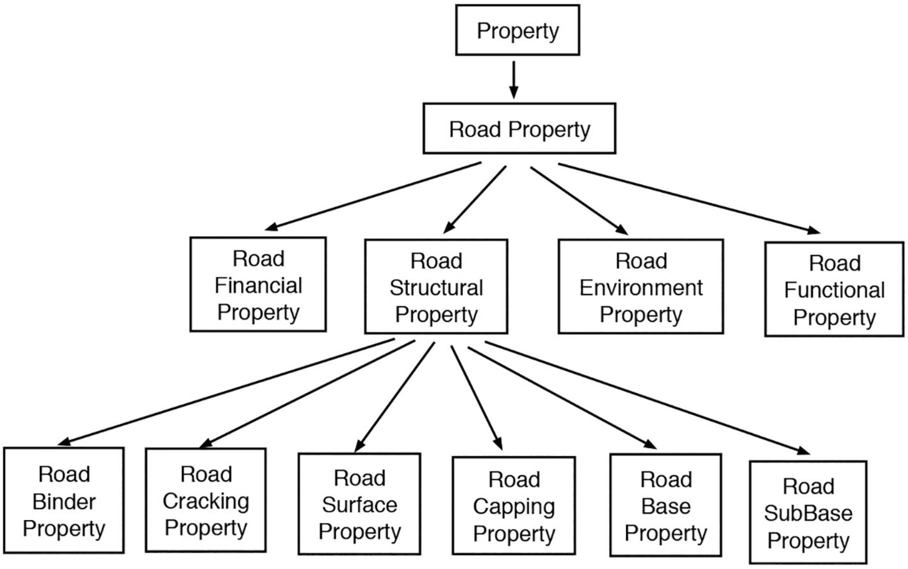


Fig. 8. A *partial* illustration of the concept hierarchy of *RoadProperty*.

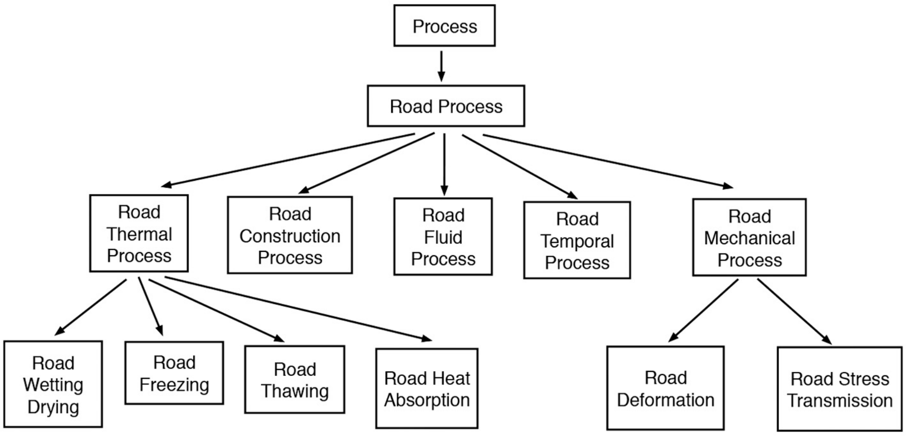
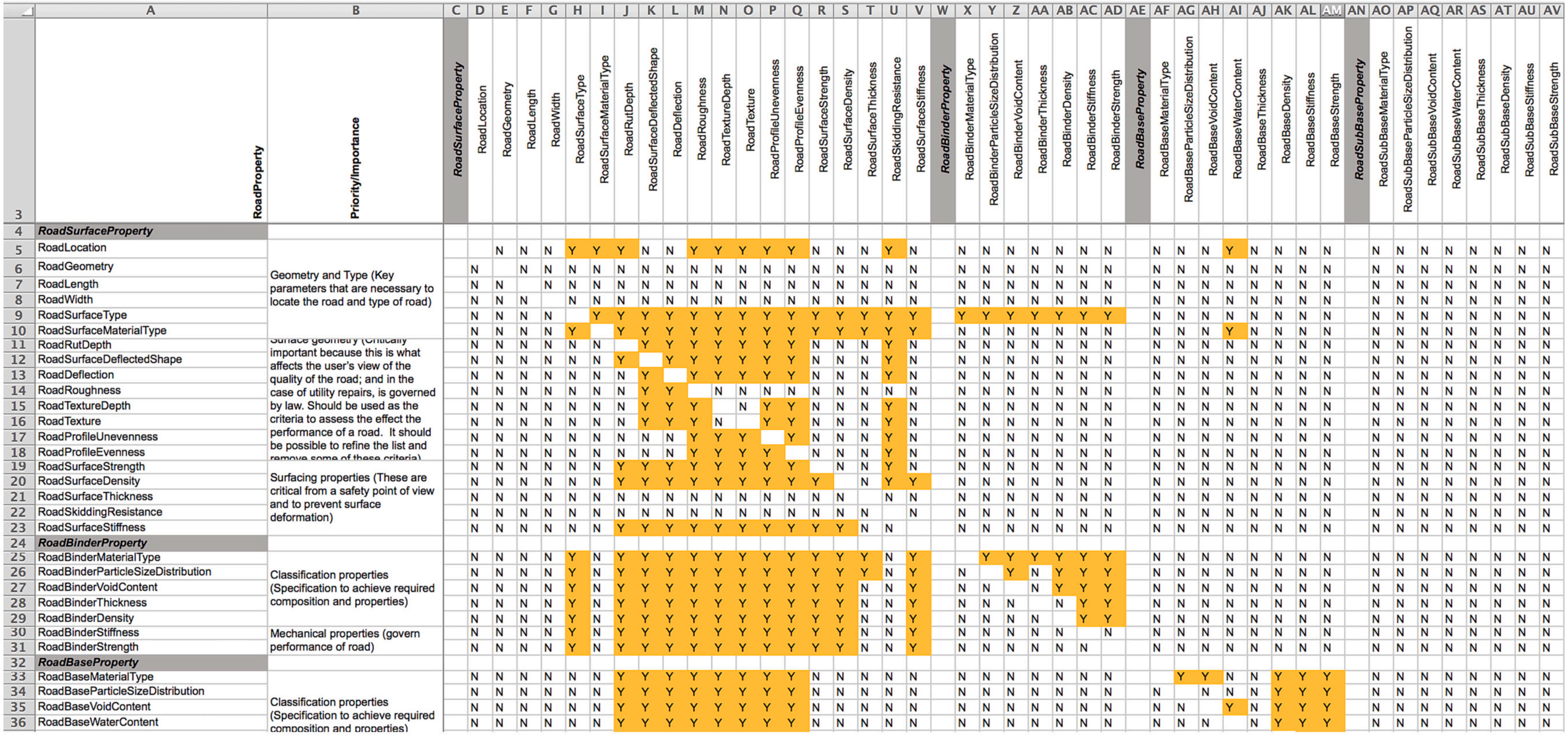


Fig. 9. A *partial* illustration of the concept hierarchy of *RoadProcess*.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT	AU	AV
3	RoadProperty	Priority/Importance	***RoadSurfaceProperty***	RoadLocation	RoadGeometry	RoadLength	RoadWidth	RoadSurfaceType	RoadSurfaceMaterialType	RoadRutDepth	RoadSurfaceDeflectedShape	RoadDeflection	RoadRoughness	RoadTextureDepth	RoadTexture	RoadProfileUnevenness	RoadProfileEvenness	RoadSurfaceStrength	RoadSurfaceDensity	RoadSurfaceThickness	RoadSkiddingResistance	RoadSurfaceStiffness	***RoadBinderProperty***	RoadBinderMaterialType	RoadBinderParticleSizeDistribution	RoadBinderVoidContent	RoadBinderThickness	RoadBinderDensity	RoadBinderStiffness	RoadBinderStrength	***RoadBaseProperty***	RoadBaseMaterialType	RoadBaseParticleSizeDistribution	RoadBaseVoidContent	RoadBaseWaterContent	RoadBaseThickness	RoadBaseDensity	RoadBaseStiffness	RoadBaseStrength	***RoadSubBaseProperty***	RoadSubBaseMaterialType	RoadSubBaseParticleSizeDistribution	RoadSubBaseVoidContent	RoadSubBaseWaterContent	RoadSubBaseThickness	RoadSubBaseDensity	RoadSubBaseStiffness	RoadSubBaseStrength
4	***RoadSurfaceProperty***																																															
5	RoadLocation				N	N	N	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N	N	N	Y	N		N	N	N	N	N	N	N		N	N	N	Y	N	N	N	N		N	N	N	N	N	N	N	N
6	RoadGeometry	Geometry and Type (Key parameters that are necessary to locate the road and type of road)		N		N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
7	RoadLength			N	N		N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
8	RoadWidth			N	N	N		N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
9	RoadSurfaceType			N	N	N	N		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y	Y	Y	Y	Y	Y		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
10	RoadSurfaceMaterialType			N	N	N	N	Y		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		N	N	N	N	N	N	N		N	N	N	Y	N	N	N	N		N	N	N	N	N	N	N	N
11	RoadRutDepth	Surface geometry (Critically important because this is what affects the user's view of the quality of the road; and in the case of utility repairs, is governed by law. Should be used as the criteria to assess the effect the performance of a road. It should be possible to refine the list and remove some of these criteria)		N	N	N	N	N	N		Y	Y	Y	Y	Y	Y	Y	N	N	N	Y	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
12	RoadSurfaceDeflectedShape			N	N	N	N	N	N	Y		Y	Y	Y	Y	Y	Y	N	N	N	Y	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
13	RoadDeflection			N	N	N	N	N	N	N	Y		Y	Y	Y	Y	Y	N	N	N	Y	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
14	RoadRoughness			N	N	N	N	N	N	N	Y	Y		N	N	N	N	N	N	N	N	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
15	RoadTextureDepth			N	N	N	N	N	N	N	Y	Y	Y		N	Y	Y	N	N	N	Y	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
16	RoadTexture			N	N	N	N	N	N	N	Y	Y	Y	N		Y	Y	N	N	N	Y	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
17	RoadProfileUnevenness			N	N	N	N	N	N	N	N	N	Y	Y	Y		Y	N	N	N	Y	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
18	RoadProfileEvenness			N	N	N	N	N	N	N	N	N	Y	Y	Y	Y		N	N	N	Y	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
19	RoadSurfaceStrength	Surfacing properties (These are critical from a safety point of view and to prevent surface deformation)		N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y		N	N	Y	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
20	RoadSurfaceDensity			N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y		N	Y	Y		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
21	RoadSurfaceThickness			N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		N	N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
22	RoadSkiddingResistance			N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		N		N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
23	RoadSurfaceStiffness			N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N			N	N	N	N	N	N	N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
24	***RoadBinderProperty***																																															
25	RoadBinderMaterialType			N	N	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y			Y	Y	Y	Y	Y	Y		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
26	RoadBinderParticleSizeDistribution	Classification properties (Specification to achieve required composition and properties)		N	N	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y		N		Y	N	Y	Y	Y		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
27	RoadBinderVoidContent			N	N	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y		N	N		N	Y	Y	Y		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
28	RoadBinderThickness			N	N	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y		N	N	N		N	Y	Y		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
29	RoadBinderDensity			N	N	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y		N	N	N	N		Y	Y		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
30	RoadBinderStiffness	Mechanical properties (govern performance of road)		N	N	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y		N	N	N	N	N		N		N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
31	RoadBinderStrength			N	N	N	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y		N	N	N	N	N	N			N	N	N	N	N	N	N	N		N	N	N	N	N	N	N	N
32	***RoadBaseProperty***																																															
33	RoadBaseMaterialType			N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N		N	N	N	N	N	N	N			Y	Y	N	N	Y	Y	Y		N	N	N	N	N	N	N	N
34	RoadBaseParticleSizeDistribution	Classification properties (Specification to achieve required composition and properties)		N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N		N	N	N	N	N	N	N		N		N	N	N	Y	Y	Y		N	N	N	N	N	N	N	N
35	RoadBaseVoidContent			N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N		N	N	N	N	N	N	N		N	N		Y	N	Y	Y	Y		N	N	N	N	N	N	N	N
36	RoadBaseWaterContent			N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N		N	N	N	N	N	N	N		N	N	N		N	Y	Y	Y		N	N	N	N	N	N	N	N

Fig. 10. A screenshot of part of the spreadsheet of how road properties affect each other.

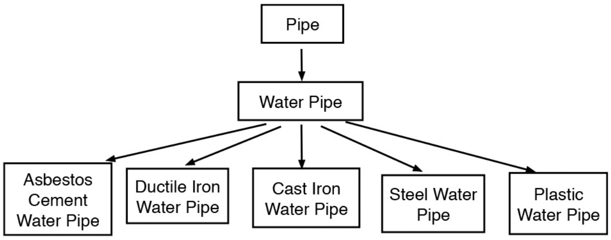


Fig. 11. The concept hierarchy of *WaterPipe*.

water would increase the ground water content and change other ground properties.

5. The ground transmits actions to the road. For example, if water enters the ground, the ground will swell, which could possibly cause heave of the road surface.
6. The ground supports roads and utilities. The ground is the subgrade of roads, hence it supports roads. The ground also provides vertical and lateral support to utilities.

5. City infrastructure ontologies

The proposed model of city infrastructure was represented as a suite of ontologies. The ontologies are written in OWL 2 Web Ontology Language Manchester Syntax (Horridge & Patel-Schneider, 2012). The top ontology is called the ATU (i.e., Assessing The Underworld) ontology. The top-level structure of the ATU ontology follows that of the SWEET ontology (Raskin & Pan, 2005). The ATU ontology inherits six top-level concepts from the SWEET ontology: *Substance*, *Property*, *Process*, *HumanActivity*, *Phenomena* and *Representation*. Additionally, it defines a new top-level concept *Method* in order to cover methods, tools and techniques used in human activities.

The ATU ontology imports the following ontologies where these top-level concepts are defined and specified further: an ontology of the ground, an ontology of roads, an ontology of water pipes, an ontology of human activities, an ontology of methods, an ontology of investigation methods, and an ontology of phenomena in the natural environment. An overview of the main high-level concepts in the ATU ontology is shown in Fig. 15.

The relations, such as *hasImpactOn*, *influencedBy*, etc., are defined as object properties in an ontology of relations. The relations *increases* and *decreases* are defined as *subPropertyOf hasImpactOn*, and their inverses *increasedBy* and *decreasedBy* are *subPropertyOf influencedBy*. Though *hasImpactOn* and *influencedBy* are the main relations used for defining the interdependencies between properties and processes of infrastructure, several other relations are defined in the relation ontology. To support the representation of quantitative spatial information, the relations *hasGeometry* and its inverse *geometryOf* are defined to link objects with its geometries. Every geometry is an instance of the concept *Geometry*, which is a subclass of *Representation*. Each geometry has a data property *asWKT* whose range is the data type *wktLiteral*, as defined in the Open Geospatial Consortium (OGC) GeoSPARQL ontology (OGC GeoSPARQL Standards Working Group, 2021). The WKT (well-known text representation) literal is a commonly used representation of geometry information in GIS layers. To support the representation and reasoning of qualitative spatial information, various qualitative spatial relations are defined in the relation ontology. Among them, topological relations are based on the region connection calculus (Randell, Cui, & Cohn, 1992; Cohn, Bennett, Gooday, & Gotts, 1997). Direction relations are classified into cardinal direction relations and relative direction relations. Cardinal direction relations (e.g., *north*, *definitelyNorth*) are defined based on the cardinal direction calculus (Ligozat, 1998), the cardinal directions for regions (Skiadopoulos & Koubarakis, 2004), the logic of directions (Du, Alechina, & Cohn, 2020). Relative direction relations (e.g., *left*, *below*) are defined based on the double cross calculus (Freksa, 1992) and the ternary point configuration calculus (Moratz & Ragni, 2008). Qualitative distance relations (e.g., *near*, *bufferedEqual*) are based on the terminology provided by Clementini, Felice, and Hernández (1997) and qualitative distance logics (Du & Alechina, 2016; Du, Alechina, Stock, & Jackson, 2013). The relation ontology is imported by the infrastructure asset ontologies (e.g., the ground ontology) and the ATU ontology itself, which enables users to use and reason with these ontologies together.

As a subclass of the top-level concept *Substance*, *InfrastructureAsset* has three subclasses: *Ground*, *Road* and *Utility*, which is the superclass of

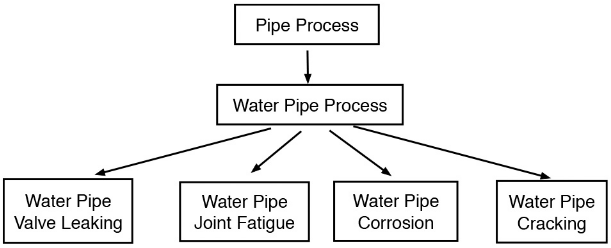


Fig. 13. The concept hierarchy of *WaterPipeProcess*.

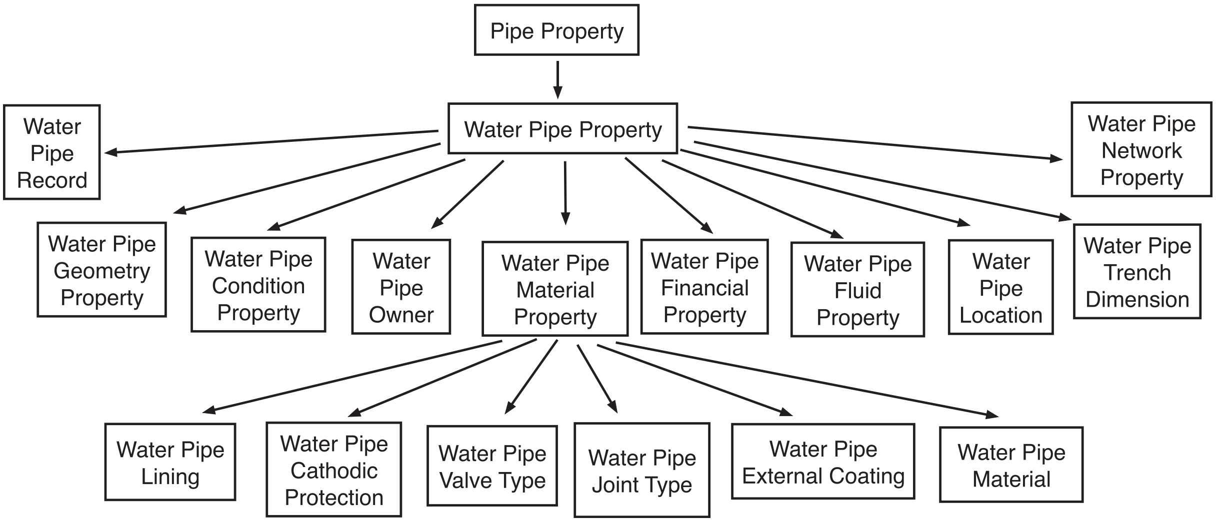
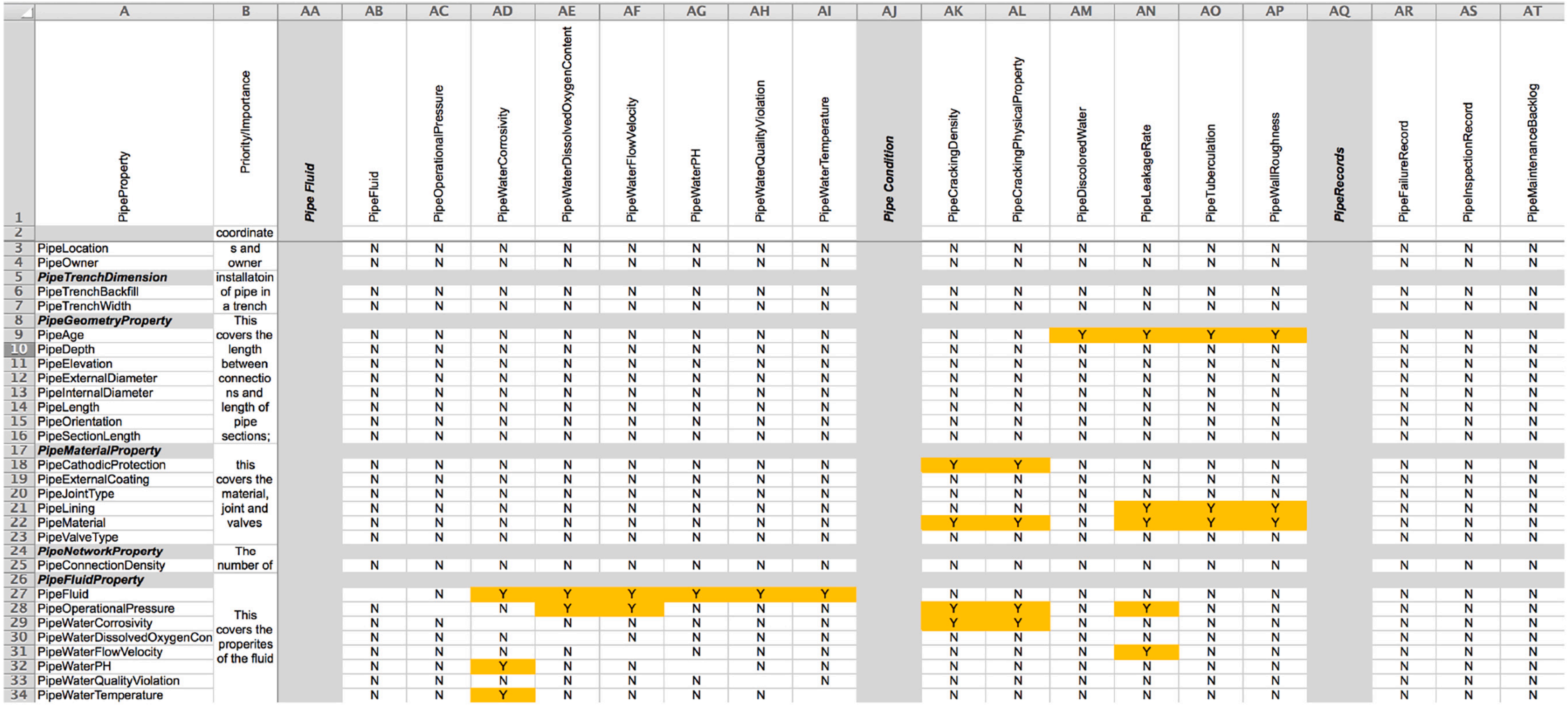


Fig. 12. A *partial* illustration of the concept hierarchy of *WaterPipeProperty*.



	A	B	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS	AT
1	PipeProperty	Priority/Importance	***Pipe Fluid***	PipeFluid	PipeOperationalPressure	PipeWaterCorrosivity	PipeWaterDissolvedOxygenContent	PipeWaterFlowVelocity	PipeWaterPH	PipeWaterQualityViolation	PipeWaterTemperature	***Pipe Condition***	PipeCrackingDensity	PipeCrackingPhysicalProperty	PipeDiscoloredWater	PipeLeakageRate	PipeTuberculation	PipeWallRoughness	***PipeRecords***	PipeFailureRecord	PipeInspectionRecord	PipeMaintenanceBacklog
2		coordinate																				
3	PipeLocation	s and		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
4	PipeOwner	owner		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
5	***PipeTrenchDimension***	installatoin																				
6	PipeTrenchBackfill	of pipe in		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
7	PipeTrenchWidth	a trench		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
8	***PipeGeometryProperty***	This																				
9	PipeAge	covers the		N	N	N	N	N	N	N	N		N	N	Y	Y	Y	Y		N	N	N
10	PipeDepth	length		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
11	PipeElevation	between		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
12	PipeExternalDiameter	connectio		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
13	PipeInternalDiameter	ns and		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
14	PipeLength	length of		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
15	PipeOrientation	pipe		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
16	PipeSectionLength	sections;		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
17	***PipeMaterialProperty***																					
18	PipeCathodicProtection	this		N	N	N	N	N	N	N	N		Y	Y	N	N	N	N		N	N	N
19	PipeExternalCoating	covers the		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
20	PipeJointType	material,		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
21	PipeLining	joint and		N	N	N	N	N	N	N	N		N	N	N	Y	Y	Y		N	N	N
22	PipeMaterial	valves		N	N	N	N	N	N	N	N		Y	Y	N	Y	Y	Y		N	N	N
23	PipeValveType			N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
24	***PipeNetworkProperty***	The																				
25	PipeConnectionDensity	number of		N	N	N	N	N	N	N	N		N	N	N	N	N	N		N	N	N
26	***PipeFluidProperty***																					
27	PipeFluid				N	Y	Y	Y	Y	Y	Y		N	N	N	N	N	N		N	N	N
28	PipeOperationalPressure	This		N		N	Y	Y	N	N	N		Y	Y	N	Y	N	N		N	N	N
29	PipeWaterCorrosivity	covers the		N	N		N	N	N	N	N		Y	Y	N	N	N	N		N	N	N
30	PipeWaterDissolvedOxygenCon	properites		N	N	N		N	N	N	N		N	N	N	N	N	N		N	N	N
31	PipeWaterFlowVelocity	of the fluid		N	N	N	N		N	N	N		N	N	N	Y	N	N		N	N	N
32	PipeWaterPH			N	N	Y	N	N		N	N		N	N	N	N	N	N		N	N	N
33	PipeWaterQualityViolation			N	N	N	N	N	N		N		N	N	N	N	N	N		N	N	N
34	PipeWaterTemperature			N	N	Y	N	N	N	N			N	N	N	N	N	N		N	N	N

Fig. 14. A screenshot of part of the spreadsheet of how water pipe properties affect each other.

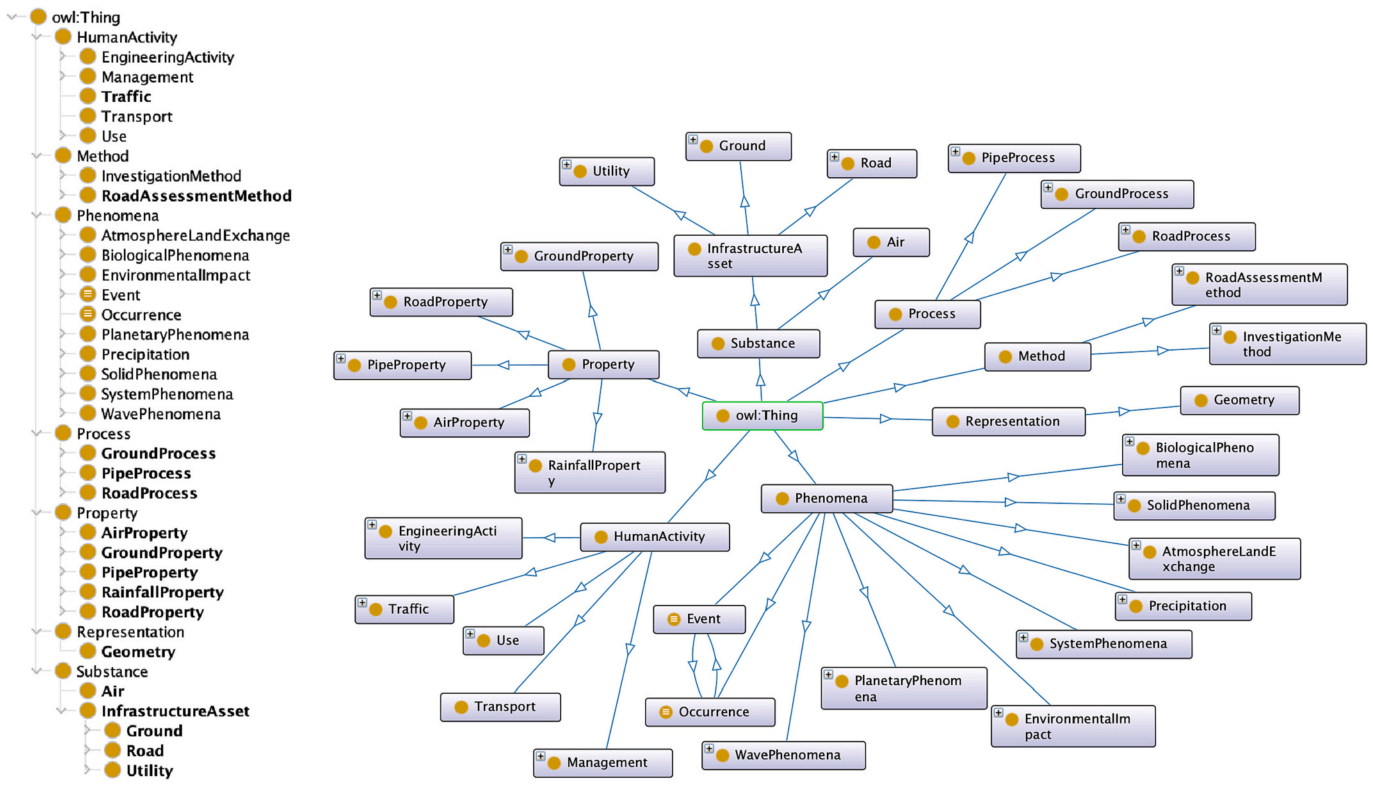


Fig. 15. An overview of the ATU ontology: an indented text list (left) and a graph (right).

Pipe and *Cable*. *Pipe* is classified into *WaterPipe*, *GasPipe*, and *SeweragePipe*. The classes *Ground*, *Road* and *WaterPipe* are specified further in the ground ontology, road ontology and water pipe ontology, respectively.

The top-level concepts *Property* and *Process* are specified further for different kinds of infrastructure assets. The classes *GroundProperty* and *GroundProcess* are specified further in the ground ontology. The classes *RoadProperty* and *RoadProcess* are specified further in the road ontology. The classes *WaterPipeProperty* and *WaterPipeProcess* are specified further in the water pipe ontology. In the ground, road and water pipe ontologies, the natural language definitions of concepts, as well as knowledge sources, are coded as annotations. The concept hierarchies and relationships captured in the spreadsheets are expressed in the form of '*SubClassOf* axioms'. For example, *GroundStiffness* is a *SubClassOf* *GroundMechanicalProperty* and a *SubClassOf* (*influencedBy* some *GroundGravelContent*).

The top-level concept *HumanActivity* is specified in the human activity ontology. It covers engineering activities (e.g., excavation), asset management, traffic, etc. The concepts *PipeManagement* and *RoadManagement* are subclasses of the concept *AssetManagement*. A subclass of *RoadManagement* is *RoadAssessment*, which has *RoadDestructiveAssessment*, *RoadNonDestructiveAssessment* and *RoadVisualInspection* as its subclasses.

The top-level concept *Method* is specified in the method ontology. *RoadAssessmentMethod* is a subclass of *Method*. It covers road destructive assessment methods and non-destructive assessment methods. The subclasses of *RoadAssessment* and *RoadAssessmentMethod* are linked by *uses* and *usedBy* relations. For example, *RoadDestructiveAssessment* uses some *RoadDestructiveAssessmentMethod*.

The top-level concept *InvestigationMethod* in the investigation ontology is also a subclass of *Method*. It has two subclasses: *GeophysicalMethod* and *NonGeophysicalMethod*. The subclasses of *GeophysicalMethod* and *NonGeophysicalMethod* are linked with the subclasses of *GroundProperty* and *GroundProcess* by *measures* and *measuredBy* relations. For example, *SeismicBoreholeSurvey* is a subclass of *SeismicMethod* and measures several ground properties and processes, including *GroundP-WaveVelocity*, *GroundFreezing*, etc. For each of the *measures* and *measuredBy* relation statements, a 'usefulness score' is assigned to it. A 'usefulness score' is a non-negative integer indicating the usefulness of a geophysical tool for measuring a specific ground property or process in shallow (0–5 m depth) streetworks surveys: 0 means 'not suitable'; 1 means 'limited use'; 2 means 'can be used but there are limitations'; 3 means 'excellent potential'; 4 means 'techniques well developed and excellent approach'.

The top-level concept *Phenomena* is specified in the phenomena ontology. The phenomena ontology extracts concepts that are related to city infrastructure from the SWEET ontology (Raskin & Pan, 2005). It covers concepts of natural phenomena (e.g., *Drought*, *ExtremeTemperature*, *Freezing*, *Earthquake*, *Precipitation*, etc.) that can affect or be affected by infrastructure assets, or trigger asset failures.

The relationships between concepts from different sub-ontologies are defined in the ATU ontology. For example, *GroundCollapse* *increases* *PipeCracking* and *RoadDeformation*; *Rainfall* *increases* *GroundWaterInfiltration*. Currently, such cross-ontology relationships are specified by domain experts and the number of these relationships is relatively small. More cross-ontology relationships can be defined and added for different use cases.

Table 3 shows the number of classes and axioms defined in the latest version of the ontologies by the end of March, 2023. These numbers were obtained by opening these ontologies in Protégé (Stanford Center for Biomedical Informatics Research, 2023).

6. Querying the ontologies

The city infrastructure ontologies can be queried separately or together. By querying a single infrastructure asset ontology, questions related to the maintenance of this asset can be answered, e.g., *'which ground properties or processes affect or are affected by ground water content?'*, *'which ground properties or processes affect ground deformation?'*, *'which road processes affect some road functional property (e.g., road*

Table 3
The number of classes and axioms in the latest version of the ontologies.

	Classes	Axioms
Ground Ontology	110	3,337
Road Ontology	110	4,545
Water Pipe Ontology	66	894
Human Activity Ontology	55	140
Method Ontology	78	269
Investigation Ontology	45	183
Phenomena Ontology	178	382
ATU Ontology	620	10,117

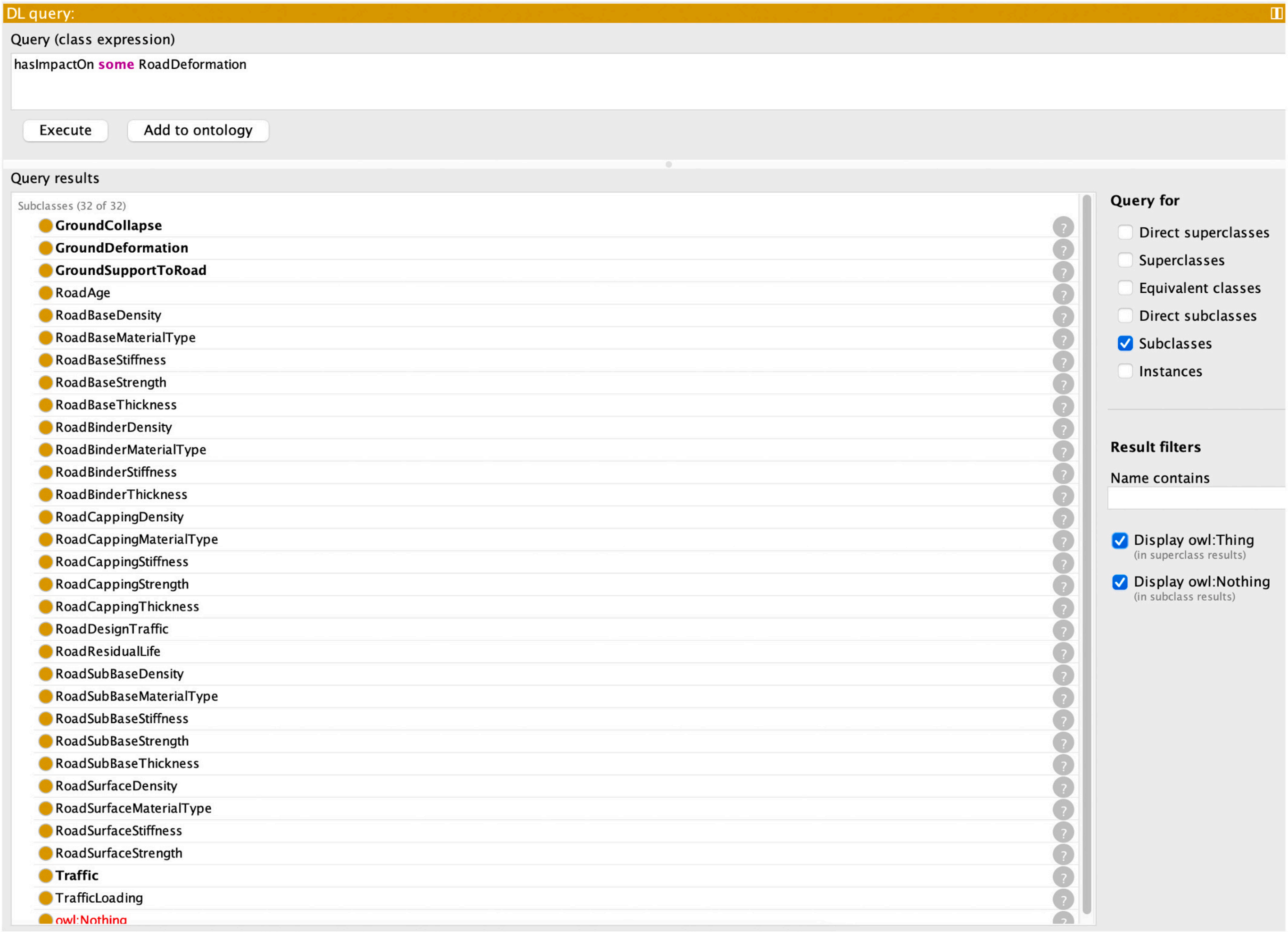
skidding resistance)?', *'which pipe properties affect pipe corrosion or cracking?'*, etc. By using and querying the ontologies together, it can answer questions about *interactions* between different infrastructure assets, for instances, *'which properties or processes of the ground and roads affect pipe corrosion and cracking?'*, *'which properties or processes of the ground and buried pipes affect road deformation and cracking?'*, etc. There are two main ways to query the ontologies. One way is to use description logic reasoners, such as Pellet (Sirin, Parsia, Grau, Kalyanpur, & Katz, 2007), FaCT++ (Tsarkov & Horrocks, 2006), HermiT (Glimm, Horrocks, Motik, Stoilos, & Wang, 2014), ELK (Kazakov & Klinov, 2015), etc. The other way is to use SPARQL (W3C, March 2013). Both ways are supported by Protégé (Stanford Center for Biomedical Informatics Research, 2023) and its plugins. Below we will provide some querying examples using Protégé.

By using the DL query tab in Protégé, one could obtain subclasses, superclasses and instances of a class expression. In this example of querying the ATU ontology, the Pellet reasoner is employed first to check the consistency of the ontology. Then, as shown in Fig. 16, by ticking the 'Subclasses' on the right and executing the query '*hasImpactOn* some *RoadDeformation*', a list of 32 (this is, 31, if *owl* : *Nothing* is not included) subclasses of the class expression '*hasImpactOn* some *RoadDeformation*' is returned. For each of the listed subclasses, one may use it in further DL queries, for instance, executing '(*hasImpactOn* some *GroundSupportToRoad*) and *GroundProperty*' to obtain a list of ground properties which affect *GroundSupportToRoad*.

Fig. 17 shows an example of querying the ATU ontology using SPARQL. The query selects three entities C_1, R and C_2 such that C_1 is a subclass of the class expression 'R some C_2'. As a result, a table consisting of three columns is returned. Each row contains a combination of possible values of C_1, R and C_2. For example, the first row means that *RoadBaseStiffness* is a subclass of the class expression '*hasImpactOn* some *RoadWaterInfiltration*'. The SPARQL query shown in Fig. 17 is a simple template. In practice, more specific or complex queries could be designed and applied to the city infrastructure ontologies. For example, the object property R could be specified using the object property *hasImpactOn* in the relation ontology. Similarly, the classes C_1 and C_2 could be specified using concepts in the city infrastructure ontologies.

7. Application of the ontologies in a decision support system

Complex decision making in city infrastructure management is a



Query (class expression)

hasImpactOn **some** RoadDeformation

Query results

Subclasses (32 of 32)

- **GroundCollapse**
- **GroundDeformation**
- **GroundSupportToRoad**
- RoadAge
- RoadBaseDensity
- RoadBaseMaterialType
- RoadBaseStiffness
- RoadBaseStrength
- RoadBaseThickness
- RoadBinderDensity
- RoadBinderMaterialType
- RoadBinderStiffness
- RoadBinderThickness
- RoadCappingDensity
- RoadCappingMaterialType
- RoadCappingStiffness
- RoadCappingStrength
- RoadCappingThickness
- RoadDesignTraffic
- RoadResidualLife
- RoadSubBaseDensity
- RoadSubBaseMaterialType
- RoadSubBaseStiffness
- RoadSubBaseStrength
- RoadSubBaseThickness
- RoadSurfaceDensity
- RoadSurfaceMaterialType
- RoadSurfaceStiffness
- RoadSurfaceStrength
- **Traffic**
- TrafficLoading
- owl:Nothing

Query for

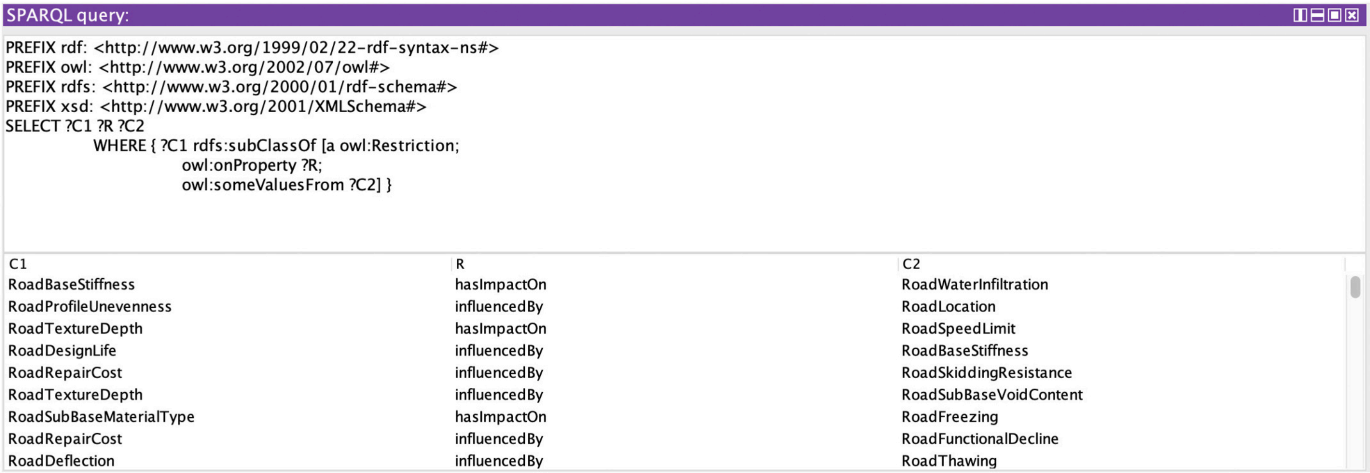
☐ Direct superclasses
☐ Superclasses
☐ Equivalent classes
☐ Direct subclasses
☑ Subclasses
☐ Instances

Result filters

Name contains

☑ Display owl:Thing (in superclass results)
☑ Display owl:Nothing (in subclass results)

Fig. 16. DL Query: all subclasses of the class expression 'hasImpactOn some RoadDeformation'.



```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
SELECT ?C1 ?R ?C2
            WHERE { ?C1 rdfs:subClassOf [a owl:Restriction;
                        owl:onProperty ?R;
                        owl:someValuesFrom ?C2] }
```

C1	R	C2
RoadBaseStiffness	hasImpactOn	RoadWaterInfiltration
RoadProfileUnevenness	influencedBy	RoadLocation
RoadTextureDepth	hasImpactOn	RoadSpeedLimit
RoadDesignLife	influencedBy	RoadBaseStiffness
RoadRepairCost	influencedBy	RoadSkiddingResistance
RoadTextureDepth	influencedBy	RoadSubBaseVoidContent
RoadSubBaseMaterialType	hasImpactOn	RoadFreezing
RoadRepairCost	influencedBy	RoadFunctionalDecline
RoadDeflection	influencedBy	RoadThawing

Fig. 17. SPARQL Query: return all the triples C_1, R, C_2, such that C_1 is a subclass of the class expression 'R some C_2', where R is an object property (i.e., a relation).

challenging task (Rogers et al., 2012). It requires different pieces of information (e.g., rainfall, traffic loading, soil type) and comprehensive multi-sector knowledge (e.g., inter-asset dependencies) for data interpretation and risk estimation. But in practice, it is difficult for a decision maker to have knowledge of all relevant areas, nor is it easy or quick to gather all relevant data. To facilitate the decision making process by relevant stakeholders, an integrated web-based decision support system was developed using the proposed ATU ontology for city infrastructure inter-asset management (Wei et al., 2018). The ATU ontology is used as a common vocabulary for defining complex inference rules and integrating various heterogeneous data.

A common vocabulary for complex rule development. The proposed city infrastructure subsystem ontologies captured the domain knowledge in different sectors. In addition to the one-vs-one rules encoded in the ontology relations (e.g., *A increases some B*), in the practice of infrastructure management, the intra-asset and inter-asset relationships among different infrastructure assets and other contextual factors (e.g., weather and human activities) are often more complex than simple ontology relations, requiring more than one condition. Therefore, based on the concepts and relations defined in the ATU ontology, logical rules were developed in collaboration with domain experts to encapsulate the broad knowledge of internal dependencies in each subsystem, as well as the external dependencies between different infrastructure assets, environment factors and human activities. For example, a list of factors which may impact *RoadWaterInfiltration* were extracted by querying the ATU ontology using description logic reasoners or SPARQL. Then, starting from such a list, main factors or conditions which may activate a *RoadWaterInfiltration* process were defined. For example, with the expression of the degrees of confidence of such main conditions, a rule *"Heavy and Long rainfall will infiltrate the road if the road crack penetrates the road surface."* can be defined referring to the concepts in the phenomena ontology and the road ontology, written as: *RainfallIntensity (Heavy)* ∧ *RainfallDuration (Long)* ∧ *RoadCrackingDepth (High)* ⇒*Definite RoadWaterInfiltration (Active)*, where 'Definite' is a qualitative confidence level, as defined by Wei et al. (2020).

A common vocabulary for data integration. Informed by the ATU ontology, various infrastructure and contextual datasets were sourced from different data owners and integrated in the decision support system to provide instant location and time specific data retrieval (Wei, Clarke, Magee, Dimitrova, & Cohn, 2018). To link the developed ontology to collected city data and GIS layers, a lookup table was defined to map the collected data into corresponding ontology concepts, as shown in Table 4. Currently, all these correspondences between data and ontology concepts are defined manually to guarantee the correctness.

For example, as shown in Table 4, several GIS data layers about the *ground condition* in the UK were sourced from the British Geological Survey (BGS) and local councils. The data column "Value" in the *GroundWaterLevels* data layer was mapped to the *GroundWaterTableDepth* concept in the proposed ATU ground ontology, and data column "Score" in the *SuDS_drain_superficial_permeability* layer was mapped to the ATU *GroundMagneticPermeability* concept.

The *water pipe* data was sourced from water companies and water pipe attributes were mapped to the corresponding concepts in the ATU water pipe ontology. For example, the water pressure, pipe depth, pipe size, pipe location (e.g., grid references, coordinates), pipe material (e.g., cast iron, concrete and plastic) and pipe owner were respectively mapped to the concepts *WaterPipeOperationalPressure*, *WaterPipeDepth*, *WaterPipeExternalDiameter*, *WaterPipeLocation*, *WaterPipeMaterial*, and *WaterPipeOwner*.

The *road and traffic* information was sourced from the Ordnance Survey Open Roads (Ordnance Survey, 2022) and the UK Department for Transport (DfT) Traffic Statistics (Department for Transport, 2022). The retrieved road type (e.g., A roads, B roads, Unclassified roads) was directly mapped to the *RoadType* concept in the ATU road ontology; the weighted annual traffic on a road was calculated based on the traffic statistics and mapped to the *TrafficLoading* concept, the road length information was mapped to the *RoadLength* concept, and the road location was mapped to the *RoadLocation* concept. The *meteorological* data was sourced from the UK Meteorological Office (Met Office, 1853) and mapped to concepts in the ATU ontologies. For example, the concrete temperature was directly mapped to the *RoadTemperature* concept in the road ontology, while the information of rainfall duration was calculated based on the historical data from nearby weather stations and then mapped to the *RainfallDuration* concept.

A use case: predicting the impact of a road crack. Here a scenario

Table 4
A predefined lookup table between external GIS data and ATU ontologies.

GIS data layer	GIS data column	Ontology	Ontology concept
GroundWaterLevels	Value	Ground Ontology	*GroundWaterTableDepth*
SuDS drain superficial permeability	Score	Ground Ontology	*GroundMagneticPermeability*
uk_road_network	length	Road Ontology	*RoadLength*
uk_road_network	Function	Road Ontology	*RoadType*
WaterPipes	pipe depth	Water Pipe Ontology	*WaterPipeDepth*
…	…	…	…

of rainfall and deep road cracks is presented to demonstrate the interaction between different infrastructure assets, as well as the applicability of the ATU ontology for asset management decision support. An initial set of rules were first defined by a domain expert to capture the asset deterioration process by considering all contextual conditions. Then, the flowcharts of captured processes were sent to additional domain experts and practitioners for additional input. Once the rules were agreed, the terminologies that appeared in the rules were referred to the ATU ontology concepts (if not already), such as *RoadCrackingDepth*, *RainfallDuration* and the subgrade *GroundPrincipalType* type, and the rules were converted into a format recognisable by selected inference engines using a Python function.

An initial prototype decision support system (DSS) employing the ATU ontologies (Wei et al., 2020) used *Python Django* (Django Software Foundation, 2023) to develop the user interface, and rule inference engine Jess[2] (interchanged with CLIPS or other rule engines) to develop the rule knowledge base and a qualitative uncertainty based reasoning module. In this DSS, once users report an event, e.g., a *RoadCracking*, at a specific location and time, relevant localised contextual data of the reported event, such as *GroundPrincipalType (Sand)*, *RainfallDuration (Long)*, is automatically retrieved and mapped to the corresponding ontology concepts, and fed into the rule engine for automated reasoning about the potential consequences. Further implementation details of the prototype decision system can be found in the work by Wei et al. (2020).

As shown in Fig. 18, for this exemplar scenario of road crack, the reported event is a *RoadTemporalProcess* defined in the ATU road ontology called *RoadCracking*. The *RoadCrackingDepth* (a *RoadStructuralProperty*) is high, the *RainfallDuration* at the time is long, and the *RainfallIntensity* is slight. Under these conditions, the water on the road is very likely to ingress through the road structure and cause *RoadWaterInfiltration* (a *RoadFluidProcess*), which will increase the *RoadBaseWaterContent* (a *RoadStructuralProperty*), the *RoadSubBaseWaterContent* (a *RoadStructuralProperty*), and will also be likely to let the water enter the ground to cause *GroundWaterInfiltration* (a *GroundFluidProcess*). Since the retrieved *GroundPrincipalType* (a *GroundDescriptionProperty*) at the reported location is sand, the *GroundWaterInfiltration* (a *GroundFluidProcess*) will further increase the *GroundWaterContent* (a *GroundStateVariable*), then decrease the *GroundStiffness* (a *GroundMechanicalProperty*). When the ground support to road decreases, *RoadDeformation* (a *RoadMechanicalProcess*) is likely or very likely to happen. Therefore, additional human inspection or maintenance will be needed at this site to prevent the occurring of the potential consequence.

Evaluation. In addition to testing the ATU ontology with real cases, users' acceptance of the prototype decision support system was evaluated in two workshops. The first workshop aimed to assess users' acceptability of the framework and the interface design of the prototype. The attendees included an experienced utility manager, a utility surveyor, and around twenty academics in the area of civil engineering, geotechnical engineering, geophysics, and computer science. The second workshop aimed to assess whether the proposed system would fit into users' current practice, with more than 30 attendees from various sectors, such as utility managers, underground utility surveyors, utility pipe lining and designing contractors, risk managers, individual consultants and representatives from local authorities.

In each workshop, an overview of the decision support system, including its framework, the associated data types and underlying semantic technologies, was given at the beginning of the workshop, followed by a live demonstration of the prototype with real data from a historic ground collapse event which caused major disruption. After that, feedback from participants was acquired via a plenary discussion and questionnaires. The participants showed great interest in the system and suggested that it could be a potentially useful tool for different stakeholders, such as incident managers, survey company developers, constructors, asset owners and local authority. Possible application areas included risk mitigation, and prioritisation and justification of asset design and maintenance activities. The participants were particularly interested in the integrated data platform that brought various critical contextual data together. They also suggested that the automated reasoning module was useful for helping determine the impact of an incident in a short period of time, identify potential consequences from seemingly insignificant triggers and potentially reduce the streetworks disruptions. For future improvements of the system, participants suggested to add additional data sources, such as bus routes, agriculture data, and archaeological data. Each of these would of course require appropriate ontologies.

It is worth mentioning that following the release of the first prototype, the inference system and rule base were upgraded with languages which are more advanced on human-readability in an MSc student research project. The upgraded version used *RuleML* and *POSL* as the language to encode the rules given by experts, and used *SWI-Prolog* (SWI-Prolog, 2020) as the core inference system. This re-implementation suggests the flexibility of the proposed ontology based DSS framework.

8. Discussion

This section discusses the spatial information handling within the proposed ontology framework first, then the advantages, limitations and implementations of the ATU ontology.

8.1. Spatial information handling

In the proposed ontology framework for building urban infrastructure decision support systems (DSS), spatial information can be handled in multiple ways. A simple way is a shallow incorporation of ontology with the traditional GIS systems. In such a DSS, GIS layers are stored as tables in a relational database, e.g., PostgreSQL, while a lookup table is manually defined to map between GIS data columns and the corresponding ontology concepts. Retrieval of the GIS information and quantitative spatial calculation, e.g., *ST_Within*(), are implemented using SQL queries. This method is easy to understand by urban informatics professionals and was used in the prototype DSS described in Section 7.

Other than this, to fully explore the power of ontology for semantic web usage, a more in-depth incorporation of ontology with GIS information is to represent the spatial information of infrastructure assets as linked data to support quantitative and qualitative spatial reasoning, such examples of linked spatial data can be found on the Ordnance Survey Linked Data Platform (Ordnance Survey, 2023). As described in Section 5, the ATU relation ontology contains object properties like *isRepresentedBy*, *hasGeometry*, as well as various spatial relations, to represent spatial information. In addition, the OGC GeoSPARQL vocabulary (OGC GeoSPARQL Standards Working Group, 2021) or other spatial ontologies may be imported into the ATU ontology to handle more complicated spatial operations or relations.

8.2. Advantages and limitations of the ATU ontology

One main advantage of the ATU ontology is that the knowledge represented in it mainly come from domain experts in geotechnical engineering, water engineering, infrastructure asset management, geography, earth and environmental sciences, hence those knowledge are of high quality and high reliability. In addition, as described in Section 5, the ATU ontology is written in OWL 2 Web Ontology Language (W3C OWL Working Group, 2012). Compared to the spreadsheets shown in Figs. 6, 10 and 14, using the OWL 2 Web Ontology Language has the following main advantages. *First*, the language OWL 2 has formal semantics, which specify the ways of assigning meanings to classes, object

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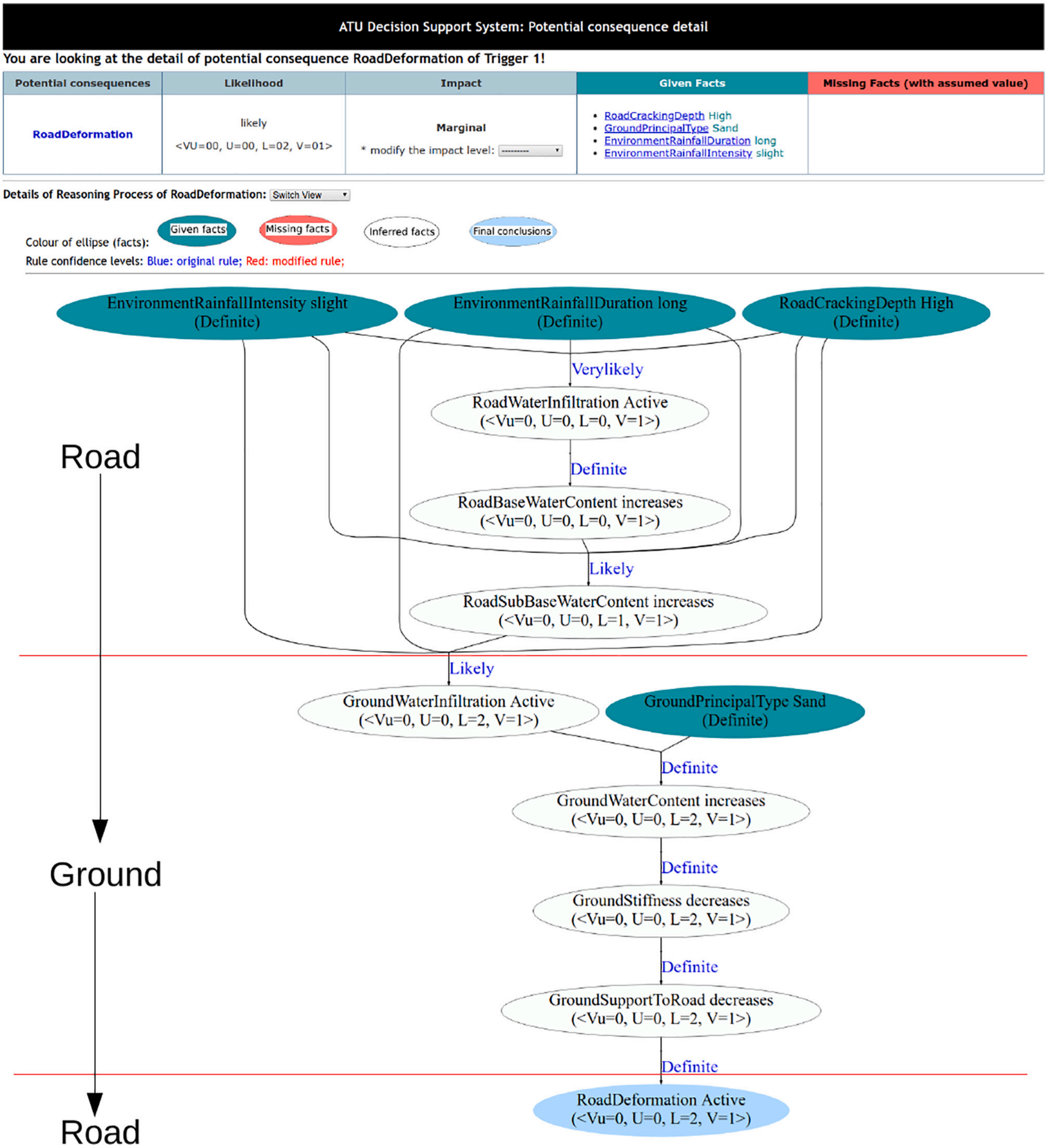
[2] http://www.jessrules.com/jess/docs/71/. Accessed: 2020–02-23.



ATU Decision Support System: Potential consequence detail

You are looking at the detail of potential consequence RoadDeformation of Trigger 1!

Potential consequences	Likelihood	Impact	Given Facts	Missing Facts (with assumed value)
RoadDeformation	likely <VU=00, U=00, L=02, V=01>	**Marginal** * modify the impact level: ---------	RoadCrackingDepth High GroundPrincipalType Sand EnvironmentRainfallDuration long EnvironmentRainfallIntensity slight	

Details of Reasoning Process of RoadDeformation: Switch View

Colour of ellipse (facts): Given facts Missing facts Inferred facts Final conclusions

Rule confidence levels: Blue: original rule; Red: modified rule;

Fig. 18. Reasoning chain of a potential road deformation when a deep road crack is observed and the rainfall is long. The *confidence vectors*$< Vu, U, L, V >$ represent accumulated levels of confidence during the inference process as rules with certainty factors are applied. For details, see the work by Wei et al. (2020).

properties and data properties in OWL 2 ontologies. *Second*, ontologies in OWL 2 can be reasoned with automatically using description logic reasoners (Sirin et al., 2007; Tsarkov & Horrocks, 2006; Glimm et al., 2014; Kazakov & Klinov, 2015). Several reasoning tasks are supported, including checking consistency, entailment, providing explanations of an entailment or the existence of a logical contradiction, etc. An example of using the Pellet reasoner (Sirin et al., 2007) to reason with the ATU ontology is provided in Section 6. *Thirdly*, by providing a shared common vocabulary, ontologies in OWL 2 are often used to integrate data from different sources, which is referred to as *ontology-based data integration* (Ekaputra, Sabou, Serral, Kiesling, & Biffl, 2017). As described in Section 7, the ATU ontology was used to integrate various infrastructure data. The ground condition data, water pipe data and road data are all stored as tables in a relational database. The data integration is achieved by establishing the correspondences or links between the schema of databases and concepts defined in the ontology. Such a practice takes the advantage of the *efficiency* of relational databases in managing data (Martínez-Cruz, Blanco, & Vila, 2012), and, at the same time, allows users to define queries over the system using semantic concepts in ontologies, without understanding specific details about databases (Baglioni, Masserotti, Renso, & Spinsanti, 2011).

The data integration described above by linking the ATU ontology and databases is quite loose, which keeps the relative independence of the ontology and the datasets. An alternative is to *populate* the ontology with objects in various datasets, which is a much tighter integration. For example, for every road object *a* described in a dataset, an individual *a*′ will be created under the class *Road*; the relationships involving *a*, the geometry and attributes of *a* in the dataset will be stored as object properties and data properties of *a*′ in the ontology. A similar practice is Yago2geo (National & Kapodistrian University of Athens, 2021), which *separately* stores the terminology of the ontology and the assertions about the individuals, which are referred to as the TBox and ABox (Baader, Calvanese, McGuinness, Nardi, & Patel-Schneider, 2003) of the ontology, respectively. In this sense, *the ATU ontology is a TBox* defining the terminology for infrastructure, their properties and processes, as well as how properties and processes affect each other. For different applications, different datasets could act as its 'ABoxes'.

The ATU ontology is limited in expressing several complex inference rules, as illustrated in Section 7. For example, though the concept *RoadCrackingDepth* is within the ATU ontology, the expression like '*RoadCrackingDepth* is *High*' is not. Similarly, *RoadWaterInfiltration* is in the ATU ontology, the expression '*RoadWaterInfiltration* is *Active*' is not. In addition, the ATU ontology does not include terminology describing changes of an infrastructure property, for instance, the *increase* of *RoadBaseWaterContent*. Furthermore, most of the 'hasImpactOn' axioms in the ATU ontology are of the form '*A hasImpactOn* some *B*', where *A* and *B* are concepts, however, in practice, the existence of more than one conditions together may trigger a process or a change in a property. These limitations of the ATU ontology described above are mainly due to the limited expressive power of OWL 2 and the restrictions of the city infrastructure model underlying the ATU ontology. For example, to include concepts like *RoadBaseWaterContentIncrease*, a higher level concept *Change* could be included, with concepts *Increase* and *Decrease* as its subclasses. The current city infrastructure model does not include *Change* as a main concept.

There are several possible extensions of the current model of city infrastructure, as well as the ontologies. First, more sub-models of infrastructure assets could be developed following similar approaches. For instance, models and ontologies of cables, gas pipes, sewerage pipes, etc. could be developed similarly. In addition, the current model of the natural environment could be extended to include terminologies for describing grass, trees, and roots, as tree roots may affect and be affected by soil, roads, pipes, cables, etc. Additionally, besides the *hasImpactOn* and *influencedBy* relations, more relations (e.g., *causes* and *causedBy*) can be defined and used to represent relationships between different concepts. Furthermore, as the ontologies are used in more use cases and applications, we will maintain the ontologies and enrich them with more related concepts and relationships both within a single ontology and between different ontologies.

8.3. Existing and future implementations of the ATU ontology

The ATU ontology was developed as part of an EPSRC funded research project (Assessing the Underworld case study, 2023). To this end, the aim of developing this ontology was to inform a decision support system (DSS) for urban infrastructure management. The developed ontology was successfully utilised in the prototype DSS and reported in various publications (Wei et al., 2020; Assessing the Underworld, 2023). The ontology and the DSS also informed some following research projects and industrial approaches, for instance, the Project Iceberg (Likhari et al., 2017; Frith, Catchpole, Home, Watson, & Kessler, 2017) which involves Future Cities Catapult, British Geological Survey and the Ordnance Survey and aims to address the issue of the lack of information about the ground under cities and the un-coordinated way in which the subsurface space is managed.

The ATU ontology, whose first version is available freely in the public domain,[3] has large potential for future research. One of its applications is for digitisation of urban infrastructure systems and their interactions. To this end, it is currently used by two PhD studies on Digital Twins for Roads, part of this ongoing study was reported (Chen, Eskandari Torbaghan, Chu, Zhang, & Garcia-Hernández, 2021). The ontology is used in these studies to realise the impact of utilities maintenance and repair, so called streetworks, on road deterioration.

The development of the ATU ontology mainly involves domain experts in geotechnical engineering, water engineering, infrastructure asset management, geography, earth and environmental sciences in the UK. We are aware that different countries may employ different classification systems of soil, roads and water pipes. In such cases, the ATU ontology, or part of it, may be adapted properly, and be linked with other ontologies to support different real world applications.

The ATU ontology could be adopted by itself or as part of a DSS. The proposed approach could be utilised to analyse and understand other complex systems of system and asset management frameworks, such as the interactions between strategic and local road networks. This could be done in connection with other ontologies or vocabularies like GEM Building Taxonomy (GEM Building Taxonomy, 2021). For example, a risk management approach could be adopted by incorporating risks and uncertainty through a probabilistic ontology (Peñaloza, 2020) for urban infrastructure asset management.

9. Conclusion

Data describing the locations and conditions of different kinds of infrastructure, as well as the knowledge of their interdependencies, can provide indispensable information for supporting decision making in infrastructure planning and maintenance. To facilitate information sharing and knowledge exchange around city infrastructure and their interdependencies, this paper presents a semantic model of city infrastructure. This model is represented as the ATU ontology written in OWL 2 Web Ontology Language Manchester Syntax, which is a widely used language in the semantic web. The ATU ontology contains thousands of axioms, which mainly define the conceptual hierarchies of the properties and processes of the ground, roads and water pipes, as well as how those properties and processes affect each other. The main knowledge source of the ATU ontology is domain experts in geotechnical engineering, water engineering, infrastructure asset management, geography, earth and environmental sciences in the UK. The knowledge represented in the ATU ontology can be queried using description logic reasoners and SPARQL. Those knowledge are useful for answering various questions about the interdependencies of the properties and processes of infrastructure, and hence informing decisions involved in the integrated management of infrastructure systems. The ATU ontology has been used in a prototype integrated web-based decision support system for city infrastructure inter-asset management. Together with the decision support system, the ATU ontology has informed several research projects, including the Project Iceberg and Digital Twins for Roads. Future work includes extending the current city infrastructure model to include more infrastructure assets (e.g., cables) and applying the ATU ontology in more use cases.

CRediT authorship contribution statement

Heshan Du: Conceptualization, Methodology, Writing-original-draft, Writing-review-editing. **Lijun Wei:** Conceptualization, Methodology, Software, Writing-original-draft, Writing-review-editing. **Vania Dimitrova:** Conceptualization, Methodology, Supervision. **Derek**

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[3] http://doi.org/10.5518/190. The latest version of the ATU ontology will be released to the public, referring to this paper.

Magee: Conceptualization, Methodology, Supervision. **Barry Clarke:** Conceptualization, Methodology, Validation, Resources, Supervision. **Richard Collins:** Conceptualization, Validation, Resources. **David Entwisle:** Conceptualization, Validation, Resources. **Mehran Eskandari Torbaghan:** Conceptualization, Writing-review-editing, Validation, Resources. **Giulio Curioni:** Conceptualization, Validation, Resources. **Ross Stirling:** Conceptualization, Validation, Resources. **Helen Reeves:** Conceptualization, Validation, Resources. **Anthony G. Cohn:** Conceptualization, Methodology, Writing-original-draft, Writing-review-editing, Validation, Supervision, Funding-acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Araya, F., & Vasquez, S. (2022). Challenges, drivers, and benefits to integrated infrastructure management of water, wastewater, stormwater and transportation systems. *Sustainable Cities and Society, 82*, Article 103913.

Assessing the Underworld (2023).https://artificial-intelligence.leeds.ac.uk/home/assessing-the-underworld/.

Assessing the Underworld case study (2023).https://www.birmingham.ac.uk/research/activity/eese/communications-sensing/acoustics-sonar-group/research-projects/assessing-the-underworld.aspx.

Baader, F., Calvanese, D., McGuinness, D. L., Nardi, D., & Patel-Schneider, P. F. (Eds.). (2003). *The Description Logic Handbook: Theory, Implementation, and Applications*. Cambridge University Press.

Baglioni, M., Masserotti, M. V., Renso, C., & Spinsanti, L. (2011). Improving geodatabase semantic querying exploiting ontologies. In , *Lecture Notes in Computer Science: Vol. 6631. In Proceedings of the 4th International Conference on GeoSpatial Semantics* (pp. 16–33). Springer.

BBC (October 2011). BT suffers huge broadband failure across much of UK,https://www.bbc.co.uk/news/technology-15154020.

Berdier, C. (2011). Road System Ontology: Organisation and Feedback. In *Ontologies in Urban Development Projects* (pp. 211–216). Springer.

Berdier, C., & Roussey, C. (2007). Urban Ontologies: the Towntology Prototype towards Case Studies. In *Ontologies for Urban Development* (pp. 143–155). Springer.

Berners-Lee, T., Hendler, J., & Lassila, O. (2001). The Semantic Web. *Scientific American, 284*(5), 34–43.

Bittner, T., & Donnelly, M. (2005). Ontology and Semantic Interoperability. In *Largescale 3D data integration: Problems and challenges* (pp. 139–160). CRC Press.

Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., & Havlin, S. (2010). Catastrophic cascade of failures in interdependent networks. *Nature, 464*, 1025–1028.

Buttigieg, P. L., Morrison, N., Smith, B., Mungall, C. J., & Lewis, S. E. (2013). The environment ontology: contextualising biological and biomedical entities. *Journal of Biomedical Semantics, 4*, 43.

Carhart, N., & Rosenberg, G. (2016). A framework for Characterising Infrastructure Interdependencies. *International Journal of Complexity in Applied Science and Technology, 1*(1), 35–60.

Chen, K., Eskandari Torbaghan, M., Chu, M., Zhang, L., & Garcia-Hernández, A. (2021). Identifying the most suitable machine learning approach for a road digital twin. *In Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction, 174*(3), 88–101.

Clair, A. M. S., & Sinha, S. (2014). Development of a Standard Data Structure for Predicting the Remaining Physical Life and Consequence of Failure of Water Pipes. *Journal of Performance of Constructed Facilities, 28*(1), 191–203.

Clarke, B. G., Magee, D., Dimitrova, V., Cohn, A. G., Du, H., Mahesar, Q., et al. (2017). A decision support system to proactively manage subsurface utilities. In *International Symposium for Next Generation Infrastructure* (pp. 1–10).

Clementini, E., Felice, P. D., & Hernández, D. (1997). Qualitative representation of positional information. *Artificial Intelligence, 95*(2), 317–356.

Cohn, A. G., Bennett, B., Gooday, J., & Gotts, N. M. (1997). Qualitative spatial representation and reasoning with the region connection calculus. *GeoInformatica, 1*(3), 275–316.

Corsar, D., Markovic, M., Edwards, P., Nelson, J. D. (2015). The Transport Disruption Ontology. In *Proceedings of the 14th International Semantic Web Conference* (pp. 329–336).

Das, M. (2010). *Building and querying soil ontology for agriculture*. Master's thesis. Indian Agricultural Research Institute.

DBpedia Association (2023). Global and Unified Access to Knowledge Graphs,https://www.dbpedia.org/.

Department for Transport (2022). Road traffic statistics,https://www.gov.uk/government/collections/road-traffic-statistics.

Django Software Foundation. django: the web framework for perfectionists with deadlines. https://www.djangoproject.com/.

dos Santos Aparício, A., de Farias, O. L. M., & dos Santos, N. (2006). Integration of Heterogeneous Databases and Ontologies. *Cadernos do IME-Série Informática, 21*, 4–10.

Du, H., & Alechina, N. (2016). Qualitative Spatial Logics for Buffered Geometries. *Journal of Artificial Intelligence Research (JAIR), 56*, 693–745.

Du, H., Dimitrova, V., Magee, D., Stirling, R., Curioni, H. Reeves, G., et al. (2016). An Ontology of Soil Properties and Processes. In *Proceedings of the 15th International Semantic Web Conference* (pp. 30–37).

Du, H., Alechina, N., Cohn, A. G. (2020). A Logic of Directions. In *Proceedings of the Twenty-Ninth International Joint Conference on Artificial Intelligence, IJCAI 2020* (pp. 1695–1702).

Du, H., Alechina, N., Stock, K., & Jackson, M. (2013). In *The Logic of NEAR and FAR.In, (COSIT)(Vol.8116*, pp. 475–494). Springer.

Ekaputra, F. J., Sabou, M., Serral, E., Kiesling, E., & Biffl, S. (2017). Ontology-Based Data Integration in Multi-Disciplinary Engineering Environments: A Review. *Open Journal of Information Systems, 4*(1), 1–26.

Elumalai, M., & Anouncia, S. M. (2021). Development of soil mineral classification using ontology mining. *Arabian Journal of Geosciences, 14*, 1371.

Food and Agriculture Organization of the United Nations (2022). AGROVOC Multilingual Thesaurus,https://agrovoc.fao.org/browse/agrovoc/en/.

Freksa, C. (1992). Using orientation information for qualitative spatial reasoning. In , *Lecture Notes in Computer Science: Vol. 639. Theories and Methods of Spatio-Temporal Reasoning in Geographic Space* (pp. 162–178). Springer.

Frith, N., Catchpole, S., Home, R., Watson, C., & Kessler, H. (2017). *A unified data: framework for mapping underground: Project Iceberg. Work package 2, defining the problem space for an integrated data operating system above and below ground, Tech. rep.* British Geological Survey.

GEM Building Taxonomy (2021),https://github.com/gem/gem_taxonomy.

Fu, G., & Cohn, A. G. (2008). *Semantic integration for mapping the underworld, (Vol. 7143*, 1–12.

General Multilingual Environmental Thesaurus. (2021). https://www.eionet.europa.eu/gemet/.

Glimm, B., Horrocks, I., Motik, B., Stoilos, G., & Wang, Z. (2014). HermiT: An OWL 2 Reasoner. *Journal of Automated Reasoning, 53*(3), 245–269.

Grafius, D. R., Varga, L., & Jude, S. (2020). Infrastructure Interdependencies: Opportunities from Complexity. *Journal of Infrastructure Systems, 26*(4), 04020036.

Gruber, T. R. (1993). A Translation Approach to Portable Ontology Specifications. *Knowledge Acquisition, 5*(2), 199–220.

Hasan, S., & Foliente, G. (2015). Modeling infrastructure system interdependencies and socioeconomic impacts of failure in extreme events: emerging R&D challenges. *Natural Hazards, 78*, 2143–2168.

Heeptaisong, T., & Srivihok, A. (2010). Ontology Development for Searching Soil Knowledge. In *Proceedings of the 9th International Conference on e-Business* (pp. 102–107).

Helfer, G. A., Costa, A. B. d., Bavaresco, R. S., & Barbosa, J. L. V. (2021). Tellus-onto: An ontology for soil classification and inference in precision agriculture. In *XVII Brazilian Symposium on Information Systems* (pp. 1–7).

Hitzler, P. (2021). A Review of the Semantic Web Field. *Communications of the ACM, 64*(2), 76–83.

HM Treasury. (2016). *National Infrastructure Delivery Plan 2016–2021, Tech. rep.* , London, UK: HM Treasury.

Horridge, M., Patel-Schneider, P. F. (2012). OWL 2 Web Ontology Language Manchester Syntax,https://www.w3.org/TR/owl2-manchester-syntax.

IPCC. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge, UK, and New York, NY, USA: Cambridge University Press.

Javed, A. R., Shahzad, F., ur Rehman, S., Zikria, Y. B., Razzak, I., Jalil, Z., et al. (2022). Future smart cities: requirements, emerging technologies, applications, challenges, and future aspects. *Cities, 129*, Article 103794.

Katsumi, M., & Fox, M. (2018). Ontologies for Transportation Research: A Survey. *Transportation Research Part C: Emerging Technologies, 89*, 53–82.

Katsumi, M., & Fox, M. (2019). *iCity Ontology Version 1.2 Report, Tech. rep.* University of Toronto.

Kazakov, Y., & Klinov, P. (2015). Advancing ELK: not only performance matters. In , *CEUR Workshop Proceedings: Vol. 1350. In Proceedings of the 28th International Workshop on Description Logics* (pp. 1–12). CEUR-WS.org.

Ligozat, G. (1998). Reasoning about Cardinal Directions. *Journal of Visual Languages & Computing, 9*(1), 23–44.

Likhari, R., Webb, S., Bricker, S., Bonsor, H., Frith, N., & Catchpole, S. (2017). *Mapping underground assets in the UK: Project Iceberg. Work Package 1, market research into current state of play and global case studies, Tech. rep.* British Geological Survey.

Lorenz, B., Ohlbach, H. J., & Yang, L. (2005). *Ontology of Transportation Networks*. Tech. rep.: University of Munich.

Martínez-Cruz, C., Blanco, I. J., & Vila, M. A. (2012). Ontologies versus relational databases: are they so different? A comparison. *Artificial Intelligence Review, 38*(4), 271–290.

Met Office (2023). Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current),https://catalogue.ceda.ac.uk/uuid/220a65615218d5c9cc9e4785a3234bd0.

Moratz, R., & Ragni, M. (2008). Qualitative spatial reasoning about relative point position. *Journal of Visual Languages and Computing, 19*(1), 75–98.

National and Kapodistrian University of Athens (2021). YAGO2geo: Extending the YAGO2 Knowledge Graph with Precise Geospatial Information,http://yago2geo.di.uoa.gr.

OGC GeoSPARQL Standards Working Group (2021). GeoSPARQL Ontology,https://opengeospatial.github.io/ogc-geosparql/geosparql11/index.html.

Open Geospatial Consortium. (2017). *OGC Underground Infrastructure Concept Study Engineering Report*. Open Geospatial Consortium.

Ordnance Survey (2022). OS Open Roads,https://osdatahub.os.uk/downloads/open/OpenRoads.

Ordnance Survey (2023). Ordnance Survey Linked Data Platform,https://data.ordnancesurvey.co.uk/.

Osman, H., & El-Diraby, T. (2006). Ontological Modeling of Infrastructure Products and Related Concepts. *Transportation Research Record, 1984*(1), 159–167.

Ouyang, M. (2014). Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering & System Safety, 121*, 43–60.

Peñaloza, R. (2020). Introduction to probabilistic ontologies. In , *Lecture Notes in Computer Science: Vol. 12258. Reasoning Web. Declarative Artificial Intelligence - 16th International Summer School 2020, Tutorial Lectures* (pp. 1–35). Springer.

Randell, D. A., Cui, Z., Cohn, A. G. (1992). A Spatial Logic based on Regions and Connection. In *Proceedings of the 3rd International Conference on Principles of Knowledge Representation and Reasoning (KR'92)* (pp. 165–176).

Raskin, R. G., & Pan, M. J. (2005). Knowledge representation in the semantic web for Earth and environmental terminology (SWEET). *Computers & Geosciences, 31*(9), 1119–1125.

Rinaldi, S. M. (2004). Modeling and Simulating Critical Infrastructures and Their Interdependencies. In *Proceedings of the 37th Hawaii International Conference on System Sciences* (pp. 1–8).

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine, 21*(6), 11–25.

Rogers, C., Hao, T., Costello, S., Burrow, M., Metje, N., Chapman, D., et al. (2012). Condition assessment of the surface and buried infrastructure – a proposal for integration. *Tunnelling and Underground Space Technology, 28*, 202–211.

Shivananda, P., & Kumar, P. S. (2013). Building Rules Based Soil Classification Ontology. *International Journal of Computer Science and Information Technology & Security, 3*(2), 208–212.

Sirin, E., Parsia, B., Grau, B. C., Kalyanpur, A., & Katz, Y. (2007). Pellet: a Practical OWL-DL Reasoner. *Web Semantics: Science, Services and Agents on the World Wide Web, 5*, 51–53.

Skiadopoulos, S., & Koubarakis, M. (2004). Composing cardinal direction relations. *Artificial Intelligence, 152*(2), 143–171.

Standards for Highways (2023). Welcome to the DMRB,https://standardsforhighways.co.uk/dmrb/.

Stanford Center for Biomedical Informatics Research (2023). Protégé: a free, open-source ontology editor and framework for building intelligent systems,http://protege.stanford.edu.

Sun, W., Bocchini, P., & Davison, B. D. (2022). Overview of Interdependency Models of Critical Infrastructure for Resilience Assessment. *Natural Hazards Review, 23*(1), 04021058.

Tsarkov, D., & Horrocks, I. (2006). FaCT++ Description Logic Reasoner: System Description. In *Proceedings of the Third International Joint Conference in Automated Reasoning (IJCAR)* (pp. 292–297).

SWI-Prolog. Robust, mature, free. Prolog for the real world. https://www.swi-prolog.org/.

Vandenbussche, P., Atemezing, G., Poveda-Villalón, M., & Vatant, B. (2017). Linked Open Vocabularies (LOV): A gateway to reusable semantic vocabularies on the Web. *Semantic Web, 8*(3), 437–452.

Varga, L., McMillan, L., Hallett, S., Russell, T., Smith, L., Truckell, I., et al. (2022). Infrastructure and city ontologies. *Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction, 10*. https://doi.org/10.1680/jsmic.22.00005

W3C (March 2013). SPARQL 1.1 Query Language,https://www.w3.org/TR/sparql11-query/.

W3C OWL Working Group (2012). OWL 2 Web Ontology Language Document Overview (2nd ed.),https://www.w3.org/TR/owl2-overview/.

Walport, M., & Wilson, A. (2016). *Future of Cities: an overview of the evidence, Tech. rep.* London, UK: Government Office for Science.

Wei, L., Du, H., Mahesar, Q., Al Ammari, K., Magee, D. R., Clarke, B., et al. (2020). A decision support system for urban infrastructure inter-asset management employing domain ontologies and qualitative uncertainty-based reasoning. *Expert Systems with Applications, 158*, Article 113461.

Wei, L., Magee, D. R., Dimitrova, V., Clarke, B., Du, H., Mahesar, Q., et al. (2018). Automated reasoning for city infrastructure maintenance decision support. In *Proceedings of the Twenty-Seventh International Joint Conference on Artificial Intelligence* (pp. 5877–5879).

Wei, L., Clarke, B., Magee, D. R., Dimitrova, V., Cohn, A. G. (2018). An integrated web-based decision support system for inter-asset streetworks management. In *Proceedings of the 26th GIScience Research UK Conference* (pp. 1–7).

Zeb, J., & Froese, T. (2014). Tangible capital asset ontology in infrastructure management. *Infrastructure Asset Management, 1*(3), 81–92.

Zhao, M., Zhao, Q., Tian, D., Qian, P., & Zhang, X. (2009). Ontology-based intelligent retrieval system for soil knowledge. *WSEAS Transactions on Information Science and Applications, 6*(7), 1196–1205.