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Framework for Life-cycle Infrastructure Information Modeling and Management

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Abstract: An effective infrastructure management system requires a better understanding of the history of these infrastructures. This need was manifested by the investigations following the collapses of bridges in Laval City, Canada and Sliver Bridge in the U.S. Despite the considerable attention given to the adoption of a whole life-cycle approach in Building Information Modeling (BIM), very little work has been done to extend the usability of 3D design and as-built models of highway infrastructures into the operation and maintenance phase. Currently, efforts are being made to standardize the use of 3D models for the design of infrastructure projects within governmental bodies; however a clear framework that delineates the way in which the operation and maintenance data can be integrated into the design model is evidently lacking. Also, there is a tangible absence of a methodology that provides a systematic and automated base for leveraging the already existing project-level life-cycle data for the integrative management of infrastructures networks. In this paper, we propose a life-cycle approach for the infrastructure information modeling, whereby the 3D model will evolve from a design platform into an all-round information management tool whose applicability spans across the entire project life-cycle. Furthermore, the idea of incrementally building an infrastructure network management system based on the aggregation of project-level information models, e.g. BIM, is explored. A case study is used to demonstrate the feasibility of the proposed approach.

1 Introduction

One of the determinant factors of the national wealth and life standard in the modern world is the extent to which the network of infrastructure serves the society. With the numerous examples of failure of civil infrastructures and their lasting and devastating effects, e.g. the collapses of bridges in Laval City, Canada and Sliver Bridge in the U.S., the significance of smooth and sustained operation of infrastructures is now irrefutable (Rinaldi, et al., 2001; Liu & Frangopol, 2006).

On the other hand, along with the development of new technologies and the introduction of new civil infrastructures, and consequently the increase of demand for enhanced efficiency, grows the complexity of infrastructure networks. It is conceivable that the management of such a complex network requires processing and analysis of an avalanche of variegated data that are most often inconsistent and heterogeneous (Halfaway, 2010; Michele & Daniela, 2011; Kubota, 2012).

Efforts for the management of infrastructure have been essentially led in two distinct lines: (1) development of tools that enable the integration of data pertinent to a product within a single model that can be used through the infrastructure life-cycle (Rebolj, et al., 2008; Shirolé, 2010; Halfawy, 2010; Kivimäki & Heikkilä, 2010; Shim, et al., 2011; Marzouk & Hisham, 2011); and (2) management of infrastructure at the network level with the main objective of enhancing network efficiency through collecting, communicating and analyzing the current and historical data about the condition and performance of the constituent infrastructures (Wolfgram, 2005; Hammad, et al., 2006; Hammad, et al., 2007; Zeng & Ouyang, 2009).

At the project level, a clear framework which delineates the way in which operation and maintenance data can be integrated into the design model is evidently lacking. In spite of a relatively rich range of commercial tools available for the geometric design of infrastructure, none establishes the necessary platform to accommodate the steady stream of construction, operation and maintenance data flowing in the course of infrastructure life-cycle.

At the network level, of the many management tools that are exclusively tailored for network-scale infrastructure management,e.g. Pontis (McLean, 2007), none provides a systematic and automated base for leveraging the already existing project-level life-cycle data for the integrative management of a network of infrastructures.

On this premise, the present research aims to explore the idea of incrementally building an infrastructure network management system based on the aggregation of the product level information models, e.g. Building Information Modeling (BIM), using a Geographical Information System (GIS) platform for integration and analysis. In line with this, two distinctive objectives are being pursued:

(1) To improve the interoperability among various infrastructure management tools by proposing a data structure based on the increasingly popular variations of Extensible Markup Language (XML) (e.g. Geography Markup Language (GML), Transportation XML (TransXML), LandXML and the International Foundation Classes (IFC).

(2) To provide a facilitated two-way data flow between the project-level and network-level data. This requires a well-structure data model that, not only creates the right association linkages between the data and object components, but also accommodates the mechanism of data flow, leaving latitude for extensibility and adjustment.

2 Proposed Framework

In this research, building on the advancements in infrastructure information modeling and infrastructure management systems, i.e. project-level and network-level information management tools, respectively, a new framework is proposed using GIS-based data integration system. The proposed framework consists of five main tiers, namely infrastructure data models, enabling technologies, dynamic data, applications, and one central GIS-based infrastructure management system as an integration and visualization platform. Figure 1 represents the overall structure of the proposed system and constituent elements.

2.1 Infrastructure Data Models

Infrastructure data models establish a standard data structure that: (1) accommodates the integration of various types of data, e.g. managerial, operational and maintenance data, linked to a 3D model, using an object-oriented design paradigm, and (2) provides a life-cycle platform for the cross-domain and cross-phase data sharing. This tier is essentially the aggregation of available BIM and to be-available Bridge Information Modeling (BrIM), Road Information Modeling (RIM) and Municipal Information Modeling (MIM).

The application of a standard data model across the entire construction industry, as opposed to different types of data models for various types of infrastructure, allows further integration for the network and urban level management. As stated earlier, one important step in the life-cycle information management is to establish a well-structured and flexible association between objects and their pertinent data. In addition to the conventional attributes such as dimension, materials and structural properties required for the 3D modeling and analysis, an infrastructure life-cycle object needs to bear linkage to many other types of data that may become relevant in the course of construction, operation and maintenance phases.

This requirement urges for the additional breadth of the product model in terms of accommodating a richer range of data-object associations.

However, although this may be a suitable measure to extend the applicability of the infrastructure model to the entire life-cycle, it does not suffice to address the interdependencies of infrastructures for the network level management. On this ground, the product data model needs to be adequately flexible to ensure the capacity needed for the network-level integration, where it is conceivable that adding new types of infrastructure can introduce new impacts and consequently new attributes that will propagate through the entire set of infrastructures in the vicinity.

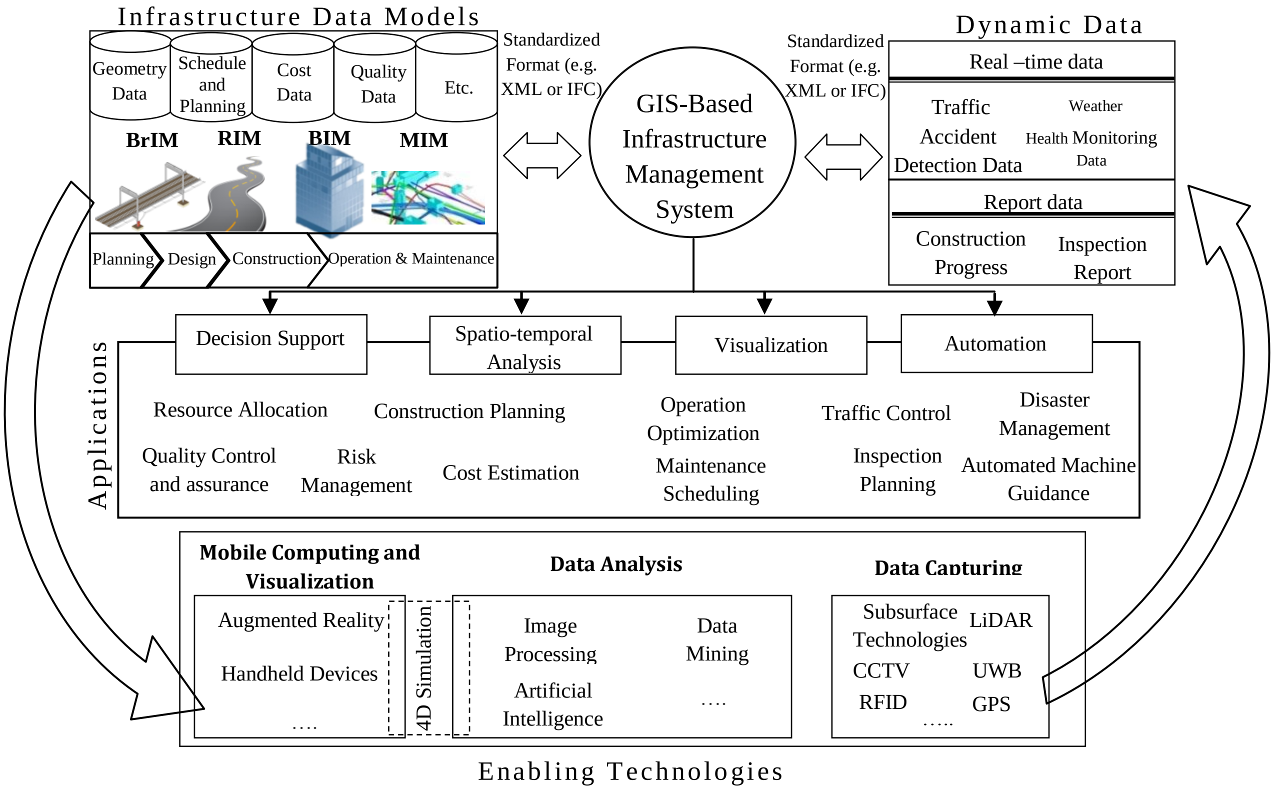

Figure 1 Framework for Integrated GIS-based Infrastructure Management System

According to our literature review, unlike buildings, there is no established data sharing standard, such as IFC, for modeling other types of infrastructures. Such a lack of standardized data models adds to the complexity of moving towards the equivalents of BIM for other types of the infrastructures, namely BrIM, RIM and MIM. Nevertheless, the literature suggests that owing to their growing popularity, proximity to natural language, extensibility, and availability of parsing tools, XML and its specialized derivatives, e.g. TransXML, GML, LandXML, etc., have the potential for growing to an accepted standard formats for the data sharing in the infrastructure modeling.

Another example is CityGML which, as a new standard format derived from XML, was developed to facilitate the exchange of 3D urban objects such as buildings, land use and transportation elements (Kolbe, 2012). In addition to its ability to visualize, CityGML can support the research objective of ensuring interoperability among different application fields such as disaster management, environmental simulations, urban facility management and city life-cycle management. However, CityGML does not have all the details of different types of infrastructures such as roads and bridges.

Figure 2 shows the simplified class diagram for the proposed framework. In the proposed framework, efforts have been made to develop a data model that safeguards extensibility and interoperability with equal emphasis. Consequently, careful attention was paid to the decision whether a parameter in the system needs to be accounted for as an entity class or an attribute of another class. To elucidate the difference between class and attribute, it can be mentioned that while an attribute provides easy access to a parameter, it is confined to the bearing, resulting in decreased extensibility. On the contrary, entity classes offer more control over a parameter in terms of the level of detail and accessibility at the cost of increased complexity of the overall data model.

With the extensibility being one of the main objectives of the proposed system, it is decided to isolate the data pertinent to the infrastructure life-cycle management as an entity class. As illustrated in Figure 2, data is defined as an entity related to the infrastructure through composition association. This measure allows for a relatively loose association between data and the pertinent object. The loose coupling enables the system to have a dynamic structure that can easily evolve and reshape in response to the changing work orders or modifications.

This data model can accommodate new types of input data at any given object levels, i.e. components, segments, products and networks, without posing new requirements for major structure modifications. Furthermore, any existing type of data can be easily associated with an existing object. The data class is instantiated by various types of data that may relate to an infrastructure, at various levels, in its life-cycle. The instances of data class include state data, plans and schedules, cost data, quality data and geometry data. Each instance of the data class can be further diversified into more specific instances. For example, maintenance, construction and inspections are some subclasses of plans and schedules.

Visualization is the representation of data through various models, e.g. 2D or 3D models. Based on this interpretation, the association between the data and visualization is of the aggregation type. Moreover, in addition to the composition association between data and infrastructure, it is assumed that every component has several instances of data associated with it. Component class is the parent class for component-level objects aggregation which constitutes the segments/sections. In turn, a collection of several segments/sections establishes the product-level infrastructure, e.g. a building. These relationships are illustrated with generalization and aggregation associations in Figure 2.

Finally, Figure 2 shows the relationship between state data, which represent the overall condition of infrastructures in terms of the components' health, and the technologies that enable the collection of the various types of data that determine the state.

2.2 Enabling Technologies

As explained in Section 2.1, enabling technologies comprise various tools and methods that can be deployed to capture, analyze and disseminate data. As for data capturing, depending on the type of the data required, a substantial number of technologies can be employed, such as subsurface technologies, Light Detection and Ranging (LIDAR), Close-circuit Television (CCTV), Ultra-Wideband (UWB), Radio Frequency Identification (RFID) and ,the Global Positioning System (GPS).

Needless to say, in most cases, the collected data are not directly usable without proper analysis and processing. Similarly, based on the type of the collected data and employed technologies, as well as the required output, a variety of data analysis and processing methods can be used, e.g. image processing and Artificial Intelligence (AI).

As the final constituent of this tier, mobile computing and visualization binds together several types of technologies and devices that help represent the data and provide access to it, such as handheld devices and augmented reality. Among different technologies falling in this category, some can perform data visualization and analysis concurrently, which is most conspicuously manifested in 4D simulation methods and technologies.

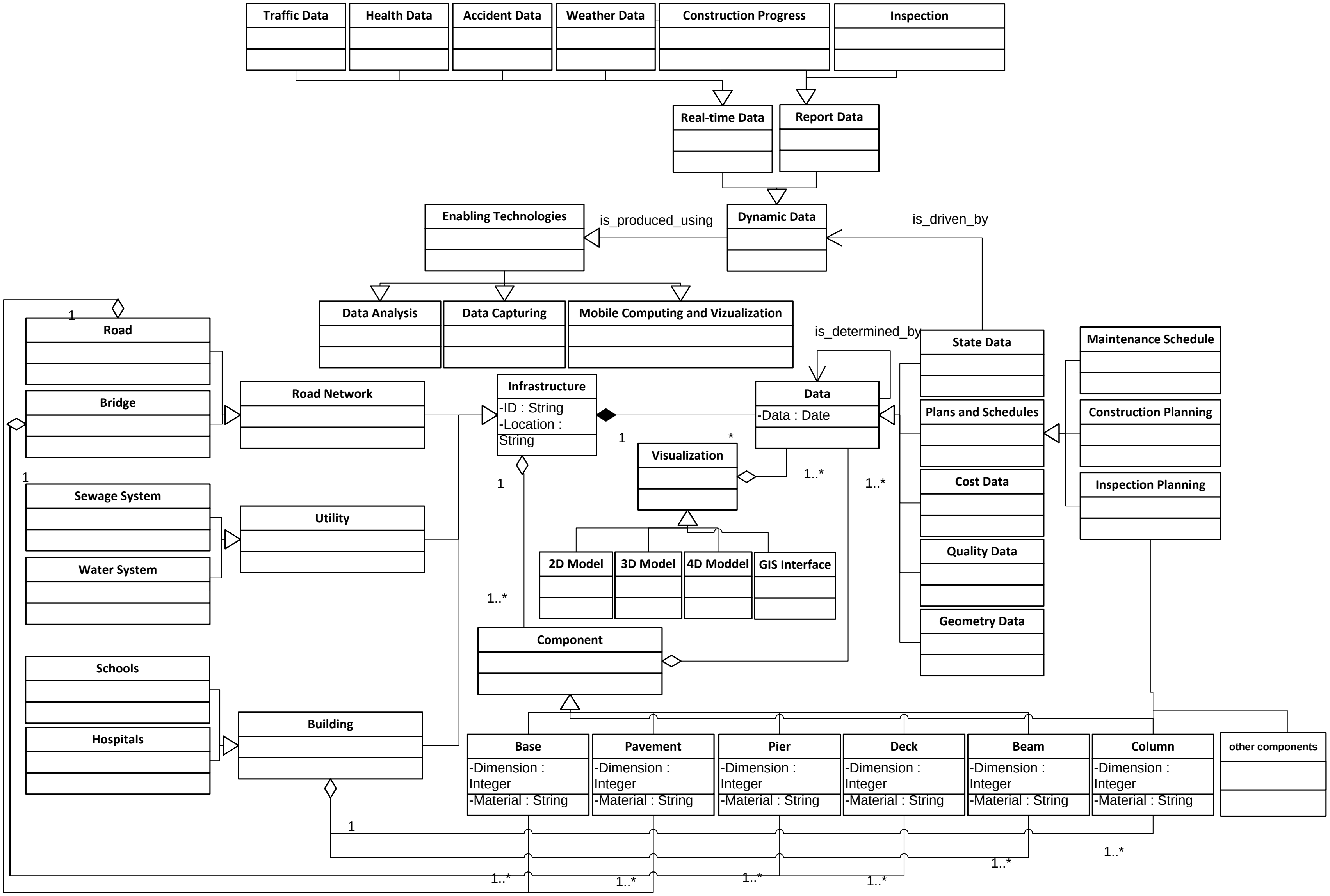

Figure 2 Class diagram for the proposed framework

2.3 Dynamic Data

Life-cycle management of an infrastructure requires the collection and processing of a wide spectrum of data. These data range from general data about the traffic and weather to specific data about the condition of components in an infrastructure.

According to the sources of data and the frequency in which the data are available or required, two types of dynamic data are identified, real-time data and report data. Real-time data pertain to the aspects of infrastructures that have instantaneous impacts on its operation and functionality, and thus require constant monitoring. Examples of this type of data are traffic data, weather data, accident data, components' health data, etc.

On the other hand, some data cannot or need not be collected at a high frequency, or perhaps require human intervention and post-processing before they can be applied. These types of data are categorized under the report data. Data about the result of inspections will be available only when inspectors submit their reports on their evaluations. The same applies to the progress monitoring of the construction activities. It should be stated that even the report data can be the result of automated processes, but their pertinence to effective management is when they are collected in longer intervals.

2.4 Applications

An infrastructure management system integrates different types of data from a wide range of sources at the network level. The significant contribution of the proposed framework is in the provision of a large amount of data in a structured manner over a wide range of domains. Thus, a large number of applications that require multi-disciplinary and cross-domain communications and data sharing can be performed more conveniently using this framework. For instance, when a new construction is being planned, the proposed framework enables designers to preempt conflicts and clashes at a large scale taking into account a wider variety of infrastructure information (e.g. the clashes between different types of underground utilities). Despite the diversity of the applications, they can be classified into four groups, namely decision support, spatio-temporal analysis, visualization and automation.

(1) Decision support: applications that assist managers in making informed decisions through the timely provision of the relevant information. Examples of these applications include traffic control and resource allocation.

(2) Spatio-temporal analysis: these applications provide solutions for the concurrent analysis of various activities in relation to time and space attributes in order to identify potential spatial and temporal conflicts.

(3) Visualization: These applications are intended to enhance the visual representation of the model, by combining various dimensions such as time and costs. 4D visualization (i.e. 3D model and construction schedule) and 5D visualization (i.e. 4D plus cost data) are used in the construction industry. However, one of the main advantages of the proposed framework is the ability to add any supplementary dimensions to the model representation, e.g. deterioration or inspection data. The loosely-coupled data model allows us to superimpose the time-stamped maintenance and inspection records to the 3D model.

(4) Automation: With the advent of the high accuracy GPS and advanced machine robotics, Automated Machine Guidance (AMG) is being increasingly used to automate the operations that require high precision, e.g. fine grading, through the provision of accurate data to the operators of the construction equipment. AMG requires a range of data input including Digital Terrain Model (DTM), the geometry of the as-designed road model, etc. The application of this technology requires a new level of interoperability between design tools and AMG that can be realized using LandXML or other similar formats. Therefore, construction automation is another application area for which the proposed approach is well suited.

2.5 GIS-based Infrastructure Management System

This tier integrates data from the infrastructure data models and dynamic data using the GIS-based platform as presented in Figure 2. As a prerequisite for this integration, all components in the system need to be geo-referenced.

It is worth mentioning that GIS is not a mere visualization tool, but it allows performing various kinds of analysis and data processing. For instance, visual analytics can especially assist in disaster management, where a large amount of data needs to be considered in order to make the optimum decisions that can prevent the collapse of a network or help fast recovery.

3 Case Study

This case study aims to test the interoperability between various software used in the design and operation phases of bridges, and to demonstrate the possibility of geo-referencing a 3D bridge model using GIS applications.

The research group of the authors has developed an interface for Quebec Bridge Database obtained from the Ministry of Transportation of Quebec (MTQ) (Yan, 2008) where the locations of bridges are added to a GIS using unique identifier (ID) numbers. This GIS application is used to locate bridges and to retrieve and display their attributes on the map (e.g. number of lanes, structure type, and bridge class). For instance, Figures 5 shows various types of bridge structures on the Island of Montreal (329 bridges).

In this case study, the overpass of Chemin de la Côte-Saint-Luc over Highway 15 in Montreal shown in Figure 5 is modeled in 3D using bridge design software (Bentley Leap Bridge), as shown in Figure 6. Some attributes of the bridge, e.g. the main dimensions of the bridge and the number of spans and girders, were extracted from the database of MTQ.

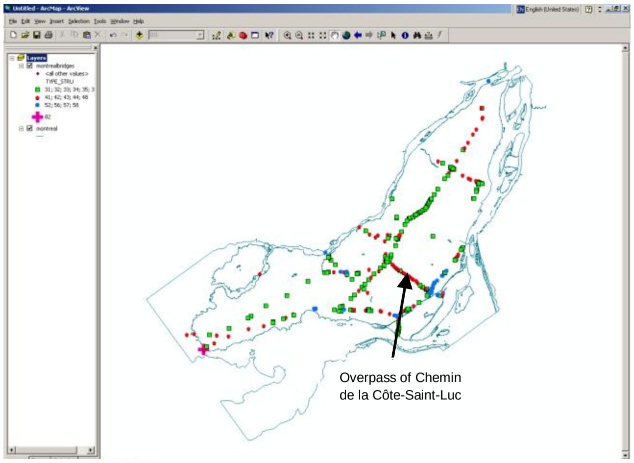

Figure 5 Structure types of bridges

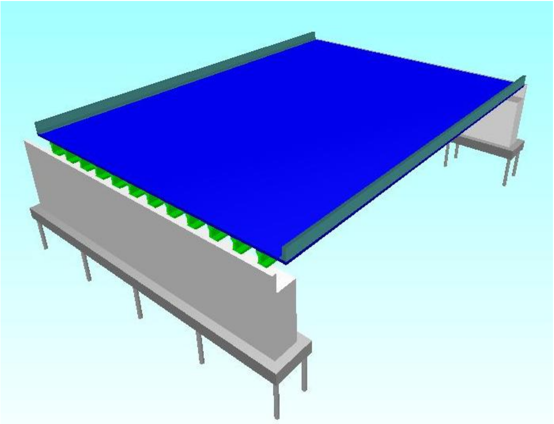

Figure 6 3D design model of the overpass of Chemin de la Côte-Saint-Luc

Bentley Navigator Software is used to geo-reference the 3D model of the bridge on Google Earth. For that purpose, an intermediate design format (DGN) is necessary between the native XML format of Leap Bridge and Navigator. In addition, a Zipped Keyhole Markup Language (KMZ) file of the area of the bridge on Google Earth was loaded to Navigator for identifying the location of the bridge. Locating the 3D model precisely on the map requires identifying at least three common points on the model and on the Digital Terrain Model (DTM). However, the Navigator software uses only one point. Therefore, the orientation of the bridge was adjusted using another application (Sketchup). The geo-referenced 3D model was imported and visualized on Google Map as shown in Figure 7.

Furthermore, in the operation and maintenance phases, defects observed by bridge inspectors can be marked and visualized on the 3D model as shown in Figure 8.The type of defects (e.g. cracks, scaling, spalling and collision damage) and severity levels (e.g. serious, moderate and light) are visualized on the 3D model by using different symbols (e.g. circle and rectangular) and different colors (e.g. red, blue and green), respectively. This function enables inspectors to easily mark new defects directly on the 3D model and access the previous bridge inspection records to facilitate the prioritisation of maintenance or rehabilitation actions.

Figure 7 View of the bridge 3D model on Google Earth

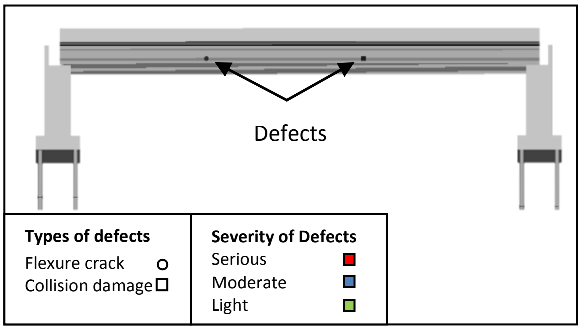

Figure 8 Location-based bridge visual inspection

4 Conclusions and Future Works

The present research proposes a new framework for life-cycle infrastructure information modeling and management, whereby the 3D model evolves from a design platform into a project life-cycle information management tool at both the project and the network levels. The case study demonstrated the possibility of realizing some of the ideas discussed in the framework and highlighted some limitations of available bridge design and management systems.

Our future work will further consider the interoperability issues for lifecycle and network integration of future infrastructure management systems, with special focus on bridge lifecycle management systems.

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