Towards Unified Ontology for Modeling Lifecycle Inspection and Repair Information of Civil Infrastructure Systems

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Abstract:

Construction Information Modeling (CIM), is a new approach to model all the information related to Civil Infrastructure Systems (CIS) by integrating this information with 3D models representing the geometrical and spatial characteristics of these systems. The main usage of CIM at the time being is limited to the design phase and some aspects of the construction phase of the lifecycle. In order to take full advantage of CIM throughout the lifecycle of CIS, inspection and repair information should be integrated with CIM to have a semantically unified model where all the stakeholders can access the information in a systematic manner. Furthermore, this integration will facilitate analyzing the information collected over time in clear spatial and temporal contexts. The resulting CIM will evolve during the different phases of the lifecycle to reflect the changes related to quality inspection and repair processes during the construction phase, as well as the inspection and maintenance processes during the Operation and Maintenance (O&M) phase. Several studies have proposed extending the usage of BIM/CIM to model defects in the construction and O&M phases. However, the research in this area is still limited and fragmented, and there is a need to streamline the research for reducing duplication in efforts and providing a high-level approach to Inspection and Repair Information Modeling (IRIM) for a specific type of defects (e.g. surface defects). The models should be independent of the type of the structure and can be applied at different phases of the lifecycle (i.e. construction and O&M). The objectives of this paper are: (1) to review the available literature related to extending BIM/CIM for IRIM, (2) to identify the requirements for developing a unified ontology for lifecycle IRIM of CIS, and (3) to develop the basic components of the ontology.

Keywords: Ontology, Inspection, Lifecycle Management, Repair, Information Modeling, Civil Infrastructure Systems, Defects

1. INTRODUCTION

The quality of newly built Civil Infrastructure Systems (CIS) (e.g. bridges, tunnels, dams, etc.) should be inspected for defects that are beyond the tolerance level, and the detected defects should be repaired before the systems are commissioned. Furthermore, these systems should be kept in good conditions throughout their lifecycle by following rigorous inspection and maintenance processes. The huge amount of data resulting from these processes should be managed in an efficient manner to avoid errors, reduce cost and make the best use of available resources.

Building Information Modeling (BIM), and more recently Construction Information Modeling (CIM), are new approaches to model all the information related to buildings and infrastructure systems, respectively, by integrating this information with 3D models representing the geometrical and spatial characteristics of these systems. While BIM has been developed to a considerable level of maturity and supported by an international standard (i.e. Industrial Foundation Classes or IFC) (buildingSMART 2013, Eastman et al. 2011), the CIM approach is still in its infancy, and several models have been developed only as proof-of-concept; for example, IFC-Bridge (Yabuki et al. 2006, Arthaud and Lebegue 2007), IFC-Tunnel (Yabuki et al. 2012, Yabuki et al. 2013), and IFC-Harbor (Chen et al. 2016).

The main usage of BIM/CIM at the time being is limited to the design and construction phases of the lifecycle. In the construction phase, the applications are mainly about supporting scheduling and cost estimation (Eastman et al. 2011). In order to take full advantage of CIM throughout the lifecycle of CIS, inspection and repair information should be integrated with CIM to have a semantically unified model where all the stakeholders can access information in a systematic manner. Furthermore, this integration will facilitate analyzing the information collected over time in clear spatial and temporal contexts (e.g. visualizing the progress of the defects over time using the 3D and 4D models). The resulting CIM will evolve during the different phases of the lifecycle to reflect the changes related to quality inspection and repair processes during the construction phase, as well as the inspection and maintenance processes during the Operation and Maintenance (O&M) phase. The distinctive names given to these models are as-designed models at the design phase, as-built models (Abudayyeh and Al-Battaineh 2003, Akinci and Boukamp 2003) at the construction phase, and as-is models at the O&M phase. It should be noted that each of these models have several versions and should be continuously updates to reflect design, construction, deterioration, and repair changes in the different phases of the lifecycle.

Several studies have proposed extending the usage of BIM/CIM to the construction phase (e.g. Kim et al. 2015) and the O&M phase (e.g. Aruga and Yabuki 2012, Aruga and Yabuki 2013, Motamedi et al. 2017). However, the research in this area is still limited and fragmented, and there is a need to streamline the research for reducing duplications in efforts and providing a high-level approach to Inspection and Repair Information Modeling (IRIM) for a specific type of defects (e.g. surface defects). The models should be independent of the type of the structure and can be applied at different phases of the lifecycle (i.e. construction and O&M).

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2. LITERATURE REVIEW

As explained in the introduction, several studies explored extending BIM/CIM for IRIM. For example, in the area of facilities management, Hassanain et al. (2003) developed an integrated maintenance management prototype that demonstrated the potential uses of IFC to improve interoperability in the Architecture, Engineering and Construction/Facilities Management (AEC/FM) industry. Hammad et al. (2006) demonstrated the applicability of 4D visualization of bridge lifecycle information based on a standard model. Hammad et al. (2013) also proposed a framework for life-cycle infrastructure information modeling and management. However, they did not discuss the details of the formal definition of this information.

Defects are considered in two different phases of the lifecycle of CIS: the construction (or manufacturing) phase and the O&M phase. In the construction phase, defects are caused by errors or imperfections in the construction. In the O&M phase, defects are caused by factors such as loads applied on the structure, environmental effects, and natural aging. Although the causes of surface defects can be very different in these two phases, there are important similarities that can be exploited in developing IRIM from the point of view of type of defects (e.g. cracks, spalling) as well as the inspection and repair processes and methods. The following sections will review the research about IRIM in the construction and O&M phases and will identify the limitations of this research. A brief review of ontology and its applications in the construction industry is also provided.

2.1 Research about IRIM in the Construction Phase

Park et al. (2013) proposed a framework for construction defect management using BIM and ontology-based data collection template. Kim et al. (2015) proposed a framework for dimensional and surface quality assessment of precast concrete elements using BIM and 3D laser scanning. The proposed IFC-based entity-relationship model for the precast concrete element quality inspection is rather simple and does not cover all the details needed for modeling the defects in a comprehensive way. For example, the location of the defects is represented using *ifcDirection*, which is obviously not enough to specify the location of the defect on the 3D model of the structure.

2.2 Research about IRIM in the O&M Phase

Aruga and Yabuki (2012, 2013) proposed a cooperative management model for structures in the O&M phase. The maintenance management framework considers both the degradation level (i.e. condition assessment) and the measured values (i.e. inspection results). The evaluation based on inspection includes identifying the probable cause of the defect and predicts its future progress. Furthermore, the framework of the degradation and measured values includes several inspection data types (e.g. sketch, photo, drawings) that could be used to identify the shape and location of the defects. However, this research did not discuss all the details of the IRIM.

Kasireddy and Akinci (2015a) proposed integrating inspection data with IFC-Bridge to support condition assessment. The advantages of this model are using *IfcRepresentation* and several contexts for representing the geometry of a defect from multiple inspections and using extended relationships from IFC and IFC-Bridge to link bridge element information with condition information. They stated that one limitation in their approach is that they used some classes from the present version of IFC-Bridge to represent other classes required for condition assessment. Motamedi et al. (2017) proposed a defect/degradation model that includes various categories defect types, relationships between elements and defects, and the processes related to inspection, evaluation and repair of defects. Their proposed model extended IFC model to include new required elements. However, they did not investigate an ontology related to maintenance and repair modeling.

Chen et al. (2016) developed a product model for harbor structures degradation. One of the main contributions of this work is that defects are classified according to the following types: surface degradation (e.g. change of color), addition degradation (e.g. corrosion), subtraction degradation (e.g. cracks), deformation, and material deterioration. However, this research focused on the defect modeling for harbor structures and did not attempt to provide a general approach for IRIM.

2.3 Limitations of Previous Research Related to IRIM

Based on the above review, in spite of the great benefits of the previous research related to IRIM, it has the following limitations:

(1) Different researchers have focused on IRIM related to different types of CIS (e.g. bridges or tunnels), different types of material/elements, or at different phases of the lifecycle (e.g. construction or O&M). For example, comparing the models proposed by Chen et al. (2016) for harbor concrete structures, Kasireddy and Akinci (2015) for bridges, and Kim et al. (2015) for precast concrete elements, it can be seen that they used very different levels of detail for representing the properties of defects (e.g. location and geometry). This will result in duplication of efforts and less efficient research progress.

(2) One common aspect of most of the previous research related to IRIM is that it focuses on mapping a rudimentary data structure of the IRIM processes and products to the entities available in IFC or its derivatives (e.g. IFC-Bridge). This approach results in a rather ad-hoc and shallow models because not all the required entities are available in the current version of IFC. On the other hand, when new entities are added, researchers are adding different entities that are duplicated but using variant terms. For example, the terms *degradation* and *defect* are used to represent the same concept.

(3) Several researchers have discussed the link between the physical measurements of defects in the inspection process and the resulting condition assessment (or severity evaluation) in the diagnosis process, and the following decision about the repair, rehabilitation and replacement (3R) actions. However, most of the previous research focused only on the modeling of defects. Therefore, more research is needed for modeling the other aspects of inspection, diagnosis and 3R information.

(4) Some of the previous research focused on a specific inspection technology and the IRIM was developed only to demonstrate how IFC can be extended to accommodate that technology (e.g. Kim et al. 2015).

2.4 Review of Ontology-related Research

2.4.1 Definition and Method for Developing Ontology

Ontology has different definitions. One of the most widely used definitions is "an explicit specification of a conceptualization" (Viljamaa and Peltomaa 2014). Another definition by Gaševic et al. (2009) is that the ontology is related to two elements: a representation vocabulary, often specialized to a certain domain or subject matter, and a body of knowledge describing the domain and using the representation vocabulary. The ontology, in simple words, is a set of relations between a set of concepts as shown in formula (1) (Thomopoulos et al. 2013).

$$\Omega = \{\mathcal{C}\ ,\ \mathcal{R}\} \tag{1}$$

Where Ω is the ontology, $\mathcal{C}$ is the set of concepts of this ontology, and $\mathcal{R}$ is the set of relations between these concepts. The main types of concepts are: (1) Entities (e.g. Project, Operation, Task, Process, Product, Resource, and Actor); (2) Attributes: Each entity has some attributes that make is different from other entities of the same type; (3) Relationships: El-Gohary and El-Diraby (2010) classified the main types of relations among concepts as *subsumption* relations and *partonomy* relations. A subsumption relation reflects the *is-a* relationship between the concepts and is used to represent the relation between the general concept and a sub-concept. A Partonomy relation is a *part-of* relationship between the concept and its parts, which are built as patronymic hierarchies; (4) Axioms: Axioms can be used to model and describe some constraints such as regulations, best-practices and client requirements; (5) Strategies: Strategies refer to the methods that are used to accomplish the operations and tasks in the project; and (6) Modalities: A modality is used as an umbrella to cover a variety of operation states and the conditions that describe them, such as stage modality, temporal modality, and situation modality. Stage modality can be used to describe a process belonging to one of the lifecycle phases (i.e. initiating, design and planning, construction, monitoring and control, and decommissioning).

The steps for developing an ontology are: (1) Defining the purpose of the ontology (i.e. needs, scope and users); (2) Building the taxonomy of concepts and their interrelations; (3) Developing the process model based on the taxonomy; (4) Ontology capturing and coding, where the terms referring to the relations and axioms are defined; (5) Ontology evaluation based mainly on experts' interviews. The Resource Description Framework (RDF) is one of the methods used to represent ontologies. RDF represents the ontology in a triplet format that contains concepts, properties, and relations (El-Diraby and Kashif 2005).

2.4.2 Ontology Language and Tools

The Web Ontology Language (OWL) is a language designed to code the knowledge in a human-readable format that can be also used by computer applications (McGuinness and Van Harmelen 2004). OWL provides the ability to describe complex concepts based on simpler ones available in the ontology. It has a reasoner that can be used for checking the consistency of the concepts defined in the ontology.

Protégé and OntoEdit are examples of ontology development tools (Singh & Anand, 2013). Ontologies typically can be developed as XML-based files and can be represented in a computer using logic languages such as Knowledge Interchange Format (KIF) (Gaševic et al. 2009). KIF is similar to the First Order Logic (FOL) and can provide the encoding of knowledge using a variety of logical operators.

2.4.3 Ontology-based Knowledge in Construction

As examples of ontology development in the infrastructure and construction domain, El-Diraby and Kashif (2005) presented a distributed ontology architecture for knowledge management in highway construction. They divided this architecture into three levels: domain knowledge, application knowledge, and user knowledge. The architecture was developed as an extension of the e-COGNOS ontology, which is an ontology-based portal that represents a comprehensive knowledge in the construction domain. El-Gohary and El-Diraby (2010) proposed an infrastructure and construction process ontology that offers a formal representation of the process knowledge in the infrastructure and construction domain. El-Diraby (2012) presented a domain ontology of construction knowledge, which contains the conceptual architecture, relationships, and behaviors of the key terms in the construction domain. Park et al. (2013) briefly discussed the benefits of developing an ontology for proactive construction defect management. Venugopal et al. (2012) proposed an ontological approach to building information model exchanges in the precast/prestressed concrete industry. Zeb and Froese (2012) developed a transaction ontology in the domain of infrastructure management.

3. PROPOSED METHOD FOR DEVELOPING UNIFIED ONTOLOGY FOR LIFECYCLE IRIM

The ontology is expected to make the IFC definitions more comprehensive and consistent based on a clear taxonomy of the related concepts and objects following the specific requirements of the ontology (Venugopal et al. 2012).

The proposed method for developing the unified ontology for lifecycle IRIM is based on the following steps and using the general approach and tools discussed in Section 2.3: (1) Defining the requirements of the ontology by analyzing the previous related research to identify the common aspects and limitations of available models. (2) Developing the basic part of the ontology based on the common aspects of previously developed models at a level of abstraction that can be applied to different structures/materials. (3) Extending the basic ontology to cover all the requirements defined in Step 1. (4) Evaluating the resulting ontology by getting feedback from engineers and experts. (5) Enhancing the ontology by repeating Steps 1-4 while considering the feedback gained in Step 4. (6) Mapping the ontology to the available resources in IFC or extending IFC by creating new resources as needed. The mapping between the concepts of the ontology and IFC can start by developing the Model View Definition (MVD) (buildingSMART 2013, Zhang et al. 2013). This approach will facilitate the development of the MVD. (7) Validating the ontology using case studies. However, the present paper will address only the first three steps.

3.1 Requirements for the Ontology

The following requirements are defined for developing a unified ontology for lifecycle IRIM based on our review and the limitations of previous research.

(1) Top-down approach: The unified ontology should follow a top-down approach where the common aspects of defects are molded at a higher level so that they can be shared by several types of structures and used at different phases of the lifecycle. For example, reinforced concrete surface cracks are very similar in tunnels and bridges although they are caused by different types of loads. This concept can be even extended to other structures made of different materials (e.g. steel) because the modeling of cracks and their inspection processes can be very similar. This modeling approach will not only avoid duplicating efforts but will also provide a better quality model which grasps the essence of IRIM and can be further extended to cover the specific details related to the specific type of structure and the phase of lifecycle.

(2) Comprehensive modeling: The unified ontology should cover as much details as possible about the generic aspects of the inspection, diagnosis and repair processes (i.e. process modeling) and the resulting defect model (i.e. product modeling). This requires developing a clear taxonomy and to consider all the semantic relationships required for modeling.

(3) Compatibility with infrastructure management systems: The unified ontology should satisfy the needs of the state-of-the-art infrastructure management systems and guidelines. For example, BrM (formerly called Pontis) is a widely used Bridge Management System (BMS) in the USA (Abudayyeh and Al-Battaineh 2003). BrM

and other BMSs have specific steps to follow for collecting inspection data and applying diagnosis and repair processes. The ontology should reflect the common aspects of these systems at an abstract level that can be applied to the widest category of structures. On the other hand, it is expected that the product and process models that can be developed based on the proposed ontology will influence the current infrastructure management practices. For example, BrM does not require having detailed models of the bridges. However, linking BrM with IFC-Bridge model enhanced with the additional aspects related to IRIM (e.g. defect modeling) will create an opportunity to re-engineer the processes used in these systems.

(4) Compatibility with IFC: Although the proposed ontology should not be restricted to the resources available in the current modeling standard (i.e. IFC), it is important to streamline the development of the ontology with this standard. For example, IFC can represent a defect using *IfcBuildingElementProxy* and the shape of defects can be represented using entities such as *IfcProductRepresentation*, *IfcShapeRepresentation*, *IfcDirection*, *IfcFace*, *IfcPolyLoop*, etc. (Chen et al. 2016). Process-related properties can be represented using entities such as *IfcDate*, *IfcTaskTime*, *IfcTask*, etc.

(5) Ability to accommodate new data collection technologies: The amount of inspection data is expected to grow exponentially with the availability of new technologies (e.g. LiDAR, photogrammetry, etc.). The ontology should support these technologies and provide the means to accommodate the collected raw data and the resulting inspection information.

(6) Ability to track changes: The proposed ontology should provide enough spatio-temporal details to support version control of inspection data and to track the changes of the 3D models of defects and the changes resulting from 3R. Several spatio-temporal levels of detail (LOD) should be available to support the different needs of lifecycle management (e.g. spatial representation of micro cracks and temporal representation of their long-term progress into large cracks that may take years). From the point of view of the technical implementation of the resulting CIM, the tools and techniques used in database version management can be used. However, this issue is beyond the scope of the present research.

4. BASIC COMPONENTS OF THE ONTOLOGY

The following components represent the main concepts that should be included in the unified ontology for lifecycle IRIM of CIS. Some of these concepts are extracted from previous research, while others are added to satisfy the requirements explained in Section 3.

4.1 Process Modeling

Process modeling includes three types of processes: inspection processes, diagnosis processes, and 3R processes as explained below.

Inspection processes should cover the following information: (1) inspection date; (2) inspector information (e.g. name, ID, qualifications); (3) inspection methods and tools, and their related attributes (e.g. type of equipment). The inspection type can be visual inspection, manual measurement, destructive or non-destructive testing (e.g. echography, ground penetrating radar), remote sensing (e.g. LiDAR, computer vision, total station), health monitoring (e.g. fiber-optic strain gauges, wireless sensors), or method for the measurement of loading and environmental conditions (e.g. temperature, humidity); (4) collected data: The collected data depend on the inspection method. For example, visual inspection will produce images and sketches, and inspection using LiDAR will produce point clouds. These data should be archived in a time series format that allows easy retrieval and processing. For this purpose, appropriate metadata should be assigned to the inspection data. In addition, the information about the surrounding conditions (i.e. loads and environmental conditions) should be also archived with appropriate metadata in a way that allows relating and synchronizing this information to the inspection data so that the diagnosis process can reduce the potential cause of the defect.

Diagnosis process can be done at the office by an engineer different from the inspector. It is based on processing the collected inspection data and the information about the surrounding conditions. The following information should be represented: (1) engineer information (e.g. name, ID, qualifications); (2) diagnosis method and method of processing inspection data (e.g. edge detection, shape extraction, clustering); (3) cause analysis of detected defects considering the relationships with the surrounding conditions, which can be reflected in the design and construction phase (e.g., errors and imperfections) and in the O&M phase (e.g., aging deterioration and excessive loads). Loads include static and dynamic over-loading, the effects of chemicals and liquids, temperature, foundation settlements, and vibration; (4) impact analysis on other elements of the structure; (5) condition assessment of a structural element based on inspection measurements on this element, the surrounding conditions, and the condition of connected elements (Kasireddy and Akinci 2015b); (6) prediction of defect progress; and (7) selecting the 3R method.

3R process has the following details: (1) 3R company; (2) host and impacted elements; (3) work order information (e.g. ID, schedule, estimated cost, status, assigned person, etc.); (4) 3R method; and (5) Execution report including actual 3R date, cost, etc. The modeling of this process is less studied in previous research and can benefit from the research related to construction processes.

4.2 Product Modeling

The additional product modeling is categorized into two main types: Defect modeling and 3R modeling as explained below.

Defect modeling should cover the following information: (1) host and impacted elements; (2) defect type. The defect type can be surface/material defect (e.g., cracks on the surface of concrete structure or corrosion of steel structure elements), section loss, deformation (e.g., large deformation of panels), etc.; (3) detection date; (4) definition including shape, location, orientation and severity; (5) potential and actual causes; and (9) related defects on the impacted elements.

3R modeling should cover the following information: (1) host and impacted elements; and (2) modified model of the element after the 3R process including changes in the geometry and materials.

5. PARTIAL IMPLEMENTATION OF THE ONTOLOGY

Figure 1 shows a partial implementation of the proposed ontology. The implementation aims to demonstrate how the entities of the proposed ontology can be defined in a generic way so that it can be extended to different types of structures and using different inspection methods and tools. The ontology is developed using Protégé, which is used to create, display, and process ontology information (Stanford 2017). As shown in Figure 1, the proposed ontology has three types of processes including inspection process, diagnosis process, and 3R process. The product types include the structural elements and defects. The relationships between entities show how the ontology components are semantically interrelated. For simplicity, only *is* and *has* relationships are used in the ontology. The *is* relationship refers to one entity being a subclass of another (e.g. visual inspection *is* a kind of inspection methods). On the other hand, the *has* relationship refers to one entity having another entity as part of it (e.g. inspection method *has* inspection tool). Other more specific relationships can be added in the future.

6. CONCLUSIONS AND FUTURE WORK

This paper focused on the development on a unified ontology for modeling lifecycle inspection, diagnosis and 3R information of civil infrastructure systems. The proposed ontology, when fully developed and implemented in practical applications, is expected to provide the following benefits: (1) All the details of the inspection and 3R will be integrated in one model. This integration will facilitate accessing and updating the information and streamlining the processes at different phases of the lifecycle resulting in improved efficiency and reduced rate of data input errors. (2) This integration will allow a new level of coordination and collaboration among the stakeholders of the project, which is the main benefit of the CIM approach. (3) The version control of the models will allow for creating new types of 4D models that can track and visualize the changes throughout the lifecycle. (4) Some of the potential applications of the proposed ontology are: re-engineered processes of infrastructure management systems, structural analysis reflecting the defects and repair changes of the structure, and visual analytics to support diagnosis processes (Motamedi et al. 2014). Our future work will be improving the ontology to include regulations and rules for processes related to defect inspection, diagnosis and 3R actions.

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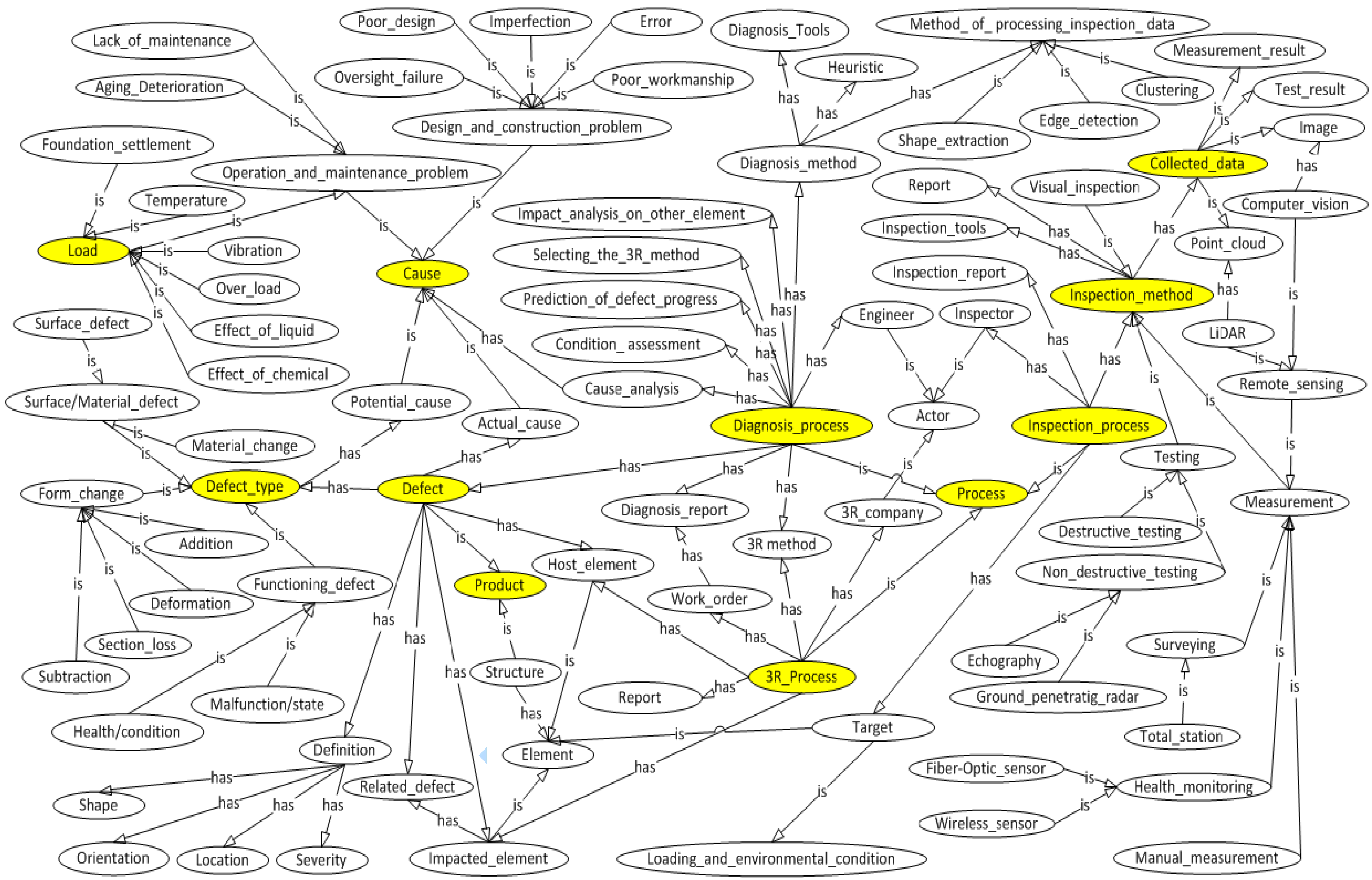

Figure 1. Partial Implementation of the Ontology (main entities marked in yellow)

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