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TANGIBLE CAPITAL ASSET ONTOLOGY TOWARDS STANDARDIZED REPORTING IN INFRASTRUCTURE MANAGEMENT

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Abstract: Municipalities manage diversified tangible capital assets (TCAs) to provide services to citizens effectively and efficiently. Municipalities either use computer or paper-based information systems to manage these assets. Currently, there are some issues associated with the management and exchange of information generated through these information systems; heterogeneity of data format; lack of uniformity in definitions of various classes of assets; and lack of aggregation of information based on infrastructure components. To address these issues, tangible capital asset ontology (TCA_Onto) is developed using a ten step methodology. As an extension of the infrastructure product ontology (IPD-Onto), the tangible capital asset ontology represents knowledge related to tangible capital assets in the facility and infrastructure sectors. This paper presents various modalities of tangible capital asset classification at an abstract level. The ontology is used to create message templates for tangible capital asset reporting, specifically between municipalities and other agencies. The ontology verification is completed; however, ontology validation is underway and beyond the scope of this paper.

Keywords: Tangible capital assets, Infrastructure management, Infrastructure, Ontology, Tangible capital asset ontology.

1. Introduction

Municipalities own, operate, and manage diversified tangible capital assets (TCA) to provide services to their citizens, and they use either computer or paper-based information systems to manage these assets. These information systems generate large amounts of asset data that are exchanged between different departments of a municipality and between a municipality and other agencies to manage these large and complex infrastructure systems. The growing trend is to automate or semi-automate these data exchanges (referred to as transactions), which requires transactions to be formalized and message templates to be explicitly defined. Examples of transactions or data exchanges are: asset inventory and condition assessment reporting, exchange of data regarding buried infrastructure, and data exchange between different parties as part of disaster management. In the work reported here, transaction and message template formalism is addressed through the development of an ontology-supported transaction formalism protocol (TFP). The protocol is a step-by-step procedure that transaction development personnel can use to efficiently formalize transactions, and the ontology supports this by explicitly defining the terms and concepts used to formalize transactions and message templates. This paper discusses the development of the tangible capital asset ontology (TCA_Onto) to support the design of standardized message templates in the domain of infrastructure management.

Currently, there are issues hampering the design of message templates for TCA reporting, including; (i) heterogeneity - every municipality records and manages asset data in a different data format; (ii) lack of uniformity – no consistency in the definitions of various classes of TCA; and (iii) lack of aggregation – lack of infrastructure component-based aggregation of TCA data (Folio, 2012); and (iv) paper-based management of TCA data. These issues make it difficult to collect and compile asset data received from city, regional, town, district, and village municipalities for financial need analysis. Financial analysis is conducted at the provincial, regional, and/or federal level to assess financial needs and allocate funds to various municipalities based on the condition of the assets under different investment programs. For instance, in the Canadian context, some of the federal investment programs are the Building Canada Plan – BCP, the Gas Tax Fund, and Municipal GST Rebate.

To address these issues, the authors have developed a TCA_Onto as an extension to a previously developed infrastructure product ontology (IPD-Onto). According to Gruber (1995), an ontology is an “explicit formal specification of the terms in the domain and the relations among them." The TCA_Onto represents the TCAs with a specific focus on infrastructure related assets; including, transportation, bridges, water, wastewater, and solid waste management. The TCA_Onto formally defines TCA classes that are to be used as payload information while creating message templates for asset inventory and condition assessment reporting (AI&CAR) between different municipalities and the provincial government. These formalized message templates are to be implemented in a prototype system – an asset information integrator system (AIIS), to be developed at the provincial level as part of this research work.

This paper describes the development, application, and evaluation of the TCA_Onto and is divided into five sections: (i) relevant research work; (ii) approach used to develop the TCA_Onto; (iii) the development of the TCA_Onto; (iv) the application of the TCA_Onto; and (v) conclusions.

2. Relevant Research Work

Building ontologies for knowledge representation is not a new concept. A number of ontologies have been developed both in architecture, engineering, construction and facilities management (AEC/FM) field and other industries to represent knowledge in a specific domain. According to Gomez-Perez et al. (2005), ontologies are created at four levels of abstraction: upper, domain, application, and user level ontologies. *Upper ontologies* represent the most generic knowledge that is the same across multiple disciplines, (e.g. project, resources, processes). *Domain ontologies* define the terms and concepts that relate to a specific domain. *Application ontologies* capture knowledge that is required to develop a specific application. *User ontologies* are created at the finest level of specialization based on the requirement of specific users. Some of the most relevant ontologies in the domain of infrastructure management are as follows.

The *infrastructure product ontology (IPD-Onto),* represents knowledge about physical infrastructure products in the domain of water, wastewater, electrical, telecommunication, and gas (e.g. pipe, value, pump) (El-Diraby, 2006). The *infrastructure and construction process ontology (IC-Pro-Onto)* capture process related knowledge over the project life cycle in diversified infrastructure sectors (El-Gohary, 2008). The *Actor ontology* represents knowledge about actors and actor-roles involved the design, implementation, and management of assets (Zhang and El-Diraby, 2009). The *transaction domain ontology (Trans_Dom_Onto)* represents knowledge to support the design and management of information transaction in the domain of infrastructure management (Zeb and Froese, 2012).

These ontologies don’t completely support the design of message templates for TCA reporting process, (i.e. asset inventory and condition assessment); therefore, there is a need to further extend and specialize the IPD-Onto to incorporate and represent knowledge related to TCAs. The TCAs are “non-financial assets having physical substance that are acquired, constructed, or developed and: are held for use in the production or supply of goods and services; have useful lives extending beyond an accounting period; are intended to be used on a continuing basis, and are not intended for sale in the ordinary course of operations” (PSAB, 2009). Examples of TCAs include: land, buildings, infrastructure (road, bridges, water, wastewater, etc.), machinery and equipment (pumps, computer hardware, software, etc.), and vehicles (transit bus, train, trolley, etc.). This gap is to be accomplished through the development of the TCA_Onto in the domain of infrastructure management.

3. The Approach Used to Develop Tangible Capital Asset Ontology

To build the TCA_Onto, a ten step hybrid approach was devised based on existing methodologies developed by: Gruninger and Fox (1995), Fernandez-Lopez et al. (1997), Uschold and Gruninger (1996), and Noy and McGuinness (2001). These steps are: (i) identify motivating scenario; (ii) define ontology coverage; (iii) capture competency questions; (iv) generate or create taxonomy; (v) reuse and merge existing ontology; (vi) develop tangible capital asset ontology; (vii) capture ontology; (viii) code ontology; (ix) evaluate ontology; and (x) document ontology. The TCA_Onto is built according to these steps.

3.1 Identify Motivating Scenario – (Step 1)

The first step is to identify a motivating scenario that emphasizes the need for the development of the TCA_Onto. The TCA reporting process, (AI&CAR)), was identified as a potential transaction for IT improvement through a municipal ICT survey conducted as part of this research work (Zeb et al. 2012). The TCA reporting takes place between different municipalities and the provincial government. The TCA reporting process and the message templates representing the TCA information need to be defined for a prototype transaction system (AIIS), to be developed as part of this research work. The TCA_Onto is built to represent the TCA knowledge to support the design of message templates that are to be used in the AIIS.

3.2 Define Ontology Coverage – (Step 2)

Ontology coverage specifies the purpose, usability, and scope of the TCA_Onto. *Purpose* - the purpose of the TCA_Onto is to represent knowledge relating to TCAs in the domain of infrastructure management. *Usability* - The TCA_Onto is used to define consistent message templates for implementation in the prototype AIIS to be developed for the exchange of TCA information between the municipal and provincial governments. *Scope* – the TCA_Onto represents knowledge related to TCAs owned, operated, or managed at the municipality level. The core focus of the knowledge representation is on four sectors: transportation including bridges, water, wastewater, and solid waste management.

3.3 Capture Competency Questions – (Step 3)

Competency questions are a set of questions representing ontology requirements. According to Gruninger and Fox (1995), an ontology should be able to answer these questions. Based on the requirements analysis, five main requirements are identified for the TCA_Onto. These requirements are: (i) the ontology should capture TCAs; (ii) the ontology should represent the notion of generalization-specialization; (iii) the ontology should represent the notion of composition-aggregation; (iv) the ontology should represent different modalities and attributes of concepts; and (v) the ontology should capture different relationships between concepts. A set of competency questions is developed for each of these five requirements; however, this paper presents one question per requirement due to space limitation. These questions are: (i) Does the ontology specify water system assets? (ii) Does the ontology represent TCA knowledge according to the notion of generalization-specialization of concepts? (iii) Is TCA knowledge organized according to the notion of composition-aggregation of concepts? (iv) Does the ontology capture attributes of TCAs? and (v) Does the ontology incorporate a variety of relationships between concepts?

3.4 Generate Taxonomy - (Step 4)

A taxonomy of TCAs was developed in four steps: (i) *capture concepts* - a set of TCAs in terms of concepts were identified based on the review of existing ontologies, information models, reports, and discussions with experts during an IT survey conducted as part of this research work; (ii) *compare concepts* – concepts were compared to identify and delete synonymous concepts (i.e. same concept with different names), to avoid duplication; (iii) *categorize concepts* – a preliminary categorization of concepts was accomplished using different modalities (views) of TCAs; (iv) *Generate or create taxonomy* – a modality-based comprehensive taxonomy of TCAs was developed using generalization-specialization relationships.

3.5 Reuse Existing Ontologies - (Step 5)

To the extent possible, use is made of the existing ontologies in the domain of infrastructure management. The TCA_Onto is developed as an extension of the already developed infrastructure product ontology (IPD-Onto). Some of the concepts identified in the IPD-Onto are further specialized and merged into the TCA_Onto.

3.6 Develop Tangible Capital Asset Ontology – (Step 6)

The TCA_Onto represents TCAs that the municipal government owns, operates, and manages. These assets are classified according to tangible capital asset modality. A *modality* describes “the characteristics of a concept and denotes it belonging to a particular group or category” (El-Gohary, 2008). The *tangible capital asset modality* describes TCAs based on the individual asset type, function, composition, and sector it belongs. The TCA modality has the following four types as shown in Figure 1. Assets represented in boxes with gray background have taken from the IPD-Ontology.

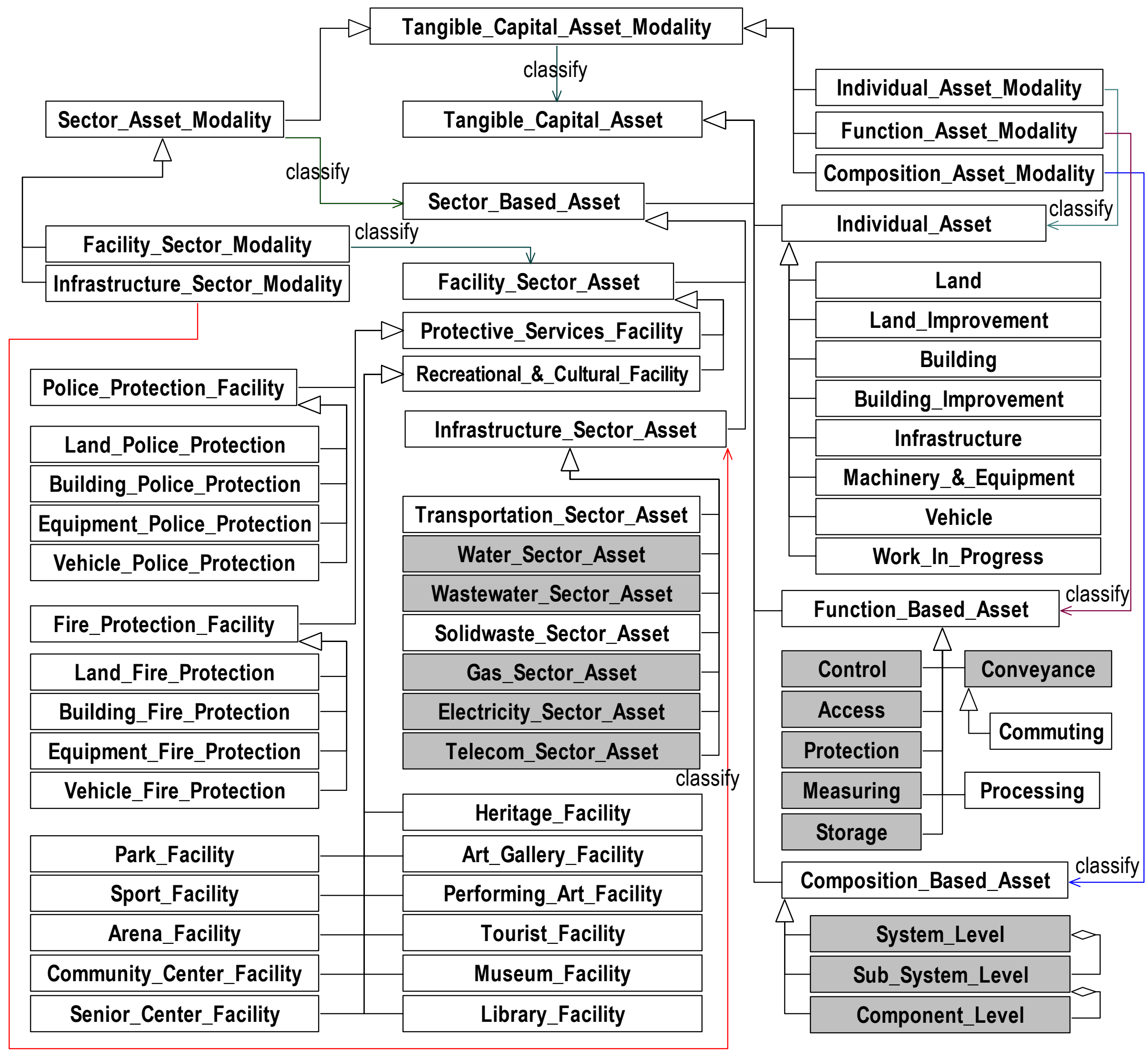

Figure 1: Modality Based Taxonomy of Tangible Capital Assets

3.6.1 Individual Asset Modality

The *individual asset modality* categorizes TCAs based on an individual or single major asset type. PSAB (2009) and TCA (2012) identify and define eight individual asset types as follows. *Land* is a territorial possession or property that is purchased or acquired for buildings, infrastructure, and other program use but not held for resale. *Land improvement* involves the development of the land of a permanent nature, e.g. fences, landscaping, pathways, etc. *Building* is a permanent, temporary, or portable structure consisting of walls or columns and a roof that is used as a shelter to persons, goods, machinery, and equipment and work space, e.g. garages, warehouse, and facilities. *Infrastructure* is a permanent linear physical structure and its associated components constructed in continuous and connected networks, e.g. road networks, bridges, water supply systems, wastewater systems, dams, solid waste system, etc. *Machinery and Equipment – machine* is a system of interconnected components used to perform useful tasks automatically or assist in performing tasks; whereas *equipment* ranges from major machinery like pumps to a smaller tool like furniture and fixtures. Machinery and equipment includes all pumping machinery, filtering machinery, repair and maintenance machinery, delivery equipment, office equipment, etc. *Vehicle* is a self-propelled conveyance that runs on road or rail. *Work in progress* includes assets that are being built.

3.6.2 Function Asset Modality

The *function asset modality* classifies TCAs based on the function they perform. Osman (2007) identified six functions for infrastructure products or assets, according to which assets are classified as follows. *Control asset* regulates the medium being supplied by the infrastructure system, e.g. water control valve, gas control valve, etc. *Access asset* provides access to other localities and assets, e.g. roads, manhole, chamber, etc. *Protection assets* are built to protect either other assets or things in the vicinity of the asset, e.g. retaining wall, manhole cover, relief valve, etc. *Measuring asset* measures the medium being supplied through the infrastructure system (e.g. water meter) or measure the performance of the infrastructure system (e.g. erosion control sensors). *Storage asset* stores the medium being supplied by the infrastructure system, e.g. water storage tanks, oxidation ponds, etc. *Conveyance asset* carries and pumps the medium (e.g. water, sewage, gas, electricity) being supplied by the infrastructure system. Examples are water lines, sewer lines, gas pipes, electric cables, and pumps. In addition, two assets are identified and defined as part of this research work. *Commuting asset* provides commuting services to users, e.g. bus, trolley, transit train, etc. *Processing asset* processes the medium being supplied or carried by the infrastructure system, e.g. water or sewage filtration plants, bio-reactors, oxidation ponds.

3.6.3 Composition Asset Modality

The *composition asset modality* classifies TCAs based on different levels of aggregation and composition, i.e. system level, sub-system level and component level. These assets follow the notion of aggregation-composition of assets, i.e. a system-level asset is composed of sub-system-level assets, and a sub-system-level asset is composed of component-level assets. According to Osman (2007), system-level assets are at the higher level of composition or at a network level, e.g. water distribution system, storm collection system. The sub-system level assets are at an intermediate composition level, e.g. water line (that is composed of pipes, valve, and fittings) and pump chamber (composed of a pump, meter, and valves). The component level assets are at the lowest level of composition, e.g. a single pipe segment.

3.6.4 Sector Asset Modality

The *sector asset modality* classifies TCAs based on the sector or domain to which they belong. Sector asset modality has two types.

1. Facility sector modality

The *facility sector asset modality* classifies TCAs based on the type of AEC/FM facility involved. *Facility sector assets* include all types of facilities and their associated components. The TCA_Onto defines a broad range of facility types, as illustrated in Figure 1.

2. Infrastructure asset modality

The *infrastructure sector modality* categorizes TCAs based on the type of discrete and linear infrastructure. The *infrastructure sector asset* includes all linear (e.g. road, canal, drain, etc.) and discrete infrastructure (e.g. solid waste system). A *linear infrastructure* item is a permanent linear physical structure and its associated components constructed in a continuous and connected network, e.g. road networks, bridges, water supply systems, wastewater systems, dams, etc. A *discrete infrastructure* item is an isolated temporary or permanent physical structure and its associated components constructed to collect, sort, and dispose of solid waste, e.g. waste collection bins, sorting facilities, landfill, etc. According to Osman (2007), infrastructure products or assets can be classified into one of the following five categories: water, wastewater, gas, electricity, and telecom. Moreover, transportation and solid waste sectors are added as part of this research. Each of the infrastructure sector assets is further categorized according to the individual asset modality, where TCA knowledge related to a specific sector is organized based on four main classes: land, building, infrastructure, and vehicle. Each sector represents all related assets and associated components to get a complete and holistic picture of a specific single sector.

The focus of this research work is on municipal infrastructure management in terms of TCA reporting between different agencies and organizations; therefore, the target is to represent TCA knowledge that is owned, operated, or managed by municipalities. Accordingly, the following four sectors are the main focus of this research work: transportation, water, wastewater, and solid waste management sector. Other three sectors: gas, electricity, and telecom are not owned, operated or managed by municipalities, so they are outside of the scope of this research work.

3.7 Capture Ontology – (Step 7)

Ontology capture refers to the development of the axioms in the ontology. An *axiom* is an unambiguous description of a concept in the ontology and constraints on its' interpretation (Osman 2007, El-Gohary 2008, and Gruninger and Fox 1995). Axioms are formulated as soft (concepts are defined in plain English language) and hard (concepts are defined in Ontology Web Language – Description Logic Syntax) for concepts represented in the TCA_Onto. Three types of hard axioms are defined: disjoint, subsumption (is-a) and property restriction (including existential and universal restrictions), using the Protégé ontology editor. As an example, hard axioms for the infrastructure sector modality are presented in Figure 2.

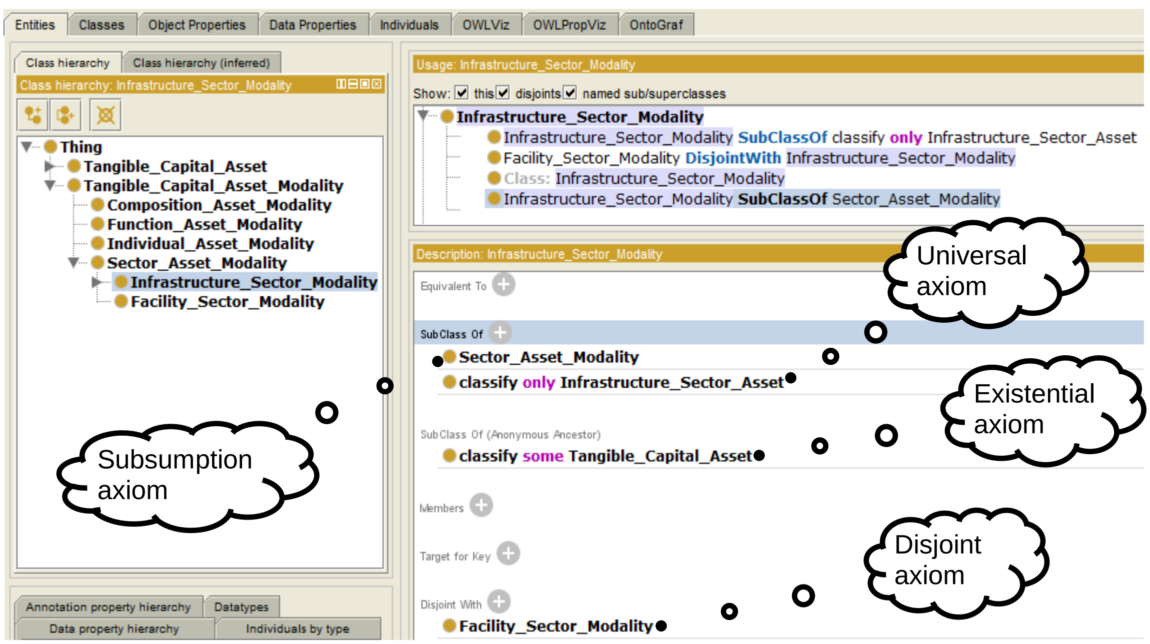

Figure 2: Hard Axioms Specification using Protégé Ontology Editor

3.8 Code Ontology – (Step 8)

Ontology coding refers to the modeling and representation of the domain knowledge using representation languages. In the TCA_Onto, the knowledge is modeled and represented using the Unified Modelling Language, UML (see Figure 1) and Web Ontology Language, OWL (See Figure 2), respectively. The open-source Protégé ontology editor (Protégé, 2013) was used to formally code and represent TCA knowledge in the OWL language.

3.9 Evaluate Ontology – (Step 9)

According to Gomez-Perez (1996), ontology evaluation refers to judging the content of the ontology with respect to some frame of reference (i.e. requirements, competency questions, and real-world model of the domain of interest). Judging the content of the ontology against a set of requirements and competency questions is *ontology verification* whereas judging its ability to capture real-world information is *ontology validation*. The validation of the complete TCA_Onto is underway and beyond the scope of this paper; however, the TCA_Onto verification is presented here using a criteria-based approach.

The proposed criteria to verify the TCA_Onto includes consistency, conciseness, completeness (Gomez-Perez, 1996) and correctness (Guarino, 1998). According to Gomez-Perez (1996), definitions of these criteria and their measures are as follows. *Consistency* measures the level to which contradictory conclusions can be drawn from the definition of a concept. Circulatory, partition, and semantic inconsistency errors are used to measure consistency. *Conciseness* measures redundancy in the knowledge representation. Grammatical redundancy and identical formal definition of classes errors are used to measure conciseness. *Completeness* measures the level to which a knowledge representation is complete. Incomplete concept classification and partition errors are used to measure completeness. According to Guarino (1998), *correctness* measure the level to which knowledge representation is correctly modelled from a real world view. Identify/class definition errors are used to measure correctness. Automated reasoners and requirement-based competency questions were the two tools used to satisfy the proposed criteria toward the TCA_Onto verification.

The automated reasoners (i.e. FaCT^{++}, HermiT 1.3.6, Pellet, and RacerPro) are plugins in Protégé 4.0.2 (Protégé, 2013) that are run to check ontology consistency and conciseness. All inconsistent classes, if any, are shown under a class named 'nothing' in the inferred class hierarchy (an automatically generated class hierarchy). None of the classes were found under the superclass 'Nothing", which means the ontology is consistent as shown in Figure 3. The automated reasoner plugins in Protégé, TCA class hierarchy, and visualization are presented in Figure 3.

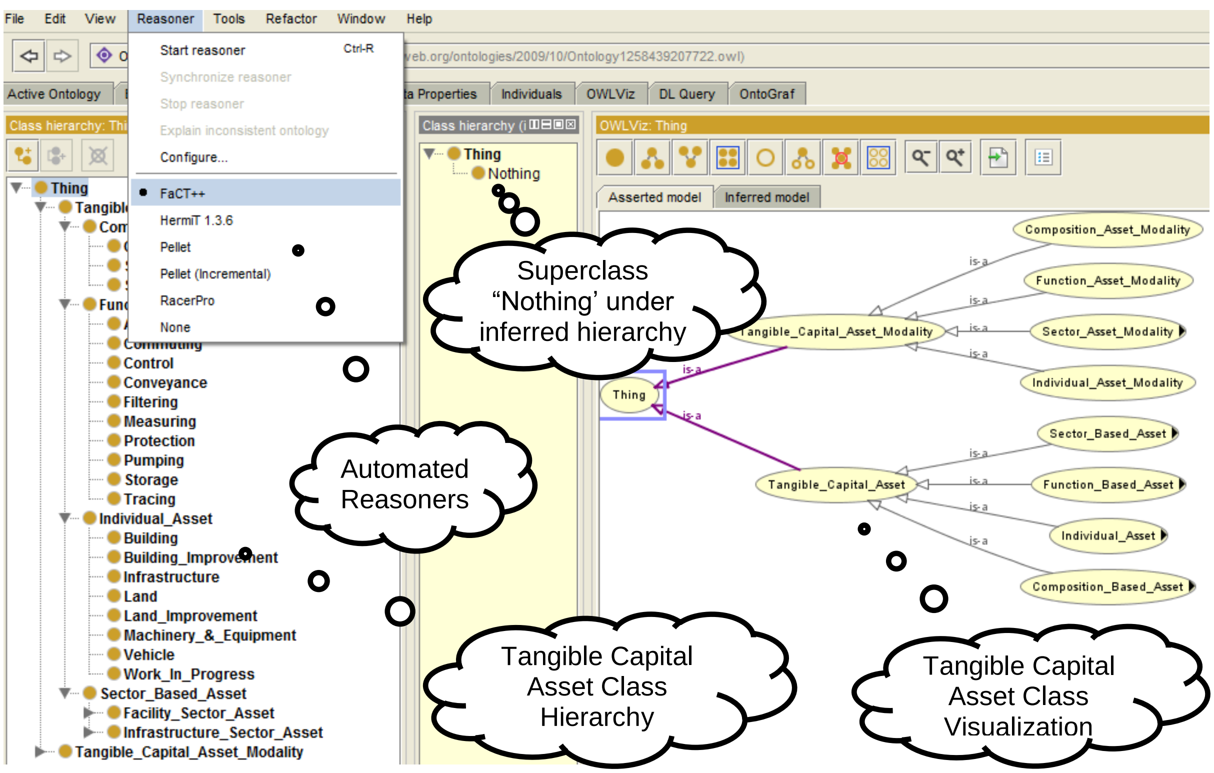

Figure 3: Automated Reasoner-based Verification of Tangible Capital Asset Ontology

Moreover, a competency question tool was used to satisfy three criteria; consistency to measure semantic inconsistency errors; completeness to measure incomplete concept classification; and correctness to measure identity errors. Each CQ was checked manually against these measures at three levels of measure compliance. *Full compliance, (F)* means a CQ is completely error-free. *Partial compliance, (P)* means a CQ is in partial compliance to a specific measure. *Non-compliance (N)* means a CQ is completely erroneous. The results of the CQ based verification indicate that the TCA_Onto is 100% free of semantic inconsistency errors; however, for incomplete concept classification and identity measures, the percentage compliance is 80% and 20% for full and partial compliance respectively. Results indicate a satisfactory response.

3.10 Document Ontology – (Step 10)

The final step is to document the ontology for future use.

4. Ontology Application - Asset Inventory and Condition Assessment Reporting

The TCA_Onto was applied to formalize message templates for the AI&CAR between the municipal and provincial governments. A prototype AIIS is to be developed as part of this research work that will use these formalized message templates for standardized reporting as shown in Figure 4.

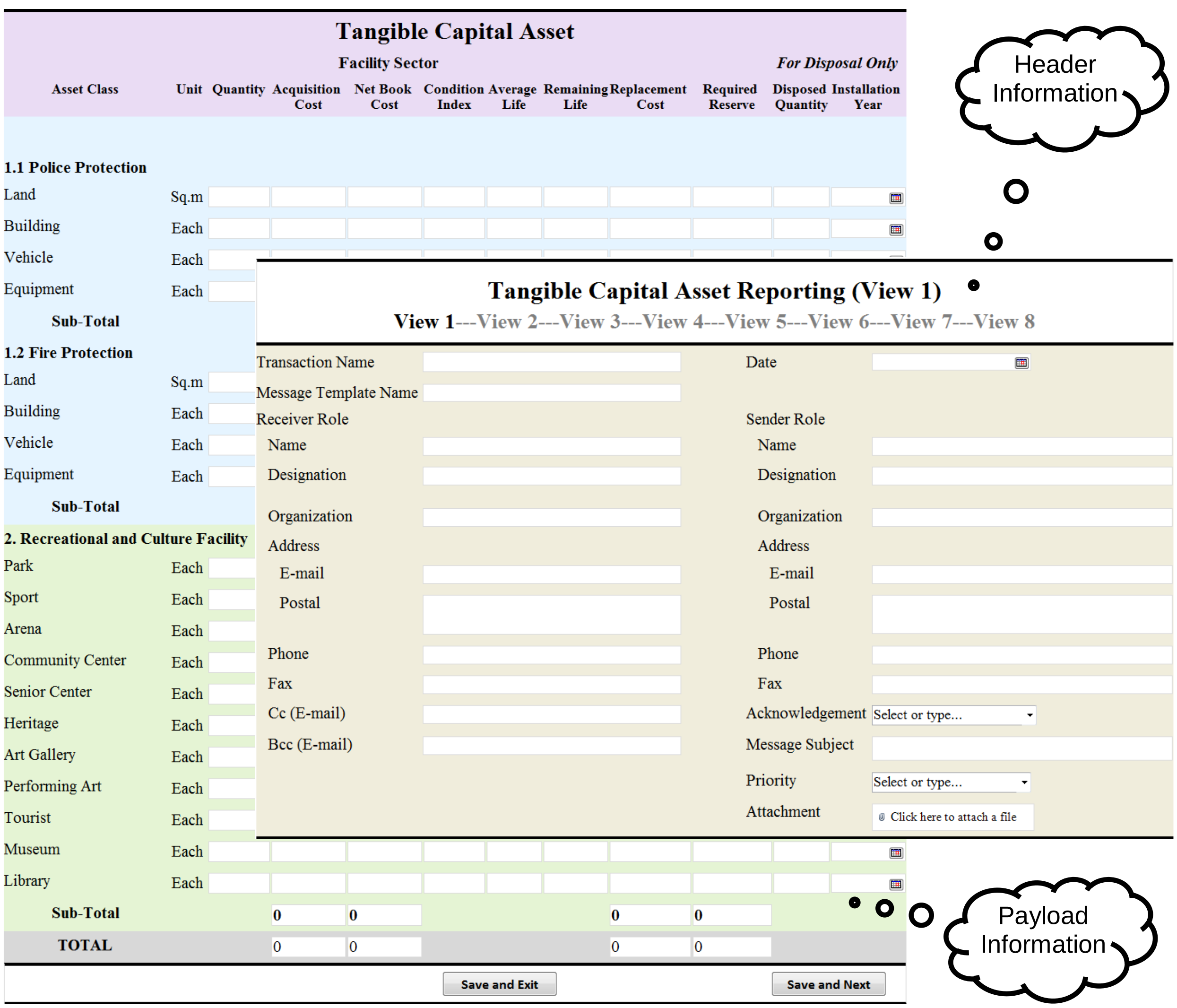

Figure 4: Message Template for Tangible Asset Capital Reporting - (View 1)

The message templates represent two types of information: header and payload as shown in Figure 4. According to Zeb and Froese (2012), the *header* represents the context of a message describing envelope information (e.g. sender and receiver name, address, phone number, etc.), whereas the payload is the actual information to be exchanged between the parties to accomplish a transaction successfully. To formalize message templates for the AI&CAR, the header information is captured from the transaction domain ontology, Trans_Dom_Onto (Zeb and Froese, 2012), developed as part of this research work whereas the payload information (e.g. transportation, water, wastewater, and solid waste assets) is captured from the TCA_Onto presented in this paper. The payload information is organized in the message templates according to TCA information represented in the TCA_Onto. The Microsoft InfoPath was used to develop a message template for TCA reporting that is comprised of 8 views. Each view representing a specific infrastructure sector; e.g. view 1 shows facility assets; view 2 represents roads and furniture; view 3 captures bridges and tunnels; view 4 defines water; view 5 specifies wastewater sanitary; view 6 shows wastewater storm; view 7 represents solid waste assets; and view 8 shows the summary of all costs based on a sector basis. Figure 4 presents view 1 only due to the scope of this paper.

5. Conclusion

Municipalities own, operate, and manage diversified TCAs to provide un-interrupted supply of services. For efficient delivery of services, municipal organizations exchange TCA information with other levels of government and infrastructure organizations. Currently, certain issues are associated with TCA data exchange; including, heterogeneity of data format; lack of uniformity in definitions of various classes of TCAs; and lack of aggregation of information based on infrastructure components. The TCA_Onto is developed to address these issues using a ten step methodology. The TCA_Onto represents TCAs in the domain of infrastructure management with a specific focus on transportation, water, wastewater and solid waste management sectors. The knowledge represented in the TCA_Onto is used to formalize message templates for TCA reporting between the municipal and provincial government. These formalized templates are to be used in an AIIS to be developed as part of this research. As part of the evaluation, ontology verification is completed using two tools: Protégé automated reasoners and requirement-based competency questions. The TCA_Onto, verification results show a satisfactory performance; however, validation is underway and beyond the scope of this paper.

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