AN INVESTIGATION OF CIVIL INFORMATION MODELLING (CIM) FOR THE MANAGEMENT OF CIVIL INFRASTRUCTURE FACILITIES AND ASSETS AND ITS VALUE-ADD POTENTIAL

by

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ABSTRACT

Information Modelling (IM) workflows are increasingly being applied to public infrastructure projects. However, it is not well understood how: (1) civil information models can be extended to post-construction lifecycle phases; and (2) how to define business value and measure economic and other social benefits that these data-rich, digital models might provide. This report captures the findings from an investigation into the value-add potential of civil infrastructure information models integrated with GIS-enabled systems for facilities and asset management. Some general conclusions from the literature indicate that full CIM integration within a GIS-enabled enterprise asset management system requires extensive work to develop the necessary ontologies for semantic modelling. Current standardized data structures such as IFC4 and CityGML v3 are not sufficient for seamless and efficient data exchange across platforms. Furthermore, there is a general lack of data and structured analysis related to the valuation of implementing IM technology in industry to justify this type of investment.

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List of Abbreviations

Abbr.	**Full form**
2d / 3d	Two-dimensional / Three-dimensional
AEC/O	Architecture, Engineering, Construction/Operations
AM	Asset Management
AMS	Asset Management System
API	Application Programming Interface
APPA	Association of Physical Plant Administrators
AR/VR	Augmented Reality/Virtual Reality
BIM	Building Information Model
BMP	Best Management Practices
CAD	Computer Aided Design
CAFM	Computer Aided Facility Management
CIM	Civil Information Model
CIRC	Canadian Infrastructure Report Card
CMMS	Computerized Maintenance Management System
COBie	Construction Operations Building Information Exchange
EAM	Enterprise Asset Management
ERP	Enterprise Resource Planning
GIS	Geographic Information System
IAM	Infrastructure Asset Management / Institute of Asset Management
IFC	Industry Foundation Class
IM	Information Modelling
IPD	Integrated Project Delivery
ISO	International Standards Organization
IWMS	Integrated Workplace Management System
KPI	Key Performance Indicator
LOD/LOD(t)	Level of Detail / Level of Development
LoS	Level of Service
O&M	Operations and Maintenance
PAS	Publicly Available Specification
ROI	Return on Investment
SQL	Structured Query Language
SW	Semantic Web
SWMM	Storm Water Management Model
UNB FM	University of New Brunswick – Facilities Management
VDC	Virtual Design and Construction

1 Introduction

In the 1980's and 90's computers largely replaced paper and pencils for architects, engineers, and designers where computer-aided design/drafting (CAD) software could produce scaled, precision line work in two and three-dimensions. As capabilities evolved, vector-based digital objects representing real world elements augmented simple graphics. Three-dimensional (3d) solid-modelling allowed designers to parametrically define those digital objects and design methodologies from the mechanical domain moved to the structural domain. Building Information Modelling (BIM) extended parametric modelling by providing the ability to attach database information to digital objects. At the same, server technology evolved, and cloud computing emerged allowing previous challenges with respect to data management and file version to be eliminated.

By combining these two technologies, design teams were able to publish and share their BIM models online and communicate design intent in a three-dimensional, and visually compelling way. This digitization is rapidly transforming building life-cycle processes from conceptual design to procurement to operations. The benefits of BIM for buildings (vertical construction) are well documented and provide evidence that BIM and Virtual Design and Construction (VDC) produce value through information sharing, reduced duplication of similar information and issue detection in the pre-construction stages and increased transparency for project management, as well as reduced project risks in the construction stage (Li et al. 2014).

However, research indicates that the application of BIM frameworks to traditional Plan-Design-Build-Manage life-cycle models (Figure 1.1) for civil infrastructure facilities

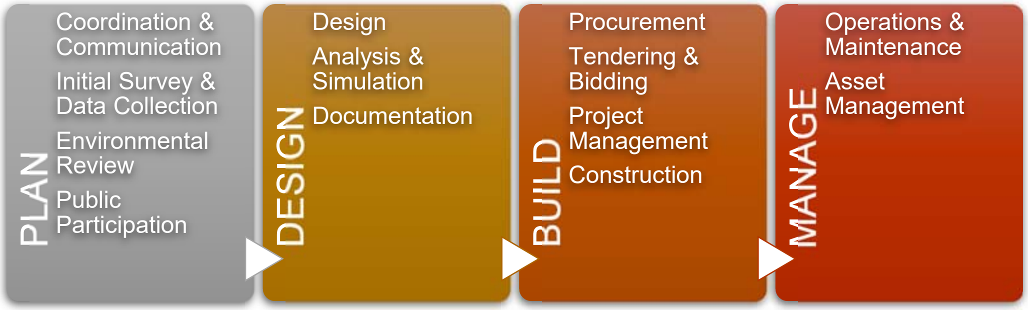

Figure 1.1 Traditional life-cycle model for capital projects

(horizontal construction) has been slower to emerge than in the vertical Architecture/Engineering/Construction/Operation (AECO) industry (Porwal and Hewage 2013).

Furthermore, it is not well understood what value these data-rich, digital models might provide for post-construction, downstream applications during operations and maintenance or for Asset Management (AM). Ultimately, the goal for Civil Information Models or CIM's (the infrastructure analogue of BIM's), especially for large public and private agencies, will be the ability to access and share as-built information with real-time conditions or system status for analysis, service, repair, rehabilitation or replacement. For example, visualizations for Levels of Service (LoS) for road networks or structural health for bridges or other assets would provide various levels of contextual information and can enhance decision-making processes, especially where multiple stakeholders are involved.

Future development promises to provide products and services that would combine Virtual Reality (VR) and Augmented Reality (AR) applications to access an information mass-model composed of up-to-date collections of both the above-ground and the below-ground services and constructions and their surrounding environments. Since many of the design technologies are mature and have been proven for vertical construction, the question arises: what are the main differences between BIM and CIM, and what is holding the industry back from fully integrating these technologies into asset management systems?

This research explores Information Modelling (IM) technology applied to civil infrastructure assets and facilities throughout their life-cycles, from conception to decommissioning, to determine how these tools can enhance the management of operations and maintenance more efficiently and provide increased value to all stakeholders.

2 Research Value

This chapter describes what the research is, how and why the research is being conducted, and the importance of what the research provides.

2.1 Problem Development

It is important to understand how we can better use our existing technologies to define more efficient processes for the future. This research considers the life-cycles of infrastructure works which are typically far longer than other manufactured products, and how the technology at each phase can be extended to the next phase to improve efficiency. Often, when developing research, it is easy to present a solution in search of a problem. Therefore, defining a research problem early can point towards the right solution, and possibly one that may already exist. The initial stages of this research considered aspects of technology integration for civil infrastructure through a framework presented in Figure 2.1 used to define the scope of the problem domain.

Given there are vast amounts of data generated for an infrastructure project, information modelling presents the potential to aggregate data from multiple sources at various stages.

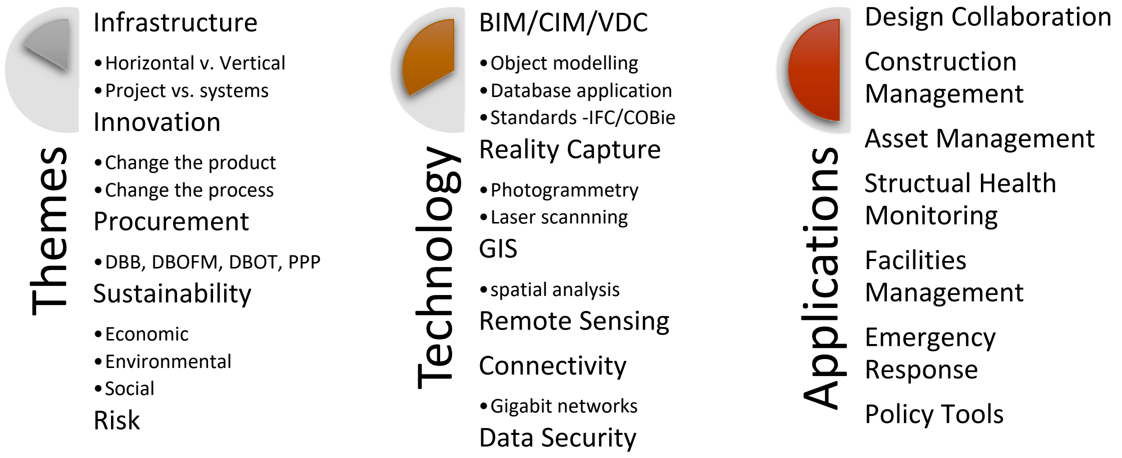

Figure 2.1 Framework for the problem domain

An assessment of the availability, access to, and quality of information for a specific infrastructure asset for a specific stakeholder can determine what value the information model holds.

2.2 Hypothesis

Fundamentally, the life-cycle value of civil infrastructure assets is derived through reductions in cost either directly or indirectly. Directly, cost can be reduced by increased efficiencies that reduce physical resources, effort or time to design, construct, operate and maintain an asset. Indirectly, value is generated through the broader social and economic benefits that the asset provides or enables. The hypothesis of this research is that ***information modelling technology applied to both new assets early in the life-cycle or to legacy systems though as-built models have inherent value beyond design and construction and can be extended to Operations and Maintenance (O&M)***. Integrating data-rich information models with facilities and Asset Management Systems (AMS) can provide value by providing better information to owners, operators, and managers in three primary ways:

1. Increased efficiency and reduction in potential errors through reduced duplication of work at various life-cycle stages.
2. Better visualization for decision-making by providing overviews and context within a network.
3. Increased efficiency through the availability of and access to information about location, position and condition of assets at a point in time.

2.3 Research Questions

This research was guided by inquiry in three knowledge domains: (1) CIM technology, (2) asset management practices and policies, and (3) business valuation analysis. Research questions within each domain were outlined as follows:

1. Related to CIM technology:
    a. Compared to BIM, how mature is CIM technology?
    b. What capabilities are available in current software solutions and can they provide a link to asset management processes?
    c. What are the current technological limitations and challenges with respect to CIM-AM integration?
2. Related to asset management:
    a. How can current asset management practices leverage CIM technology?
    b. How can CIM be integrated with asset management at an asset level and at network level?
    c. What technologies and practices are being utilized in each process?
    d. Are there current asset management challenges that can be addressed through CIM?
3. Related to business valuation:
    a. What type of potential value can be generated by integrating CIM with asset management?
    b. Where can this value be found?

2.4 Research Goal

By encouraging the adoption and promotion of new technologies, innovation in this sector can increase at a rate on par with other sectors employing advanced modelling technology such as vertical construction or manufacturing. As such, the original goal of this research was to provide infrastructure owners with evidence that CIM can provide an increase in positive Return on Investment (ROI) by extending the use of civil information models past the design and construction lifecycle stage of an infrastructure facility to the operations and maintenance stage. As the work developed, it became clear that determining the business value of deploying a developing technology required a greater understanding of how the technology is structured and implemented. To that end, this research sought to understand the gaps between the technology, the application (i.e. asset management), and its implementation within the AECO industry.

2.5 Motivation

New technology can enable innovation necessary for better asset management where financial capital resources are ubiquitously limited. However, when new technologies are implemented, it is often not apparent what effects it may have downstream. For instance, enhanced capabilities that are being developed within information modelling tools can utilize project data beyond the design and construction phase of a project; however, in many cases these tools are unknown, overlooked or not properly leveraged by stakeholders outside of those processes. Considering the resources involved in the design process, it is being recognized that business value can be extracted by extending these knowledge products into operations and maintenance, facilities maintenance, and asset management.

2.6 Scope

This research considers three aspects of post-construction applications of civil infrastructure information models: technology integration, process integration and business value potential. An effort is made to maintain analyses from an owner/operator perspective, whose role is to provide responsible policies and strategies for planning and decision-making to optimize cost, risk, and life-cycle performance. While outside the scope of this research which is focused on infrastructure or horizontal construction, research in BIM or vertical construction research is often referenced to support similar or analogous ideas and arguments where buildings and infrastructure knowledge domains overlap.

2.7 Methodology

The initial proposal for this research considered a more comprehensive technological study and the development of a proof of concept. However, after understanding the extent of the problem domain, the project focused on a literature review to investigate the current state of the technology and the maturity of its application related to operations and maintenance, Facilities Management (FM) and asset management; first as isolated processes and then as an integrated system. A partial case study is considered, and to the extent it was developed, the results are presented with some discussion on ways to advance a future version of that project. The methodology for the case study is detailed in Chapter 6.

2.7.1 Literature Review

The literature review was conducted in each of the knowledge domains identified earlier and was broken down into several objectives outlined below.

Literature Review – Civil Infrastructure Modelling (CIM)

The following objectives were considered to understand the extent of the CIM knowledge domain:

- To understand the maturity of CIM technology compared to BIM.
- To understand the extent to which CIM technology is currently deployed.
- To understand the extent to which CIM is currently implemented across various types of infrastructure with respect to a life-cycle phase.

Literature Review – Asset Management (AM)

The following objectives were considered to understand the extent of the AM knowledge domain:

- To understand AM best practices with respect to information technology (IT).
- To understand how spatial-temporal technology can support asset management.
- To understand how IT is incorporated in AM policy frameworks.

Literature Review – Integration Potential (CIM-AM)

The following objectives were considered to understand the extent of the CIM-AM knowledge domain:

- To understand the state of CIM-AM integration from a technology perspective.
- To understand the state of CIM-AM integration from a process perspective.
- To understand the challenges of integration presented by technological disparity.

Literature Review – Value-add potential

The following objectives were considered to understand the value-add knowledge domain:

- To understand the business case for implementing CIM at the project level.
- To understand the business case of AM from a policy perspective.
- To understand how to measure the value of integrated systems both quantitatively and qualitatively.
- To understand the challenges related to aligning the value propositions of CIM and AM.

2.7.2 Sources

An internet search using both the Google and Google Scholar search engines was conducted throughout various phases of the research using the databases and keywords described below. The Mendeley database proved exceptionally useful for recommending related articles. Grey literature such as product literature, like the Autodesk white papers, were used to develop a baseline insight into industry applications and implementations, albeit a biased one.

Databases

Databases used to search for peer-reviewed academic paper include Scopus, SpringerLink, JSTOR, Mendeley, Science Direct, Google Scholar, WorldCat, Semantic Scholar, CiteSeerX, JournalSeek, and Web of Science.

2.7.3 Key Words

The primary key words used for internet searches included: Information modelling, BIM, CIM, civil, infrastructure, facilities, management, operations and maintenance, asset management, geo-spatial information systems, GIS, and integration.

3 Background: Infrastructure, Asset Management, GIS, and Information Modelling

This chapter provides a broad overview of the foundational topics being researched. It contains descriptions and definitions of infrastructure, asset management and information modelling making the distinction between BIM for vertically constructed buildings and CIM for horizontally constructed civil infrastructure.

3.1 Infrastructure

3.1.1 Reliable Civil Infrastructure for Productivity and Competitiveness

The World Economic Forum (WEF), a non-profit, international, organization for public-private cooperation published its concept of the twelve pillars of competitiveness (see Figure 3.1) to define “the institutions, policies and factors that determine the level of

Figure 3.1 The 12 Pillars of Competitiveness
(http://reports.weforum.org/global-competitiveness-report-2014-2015/methodology/)

productivity of a country" which, in turn, indicates its "economic growth potential" (Schwab 2014). After *public and private institutions* (1st pillar), the "quality and availability" of *infrastructure* was identified as the second (2nd) pillar and the "capacity for, and commitment to technological *innovation*" is identified as the twelfth (12th) pillar. This concept highlights the foundational importance that reliable civil infrastructure contributes to modern society and its relationship to innovation. Furthermore, the Brookings Institute asserts that infrastructure development is critical for economic and social growth that also considers poverty reduction and environmental sustainability (Bhattacharya et al. 2015).

However, it is widely recognized that global investment in infrastructure, as a percentage of GDP, has been generally in steady decline. In Canada, investment in infrastructure had declined from over 3% of GDP between 1955 and 1965 to less than 1.5% between 1997 and 2000 (Mackenzie 2013). At the same time, ownership of public civil infrastructure has shifted away from the federal government towards municipalities. The 2016 Canadian Infrastructure Report Card (CIRC) reports that municipal governments are now responsible for almost 60% of public capital compared to 22% in 1955. Furthermore, the replacement value of all assets is estimated at $1.1 trillion with 12% of those being in poor to very poor condition and 22% being in fair condition and all asset classes studied were determined to be in a declining condition based on current reinvestment levels (*Canadian Infrastructure Report Card* 2012).

Understanding the economic conditions surrounding investments in civil infrastructure provides the impetus for all infrastructure AM programs and new technologies such as information modelling can potentially add business value to further justify the cost of implementation.

3.1.2 Categorization of Civil Infrastructure Facilities

The CIRC classifies infrastructure into seven (7) categories: Potable Water, Wastewater, Stormwater, Roads and Bridges, Buildings, Sport and Recreation Facilities, and Public Transit. Comparing this system to the classification introduced by Cheng et al. (2016) and shown in Table 3-1 that uses thirteen (13) types under five (5) domains, it can be seen that each system differs in granularity and perspective. For instance, the CIRC separates water networks but combines asset classes such as roads and roads and bridges while Cheng groups similar asset classes into domains.

Table 3-1 Categorization of civil infrastructure facilities (Cheng et al. 2016)

Categories of civil infrastructure			Infrastructure Domain
I	(1)	Bridges	Transportation
II	(2)	Roads	
III	(3)	Railways	
IV	(4)	Tunnels	
V	(5)	Airports	
	(6)	Seaports & harbours	
VI	(7)	Power generation	Energy
	(8)	Oil & gas	
	(9)	Mine	
VII	(10)	Utility (telco)	Utility
VIII	(11)	Recreational facilities	Recreational
IX	(12)	Water & wastewater facilities	Water
	(13)	Dams, canals & levees	

One reason may be that the CIRC's asset classes are within the purview of distinct municipal departments, while Cheng's system focuses on the technology to develop different types of infrastructure assets. While CIRC's classification is useful in the discussion of infrastructure asset management in Canada, Cheng's classification is useful for highlighting the differences in technology for horizontal and vertical facilities which is discussed further in Section 4.1.

3.2 Information Modelling for Civil Infrastructure

Building Information Modelling or "BIM" can be an ambiguous term used to describe various digital technologies that link database information to three-dimensional models. The definition developed by the US National Building Information Model Standard Project Committee is *"… a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition."* (National Institute of Building Sciences 2015). More generally, BIM can be thought of as a process to manage and streamline all project data, digitally, through a set of policies, processes and technologies to create a knowledge product that enables collaborative stakeholder engagement throughout the project life-cycle. Information modelling for both buildings and civil infrastructure can provide a single, up-to-date record that captures and retains information about a facility throughout the life-cycle.

3.2.1 BIM vs. CAD

For industry practitioners new to BIM, the difference between 3d CAD models and BIM may seem trivial, however the real difference is realized through adopting the BIM workflow. Where 3d CAD lacks true intelligence, BIM allows for the creation of intelligent objects within intelligent models. For instance, a 3d design of a storm water drainage system would utilize geometric objects such as lines, arcs and solids to display a 3d image in the same way as a 2d image. This system may even have tags or attributes attached to different geometries that might be grouped to represent a real object like a catch basin or manhole.

This type of design makes it easier to extract data for counting catch basins or manhole covers, but the system model comprised of the pipe network and all the catch basins, manholes, valves, etc. would require additional rework if the catch basin was moved, resized or eliminated from the system model. Additionally, for the storm water analysis, the 3d CAD civil designs are typically not compatible with storm water management modelling software and the system would require the storm water management model team to re-create the relevant parts of the model. With BIM, these data reside in the model and the objects which embody the required specifications defined at the outset. BIM can contribute to multiple processes without requiring additional work.

The power of BIM comes from having a more complete model. Adding information models for the road network, electrical and communication utilities, sanitary sewer, water supply pipe network, recreational spaces, and buildings allows for immediate visualization of all related connections. Returning to the storm water drainage example, imagine a failure has been detected in the drainage system that is causing some degree of flooding. Instead of searching for multiple files with the required visual representation for each of the interacting components (road alignments and cross sections, pipe locations, etc.) potentially residing across different departments or offices, a single coordinated BIM model provides information about how to locate and analyze damage, evaluate potential risks, re-route traffic, mobilize repair crews and estimate costs that can be efficiently accessed and shared among critical team members for effective decision making. It was recognized that integrating information modelling (BIM) with asset management is a key strategy to guide effective management of asset information (Parlikad and Jafari 2016).

3.2.2 BIM vs. CIM

The term “civil information modelling” , or CIM, can be used to describe the application of BIM technologies and processes for civil infrastructure systems such as roads, bridges, pipe networks, communications networks, airports, seaports, energy facilities, and other associated structures and facilities. The production of these types of facilities is often referred to as “horizontal” construction to differentiate it from “vertical” construction required in the production of buildings and other edifices. Likewise, “Horizontal BIM”, “Heavy BIM”, and i-BIM are also used to describe BIM for civil infrastructure models (McGraw-Hill Construction 2012). However, there can be some confusion of terms as various institutions and practitioners assign different definitions to the acronym CIM including “civil integrated management” and “construction information modelling”. For clarity, this research uses the term “civil information modelling” (CIM) to denote the application of BIM, as defined above, to non-building civil infrastructure classified in Table 3-1.

Bradley et al. (2016) recognize that compared to IM for buildings, infrastructure classes formed by a mesh network of assets inherently have different project breakdown structures, utilize GIS to a greater extent, require a more mature AM process and create greater value focus on non-graphical data and thus have different: data structures; connectivity and variety; project size, and project team.

Although this research is focused on infrastructure modelling, throughout this discussion the term BIM is often substituted for CIM and can be understood as a reference to model authoring platforms and generic project delivery processes rather than vertical construction models. Additionally, research focused in vertical BIM processes that is cited is often used to draw conclusions for similar CIM practices.

3.2.3 BIM Dimensions, Level of Development and Level of Maturity

BIM/CIM can be used to represent a structure in a vast number of ways including massing models, energy simulations, and fully coordinated construction models depending on the information provided. Different aspects of the model are provided through independent workflows. For instance, Mechanical, Electrical, and Plumbing (MEP) detail will be provided by the mechanical contractor but the MEP model is dependent on the structural and architectural models.

These workflows define BIM as a process that provides different stakeholders with the necessary information at the right time throughout the delivery of the project. They can also be adopted to civil infrastructure processes which can generate and link surface models, create corridor models and pipe networks, produce dynamic profiles and cross sections, perform clash detections and earthwork quantities, and generate reports and cost estimates. When considering BIM workflows, understanding each contributor's ability to digitally exchange graphical and non-graphical information in a Common Data Environment (CDE) requires awareness of three fundamental concepts used to define BIM: BIM dimensions, Level of Development and Level of Maturity are discussed below.

3.2.3.1 BIM Dimensions

BIM dimensions refer to types of information and how they are linked. Dimensions can feasibly (if not practically) occur at different Levels of Maturity (see below). Dimensions define both the 2-dimensional (2d) and 3-dimensional (3d) geometric requirements and higher dimensions can include time-dependent (4d) scheduling and sequencing, cost information (5d) for monitoring and control, and life-cycle management data (6d) for asset management purposes past the construction phase and into the operations and maintenance phase, and possibly the decommissioning and demolition phase with or without recycling.

3.2.3.2 Level of Development and Level of Detail (LOD)

In addition to the dimensions of the model, two other fundamental and related concepts must be considered, Level of Detail and Level of Development which can be confusing as they are both referred to by the acronym LOD. Level of Development is sometimes abbreviated LODt. To compare, Level of Detail is a measure of the quality of information provided for a model element, whereas, Level of Development is more about BIM process and provides a measure of the quantity of the information or the significance of the information represented by a BIM element (McPhee 2013).

Level of Development (quantity of information)

In an effort to standardize the language around the stage of model development, the AIA (American Institute of Architects) Level of Development Specification defines LOD 100, LOD 200, LOD 300, LOD 400 and LOD 500 (BIMForum 2015) described in Table 3-2 below. Level of Development describes the level of completeness to which a model element is developed and provides information about the minimum dimensional, spatial, quantitative, qualitative and other data included in a model element to support the authorized uses associated with a specific LOD. In 2008, this specification formed the contract document *AIAE202-2008 BIM Protocol Exhibit* for facilities management.

Table 3-2 AIA Levels of Development (http://aiad8.prod.acquia-sites.com/sites/default/files/2016-09/AIA-G202-2013-Free-Sample-Preview.pdf)

LOD(t)	Life-cycle Phase	Model Element (ME) content requirement
100	Concept	A ME may be graphically represented in the Model with a symbol or other generic representation.
200	Design	A ME is graphically represented within the Model as a generic system, object, or assembly with approximate size, shape, location, quantities and orientation. Non-graphic information may also be attached to the model element.
300	Documentation	A ME is graphically represented within the Model as a specific system, object, or assembly in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the model element.
400	Construction	A ME is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation. Detailing, fabrication, assembly, and installation information included. Non-graphic information may also be attached to the model element.
500	Facilities Management	A ME is a field verified representation (i.e., as-built) in terms of size, shape, location, quantity, and orientation. Supplier information Non-graphic information may also be attached to the model elements.

Level of Detail (quality of information)

Level of Detail frameworks have been developed by various groups and the AIA has adopted and augmented a level of development framework that defines model element requirements and serves as a reference guide for stakeholders (typically owners) to use to clearly specify the content and reliability of Building Information Models (BIMs) at various stages in the design and construction process. Table 3-3, Figure 3.2, and Figure 3.3 present the differences between Level of Detail and Level of Development using the analogy of an office chair.

Table 3-3 LOD comparisons

LOD		Level of Detail
G0	Schematic	Not meant to be very definitive, Area or volume rates are accurate enough.
G1	Concept	The number of items in the model are assumed to be correct, but cost should be estimated for each.
G2	Defined	Items are identified, and actual cost can be used.
G3	Rendered	Items that have actually been supplied and can be used to assess payments.

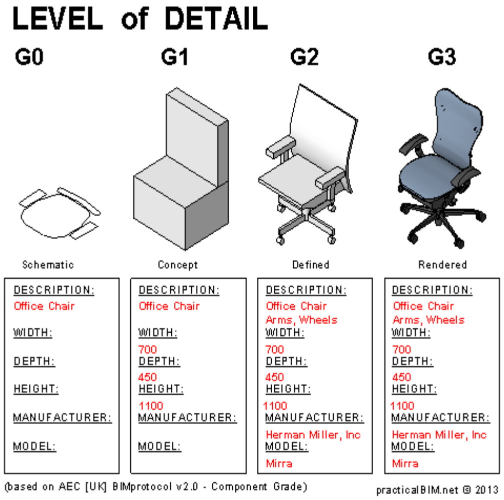

Figure 3.2 Level of Detail

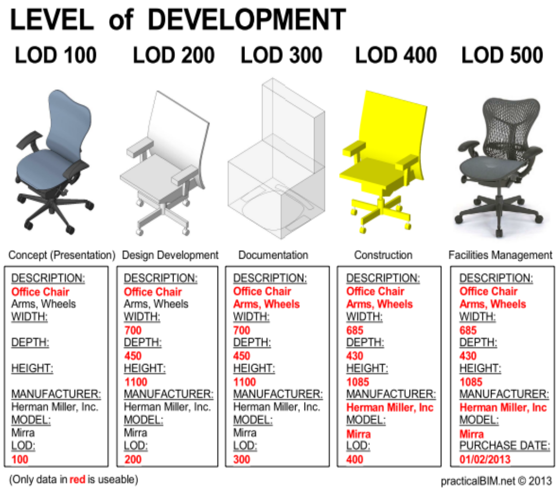

Figure 3.3 Level of Development

(http://practicalbim.blogspot.ca/2013/03/what-is-this-thing-called-lod.html)

3.2.3.3 Level of Maturity

In the UK, the NBS (National Building Specification), an organization owned by the Royal Institute of British Architects (RIBA), has been codifying BIM implementation since 2011 to support the government's strategy for BIM adoption. Separate from LOD, the concept of level of maturity relates to compliance and generally defines the level of shared collaboration within a BIM workflow. Figure 3.4 developed by Mark Bew and Mervyn Richards (National Bureau of Standards (NBS) 2016) shows the UK maturity model (also called the maturity wedge) that illustrates how policy makers have categorized BIM implementation that considers the 'dimensions' of BIM using a top-down approach and Table 3-4 provides the characterization of each level.

Most recently in April 2016, all UK government building projects are required to be BIM Level 2 compliant (Cabinet Office 2011). As such, design data and specifications must be in a format capable of being exported to common data formats such as Industry Foundation Class (IFC) or Construction Operations Building Information Exchange (COBie), a non-proprietary spreadsheet data format.

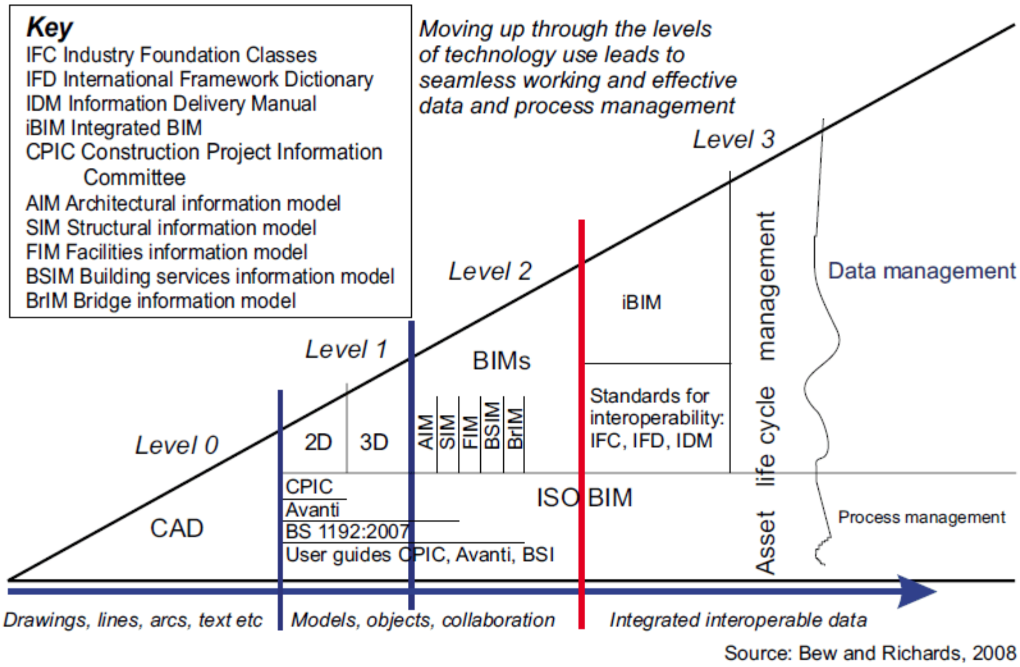

Figure 3.4 BIM Level of Maturity (http://www.bimtaskgroup.org/bim-faqs/)

Table 3-4 BIM Levels of Maturity (https://www.thenbs.com/knowledge/bim-levels-explained)

Level of Maturity	Characterization	Description
Level 0 BIM	No or low collaboration	2d-CAD drafting only is utilised. Output and distribution are via paper or electronic files, or a mixture of both. Mainly for Production Information.
Level 1 BIM	Partial collaboration	Comprises a mixture of 3D CAD for concept work, and 2D for drafting of approval documentation and Production Information. Electronic sharing of data is carried out from a common data environment (CDE), often managed by the contractor.
Level 2 BIM	Full collaboration	Collaborative working. Requires "an information exchange process which is specific to that project and coordinated between various systems and project participants" (Source: Scottish Futures Trust).
Level 3 BIM	Full integration (not fully defined)	International 'Open Data' standards for easy sharing of data across the entire market. Includes a contractual framework for projects which have been procured with BIM to ensure consistency, avoid confusion and encourage, open, collaborative working.

3.3 Geographic Information System (GIS)

A geographic information system (GIS) is a computer system that captures, stores, analyzes and displays spatial and geographic information related to positions on Earth's surface. GIS information is represented as a map which can include many data types. Visualizing data in this way can help identify patterns and relationships as well as enable more complex analyses.

GIS systems have become increasingly affordable, provide ease of use, and are highly customizable for advanced functionality. Geo-referenced location data has enabled centralized asset information and as a result, GIS systems are currently being used extensively as a system of record for infrastructure asset management often in combination with other enterprise management systems. GIS systems typically rely more on 2d visualization where data are not represented by complex 3d objects. This enables these systems to merge multiple, disparate datasets in a way BIM cannot.

However, GIS capabilities are expanding to provide the creation of 3d data models that support both geometric and hierarchical needs; and web-based GIS can easily aggregate information from multiple sources to allow stakeholders to engage more meaningfully throughout a project life-cycle. The demand for final as-built designs delivered digitally and georeferenced to facilitate long-term operations and maintenance of sites is becoming the norm rather than the exception.

3.4 Infrastructure Asset Management

Infrastructure asset management is broadly defined by a set of policies, strategies and activities throughout the life-cycle of a physical asset to maximize its service life and provide sustainable levels of service. The core principle of asset management is about utilizing assets to deliver value by balancing performance benefits, costs, risks and opportunities to achieve business objectives. However, the geographic distribution of civil infrastructure assets presents governments and organizations with several asset management challenges. Financial sustainability and competitiveness have put more pressure on owners and managers to minimize total cost of ownership and streamline their asset management operations (Zhang et al. 2009).

The Institute of Asset Management (IAM) states that the practice of asset management "includes the development of a strategic framework that translates business objectives into decisions, plans, and actions to optimize cost, risk and performance of assets over their life-cycle" ("Building Information Modelling | The IAM" n.d.). The IAM has developed a conceptual model of an Asset Management System (Holdsworth et al. 2015) comprised of six "Subject Groups" as shown in Figure 3.5 that cover 39 AM subjects (listed in Appendix B). According to the IAM, the model is not a roadmap for implementation but rather the goal is to illustrate the following:

- The breadth of activities within the scope of asset management;
- The inter-relationships between activities and the need to integrate them; and
- The critical role for asset management to align with and deliver the goals of an organization's strategic plan.

The IAM recognizes that not all tools and processes are applicable to all organizations and despite the complexity of the IAM's asset management tools, the practice of AM can be condensed to two questions: 1) What do you have? and 2) What are you doing about it?

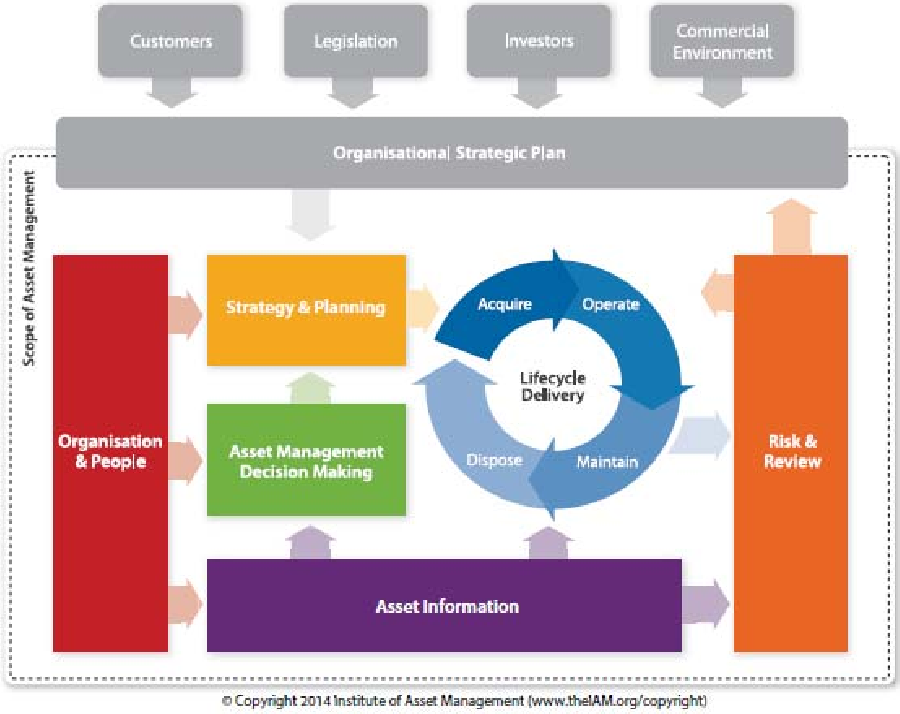

Figure 3.5 The IAM's conceptual AM Model (Holdsworth et al. 2015)

When developing a guide for the practical application of GIS in asset management, the software developer Environmental Systems Research Institute (ESRI), concluded that an AM program could be implemented through a seven-steps as follows (ESRI 2017):

1. Complete an asset inventory.
2. Complete an inventory of programs (related to the asset class).
3. Determine levels of service.
4. Define roles and responsibilities (in the context of the asset class and program).
5. Identify and calculate risk.
6. Extrapolate a forecast.
7. Adjust the budget accordingly

While the IAM model provides the tools to generate high-level organizational strategies and documents, the ESRI model provides a roadmap to develop technical decision-making algorithms. Necessarily, to determine where reinvestment should be applied, various Asset Management Systems (AMS) are now in use throughout municipalities of all population sizes. However, the complexity, sophistication and cost to implement such systems, including the acquisition of the required data determines the effectiveness for a specific AMS. Consequently, only thirty-five percent of small municipalities in Canada reported having formal AM plans in place (*Canadian Infrastructure Report Card: Informing the Future* 2016).

3.4.1 Facilities Management (FM) Versus Asset Management (AM)

In practice, facilities management and asset management are different in scope of application. Where facilities management is concerned with assets that are used to support day-to-day business functions, asset management is concerned with all assets that are used to conduct primary business functions. Guillen et al. (2016) suggest that BIM in the literature (in the context of vertical construction) is more properly linked with FM than AM, however, FM can be understood as a part or tool of AM as defined by the standard ISO 55000 (Guillen et al. 2016). Figure 3.6 illustrates the relationship between operations and maintenance, facilities management and asset management.

Discussion of FM or AM in the context of information modelling often blurs this distinction and while the end use may differ, the process of attaching information to the digital representations of the physical assets remains a singular process.

Additionally, while facilities management is generally recognized to make up over 80% of total costs over a project life-cycle, Nicał and Wodyński (2016) explain that, traditionally, (FM) is recognized as a "non-core" part of the construction sector, with no real business value. Furthermore, they assert that current handover processes are inefficient at collecting and entering project information into FM systems and suggest that, although FM focused BIM implementation is lagging behind construction and design, the opportunities for leveraging this concept for the operational stage are compelling (Nicał and Wodyński 2016).

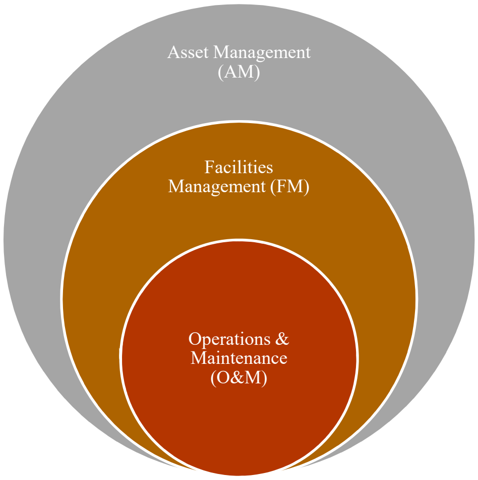

Figure 3.6 Relationship between AM, FM and O&M

4 Literature Review and Previous Research

This chapter covers specific findings from previous investigations of both information modelling for civil infrastructure and asset management as well as their potential and capacity to integrate. The literature review, while far from exhaustive, explores current efforts made to understand fundamental concepts in the three knowledge domains: CIM technology, asset management, and business value in four sections as follows:

- Section 4.1 looks at the state-of-the-art and the state-of-the-practice of information modelling by first comparing vertical and horizontal applications, for civil infrastructure. Data schema and standards are introduced and use cases are explored.
- Section 4.2 examines GIS technology and how these systems provide a foundational technology for asset management. Again, data schema and standards are explored to identify differences and commonalities across technologies.
- Section 4.3 investigates Infrastructure asset management standards, systems, policies and plans to identify how data is used to support both manual and automated processes from three perspectives: data requirements, data management, and data governance.
- Section 4.4 discusses how the previous systems can be integrated, efforts made so far, and the challenges presented both technologically and culturally.

4.1 Information Modelling for Civil Infrastructure (CIM)

Two key papers summarize the current state of CIM technology. The first discusses the comparisons between BIM and CIM while the second provides an analytical review and evaluation of CIM implementation across various types of infrastructure. It should be noted that a common thread observed in much of the recent literature pertaining to the science of BIM-GIS integration is work contributed by Jack C.P. Cheng, an associate professor with the department of Civil and Environmental Engineering at the Hong Kong University of Science and Technology.

4.1.1 Capability and Capacity

BIM vs. CIM

Over the last decade, advances in computer processing have enabled BIM capabilities to deliver more efficient and effective design and construction processes for buildings that are now beginning to be seen in infrastructure projects. While the benefits BIM technology applied to civil infrastructure is easily recognized by technology proponents, Ng suggests that early adoption was slower due to the perceived requirements by civil engineers. Ng reflected, that often schematic and symbolic representations of real objects was adequate to communicate project information between engineers and contractors and that functional requirements, such as those for gravity pipe drains for example, are not dependent on physical dimensions, which he argued was the main benefit to 3d modelling (Ng 2012).

Although the underlying computer technology is similar for BIM and CIM, there is evidence that some BIM processes cannot be applied directly to civil projects as CIM. Research by Cheng et al. (2016) identifies three significant differences between BIM and CIM as follows.

First, the physical structure and components differ between building and infrastructure facilities. For comparison, a building contains doors and windows whereas a bridge contains piers and shear pockets, neither of which exist in roads or pipe networks. The implication here is that BIM tools are not readily adaptable to be implemented in an infrastructure project. Furthermore, for intelligent objects to interact with each other, the relationships between the model elements require complex definitions. Additionally, they point out that buildings are geographically constrained by their foundations and the overall dimensional geometry of a building has a limited impact on its construction, whereas construction of large infrastructure facilities can require extensive earthworks over large areas and continuously changing terrain. This suggests that for BIM (not CIM) workflows for collaborators can be procedural and provide reusability from building to building; whereas, in contrast, a CIM solution for a road network may be different than for a bridge project which may require larger investments in organizational assets and cultural changes.

Second, data schema (discussed below), such as Industry Foundation Classes (IFC's) utilize different terminology to represent structures and components. For instance, in buildings "vertical structural supports are called *columns* while those in bridges are called *piers*." (Cheng et al. 2016)

Third, BIM and CIM modelling is technically different. In BIM, floor plans are defined at points on a vertical axis, whereas CIM utilizes profiles and alignments along a horizontal axis or reference line (Cheng et al. 2016).

4.1.2 Data Standards and Schema

4.1.2.1 Data Standards

The collaborative nature of BIM/CIM necessitates information sharing. Authoring tools will differ depending on the application and role of each contributor or stakeholder and it is essential that, when sharing models, information is preserved across platforms. Standards allow each stakeholder to understand, not only, what information needs to be made available at each stage of development, but also who owns the data and how data access permissions are assigned. Standards also provide guidance on unifying data types for interoperability and providing common data environments. Standards often specify model development in terms of LOD, however, many standards exist. Shou et al. (2015) examined forty-two standards or guidelines developed across various academic, government, and non-profit institutions for implementing BIM in different countries and Bradley et al. (2016) categorized BIM standards by geographic region illustrated below in Table 4-1.

Table 4-1 BIM standards by geographic region (Bradley et al. 2016)

Region	Standard	Comments
International	ISO 19650 (information management) ISO 16739 and 29481 (IFC4)	Open data format Often requires the Information Delivery Manual and Model View Definitions (IMD-MVD) for implementation
UK	1192 series, CIC BIM Protocol, Uniclass classification system	PAS 1192-3:2014 provides a standard for data to generate an Asset Information Model (AIM) for the operation life-cycle phase.
US	NBIMS v3	References IFC, Omniclass, and BuildingSmart Data Dictionary.
EU	COBIM (Finland), Statsbygg (Norway), Rgd Bim Standard (Netherlands)	Focused on vertical construction
Asia and Australia	NATSPEC (Australia), Singapore's BIM Guide	Mostly procedural

4.1.2.2 Data Schema

Industry Foundation Classes (IFC)

The IFC file format is a global standard registered as ISO 16739:2013 and maintained by the organization buildingSMART. IFC defines an object-based format with an open-source data model used to describe, share and exchange construction and facilities management information. It is essentially a container of data. However, in practice, the use of IFC has not provided seamless integration or interoperability since it requires software developers to properly implement and support the standard. For instance, BIM models created in one application may not display identically in a similar application developed by a competitor; and information not supported or mapped to IFC can be lost and errors generated during a data conversion. Often, only basic information such as geometry and material data are retained, and unknown object types can lose semantic meaning. To facilitate data exchange, larger software developers are creating product life-cycle ecosystems that rely on proprietary formats such as Autodesk's .IMX to share information across design platforms. Furthermore, IFC is only beginning to define infrastructure specific objects through extensions such as IFC-Bridge or IFC-Roads and more development is required.

With respect to GIS integration, (Stoter 2018) argues that with over a thousand IFC classes available, there are many ways to model a specific situation, which makes it impossible to develop a uniform translation that works for any IFC model. Additionally, it may not be feasible to translate thousands of constructional elements (modelled as physical masses or volumes) that constitute a BIM model into a single, closed building object, defined with surfaces as required for geospatial analysis (Stoter 2018). At this time, IFC cannot fully support client-based dataflow programming in BIM authoring tools such as Grasshopper for Rhino3D or Dynamo for Revit.

Model View Definition (MVD)

Model View Definitions are a specification which identifies the properties and specifies the exchange requirements of Model Views. A 'standard' Model View Definition (MVD) is a subset of the Industry Foundation Classes (IFC) schema intended for software developers to implement into customized APIs. The official Model View Definitions are published by buildingSMART using the mvdXML format. buildingSMART has developed the software tool ifcDoc for defining and documenting MVDs (“Model View Definition Summary — Welcome to buildingSMART-Tech.org” n.d.).

4.1.3 Implementation and Workflow

A major challenge of implementing CIM is in the change of processes from traditional drafting to modelling and data input. The delivery of data models using independent file formats such as IFC is still inadequate for civil infrastructure and organizational culture change is needed to implement CIM workflows. Hence, information modelling workflows are more about organizational and business culture environments than technological processes.

Workflows are meant to prevent information being siloed across a project while maintaining data integrity. Organizations that successfully implement BIM workflows understand the need to pre-determine and standardize information flow. The PAS1192 is one standard that provides guidance on how to coordinate and manage data for multiple stakeholders across shared databases. Love et al. (2013a) suggested that recently, civil infrastructure workflows experienced two major revolutions in design: 1) models are created first rather than created from design documentation; and 2) models need to have high levels of detail in the context of real existing conditions (Love et al. 2013a).

Table 4-2 and Figure 4.1 below outline a basic CIM workflow for the design and construct phases of a project. However, what is not captured in Table 4-2 and Figure 4.1 is how the information flows between stakeholders which can vary depending on the procurement and delivery method for a project. It is important to note also, that stakeholder interaction is potentially more influential during the substantially longer operations phase of an infrastructure facility.

Table 4-2 Basic CIM design/construct process workflow

Process	Data Type	Software	Benefits	Process Flow
Capture existing conditions	GIS data surveys, LiDAR	Autodesk Map3D Infraworks360	Provides a large number of reference points in 3d rather than 2d boundary conditions	↓
	Point cloud, photo, LiDAR	ReCap		
	Photo	Raster Design		
Planning & Preliminary Design	Vector-based objects Model (.IMX)	Infraworks360	Establishes a shared data source. Web-based collaboration, fast iteration, simulation, large-scale integration	↕
Detailed Design & Documentation	Vector-based objects (.DWG)	Civil 3D Navisworks	Simulation, project management	

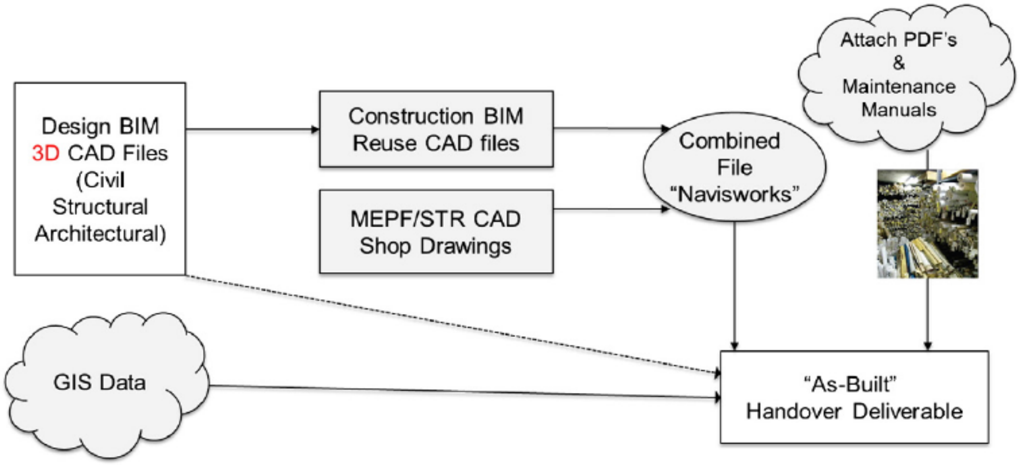

Figure 4.1 A simplified BIM workflow for an asset owner (Love et al. 2013a)

4.1.4 Maturity and Application

By classifying civil infrastructure into the nine categories presented in Table 3-1, Cheng et al. (2016) evaluated CIM maturity, practices and adoption using 171 industry case studies and 6 academic papers from two perspectives, industry effort and academic effort. Each perspective considered six aspects: 1) number of industry cases or academic papers; 2) use cases; 3) Level of Detail (industry cases); 4) data schema and representation development academic papers); 5) data delivery and management; and 6) software tools. Using this framework (Figure 4.2) the following conclusions were made:

1) Industry cases studies are primarily published by the dominant software developers; Autodesk are predominantly building and Bentley and are predominantly energy infrastructure projects. Academic studies explore possible uses as well as developing data schema for specific types of civil infrastructure with the majority of papers focusing on bridges.
2) Most industry cases for infrastructure developed LOD 300 or 400 models, however, server-based data delivery is lacking, indicating that model development and sharing is not truly collaborative.
3) Data schema for civil infrastructure other than bridges, roads and tunnels is minimal. Further development, especially for airports and seaports, is required and should be integrated with building data schemas to increase interoperability.
4) Some research is being done to integrate CIM models with data management systems for facilities and asset management.

Cheng et al. (2016) also identified CIM use cases and classified them using the “five levels of model” described by the Virtual Design and Construction (VDC) innovation maturity

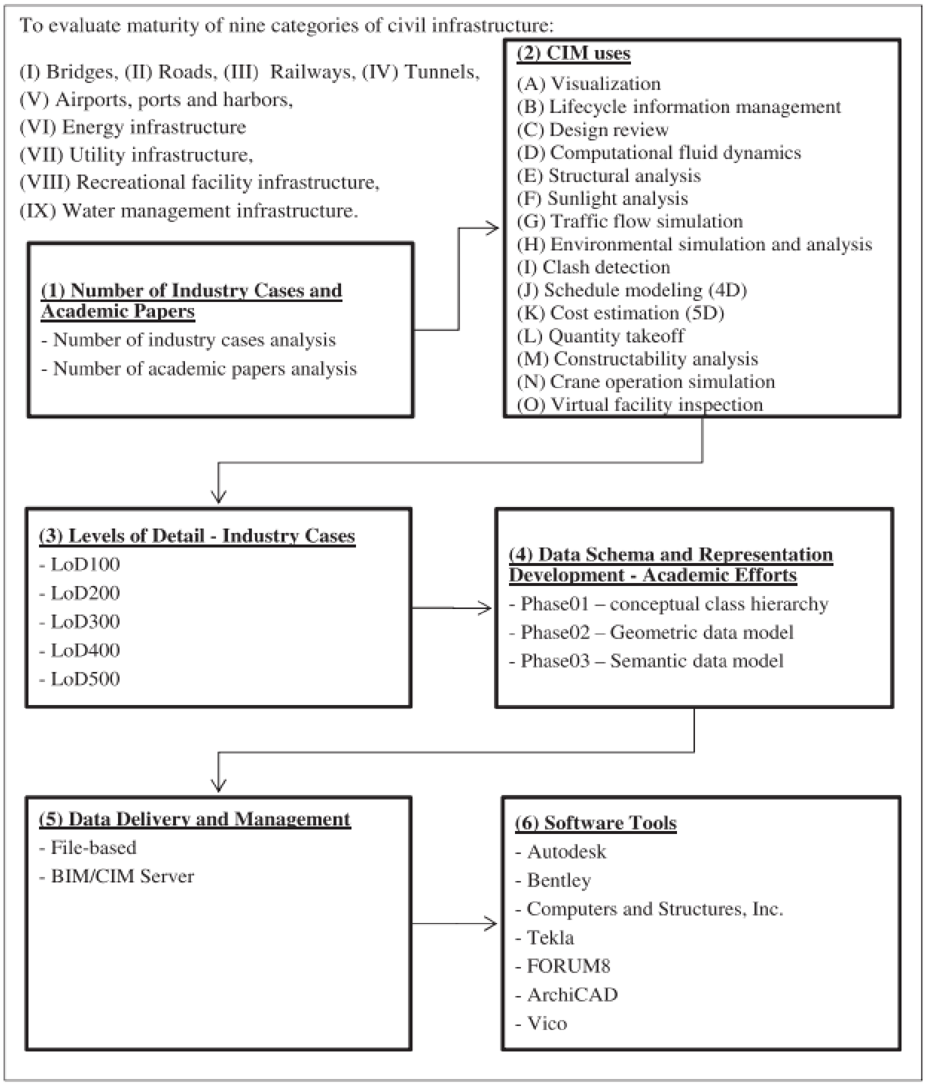

Figure 4.2 CIM evaluation framework (Cheng et al. 2016)

scorecard developed by the Center for Integrated Facility Engineering (CIFE) at Stanford University and outlined in Table 4-3 below. The research concluded that most of the CIM use cases identified in their research were at Level 1 and 2, some CIM firms were implementing Level 3 and 4, and Level 5 uses were rare (Cheng et al. 2016).

Conversely, other research comparing information modelling between buildings and infrastructure suggests CIM adoption has benefited from lessons learned in the vertical

Table 4-3 VDC Innovation Maturity Scorecard Use Cases

Level	CIM Use	Description
1	Visualization	Models are created for visualization purposes, such as visualization and design review.
2	Documentation	Models are used for documentation with accuracy, like quantity takeoff, etc.
3	Model-based analysis	Models are created for a single-disciplinary analysis, such as sunlight analysis, traffic flow analysis, cost estimation, etc.
4	Integrated analysis	Cross-disciplinary collaboration is needed for analysis based on the models created, like clash detection (among different disciplines), etc.
5	Automation and Optimization	Routine analyses or fabrication are automated.

construction industry and that the level of maturity of CIM is greater for later stages of project life-cycles. For instance, the ability to integrate model-driven data into e-procurement systems for enhanced project management towards total integrated project delivery (IPD) (Shou et al. 2015).

Working from the Eastman definition of BIM as a process, Shou et al. (2015) reviewed BIM implementation in both the building and infrastructure industries. The research looked at case studies of implementation in practice from an academic perspective (40 journal articles) and an industry perspective (24 industry reports) and concluded that BIM implementation was adopted to leverage three characteristics: enhanced life-cycle information management; improved productivity by reducing manual rework and error through task automation; and improved project performance by integrating emerging technologies such as mobile and cloud computing. The CIM use cases analyzed were categorized by life-cycle phase using Thomas Liebich's (2013) thematic classification as shown in Table 4-4.

Table 4-4 A comparison of life-cycle uses for BIM and CIM (Liebich 2013)

Life-cycle Phase	CIM Use Case (Thematic)	
Plan	Land use and transportation planning	
Design	Public information and communication	Constructability reviews
	Traffic impact simulations	3D coordination
	Engineering analysis	Rule-based model validation
	Target quality tracking	
Procure	Product master data	Product vendor management
	Enterprise buying	Business to business transactions
	Product inventory management	Material tagging and tracking
	Automated procurement	
Construct	Virtual project scheduling	Work zone safety planning
	Virtual work planning	Virtual cost reporting
	Visual progress reporting	Equipment machine control
	Field survey	Mobile progress claiming
	Site logistics (JIT)	Maintenance of traffic
	Geospatial issue tracking	Field design changes
	Equipment management	Material testing and analysis
	Equipment telematics	Quality issue tracking and reporting
	Product inspection and testing	
Operate	Road management	Water mitigation and planning
	Toll and facility management	Traffic volume simulations
	Bridge maintenance	Event planning
	Emergency response and repair	Maintenance and repair information
	Transportation management systems	Disaster planning
	GIS asset tracking	

Bradley et al. (2016) suggest that BIM technology that is easily transferable from the vertical construction domain has already taken place and that CIM research has been focused on general implementation and integration with GIS. A key insight from this work is in recognizing that “the driving forces for BIM adoption in Infrastructure coming from the operational phase working backwards, due to the advanced asset management capabilities of infrastructure clients, compared with buildings where the BIM driving force started from the design practitioners and has been driven forwards through the phases.” (Bradley et al. 2016)

However, they also commit to the notion that BIM technologies are pushing into domains not originally designed for and examine the use of CIM from a UK constructor perspective. This perception resonates on a personal level and relates to a recent experience at a conference on 3d technologies. At the conference, many presenters were suggesting methods for extending uses for digital products developed with off-the-self applications. Later in an informal conversation, one of the original Revit software architects sharply scoffed at the idea of FM being shoe-horned into BIM authoring platforms. Nonetheless, as the research shows, there is a keen interest across disciplines to achieve just that.

4.1.5 Strengths and Limitations

BIM and CIM can provide a data-rich digital representation of both physical and functional components of a facility that capture detailed construction and project information. Far reaching, potential use cases identified in research promise major improvements in performance and efficiency across the project life-cycle (Liebich 2013). While CIM can be used for design coordination, constructability reviews, construction scheduling, quantity take off, GPS and model-based machine control for trench excavation and site grading, CIM also has a fewer comprehensive tools set compared to BIM and current CIM technology is subject to severe technological limitations. For instance, models can lack tools for spatial planning where topographic information cannot be sufficiently represented. At times, different disciplines create models by using industry specific platforms throughout the design phase only to discover problems in interoperability during handover at the operations phase. Bradley et al. (2016) identified four research gaps in CIM technology:

1. Information integration: this relates to the inability of common data formats, such as IFC, to fully support CIM. A "universally agreed conceptual vocabulary or data structure" is an important area of research that can include technologies such as RDF, ontologies, and sematic web to reduce the need for complex relational data structures. This is discussed further in section.
2. Data integration engines – for holistic information management: this relates to the ability to share data in specific formats for different applications while addressing issues with scalability, data ownership and security, data responsibility, and data conversion.
3. Alignment of business processes with CIM processes – this relates to the relationship between the IM processes and business processes of AECOO stakeholders at the organization level rather than at the project level.
4. Information governance frameworks – this relates to issues surrounding who produces data (responsibility), what processes generate data (generator), and who consumes data (consumer).

While the technological challenges remain complex, cultural challenges around data governance and data management will require multiple policy actors to develop standardized protocols and best practices.

4.2 Geospatial Information Systems (GIS)

4.2.1 Capability and Capacity

GIS data can be vector (math instructions) or raster (pixels) data. Vector type shapefiles are a common data format and are composed of at least four data types: .SHP (contains geometric data), .DBF (contains attribute data), .SHX (contains the spatial index) and, .PRJ (contains projection information). The collection of these files forms a database managed by the GIS, a type of database management system (DBMS). There are three types of DBMS's relevant to GIS: hierarchical, network and relational. A relational database is a set of formally described tables from which data can be accessed or reassembled in many ways without having to reorganize the database tables. The standard user and application programming interface (API) of a relational database is the Structured Query Language (SQL). SQL statements are used both for interactive queries for information from a relational database and for gathering data for reports. Relational databases are the most common for complex GIS operations and makes GIS a foundational technology for asset management.

4.2.2 Data Standards and Schema

According to gistandards.eu there are over 100 existing geospatial standards including data formats, metadata and services. Some of the governing bodies include:

- FGDC – Federal Geographic Data Committee and
- OGC – Open Geospatial Consortium.
- ANSI – American National Standards Institute,
- ISO – International Organization for Standardization,
- IEC – International Electrotechnical Commission,
- ASTM – American Society for Testing and Materials,

- IHO – International Hydrographic Organization,
- ASPRS – American Society for Photogrammetry and Remote Sensing.

The Open Geospatial Consortium (OGC) was founded in 1994 to solve issues of spatial data sharing and interoperability. Some key OGC standards include:

- Simple Feature - defines what a geographic feature is (at a minimum a point, line or polygon) and sets out a common format for text and binary representations of geographic features.
- KML (Keyhole Markup Language) - expresses geographic data, labels, and symbology in 2D and 3D for web map and globes.
- Geographic Markup Language (GML) - an extension of XML schema (or grammar) for the expression of geographical features. It is used as an interoperability format for features that are too complex to express using the Simple Feature standard.
- UML - an open and standardized way of representing programming and modelling entities, their properties and their relationships, and formulating their parameters and actions.
- CityGML- an open standardized and semantic data model and exchange format to store digital 3D models of cities and landscapes. It defines ways to describe most of the common 3D features and objects found in cities (such as buildings, roads, rivers, bridges, vegetation and city furniture) and the relationships between them. It also defines different standard levels of detail (LODs) for the 3D objects, which allows us to represent objects for different applications and purposes.

There is substantial research involving the use of CityGML to map BIM data for use in GIS applications. Liu et al. (2017) suggests that currently "CityGML is the most comprehensive standard exchange of urban information in geospatial domain" and is "one of the most prominent semantic 3D modelling formats and represents a significant step towards the integration of BIM and GIS" (Liu et al. 2017). While this may prove valuable to advancing true integration, much work is needed to align BIM data schema to CityGML formats.

4.2.3 Strengths and Limitations

The ability of GIS platforms to combine and manage multiple layers of spatial data make its use for asset management particularly compelling. GIS can facilitate data collection, processing, and visualization as well as integrate asset mapping with project management and budgeting tools so maintenance, inspections, and expenses can be accounted for in the same place (Zhang et al. 2009). Increasingly, the service-based architecture of GIS platforms allows better integration with third-party Enterprise Asset Management (EAM) and Enterprise Resource Planning (ERP) platforms and support for big data systems such as Hadoop and demonstrates the flexibility and adaptability of GIS as an AM platform. These integrated systems are currently being used by many transportation departments due to ease of use and customization. Readily accessible API's and user support such as the ESRI User Conferences promote wide-scale adoption by governments and large organizations.

When combined with project BIM data, GIS can provide advanced visualization to validate design choices. However, while GIS systems can perform spatial analysis based on the functional and physical relationships of objects at a large spatial scale, it is not natively suited to retaining detailed and comprehensive building information. For example, road authorities are generally interested in both the road planning and geographic context as well as the standardized "as designed" road information, which is not available in a traditional geospatial database, but can be stored in a BIM system (Liu et al. 2017).

4.3 Infrastructure Asset Management (AM)

Pell et al. (2015) argue that infrastructure sectors such as rail, road, and water, that have assets of differing origins, ages and operating conditions, are often less sophisticated in their approach to asset management when compared with the sectors such aviation or manufacturing.

While most organizations have some type of information system for capital planning and work order management, often these systems and processes remain siloed and real-time condition data may not be available. This can create major barriers to improvements in performance and efficiency. Furthermore, risk-aversion can be a common weakness in many infrastructure organizations that contributes to an inability to implement AM in a sufficiently holistic way.

Often, organizations adopt parts of a comprehensive AM program, such as predictive maintenance processes, but fail to put them together in a way that would provide significant benefit. Integrated systems that can handle semantically linked data promise to provide tools necessary for better asset management.

4.3.1 Asset Management Plans and Practices

A 2008-2009 report by the City of Hamilton and the firm R.V. Anderson on the State of Infrastructure (SOTI) led to national recognition of the city as a leader in asset management practice. The current (2016) Public Works Asset Management Plan (CH2MHill and Stantec 2014) details activities, procedures and policies as a part of its AM strategy. An analysis of AM activities shows limited integration between fragmented systems such as the legacy asset inventory system (HANSEN), the bridge management system (BMS), condition assessments, and the Integrated Right of Way Infrastructure Support System (IRISS).

This could indicate that if an industry leader in AM is lagging behind researchers, then the AM industry may not be providing sufficient demand for advanced technology adoption. Reasons for this could include: 1) AM practitioners don't perceive a significant increase in the value proposition by adopting systems with tighter integration (i.e. no increase in the quality of the fundamental data); 2) AM practitioners lack the resources (financial and human) to deploy more advanced solutions (i.e. higher quality data is unaffordable); or 3) existing technology is perceived to be insufficient to justify an incremental increase in capability (i.e. better technology might be available in the near future).

4.3.2 Components of an Asset Management System

The rapid growth and availability of voluminous amounts of data from such asset management systems can result in clouds of both structured and unstructured "big data" and present analytical challenges for various stakeholders. An essential component of any asset management system is an asset inventory database or registry that contains multiple data types such as asset class, location, physical attributes, construction data, cost data, risk assessments, and environmental assessments.

Current AM software systems such as those developed by Infor and SAP SE can be classified as Enterprise Asset Management systems and Enterprise Resource Planning systems. They are functionally different and are described below. The term 'Enterprise' often refers to the scope for which the software is deployed and relates to the organization level as opposed to the department, project, or user level.

Enterprise Asset Management (EAM) is both a concept and a class of software that encompasses all policies, processes, operating models, management, economics, documentation, and sustainable aspects that relate to physical assets such as infrastructure networks, buildings, equipment and real estate to manage the entire life-cycle (including design, construction, commissioning, operations, maintenance, replacement, and decommissioning) across all locations, throughout the organization or jurisdiction. An EAM system is made up of three core components, which can be described as:

1. A system of record – as a repository of authoritative data
2. A system of engagement – for sharing and interacting with the data
3. A system of insight – to facilitate actionable decisions

The primary goal of EAM's are to algorithmically optimize the full life-cycle of these assets by standardizing, integrating, and continuously updating asset related processes. This enables organizations to make better decisions to prolong the life-cycle of their assets, to use resources effectively and reduce overall costs. The following modules may be stand-alone applications or features of an EAM system:

- Integrated Workplace Management Systems (IWMS)
    - General functions include real estate and lease management, facilities and space management, maintenance management, capital project management, environmental sustainability. Supports integration with CAD, BIM.
- Computer Aided Facility Management System (CAFM)
    - General functions include space management and planning, move management, work order requests, and other modules for assets and maintenance.
- Computerized Maintenance Management System (CMMS)

    - General functions include equipment maintenance, tracking the cost of work, asset location tracking, monitoring labor resources, preventative maintenance, inventory management.
- Geographic Information System (GIS)
    - General functions include management of spatial location and associated descriptive attributes of assets.

Enterprise Resource Planning (ERP) is business management software that allows an organization to use a system of integrated processes to manage its core business activities such as financial analysis, logistics, and procurement. ERP is designed to combine all the company's activities into a single database, eliminating incompatible and duplicate technologies. An ERP may include an EAM but often they are separate systems that require integration. At first, utilizing an ERP system to support EAM processes looks interesting; since there is only one software system and all data is in one place. However, integrating these ERP systems can be difficult and costly to implement and operate.

4.3.3 Asset Management Standards

In 1990, the New Zealand Asset Management Support (NAMS) group published the International Infrastructure Management Manual (IIMM) introducing Best Management Practices (BMPs) for asset management. The next major publication came in 2003 from the British Institute of Standards as the Publicly Available Specification 55 (PAS-55). Again, in 2014, under the direction of the International Standards Organization (ISO) Technical Committee 251, the BSI-PAS5 55:2008 was reorganized into:

- ISO-55000:2014 (Asset management – Overview, principles and terminology),
- ISO-55001:2014 (Asset management – Management Systems – Requirements),
- ISO-55002:2014 (Guidelines for the application of ISO 55001).

These “represent a global consensus on what asset management is and what it can do to increase value generated by all organisations” (“What is ISO 55000? | The IAM” n.d.). According to ISO, these standards provide guidance on how to deliver the greatest value for a range of stakeholders over the longer life-cycles of typical infrastructure assets. ISO 55000 remains the standard today.

4.4 Integration Potential – Putting it all together

Whether as part of an EAM or as a stand-alone solution, GIS systems provide city, region and larger-scale spatial information and analysis tools necessary for planning and operating civil infrastructure, while BIM provides information at the site, structure and object level for the design and construction of those projects. The addition of geospatial data within the BIM model can provide designers with insights, at a level of accuracy, that can influence a structure’s location, orientation, and possibly construction materials to deliver superior performance in terms of project delivery in the short-term and operation management in the long-run.

These intelligent models, when combined with sensor data would provide real-time information across projects for better management, eliminate data redundancy, contribute to sustainability efforts and provide the “infrastructure” for smart cities. In terms of facilities management, the use cases for integrated systems can include urban energy assessment and management, emergency response, climate adaption, and environmental and ecological impacts (Song et al. 2017).

Early work by Halfawy and Pyzoha (2002) identified the potential of infrastructure information models and their need to be integrated into GIS systems. Their proposed framework envisioned GIS systems as an interface for both graphical and non-graphical information to be accessed across life-cycle domains (Halfawy and Pyzoha 2002). Although, their work was able to combine data from separate processes in a limited way, they were unable to conceive of a common interface for integrated n-dimensional analysis and object-based 3-dimensional design models did not yet exist.

Until recently, research in integrating BIM and GIS remained focused on data conversion and translation of individual BIM elements to GIS features through intermediary processes or converting entire BIM project files into complex features on a GIS map. This lack of data interoperability has traditionally meant that GIS and BIM systems were left as separate workflows. Technologically, it's complicated and true integration has yet to emerge, however, integration remains a large area of research and two important concepts from computer science, ontology and semantic web, are providing the framework for manipulating and combining data from these two systems.

4.4.1 Integration Technology

4.4.1.1 Ontologies

An ontology is a combination of a dictionary and taxonomy (classification scheme) within a specific domain to establish both a meaning for the terms and a classification system. Ontologies provide a way of defining and classifying objects in relation to each other and are often developed to identify domain specific vocabulary, structure domain knowledge, and exchange information. By executing an ontology within a product model, a conceptual schema or framework of data can be properly structured and stored (Wetzel and Thabet 2015). The foundational work in knowledge sharing and AI by Stanford professor Thomas Gruber provides a definition for ontology as a *"formal or explicit specification of a* *conceptualization."* (Gruber 1993) In discussing ontologies as a function of the semantic web, Tim Berners-Lee wrote that “A program that wants to compare or combine information across the two databases has to know that these two terms are being used to mean the same thing. Ideally, the program must have a way to discover such common meanings for whatever databases it encounters.” (Berners-Lee et al. 2001)

In terms of BIM, ontologies are being explored to produce standard data structures for different processes. For example, an Australian-based, non-profit BIM research initiative headed by Dr. Bilal Succar has developed a conceptual BIM ontology related to BIM implementation and performance analysis yet to be formalized as a Web Ontology Language (OWL).

While, Abanda, Kamsu-Foguem and Tah methodically detail their development of an ontology for quantity take-offs used in construction cost estimating after identifying challenges in current 5d modelling (Abanda et al. 2017); Mignard and Nicolle created an ontology based on a new type of information model (Urban Information Model) that allowed information exchange with the ACTIVe3D AM platform (Mignard and Nicolle 2014).

Kreider’s PhD dissertation defined a BIM Use as “a method of applying Building Information Modelling during a facility’s life-cycle to achieve one or more specific objectives” and developed an ontology that “primarily classifies the BIM Uses based on the purpose of implementing BIM on a facility or within an organization; and secondarily classifies BIM Uses based on characteristics of the BIM Use (Kreider 2013).

More recently, Niknam and Karshenas (2017) explored the IFC-based ontology ifcOWL and conclude that a single large ontology may not be practical. In their work, they develop a shared BIM ontology that included all elements in the UNIFORMAT II classification system to represent semantic BIM data (Niknam and Karshenas 2017). The shared ontology approach enabled semantic querying for domain-specific elements across different knowledge bases used in their case study.

These examples illustrate the depth of data interaction for specific use cases and highlight the need to unify isolated ontologies under a single BIM domain. This is thought to be achievable with semantic web technologies that can link specialized, local ontologies.

4.4.1.2 Semantic Web Technology

Semantic models can correlate things in the physical world. For example, infrastructure assets such as a pipe or road network can be linked to financial systems and other business operations data to extract insights into otherwise unknown relationships. Semantic Web (SW) technologies can be thought of as a "stack" of technologies (Figure 4.3) and standards that was conceptualized by Tim Berners-Lee (2001) aimed at achieving the vision of converting the current World Wide Web from a "web of documents" into a "web of data". The web of data enables people and machines to link and process data either manually or automatically. These technologies include data models such as the Ontology Web Language (OWL) and the Resource Description Framework (RDF) ("The Semantic Web made easy" n.d.).

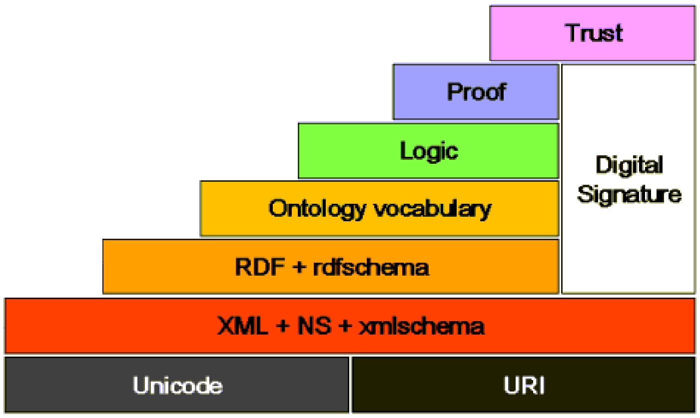

Figure 4.3 Sematic Web Stack (Hor 2016)

According to Hor (2016), semantic models are preferred over a syntactic approach for different AEC applications to produce heuristic data structures that can perform complex querying and analysis (Hor 2016).

However, while the concept of the semantic web has been around since the turn of the millennium, these technologies are still maturing and finding applications. Janev and Vraneš (2011) conclude that "SW technologies are finding their ways to applications, and that rather than being another research project, the Semantic web is becoming our reality." (Janev and Vraneš 2011)

Development of ontologies and semantic web technologies is required to move IM data into a GIS environment for greater contextual visualization. Bradley et al. conclude that "graph-based technologies and distributed data environments are the way forward in meshing together and leveraging the vast amount of data produced by modern day AECOO projects." (Bradley et al. 2016) Development is this area would support the conclusion that full BIM-GIS integration will come from better mapping into the CityGML data type (de Laat and van Berlo 2011).

4.4.2 Current Efforts

4.4.2.1 BIM and GIS

Work on integrating BIM with GIS has been developing quickly in recent years as GIS systems increasingly utilize 3d modelling. In late 2017, Autodesk and ESRI - two leading software vendors, entered into a partnership to bridge these technologies with the goal of improving project design capabilities through connected workflows that allows projects to be designed accurately within the context of the site as well as the surrounding environment. This "digital twinning" of physical structures can bake-in process efficiencies and lower project risks across disciplines. Using cloud-computing technologies, all stakeholders would have the ability to interact or repurpose data from a single source without fidelity loss through conversion processes. However, outside of proprietary solutions, that may not address all use cases and there are significant gaps in the technology.

In their 2016 state-of-the-art review paper, Liu et al. (2017) point out that while IFC and CityGML are both object-based, they use different modelling languages and LOD is defined differently for each standard. This is mostly due to the fact that GIS is concerned with geo-referencing real-world objects that exist prior to model generation and BIM is focused on design processes for facilities yet to be constructed. They reiterate the dissimilarities and mismatches as being different in users, application focuses, developmental stages, spatial scales, coordinate system, semantic and geometric representations, levels of granularity, and information storage and access methods. They concede however, that there is increasing overlap and conclude that work in integration can be seen at three levels: The Data level, the Process level and the Application level. In their study each level was evaluated using Effectiveness, Extensibility, Effort, and Flexibility criteria.

The Data level focuses on the conversion, translation and extension of standards and data model formats such as IFC and CityGML. The Process level looks at the use of semantic web technologies and service-based methods such as Web Feature Server (WFS) without changing data structures. At the Process level, a reference ontology would be developed to extend other high-level ontologies. The Application level can exchange data through customized plug-ins that extracts and exports data usually for a specific use case.

Asset management as a use case, is specifically discussed and four case studies, presented by others, that mostly use Application level integration are reviewed. Liu et al. (2017) conclude that data loss and mismatched information can be mitigated through open and collaborative development of new standards.

Song et. al, (2017) look at the evolution of BIM-GIS integration and suggest that current stand-alone BIM processes, that can collect large amounts of data, cannot fully support or satisfy user requirements for improved quality and productivity, decreased project costs, real-time tracking across the construction space, ensuring safety, decreasing environmental risks, and effective information update, interaction and management (all value-add processes) since “the requirements during the construction phase cannot be accurately and dynamically described, modeled and managed”. In their review, they hypothesize three trends will form in future BIM-GIS integration: Loose integration - using application technologies, tight integration - based on BIM and GIS as sciences, and BIM as a data source for GIS applications (Song et al. 2017).

Al-Saggaf and Jrade (2015) propose a BIM-GIS integration model that facilitates construction and demolition waste management and control for megaprojects. While they concluded their model was successful in demonstrating a solution for the estimation of C&D waste for a building project, their model lacked semantic ability and relied on well-defined IFC elements manually linked to a GIS database (Al-saggaf and Jrade 2015).

Karan et al. (2016) suggest that the syntactic approach of current common data formats such as IFC are insufficient to completely share the semantic data unique in each GIS or BIM system and instead use semantic web technology to ensure interoperability. Their work included a new ontology to demonstrate seamless integration which led to the conclusion that “further work needs to be done to develop globally-agreed ontologies for the construction domain.” (Karan et al. 2016)

Jusuf et al. (2017) summarize efforts to integrate GIS and BIM data through three approaches: application domain extensions (ADE’s), unidirectional transformations of IFC’s to CityGML, or the creation of new formats such as the Unified Building Model (UBM) proposed by El-Mekawy and Östman (Kardinal Jusuf et al. 2017). Their own work uses a spatial Extract-Transform-Load (ETL) workflow, using Safe Software Inc.’s Feature Manipulation Engine (FME), to generate a transformation schema in different LOD’s similar to Deng, Cheng and Anumba’s (2016) work that developed and validated bidirectional mapping between IFC and CityGML (Deng et al. 2016).

Irizarry et al. (2013) concluded that information models comprising the entire scope of the construction supply chain are limited and developed a framework and API plug-in tools to visualize and monitor supply chain status (Irizarry et al. 2013). This work utilized value-stream mapping (VSM) to evaluate logistics constraints by identifying the location of suppliers, transportation routes, value-adding, and non-value-adding activities and displaying VSM symbology in a GIS map (Irizarry et al. 2013). However, Irizarry et al. (2013) acknowledge the lack of BIM-GIS interoperability and concede that their approach is limited in semantic level interoperability and suggest, like others, that more work is needed. This conclusion adds to the body of evidence that indicates true integration is a far greater problem than might be initially understood. Although this work is focused on business processes during the construction phase, the potential for this type of model to be extended into operations is vast.

4.4.2.2 BIM-GIS and Asset Management

The Cambridge Centre for Smart Infrastructure and Construction (CSIC) asserts that AM decisions must be 'value-driven" and not 'cost-focused' and proposes a framework that builds on the PAS1192 and ISO55000 standards. Moreover, an outcome of the study recognized that structures with BIM models are in the minority but that existing structures could benefit from this having this data. The study suggests that with limited resources to produce digital twining of all assets, risk-based strategies to identify (existing) assets which would benefit from BIM should be developed (Parlikad et al. 2015).

Although IM is designed to be a collaborative platform, with respect to AM, communication silos still exist in practice, as a result of two deficiencies: first, many facility managers lack the necessary knowledge and skills to implement CIM for FM; and second, designers and constructors are not familiar with what FM information should be collected and what FM requirements should be considered in their IM practices (Liu and

Issa 2016). Even as operators are included as stakeholders in the BIM process, a fully equipped BIM model is difficult and expensive to produce for the later life-cycle phases.

Other research involving, academics, utilities and asset management practitioners across different infrastructure sectors identified key challenges to infrastructure asset management under four categories: asset performance monitoring and prediction, data management, optimizing investment/expenditure, and organizational culture change. Outside of organizational culture change, these challenges are being addressed to varying degrees through technology platforms delivered by a myriad of software companies and some are quick to recognize the advantages integrated GIS-BIM systems can deliver. For example, related to data management, Liu and Issa (2016) state that the "sharing of data and information in an open semantic form across industry stakeholders to deliver enhanced customer experience is a major challenge" and suggest that the enforcement of data sharing standards such as PAS1192 (discussed below) through the BIM Level 2 mandate can mitigate some of these challenges. Furthermore, Parlikad and Jafari (2016) suggest that data sharing amongst organizations that operate assets within common networks and might not be otherwise incentivized to share, can present opportunities to collect and manage better data.

Liu and Issa (2016) contend that, on the asset management side, there is a knowledge and technology gap between design and facility management professionals and that the first step in using BIM for FM/AM is identify the requirements of facility managers and to determine the problems and concerns that affect the performance of facility operation and maintenance activities.

Recent work by Guillen et al. (2016) highlights requirements and challenges of using BIM for FM/AM. Specifically, they identify the need to align model view definitions (MVD) to EAM inputs and suggest cross-referencing the PAS1192 BIM standard (soon to be superseded by ISO EN 19650) and the ISO 55000 standard for AM.

Research by Talida Boanca at Wageningen University and Research in the Netherlands demonstrates two approaches for BIM enabled AM; 1) an application level integration for visualization of AM data through a BIM-GIS system integration and; 2) a data level integration that converts element LOD data and semantically maps it to a chosen standard (Boanca 2014).

4.4.3 Mapping Asset Management Processes

While there are no standard workflows linking asset data with information models, the UK PAS1192-3:2014 standard applies to both buildings and infrastructure and sets out collaborative working and information requirements for achieving BIM Level 2 focused on use and maintenance of the Asset Information Model (AIM) described by Manning (2014). Manning (2014) explains that the AIM is managed within a common data environment and should deliver a fully-populated asset data set that can, if required, be used by computer-aided facility management systems (CAFM) or GIS enabled EAM. Figure 4.4 provides an overview of how an organization can approach the development of its information requirements and how the information relates to the Asset Information Model (AIM) PAS 1192:3 and the Project Information Model (PIM) PAS 1192:2 (Manning 2014).

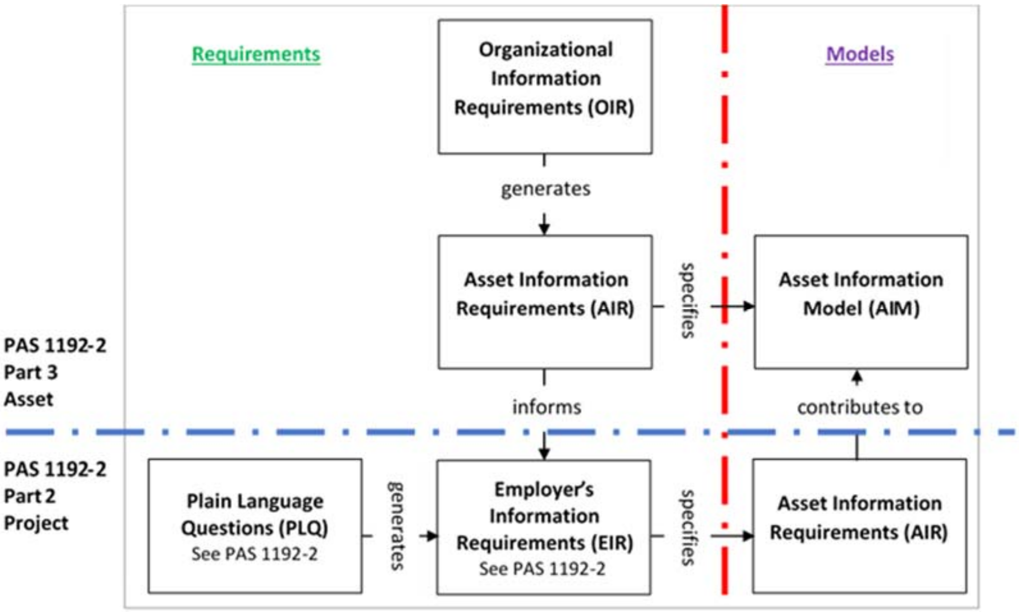

Figure 4.4 Essential components to develop an AIM (Manning 2014)

This process conceptualizes the AIM as a product of the shared BIM/CIM (or Project Information Model - PIM as defined in the PAS1192-2) model developed during the initial procurement. The advantage to this approach is the AIM retains the flexibility and adaptability required for various types of EAM deployment as well as the ability to manage future requirements such as Level 3 BIM implementation that can facilitate bi-directional data exchange and interoperability.

The high-level PAS1192-3 documents provides examples of typical AM data that might be incorporated in the PIM such as the condition and duty of assets, condition and performance targets or standards, key performance indicators, etc. However, these data would be required to be defined as custom data types within the PIM and linked through a new ontology yet to be defined by the common data environment.

4.5 Summary

CIM can provide a data-rich digital representation of both physical and functional components of an infrastructure facility that captures detailed project information. However, from the research outlined above, current efforts in BIM-GIS (vertical) integration is fragmented and falls into one of two categories: proof of concept models for specific use cases or interoperability models involving the unification of domains at the sematic level. It can be seen that very little research is being done on specific use cases for CIM-GIS (horizontal) integration in the same manner. This is likely due to the dependence on the IFC format which is not well defined for infrastructure. Overall, data schema for infrastructure models is minimal with the majority of research focused on bridge modelling. At the same time, semantic web technologies are still in a nascent stage of development. Furthermore, it was found that CIM use in industry is predominantly for visualization and documentation while model-based analysis, integrated analysis, and automation and optimization uses were rare or underutilized.

A preliminary level of integration of information models with asset management is happening within current EAM or ERP systems via customized API's or plug-ins to enhance visualization. However, more work is needed to develop high-level links between codified AM processes and information models in terms of data management and governance. Research related to owner/operator data requirements specific to a class of infrastructure assets is scant. Additionally, since infrastructure assets do not function in isolation, systems for aggregating and merging data types in a common data environment suffer from a lack of standardization and more research is needed to connect standards such as ISO 55000 for asset management and ISO 19650 for BIM.

5 Value-add Potential

This chapter discusses the business case surrounding the implementation of BIM and CIM for Asset Management. Benefits versus costs as well as challenges and barriers are explored in the context of integration and deployment.

5.1 Business Value

The digital age is maturing at an exponential pace and with it, the need for businesses and organisations to increase their capacity for adopting automated, data-driven decision-making (Pärn and Edwards 2017). A 2014 McKinsey report outlining the gap between institutional investors and infrastructure projects identified a lack of performance monitoring as a challenge to attracting investment capital (Blanc-Brude 2014). Moreover, McKinsey predicts that by 2025 disruptive technologies that automate knowledge work could have a five to seven-trillion dollar economic impact (Manyika et al. 2013). Information modelling when combined with asset management will increasingly automate information management in the operations phase of civil infrastructure by providing real-time data to drive investment decisions.

Answering the question: How can Information Modelling (IM) add value? depends, of course, on one's perspective as an owner, designer, constructor, or operator. From an operational perspective, information models can store key asset data in a visually accessible way that can be used to improve information management. Pärn and Edwards (2017) assert that the inherent value of integrating IM and AM systems is derived from improvements to current manual processes of information handover; accuracy of, and accessibility to rich semantic FM data; and efficiency increases in work order execution (Pärn and Edwards 2017).

Bradley et al. (2016) discuss, at length, the use of CIM to improve and streamline "business logic" and project management processes by linking databases, specifically for scheduling, cost, and quality. They argue that the value of information modelling with respect to infrastructure comes from implementing the "collaboration methodology", advanced visualization, coordination, and visual integration of non-graphical data. Furthermore, they suggest that the large amount of research in 4d and 5d-modelling provides evidence that CIM, specifically, stands to provide the greatest value from increases in efficiency and quality, rather than through model analysis tools such as clash detection that were developed for vertical construction. They also show that the level of research in CIM for FM indicates there is enormous perceived potential for CIM to integrate with AM systems and that the way forward is through "graph-based data schema" and "semantic models" (Bradley et al. 2016).

In their analytical analysis, Cheng et al. (2016) found that although current infrastructure IM capabilities can provide data-rich visualization that enhances decision-making, most of the CIM uses in industry are not implemented past conceptual design. They argue that the benefits appear to stop being apparent in pre-construction where low-cost simulations can directly impact cost and schedule. Moreover, project owners, in general, have difficulty early in the project identifying the advantages that life-cycle information management can have at the operations & maintenance phase where facility managers can benefit from design and construction data (Cheng et al. 2016).

Kassem et al. (2015) write that the current handover processes to the FM phase are often manual document dumps where information can be inaccurate or incomplete, requiring extensive resources to recreate integrated information models. Furthermore, that "despite current interoperability challenges, BIM data and information collected during the building life-cycle will reduce the cost and time required to collect and build FM systems" (Kassem et al. 2015).

Thomas Mills concluded that "the key Facilities Information Modelling (FIM) business question facing the AEC/O industry is: what strategies can be employed throughout the project process to coordinate and validate included and linked facility information that is intended to be stored, exchanged, reused, and ultimately archived as it transits the project life-cycle." (Mills 2010) Mills (2010) contends that "the real driver for extracting maximum value from BIM processes will be owners and operators". However, Mills (2010) also states "there is little understanding by owners and operators on what can be delivered, how it can be delivered, and what it will cost in return". Mills (2010) suggest that "without some form of business rules governing exchange processes that recognize owners as end users, the industry will be unable to define BIM deliverables nor fully implement BIM as a value-added deliverable."

Interestingly, Mills believes that CIM presents an opportunity to produce equal if not greater value than vertical BIM by creating Facility Information Models (FIM) so long as accuracy can be maintained through information exchanges. As such, it is suggested that information modelling belongs to the domain of quality management (QM) and a framework is proposed that maps QM deliverables to proposed IM capabilities (Mills 2010).

5.2 The Business Case for CIM Implementation

While it is generally recognized that BIM platforms can enable improved coordination, enhance information accuracy, support lean construction processes, and allow early detection of quality issues to enable better decision making, the ability to extend information models beyond design and into the operations phase promises to generate significant value.

A whitepaper published by Autodesk draws on several case studies from industry participants and argues that CIM can be a "vehicle for business transformation" in three ways; it can increase clarity of project intent for all stakeholders, better informing decision making and reducing risk; it can ensure data fidelity and continuity across the life-cycle of a project, improving quality and productivity; and it can provide the foundation for business agility by utilizing technology enablers to maximize profit and growth (Autodesk 2012). The resulting value of CIM differs for owners and their consultants and reported benefits range from improved marketing and project quality to higher profit margins, reduced risk, and new opportunities for growth (McGraw-Hill Construction 2012).

While it is easier to justify the cost of using BIM/CIM for new construction, producing models for legacy assets, particularly, simple, low value assets, would require a cost-benefit analysis. In a case study conducted by Northumbria University in 2010, five developers were commissioned to produce Revit models for all 32 buildings with a gross area of 120,000m^2. It was reported that the cost was approximately £0.33 (2010)/m^2 or about $67,200 CAD (unadjusted). The case study concluded that BIM for FM is an emerging field and its business value is yet to be demonstrated; that BIM for FM can offer efficiency gains by reducing iterations in the updating of the drawings and information;

and FM-BIM processes require multi-technology platforms that can serve specific business requirements for each organization (Kassem et al. 2015).

5.2.1 Measuring Value

Evaluating information technology starts with a high degree of uncertainty with respect to the expected value and has been reported to be characteristically difficult. Quantifying costs and benefits in monetary terms is often challenging due to data availability, reliability and confidentiality issues. For the construction industry, this is complicated by the fact that each project is unique in terms of "financing, contractual relationships, and end user requirements" (Becerik-Gerber and Rice 2010).

5.2.2 Benchmarking

Becerik-Gerber and Rice (2010) write that "an increase in the availability of financial information will be significant, as one of the primary motivators for professionals in the building industry to adopt new technologies" and that "research shows that most construction organizations do not employ a formal methodology to evaluate the benefit of IT investments, and formal cost-benefit analyses are not widely used." (Becerik-Gerber and Rice 2010)

Their 2010 study identified the need for benchmarking and categorized IT benefits in three areas: (1) tangible benefits: quantifiable in monetary terms; (2) semi tangible benefits: quantifiable, but not in monetary terms; and (3) intangible benefits: non-quantifiable, described qualitatively. They acknowledge that many of the benefits fall into the semi-intangible or intangible category (for example, improved product quality, better decision-making capabilities, increased availability of data) and therefore "lack the weight of clear revenue improvements" (Becerik-Gerber and Rice 2010). To capture benchmark data, they suggest that the impact of BIM can be measured with respect to six construction key performance indicators (KPI's): safety, cost, cost per unit, units per man-hour, duration, and quality. However, the study focuses on industry perceptions captured through a survey and fails to deliver a quantitative framework.

A 2014 case study on the implementation of CIM considered two similar, concurrent bridge construction projects in the Denver metropolitan area. By comparing metrics related to substructure costs, requests for information (RFI's), change orders, rework, and schedule, it was concluded that the first-time implementation produced substantial negative cost impacts likely due to learning curve barriers as well as increased project complexity (Fanning et al. 2015). However, it was also found that for the same project, BIM implementation may have reduced the number of RFI's and change orders to provide a cost savings of approximately 5% and suggest that follow-on implementation would continue to generate increased benefits (Fanning et al. 2015). This study provides a more quantitative approach to measuring value.

Lu et al. (2014) developed an analytical model to quantifying cost-benefit criteria through the analysis of time-effort distribution curves following the well-known example by Patrick M^{ac}Leamy (Figure 5.1) that illustrates the concept of making design decisions earlier in the project when the opportunity to influence positive outcomes is maximized and the cost of changes is minimized. While they showed good results, they concluded that the study was limited, and more data was required to make industry-wide generalizations about costs versus benefits of BIM implementation.

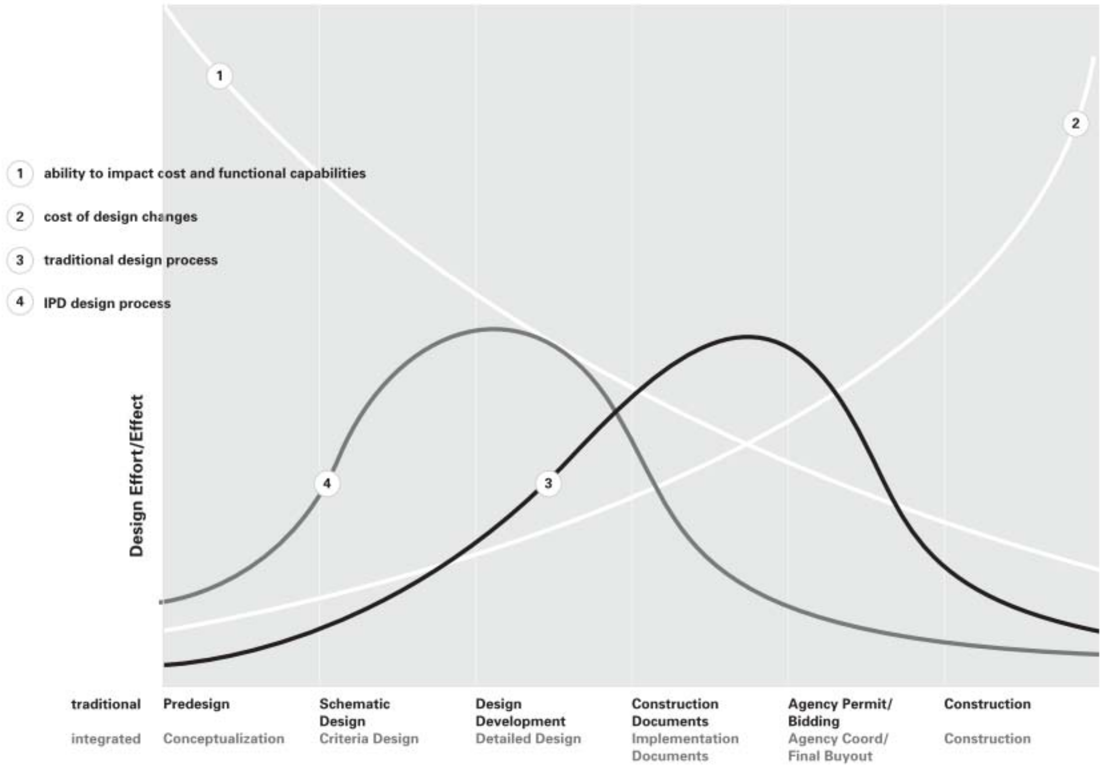

Figure 5.1 MacLeamy Curve - Illustrates the concept of making design decisions earlier in the project

5.2.3 Return on Investment (ROI)

Generally, the objective of an enterprise is to generate as much Return on Investment (ROI) as possible. The ROI performance measure is quantified by the benefit of an investment divided by the cost of the investment. ROI has been historically used to justify the investment in BIM, yet this measure does not accurately reflect the 'real' costs and benefits that can be associated with BIM implementation. A business case analysis of BIM implementation can be generally measured with industry accepted KPI's such as:

- Cost: cost variance in actual costs to budgeted costs
- Quality: percentage of rework to overall cost
- On-time completion: time variance and costs due to time overrun
- Productivity: performance (costs or man hour per unit), increased profits
- Safety: lost man hours

Other KPIs may include turnaround times (time effectiveness), revenue per head, reduced costs of traditional approach (printing, travelling), business won (bids won percentage), or overall client satisfaction. The most quantifiable returns result from better coordination, clash detection, and fewer RFIs and change orders.

Love et al. (2013b) argue that a major factor to cost overruns in construction projects has been the creation and transfer of poor-quality information, which has manifested as errors, omissions and information redundancy and that BIM has the potential to mitigate these problems. However, despite the benefits, many firms remain cautious in their approach to implementation due to the investment cost. To quantify Value for Money (VfM) in implementing a BIM workflow, it was acknowledged that, in addition to ROI analysis, other methodologies such as Return on Management, Information Economics Approach, Multi-object, Multi-criteria methods, Value Analysis, and Options Theory may also be employed.

In their evaluation framework for asset owners, Love et al. (2013b) present several assumptions with respect to ROI analysis: 1) that many ROI "studies" do not accurate capture the real costs and benefits associated with this technology; 2) BIM implementation based solely on ROI neglects supply chain participants; and 3) direct cost analysis, cash flow projections, and financial assessments ignore the indirect and intangible costs and benefits associated with implementing BIM. With those assumptions stated, Love et al. (2013b) identify the following metrics within the context of a BIM project developed to LOD 500 to generate a reasonable ROI analysis:

1. Quality control (rework reduction)

2. On-time completion (reduction in delay)
3. Overall cost (cost reduction)
4. Units (square feet/meters)/person hour
5. Dollars/unit (square feet/meters)/person hour
6. Safety (reduction in lost person-hours).

In conjunction with financial information, Love et al. (2013b) suggest that asset owners need to also consider the following:

- assumptions underlying the cost of the project
- assumptions underlying its potential benefits
- the ability to measure and quantify costs and benefits;
- the risk that the developed model will not deliver what is required;
- the risk that the project will not be completed on time and on budget and will not deliver the expected benefits; and
- skills and expertise of consultants/contractors/subcontractors to deliver a fully integrated and functional model.

However, they caution that ROI used to justify BIM implementation is a “myopic mechanism for considering technology investments” and that “evaluation should not only focus on the operational improvements enabled by BIM, but those of a managerial, organizational, infrastructure and strategic nature.” (Love et al. 2013b)

5.2.4 Smart Market Reports 2012 and 2017

McGraw Hill Construction first published the results of an industry survey titled “The Business Value of BIM for Infrastructure” in a Smart Market Report in 2012 (McGraw-Hill Construction 2012). A follow-on update (under its Dodge Global Network Platform) was again published in 2017 to provide a comparison of how the industry had evolved over a five-year period from the perspectives of A/E firms, Contractors, and Owners (Jones and Laquidara-Carr 2017). The key findings from the 2012 report can be summarized as:

- Adoption: 46% of infrastructure organization respondents reported using BIM on infrastructure projects and 89% reported that they received some form of value from it.
- Level of Use: The percentage of those using BIM on more than 50% of their projects will grow from 30% now to 52% in just two years, indicating continued use.
- Outlook: 79% of current non-users feel positively about future adoption, with only 4% opposed. Education and best practices should be effective at accelerating adoption.
- Value: 67% of all users report a positive ROI on their BIM investments, even higher than the 63% of BIM users for buildings who reported the same in 2009.
- Benefits: Top benefits achieved now include reduced conflicts and changes (58%) and improved project quality (48%). Achieving lower project risk and better predictability of project outcomes is also perceived by 60% as a top benefit in the next five years.

The key findings from the 2017 report can be summarized as:

- Adoption: BIM users at a high level of implementation (on at least half of their projects) grew from 20% in 2015 to 52% in 2017
- Outlook: By 2019, 61% forecast that they will be at that high level of implementation. The growth in BIM implementation is most dramatic among those deploying BIM on nearly all (75% or more) of their projects.
- Value: Most BIM users (87%) report that they see positive value from their use of BIM. Nearly two thirds believe that they are seeing a positive ROI from their use of BIM, with about half of those reporting an ROI of 25% or more.
- Benefits: Most of them find that using BIM improves their processes and project outcomes most by reducing errors and providing greater cost predictability. Over

half also report that BIM helps them to achieve two types of business benefits: They can do business better, and they can find more work.

It is difficult to draw straight comparisons since the focus of the 2012 survey was to highlight differences between stakeholders, while the focus of the 2017 highlighted differences between geographic regions. Results suggest a considerably higher adoption rate of CIM across stakeholders five years on that more recently, realistic outcomes are perceived. These and other notable comparisons with respect to value perceptions with CIM are presented below in Table 5-1, Table 5-2, and Table 5-3.

Table 5-1 Perceived value of CIM at levels of adoption

Overall Business Value from BIM	
2012 (Owners)	**2017 (A/E Firms and Contractors- global avg)**
Getting no meaningful value - 16%	< 25% full BIM potential – 32%
Just scratching the surface - 53%	25-49% full BIM potential – 40%
Getting a lot of value – 26%	
Getting max. value – 5%	50-100% full BIM potential – 28.5%

Table 5-2 Perceived CIM Business Process benefits

Top Business Benefits	
2012	**2017**
Overall better outcomes Reduced rework Reduced errors in documentations Reduced workflow cycle times Reduced project duration Reduced construction cost	Improving ability to show younger staff how projects go together Offering services Establishing consistent and repeatable project delivery processes Maintaining business with past clients Less time documenting, more time designing

Table 5-3 CIM Benefit by project phase

Top Benefits by Phase	2012	2017 (global avg.)
Programming	24%	3%
Planning	44%	52%
Design	44%	45%
Construction Documentation	47%	11%
Bid Letting	6%	1%
Construction	41%	26%
Project Closeout	24%	5%
Maintenance	29%	<1%

The results in Table 5-3 suggest two things: an initial lack of knowledge about CIM capability; and an increase in IM application across project phases. With respect to ROI, the 2012 survey focused on perceptions of how ROI was being delivered through a series of ranked questions shown in Table 5-4.

Table 5-4 ROI Indicators and Industry perceptions (2012 survey only)

2012	
How to Improve ROI	***How to Improve the Value of BIM***
Improved Project Process Outcomes - 66%	Better multi-party communications – 63%
Better multi-party communications – 63%	Positive impact on marketing – 46%
Positive impact on marketing – 60%	Improved Project Process Outcomes – 43%
Reduced cycle time for activities – 56%	Improved Productivity – 42%
Lower project cost – 52%	Reduced cycle time for activities – 35%
Positive impact on sustainability – 44%	Lower project cost – 31%
Increased prefabrication – 38%	Positive impact on sustainability – 44%
Faster plan approval and permits – 37%	Increased prefabrication – 27%
Positive impact on recruiting/retaining staff – 36%	Faster plan approval and permits – 24%
Improved jobsite safety – 32%	

The 2017 survey focused on stakeholder's ability to formally measure ROI and reported that an astounding 74% of respondents formally measured ROI. This is surprising considering the lack of research and case studies before 2016 that identifies key ROI indicators and how to measure them.

5.2.5 Benefits and Challenges

Becerik-Gerber and Rice (2010) argue that while previous studies indicate that BIM/CIM can deliver benefits through accurate and consistent drawing sets, early collaboration, synchronized design and construction planning, clash detection, model-driven fabrication and greater use of pre-fabricated components, support of lean construction techniques, and streamlined supply chain management, these case studies are often conducted in isolation and fail to provide a complete and comprehensive list of benefits and associated costs and rarely assign quantitative values (Becerik-Gerber and Rice 2010).

Research by the UK Construction Industry Council suggests that core benefits for BIM employed at Level 3 Maturity include:

- Improved productivity: though centrally managed data to eliminate version control issues and reduce re-work and iteration time and reducing inefficient RFI's and change orders.
- Reduced risks per project: by implementing repetitive processes and identifying potential points of conflict.

Love et al. (2013a) argue that the benefits of implementing BIM to control and manage project costs and schedule during the design and construction phase are marginal compared to the duration of an asset's life-cycle and suggest that the impetus for BIM adoption should come from benefits accrued during the operation and maintenance phase. They suggest that for an asset owner, the implementation of BIM should not be seen as a discrete information technology (IT) project, but as a business change program and "simply identifying and estimating the benefits of BIM are not sufficient as attention should focus on ‘how’ benefits will materialize and over what period of time.” (Love et al. 2013a)

Additionally, they believe that benefits realization should be “proactively managed” and their work proposes a conceptual framework (Figure 5.2) that assesses the benefits of BIM implementation through capability, competency and practices with respect to governance, performance measurement, change management and stakeholder management by asking four questions:

1. Are we doing the right things?
2. Are we doing them the right way?
3. Are we getting them well done?
4. Are we getting the benefits?

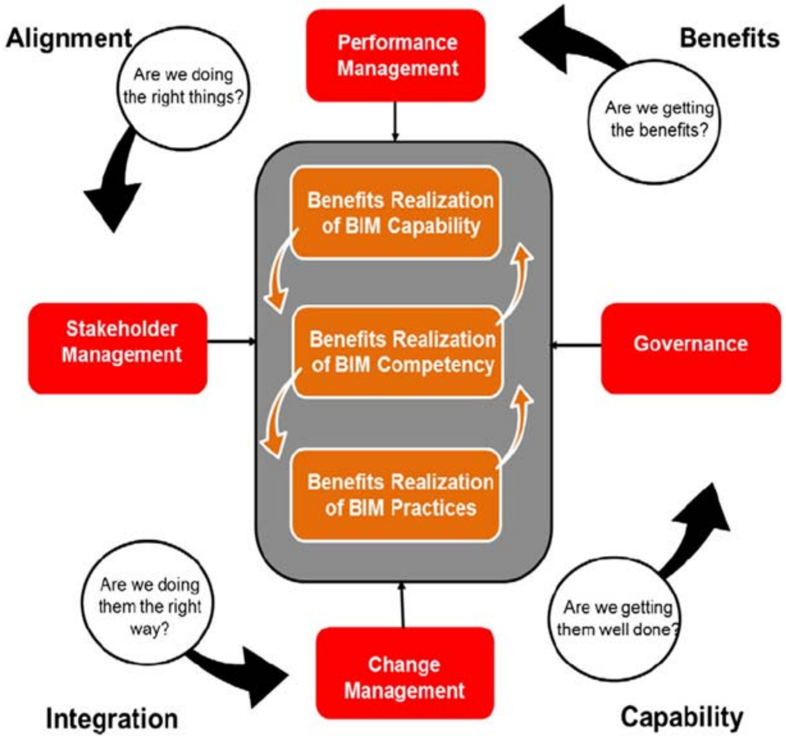

Figure 5.2 Framework for realizing the value of BIM for asset owners (Love et al. 2013a)

The framework can help asset owners develop an organizational strategy that considers how BIM implementation can provide long-term value.

A major factor that has contributed to overruns being experienced in construction projects has been the creation and transfer of poor-quality information, which has manifested as errors, omissions and information redundancy (Love et al. 2013b). A study by the U.S. National Institute of Standards and Technology (NIST) showed that the annual costs associated with inadequate interoperability among software systems was $15.8 billion. Two-thirds of this cost was incurred as a result of ongoing facility operation and maintenance activities due to the need for similar information to be collected at different phases of the project. With the use of BIM, it should be possible to reduce information collection requirements over throughout the life-cycle of the facility (Liu and Issa 2016).

In discussing challenges realted to BIM-FM technology valuation, Pärn and Edwards (2017) present several key insights:

- BIM-FM integration literature suggests that specific limitations of data integration between BIM and FM are related to proprietary formats for data authoring platforms, as well as the lack of standardized methodology for such data transfer.
- The rapid pace of digital technology development creates difficulty for industry and academia researchers to stay current of the latest knowledge and development.
- Access to quality and quantity of analytic data with respect to technology valuation are related to the ability to secure a client's approval for “access to large construction project developments”.

Additionally, they argue that legal contracts for data disclosure, can lead to “significant costs being incurred by a research team and delays to secure agreements with all parties concerned” (Pärn and Edwards 2017).

Forgues and Becerik-Gerber (2013) argue that the absence of standard BIM contract documents and issues arising from how BIM is used as a collaborative framework are two major obstacles to full adoption.

Conversely to the rapid pace of technological development, the slow pace of technological adoption can present other challenges. Porwal and Hewage (2013) maintain that even as BIM adoption in the Canadian construction industry is slower compared to the US or the UK, it is organizational and “people-centered issues” that pose the greatest challenge to BIM implementation. To increase client-driven BIM adoption, they suggest the public sector needs to play a greater role in demanding higher levels of integrated technology and propose a “BIM-partnering based on public procurement framework to ensure best value for construction projects” (Porwal and Hewage 2013).

Kassem et al. (2015) summarizes several key challenges to BIM for FM that include: inadequate as-built model updating processes; poorly defined roles and responsibilities for data and model management; exclusion of FM stakeholders during the planning and design phase; contractual changes throughout the operational phase; cultural approaches to FM by the FM industry including lack of awareness and lack of demand; poor alignment with legacy systems; underdeveloped business models for BIM utilization by facilities managers; limited knowledge in the identification of such requirements; and the lack of contractual and legal framework to set-out clear rules of data ownership (Kassem et al. 2015).

5.3 Summary

Information modelling when combined with asset management will increasingly automate information management in the operations phase of civil infrastructure by providing real-time data to drive investment decisions. The inherent value of integrating IM and AM systems is derived from improvements to current manual processes of information handover, accuracy of, and accessibility to semantic data (representational objects imbued meaning), and efficiency increases in work order execution.

Research suggests that owners and operators are often unaware or lack an understanding of what can be delivered, how it is delivered and what the costs will be. Furthermore, quantifying costs and benefits in monetary terms can present challenges in the form of data availability, reliability and confidentiality issues. As a result, Becerik-Gerber and Rice (2010) conclude that the "increase in the availability of financial information will be significant, as one of the primary motivators for professionals in the building industry to adopt new technologies" and that "research shows that most construction organizations do not employ a formal methodology to evaluate the benefit of IT investments, and formal cost-benefit analyses are not widely used." (Becerik-Gerber and Rice 2010)

Two case studies were presented that concluded that: (1) that BIM for FM is an emerging field and its business value is yet to be demonstrated; and (2) initial implementation may provide a negative return in the short-term but follow-on implementation would continue to generate increased benefits. The Fanning et al. (2015) case study of the construction of two similar, concurrent bridges projects used a quantitative approach to measuring value by comparing metrics related to substructure costs, requests for information (RFI's), change orders, rework, and schedule. Other standard KPI's such cost variance, percentage of rework, on-time completion, and man-hour performance measures could also be explored. This study could provide a model for subsequent studies on specific infrastructure asset classes (e.g. roads).

Key challenges to BIM for FM identified in the research include: inadequate as-built model updating processes; poorly defined roles and responsibilities for data and model management; exclusion of FM stakeholders during the planning and design phase; contractual changes throughout the operational phase; cultural approaches to FM by the FM industry including lack of awareness and lack of demand; poor alignment with legacy systems; underdeveloped business models for BIM utilization by facilities managers; and limited knowledge in the identification of such requirements.

6 Discussion

This chapter discusses the findings from Chapter 5 and presents a case study conducted with University of New Brunswick Facilities Management (UNB FM) that highlights the challenges surrounding the technological challenges of integration of CIM with Enterprise Asset Management systems as well as the policy requirements for implementation.

The initial proposal for this research detailed a three-phase approach to investigate the value-add potential of CIM for asset management. In retrospect, while the methodology was sound, the boundaries of the scope were overly ambitious. The Phase 1 literature search was largely successful in that a comprehensive literature review was conducted and presented in this report and a good understanding of the current state-of-the-practice and technology (state-of-the-art) was developed. The results of Phase 1 confirm that the Phase 2 development of an interoperable CIM model would have met the criteria for a stand-alone project. Likewise, the Phase 3 deliverables for measuring business related performance indicators were far too broad in scope.

6.1 UNB Facilities Management: Proposed Case Study

To validate the research outlined in Chapter 4, UNB FM was selected as the industry partner. UNB FM was in the process of re-structuring the organization to merge the Maintenance Department and the Projects Department in part to fulfil objectives identified through a Lean Management training program. Figure 6.1 shows the organizational structure of UNB FM at the time this project was proposed. The Maintenance Manager (MM) was the point of contact for this project and it was hypothesized that this project could leverage data gained from the results of the Lean Management training program to validate the value-add potential of BIM-AM integrated systems.

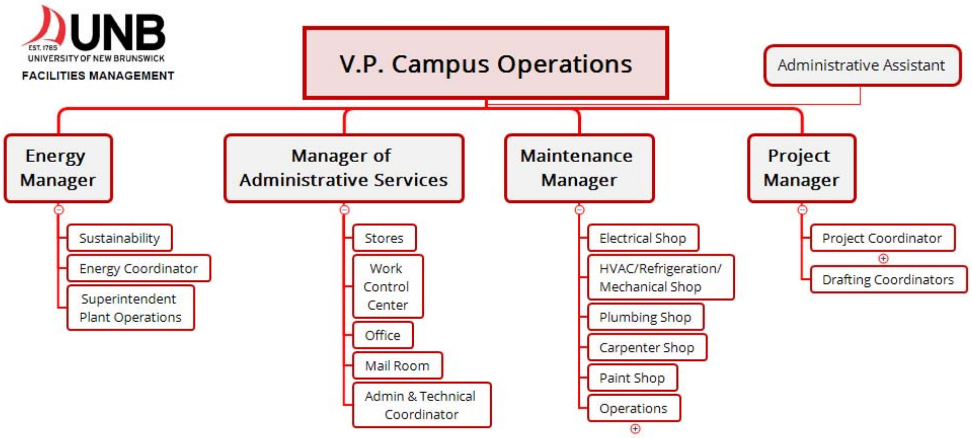

Figure 6.1 UNB FM organization chart

Currently, UNB FM has a maintenance budget of $1.3M and an overall budget of $8M through the provincial University Deferred Maintenance Program (UDMP). Through a structured interview, the MM indicated that UNB FM takes a two-prong approach to fulfill its organizational mandate. First, a value-stream mapping (VSM) approach (VSM is a Lean concept that focuses on customer satisfaction) is considered where, to some extent, operation and maintenance is driven by customer satisfaction which equates to student demand; since UNB FM budgets are tied to student enrollment and government funding. He also affirmed that, even though UNB is a business, UNB FM is working to move past responding only to complaints. Second, a value-chain approach, defined as a strategic concept that focuses on competitive advantage and measured by cost of service, is employed, again, to some extent.

The approach to this project was to first construct a CIM model for the UNB campus and create an information exchange protocol between the model and UNB FM's VFA Capital Planning Software supplied by Accruent, LLC. Second, utilizing data from the UNB FM's

Lean Management Training program, AM data and processes would be identified for the assets modeled in the CIM and incorporated into the model. Lastly, utilizing the prototype CIM-AM integrated system, current AM process would be evaluated pre and post application of the new technology to quantify value-add potential. Work completed throughout this research is presented below.

6.1.1 CIM Modelling

Initial attempts to create a 3d model of selected UNB campus infrastructure in Autodesk Civil 3D r2017 ("Civil 3D | Civil Engineering Software | Autodesk" n.d.) using legacy 2d CAD data as illustrated in Figure 6.2, proved difficult with respect to geo-referencing and the volume of data would be extraordinarily time consuming to re-create. A second attempt was met with moderate success for surface asset classes using Autodesk's Infraworks r2017 ("InfraWorks | Infrastructure Design Software | Autodesk" n.d.) shown in Figure 6.3.

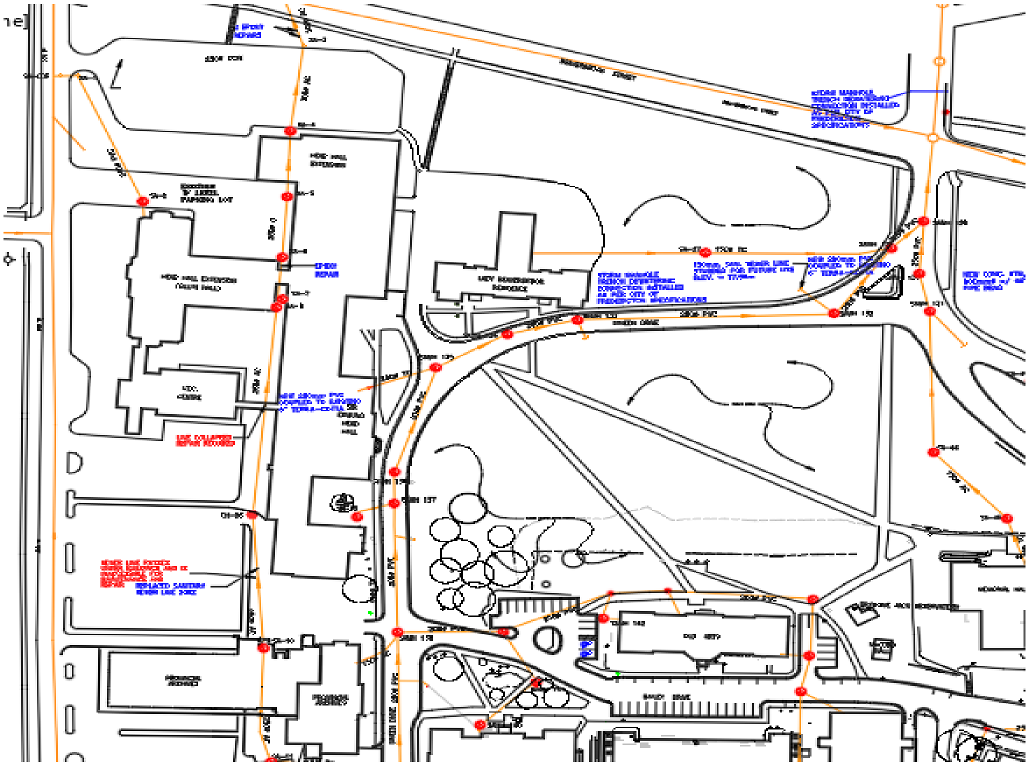

Figure 6.2 UNB campus - legacy 2d storm sewer drawing

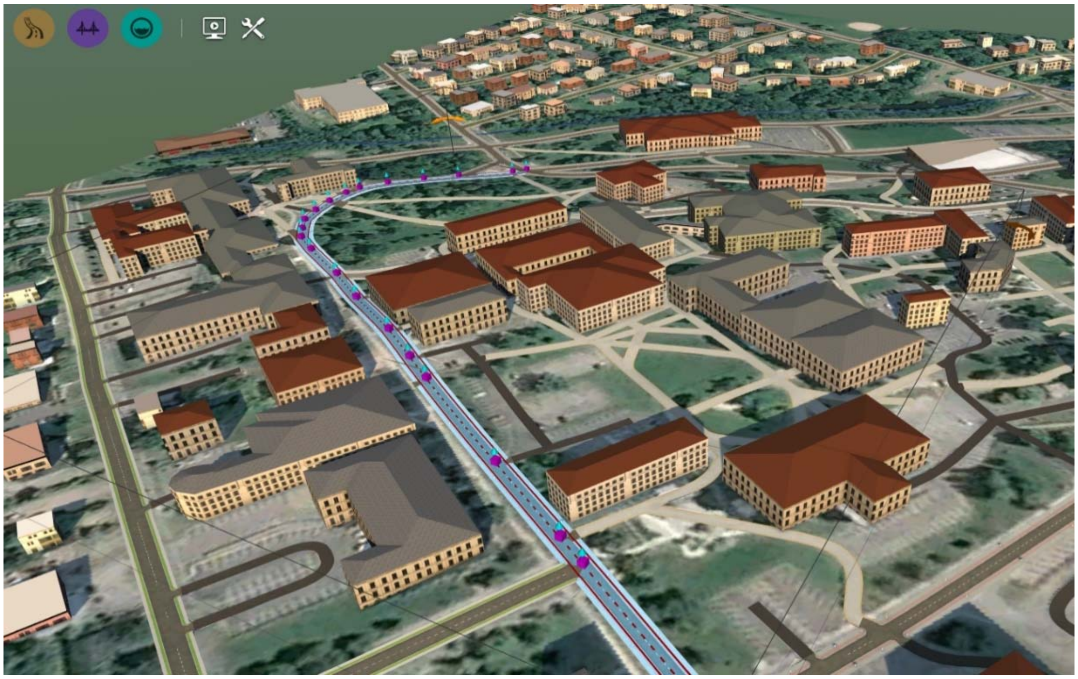

Figure 6.3 UNB campus - Infraworks 360 model

The learning curve involved in utilizing the modelling tools prevented successful accurate modelling of the entire sub-surface waste water pipe network. Again, a subset of this asset class was modeled in Civil 3D and exported but failed to be imported in the Infraworks model in a way that was visually useful. Furthermore, as the literature above illustrates, the process for extracting relevant AM data from the Infraworks CIM requires extensive knowledge in IFC extraction and processing. This capability was not developed or supported during this project.

6.1.2 Identifying Relevant AM Data and Data Structures and Processes

6.1.2.1 Asset Management Capability Baseline

To determine a baseline for current asset management capabilities, an informal interview was conducted with the Maintenance Manager, who is responsible for implementing the new Lean strategies. Using the Institute of Asset Management's (IAM) document *Asset Management – an anatomy* (The Institute of Asset Management 2015) as a guide, an attempt to assess the state of asset management at UNB FM was approached through three topics: AM Relevance, Components of an AM System, and value perception of AM within the organization. UNB FM's recent commitment to the implementing the APPA Level 3 (Association of Physical Plant Administrators) programme presented obstacles with respect to workplace culture as well as human resources when considering deeper aspects of value perception related to CIM-AM integration.

6.1.2.2 Asset Management Relevance

The IAM introduces the concept of AM with a set of ten questions to determine whether the reader should invest time into understanding the definitions and framework developed to help asset managers implement the ISO 55000 standard. Although basic in nature, the questions were helpful to set the tone for a more in-depth analysis of UNB FM's AM program (see Appendix A). The results of the "Relevance" survey showed consistent matches to the maturity characteristic that describe a Level 2 or "Developing" state of AM maturity. Further analysis, however, would characterize UNB FM's AM program closer to Level 1 "Aware" state.

6.1.2.3 Components of an Asset Management System

The conceptual model shown in Figure 3.5 in Chapter 3 above represents a fully implemented, idealized, asset management system. In developing the baseline for UNB FM, it is understood that not all AMS's are required to possess all characteristics to be useful or successful. The model identifies 39 characteristics (see Appendix B) within six subject groups that define the scope of asset management. An attempt was made to clarify the existence of each characteristic within the current AM framework employed by UNB FM. In an unstructured interview with UNB FM, the characteristic descriptions were posed as questions to determine the state of development for each group:

1. Strategy and Planning
2. Asset Management Decision-Making
3. Life-cycle Delivery
4. Asset Information
5. Organization and People
6. Risk and Review

Strategy and Planning

UNB FM strategy and planning happens at some level and is broadly tied to UNB's business objectives in a strict operations and maintenance sense, however, no formal framework exists to craft proactive policies for short, medium or long-term asset management in a holistic sense. While the MM indicated that UNB FM has an asset management strategy, it is unclear how AM objectives are tied to UNB organizational objectives beyond meeting safety standards. UNB FM does not engage in Demand Analysis activities, however, detailed activities planning seems to be the most robust aspect of AM Strategy and Planning employed by UNB FM.

Asset Management Decision-Making

The MM indicated that UNB FM engaged in a form of AM decision-making that involved planning scenarios and some degree of cost-benefit analysis, but no formal AM processes are codified. There is some degree of confusion between operations and maintenance life-cycle activities and cultural asset management, however, it was acknowledged that operations and maintenance decision-making is largely a reactive response to routine operations and maintenance requests.

Although it was indicated that UNB FM has a Resource Strategy in place, further discussion revealed this is done to the extent that out-sourcing cost is evaluated as part of operations and maintenance activities. Shutdowns and Outages are robustly planned for, but not codified. Much of the AM framework set-out by the IAM requires a large investment in human effort to initiate and maintain a well thought out AM program. While UNB FM is taking steps to address certain aspects within an AM framework, a formalized program would be beneficial.

Life-cycle Delivery

The MM indicated that UNB FM is working to implement an APPA Level 3 performance standard across all assets. Each shop is responsible for monitoring and capturing actual costs and Project Managers are responsible for managing operational information throughout the life-cycle. Work-order data is currently managed through a CAFM system not currently integrated into the capital planning software. A lack of funding prevents UNB FM from implementing reliability engineering but there are processes in place to manage routine shutdowns and outages. Likewise, no formal management processes have been implemented for fault and incident response. Depending on the value of an asset, it may be subject to the UNB FM Asset Disposal Policy.

Asset Information

This was an important area of interest related to the integration potential of this research in order to identify areas of overlap or where new technology can play a role in AM. It was indicated that UNB FM does not possess an asset inventory beyond what currently exists within the VFA system deployed by UNB FM. There is no strategic approach to the definition, collection management, reporting and overall governance of asset information at this time. Due to lack of human resources, the MM estimated that less than 50% of UNB FM's AM data has been digitized an input into the current capital planning system.

Organization and People

A key challenge for UNB FM is the lack of human resources to deliver AM objectives. Currently, training is supported by needs identified in shops. However, with limited resources, identifying and creating efficiencies is the current strategy. There are no formal processes to analyze and evaluate supply chain management or job performance and human resource management is policy-based at the organization level.

Risk and Review

Risk and Review processes are the least mature within UNB FM. No formal risk assessment or asset effectiveness auditing processes exist. Contingency planning and resilience analysis are not utilized. Sustainable practices are limited to asbestos and hazardous chemicals mitigation. KPI's and operating specification have not been defined across asset classes. Asset costing and valuation can be analyzed through the VFA capital planning software, but the lack of data input means that this function is not currently utilized. Stakeholder engagement is managed through the larger university organization program.

6.1.3 Identifying Value-add Potential

The Computer Integrated Construction (CIC) research group at Pennsylvania State University (PSU) has been deeply involved in BIM research and works closely with the Penn State Office of Physical Plant (OPP) that manages the facilities for PSU to utilize BIM for ongoing FM. Early in the project, communications with Saratu Terreno (Terreno 2017), a CIC PhD candidate and researcher, suggested that value stream mapping (VSM) could be employed to evaluate AM processes pre and post a new technology deployment. As such, with UNB FM, an initial study was conducted for a past maintenance issue at the Maggie Jean Chestnut Building.

6.1.3.1 Maggie Jean Chestnut (MJC) Building

In 2010, multiple instances of sewage back-up occurred in the Maggie Jean Chestnut Building located at the UNB Fredericton Campus. UNB FM completed an investigation together with outside consultants to determine the cause and conducted repairs to mitigate the sewage problem. In 2012, sewage back-up continued to occur at the same location indicating that the 2010 repairs may have been insufficient, and the investigation had not determined the totality of causes. Again, an investigation was conducted with outside consultants and repairs were made.

A report was made to outline the conclusions of the 2012 work. The *Maggie Jean Chestnut Building Blocked Sanitary Sewer Laterals Summary Report* was prepared by PEAM Services Limited and provided to UNB FM and discusses the results of the two separate investigations into the cause of the sewage back-up and the steps taken to mitigate the problem (PEAM Services Limited 2012). The report provided a scenario to create a baseline process utilized by UNB for Facilities Management.

By comparing the current process to some future process, it was hypothesized that value-add activities could be identified. The current process for facilities management at the project (or incident) level was identified as a 5-step process and included the following basic hierarchy of steps as shown in Figure 6.4: (1) Detect the problem; (2) Treat the problem; (3) Investigate the problem; (4) Document the problem; (5) Mitigate the problem.

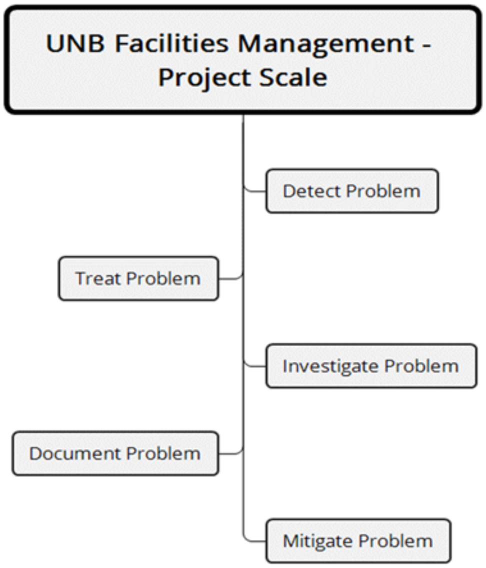

Figure 6.4 UNB FM AM incident process hierarchy

Utilizing this hierarchy, a timeline was recreated from the report details and a decision tree was constructed to map the maintenance processes associated with the detection, repairs and monitoring of this asset as shown in Appendix C. A sample set of AM variables were assigned to indicate the status of the pipe network assets as shown in Figure 6.5.

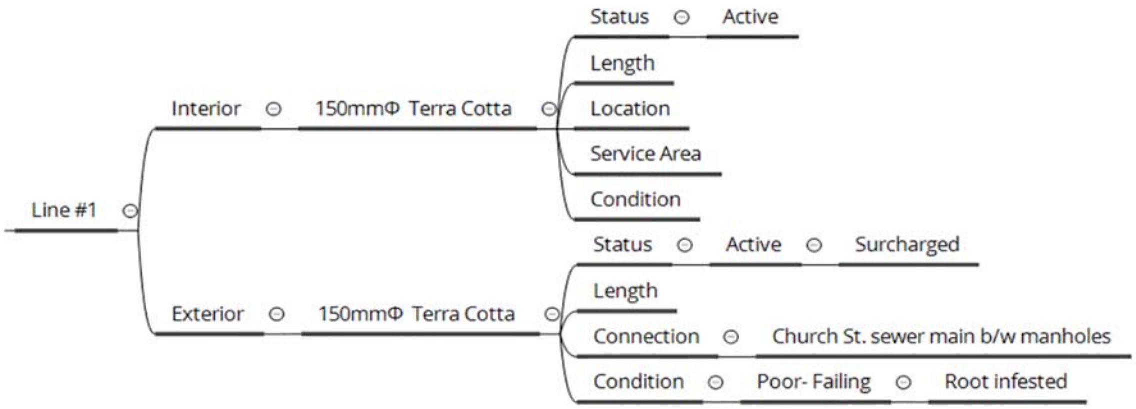

Figure 6.5 Proposed classification of status variables for CIM-enabled AM

The MJC analysis demonstrated differences in maintenance, facilities management and asset management activities and process. Key insights highlighted the difficulty of how to capture contextual historical data as well as current conditions to inform proper maintenance activities as well as classifying network versus point source AM data; and harmonizing existing data from ongoing FM/AM activities, legacy systems and CIM enabled AMS's presents large organizational and technological challenges that may be mitigated with further research and the application of standards that were not considered at this stage of the project.

6.1.3.2 Value Stream Mapping (VSM)

Value stream mapping is a lean management tool that makes disconnects and obstacles to flow visible at a macro level and promotes system efficiency. Mapping also provides a visual way to show links between information and material flow as shown in Figure 6.6. A value stream map is created for both the current state of a system and a theoretical future state where processes have been changed or eliminated without changing the outcome. The primary metric is process time and net-negative changes in process time identify waste.

Applying the VSM in practice requires training to fully understand how to capture the appropriate data. To guide this process, Tim McEwan, a consultant with Simplicity and a Quality Management lecturer for UNB's department of Technology, Management and Entrepreneurship (TME) was contacted. After initial attempts, it was recommended that the standard VSM analysis be modified and subsequently a hybrid quality management model was proposed (McEwan 2017).

One reason for the modification was that the VSM analysis was developed specifically for use in the manufacturing industry where well-defined, repeatable activities are easily measured and mapped as illustrated by the standard VSM template shown in Figure 6.6 below ("Value Stream Mapping Template | Lucidchart" n.d.). Although the concept of waste detection and elimination can be applied to FM activities, mapping maintenance activity processes directly to standard VSM variables is difficult. The new model would capture value-add potential through efficiency gains in key KPI's already utilized by UNB FM. After the AM baseline analysis was conducted and it was determined that UNB FM had no formally defined AM KPI's, the value analysis was abandoned. Research by Beck et al. confirms the nascent state of maturity for VSM analysis with respect to BIM (Beck et al. 2016).

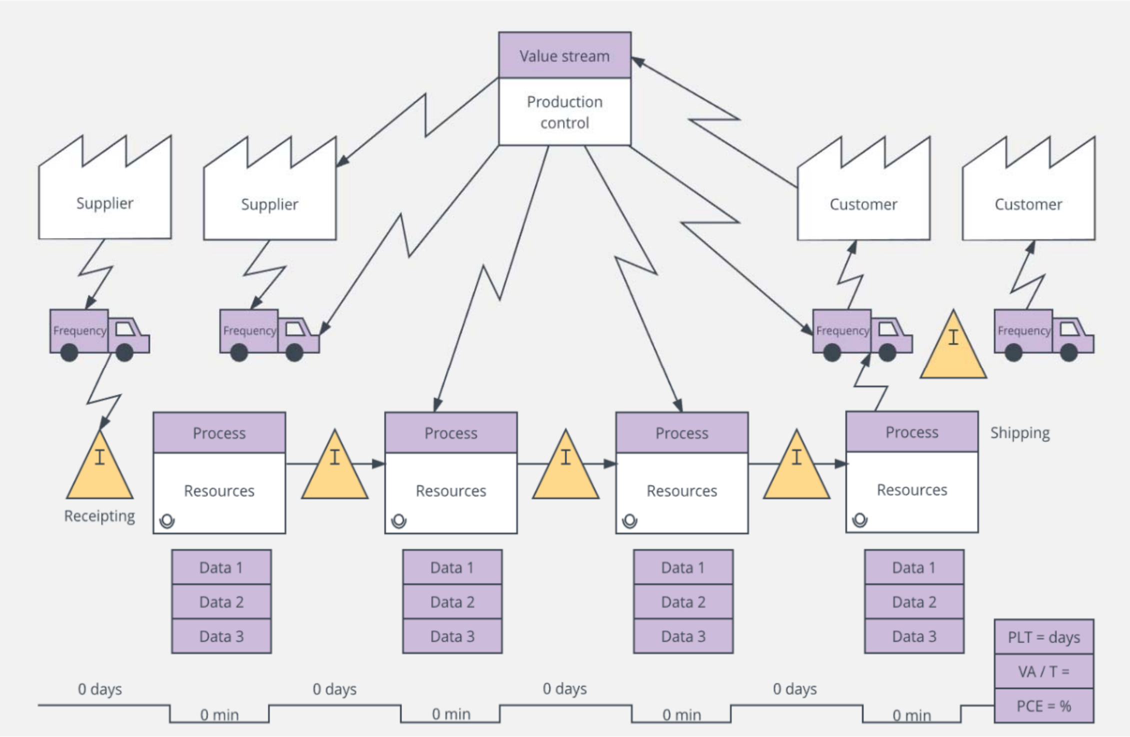

Figure 6.6 A standard VSM template

(https://www.lucidchart.com/pages/templates/value-stream-map/value-stream-mapping-template)

7 Contribution & Recommendations

Through a comprehensive literature review, this work details the investigation and analysis of software applications used to create civil infrastructure information models and the ability of those digital products to supply or integrate design and operational data into existing computerized facilities and asset management systems. It contributes an understanding of the state-of-the art and outlines both the technical and cultural limitations these systems currently face in providing added business value.

The literature demonstrates that significant advancement in both technology and implementation is required to deliver the full range of benefits that full CIM-AM integration can provide. The following section summarizes the findings previously discussed from three perspectives: a researcher perspective, an industry perspective; and a user perspective, which are from the UNB FM case study.

7.1 Researcher Perspective

The researcher perspective considers the technological maturity of civil information modelling from all levels of deployment including data, application and process (or implementation). At a data level, full CIM-AM integration currently is unavailable due to interoperability challenges. Generic file formats such as IFC that preserves complete element data, both graphical and non-graphical, are required for cross-platform data exchange.

Research by others supports the conclusion that further work is required to develop extensions for sector specific infrastructure data. For example, IFC Bridge is reasonably well-defined for bridge elements but IFC Road or IFC Rail have limited support. An interesting addition would be a subsurface utility Level of Confidence Layer of information. In a more fundamental way, development of ontologies and semantic web technologies is seen as critical to move IM data into a GIS environment and full CIM-GIS integration is likely to come from better mapping into the CityGML data type.

As many standards organizations such as buildingSMART continue to make progress with organizing and providing the necessary data structures, a significant effort must come from the software industry to fully support and implement these standards in the IM authoring platforms. At the application level, the case study illustrates the need to have processes and policies in place that standardizes asset information in a way that can be utilized by CIM-enabled enterprise asset management systems. Future work could include efforts to identify AM variables that map to IFC elements.

As the BIM Level 3 Mandate in the UK is forcing change across the industry, owners are demanding intelligent information models, driving increased adoption rates, and developing new use-cases. These conditions provide enormous research potential to produce infrastructure focused studies based on their BIM analogues from various stakeholder perspectives. For example, the analysis by Bradley et al. (2016) could be conducted from an FM perspective rather than the constructor perspective used, and the work by Fanning et al. (2014) on CIM for bridge projects could be replicated on road or other classes of infrastructure projects.

The literature also suggests that CIM-AM integration can deliver substantial value to asset owners when properly implemented. However, capturing and proving the true value has proven difficult for academics for several reasons. First, detailed project business data is difficult to secure from industry, sometimes for privacy reasons and sometimes for legal reasons. Second, value coming directly from CIM implementation (i.e. software deployment) is often expressed as an increase in “productivity”, a characteristic that can be composed of both quantitative and qualitative variables which can be difficult to objectively identify and measure. Also, when considering valuation after project handover would require an analysis of the use cases and would depend extensively on the AM processes utilized by the organization.

Lastly, with respect to technology, research in the use of ubiquitous sensor networks and the Internet of Things (IoT) for real-time condition updating or structural health monitoring is in its infancy but has enormous potential to combine with fully integrated systems.

7.2 Industry Perspective

The industry perspective considers the current general approach to CIM-AM integration at the process or implementation level. Probably more than the maturity and technological limitations of CIM-AM integration, the challenges surrounding implementation present the greatest barriers for integration. With respect to model development, bringing FM and AM personnel into the planning and design phases of capital projects is only beginning to be recognized as a benefit for downstream model use and often, there is no clear vision as to the requirements that might be necessary.

In the UK, this process is being driven by standardized high-level policy and technology implementation across workflows for all public projects. While this is mostly conceptual and requires significant resources to implement, this approach can provide the necessary roadmap for asset owners to capture the maximum value from CIM. For example, the

PAS1192 and ISO5500 standards are increasingly able to align project data and workflows to support the intended outcomes.

With respect to business value, the use of standard value stream mapping for capturing CIM-AM value-add potential may provide limited results since AM processes are often not linear and activity times are not well defined. Similarly, it has been shown that ROI has limited use in capturing value and would require extensive analysis to develop the necessary KPI’s. The UNB FM case study shows that a combination of valuation techniques should be employed to capture the value-add potential of CIM for asset management. Future work could focus on aligning business data such as KPI’s within a CIM.

7.3 User Perspective

The user or organization perspective considers the changes in moving from a current state to a future state with respect to a unique application of the technologies and processes outlined previously. Although the UNB FM case study was not fully implemented, the data collected from this research could provide a road map for full study in the future.

The UNB FM research project consisted of three modules that were considered in the following order:

1. **CIM Module**: The CIM module was structured to first understand the current technology and commercially available infrastructure information modelling capabilities, as well as the limitations with respect to integration with AM systems. Secondly, an information exchange model was required to understand data categories or classes of data and data structures or types, and the requirements to develop a prototype CIM-AM user interface.

2. **Asset Management Module**: The Asset Management module considered current AM standards, as well as the current practices and technologies developed and deployed by the organization. An analysis of the current capabilities and desired capabilities should identify AM requirements and provide the classes of data for use in the CIM module.
3. **Business Value Analysis Module**: The Business Value Analysis module considered methods for evaluating the effectiveness of integrated CIM-AM to deliver business value. An effort to identify qualitative and quantitate benefits and costs associated with implementing a CIM-AM integrated system through current workflows are required to generate a value analysis.

In terms of lessons learned, the information collected and developed in the Asset Management module should be developed first, followed by the Business Value Analysis module and then the CIM module. By developing the AM model first, the critical aspects of CIM-AM technology integration can be better understood early in the project and defining AM requirements and processes earlier would have identified the KPI's necessary to perform an efficient value analysis. However, more importantly than the actual new technology, the cultural issues surrounding the implementation of a new technology, as well as data governance challenges, are seen as the greatest barriers in project execution.

A full understanding of the requirements and scope of a project that challenges the status quo is critical and clear, frequent, communication is necessary to manage expectations. A well-defined project charter understood by all stakeholders is necessary to provide a mandate for personnel at all levels to engage with the process.

The development of a preliminary CIM like the Infraworks model in Figure 6.3 has the potential to identify gaps in the AM data and engaging with external expertise in computer science such as software coders to develop a prototype API or even a conceptual CIM-AM ontology; or business analysts to understand VSM symbology could potentially further most of the objectives set-out.

A properly structured and rigorously categorized literature review can provide a clear academic framework from which to approach the case study. While not necessary for an initial project proposal, documenting the methodology and results of a preliminary literature review at a pre-determined milestone can greatly help determine the scope of the project.

7.4 Summary

In summary, at both the process and application level, asset management tools are fully mature and commercially available software include capabilities for extensive customization for data analysis; whereas authoring tools for Civil Infrastructure Modelling are approaching a level of maturity on par with those for vertical construction within proprietary software environments. For instance, Autodesk products have comprehensive functionality and "play well" with other Autodesk products, and likewise for Bentley Systems products. As both companies continue to move authoring platforms to a Software as a Service (SaaS) subscription model, project information is increasingly able to leverage more powerful parallel computing through cloud-based services.

However, as information models become more complex and include greater and finer detail, challenges in terms of interoperability and data management can increase exponentially. Moreover, implementation of information modelling as a process for delivering civil infrastructure projects has yet to be standardized for all phases and typically requires a large investment in information-technology infrastructure. IM and VDC coordinators are currently filling this role but the lack of information management plans and policies as well as stakeholder participation, particularly at the concept and planning phases, can limit the usefulness of CIM's downstream. For public or P3 projects, it must be incumbent on the procurement agency to have a comprehensive digital information management strategy that can utilize CIM as a real-time data repository and delivery method.

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Appendix A

Is AM relevant to UNB FM?

The following questions were posed with respect to infrastructure asset classes within UNB.

Do any of the following apply? - Indicate True or False (T/F)

1) It is difficult to demonstrate cost effectiveness to key stakeholders (customers, government agencies, regulators, shareholders, etc.). T/F

2) Financial/Commercial and technical / engineering staff and parts of the organization do not speak the same language, and this results in delays, frustrations and missed opportunities. **T**/F *- to some extent. This is being mitigated through an initiative by the V.P. of Campus Operations*

3) Risk management is patchy and inconsistent, and not a systemic part of normal decision-making processes, or different approaches are used in safety, environmental management, asset reliability performance and enterprise risk management. ***T*** *– Project group vs Maint. Group - also* ***F****- Safety is systemic*

4) Organizational culture is fragmented – with departments working on their own agendas and performance measures, creating conflict and de-motivation. T/**F** *– felt they are past this. Used to be siloed*

5) There are operational cost inefficiencies, with too many teams competing and duplicating activities, without alignment of objectives and resources. T/**F**

6) There are too many surprises and too many incidents requiring tactical “fire-fighting”, despite increased levels of asset investment. **T**/F

7) There is no clear strategy to address gaps between what the organization requires of its assets in the medium and long-term and their current capability. T/**F**

8) There is a lack of, or inconsistency in, long-term investment plans and business justification for which projects should go-ahead, and with what urgency. T/**F**

9) The asset portfolio is aging, or subject to technology obsolescence, and needs significant re-investment but funds are constrained and there is no process for evaluating which investments are most important or how urgent. T/**F** - *Process in place*

10) There is no single, correct source of information about what assets actually exist, in what condition, providing what function, and where. Data is fragmented, out of date and/or not trusted. T/**F** – *to some extent. VFA is used but not to full capacity. This is a gap that is being bridged*

Appendix B

The IAM's Asset Management Conceptual Model – Maturity Assessment Criteria

No.	Subject Group	Subject Title	Criteria *(per subject)*	Criteria *(per group)*
1	Strategy and Planning	Asset Management Policy	8	41
2		Asset Management Strategy and Objectives	12	
3		Demand Analysis	6	
4		Strategic Planning	5	
5		Asset Management Planning	10	
6	Asset Management Decision-Making	Capital Investment Decision-Making	8	33
7		Operations and Maintenance Decision-Making	6	
8		Lifecycle Value Realization	5	
9		Resourcing Strategy	8	
10		Shutdowns and Outage Strategy	6	
11	Lifecycle Delivery	Technical Standards and Legislation	9	90
12		Asset Creation and Acquisition	7	
13		Systems Engineering	7	
14		Configuration Management	9	
15		Maintenance Delivery	9	
16		Reliability Engineering	10	
17		Asset Operations	10	
18		Resource Management	8	
19		Shutdown and Outage Management	6	
20		Faults and Incident Response	9	
21		Asset Decommissioning and Disposal	6	
22	Asset Information	Asset Information Strategy	10	32
23		Asset Information Standards	6	
24		Asset Information Systems	6	
25		Data and Information Management	10	

26	Organization and People	Procurement and Supply Chain Management	12	48
27		Asset Management Leadership	13	
28		Organizational Structure	11	
29		Organizational Culture	12	
30	Risk and Review	Competence Management	9	71
31		Risk Assessment and Management	13	
32		Contingency Planning and Resilience Analysis	7	
33		Sustainable Development	3	
34		Management of Change	5	
35		Asset Performance and Health Monitoring	7	
36		Asset Management System Monitoring	7	
37		Management Review, Audit and Assurance	8	
38		Asset Costing and Valuation	7	
39		Stakeholder Engagement	5	
		Total	315	315

Figure B.1 The IAM's AM Conceptual Model – Maturity Assessment Criteria

(Holdsworth et al. 2015)

Appendix C

Maggie Jean Chestnut Building AM Activity Decision Tree

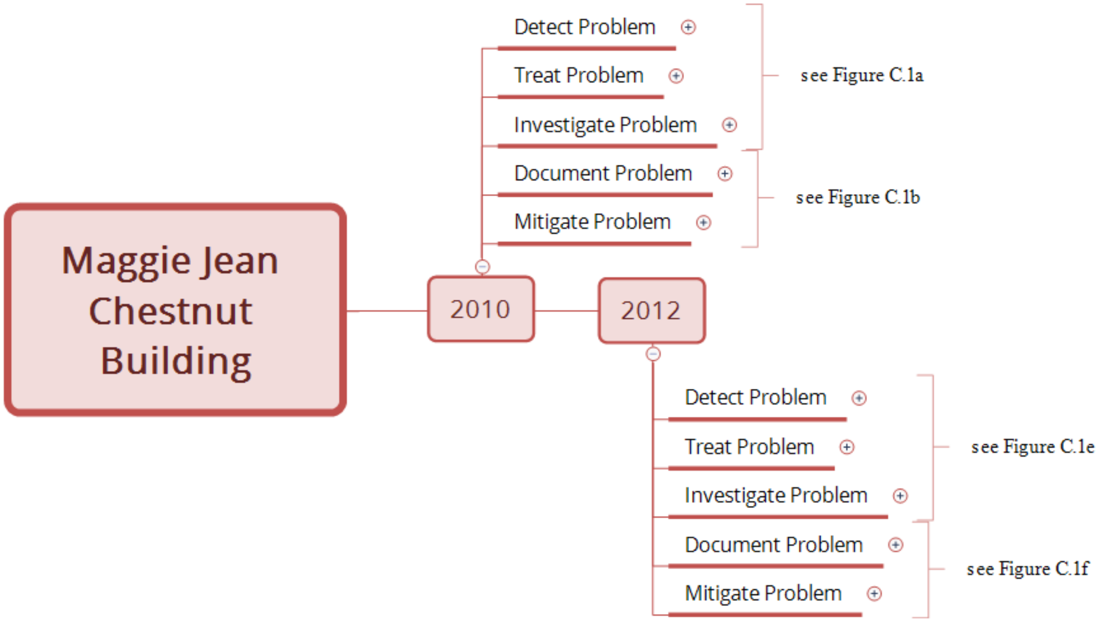

Figure C.1 Maggie Jean Chestnut Building AM Activity Decision Tree

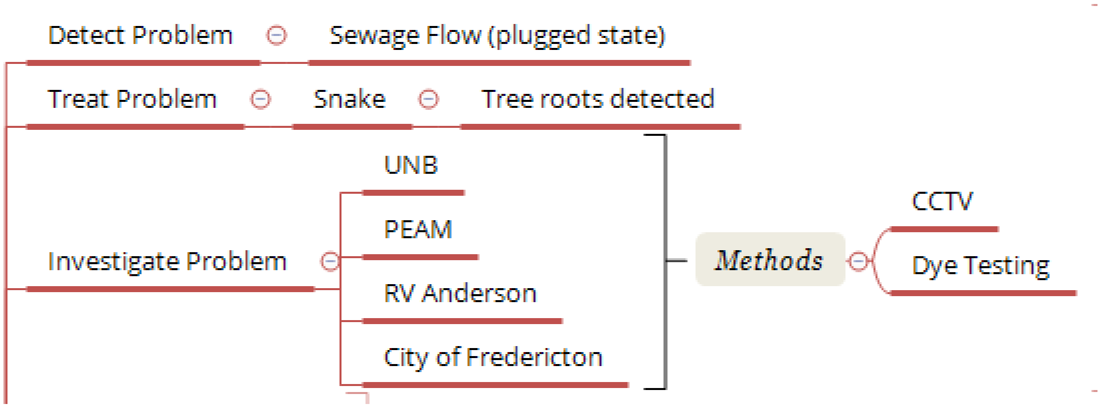

Figure C.1a

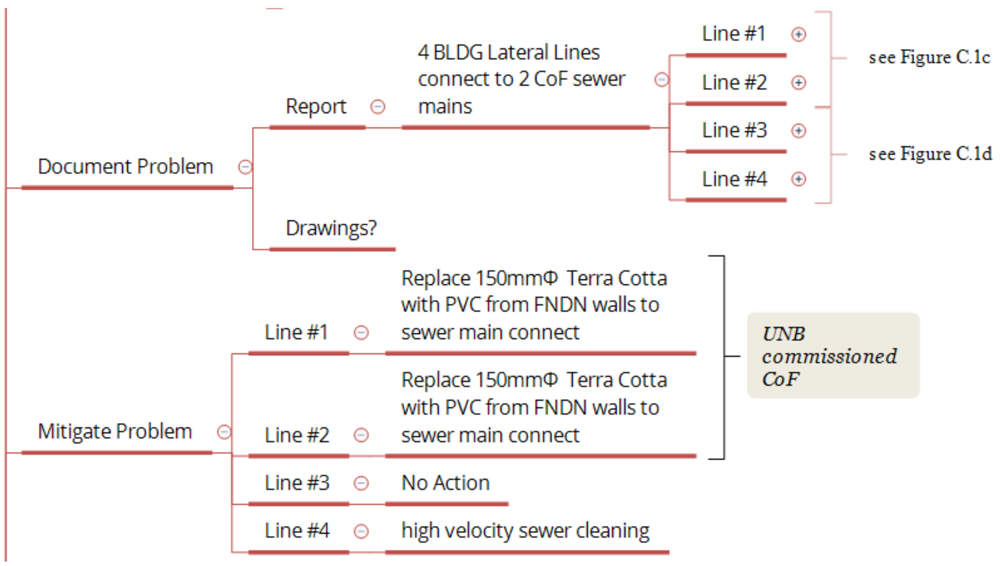

Figure C.1b

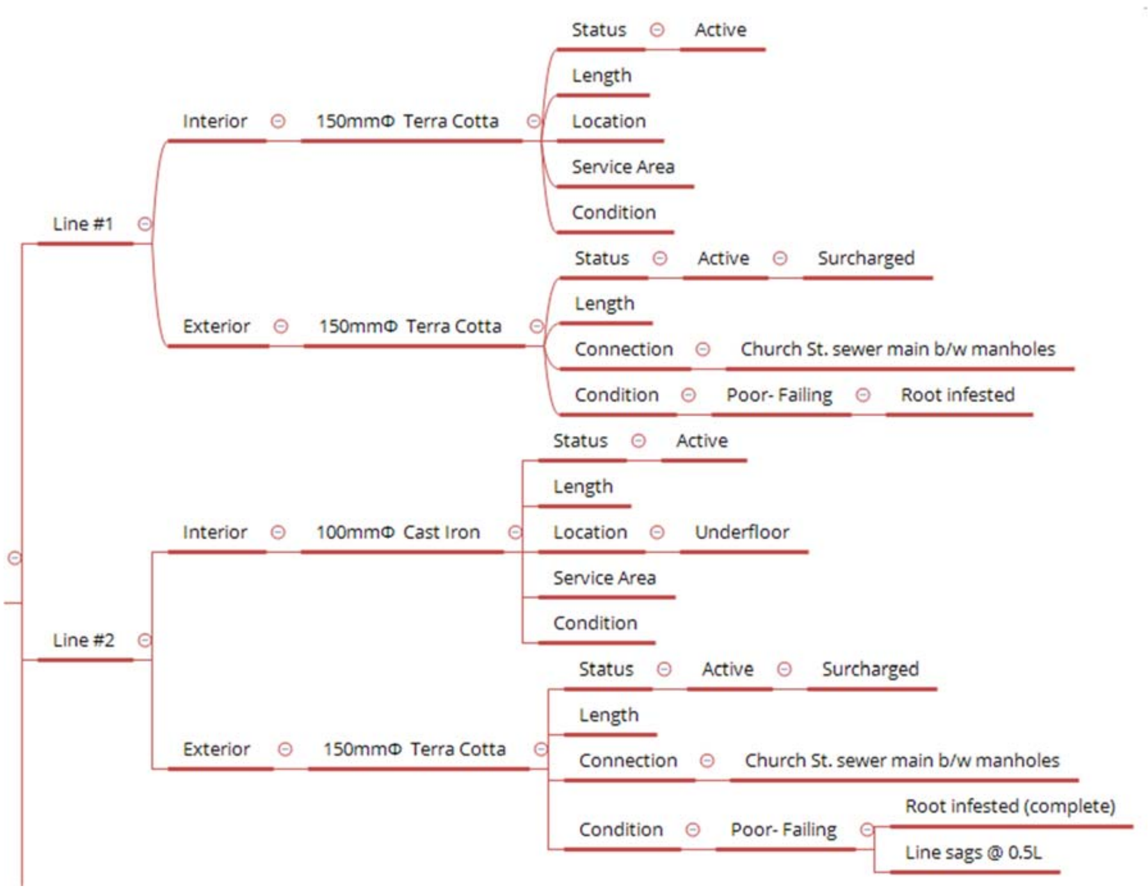

Figure C.1c

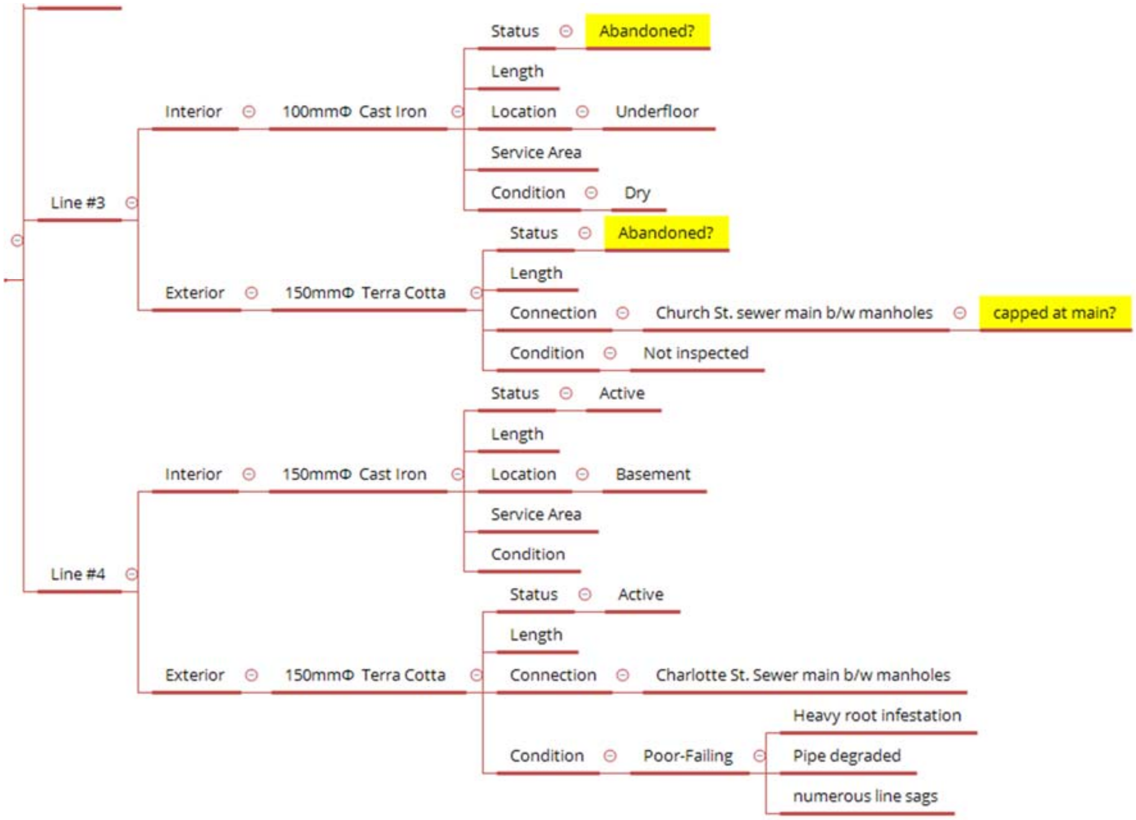
Line #3
Interior
100mmΦ Cast Iron
Status
Abandoned?
Length
Location
Underfloor
Service Area
Condition
Dry
Exterior
150mmΦ Terra Cotta
Status
Abandoned?
Length
Connection
Church St. sewer main b/w manholes
capped at main?
Condition
Not inspected
Line #4
Interior
150mmΦ Cast Iron
Status
Active
Length
Location
Basement
Service Area
Condition
Exterior
150mmΦ Terra Cotta
Status
Active
Length
Connection
Charlotte St. Sewer main b/w manholes
Condition
Poor-Failing
Heavy root infestation
Pipe degraded
numerous line sags

Figure C.1d

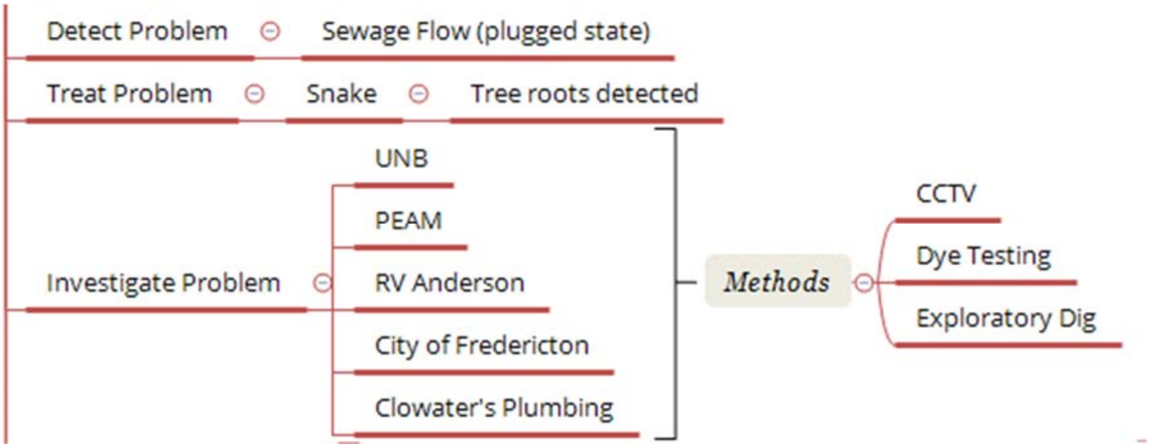

Figure C.1e

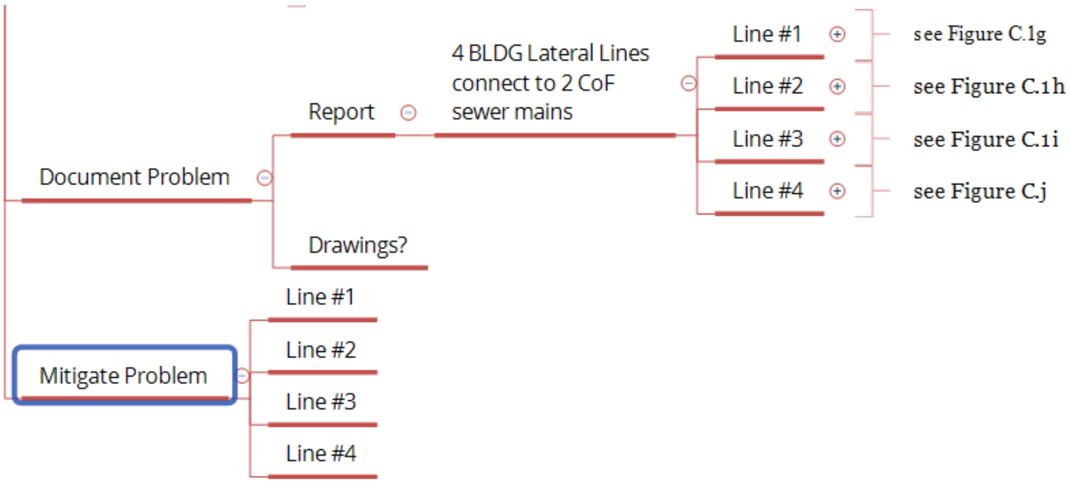

Figure C.1f

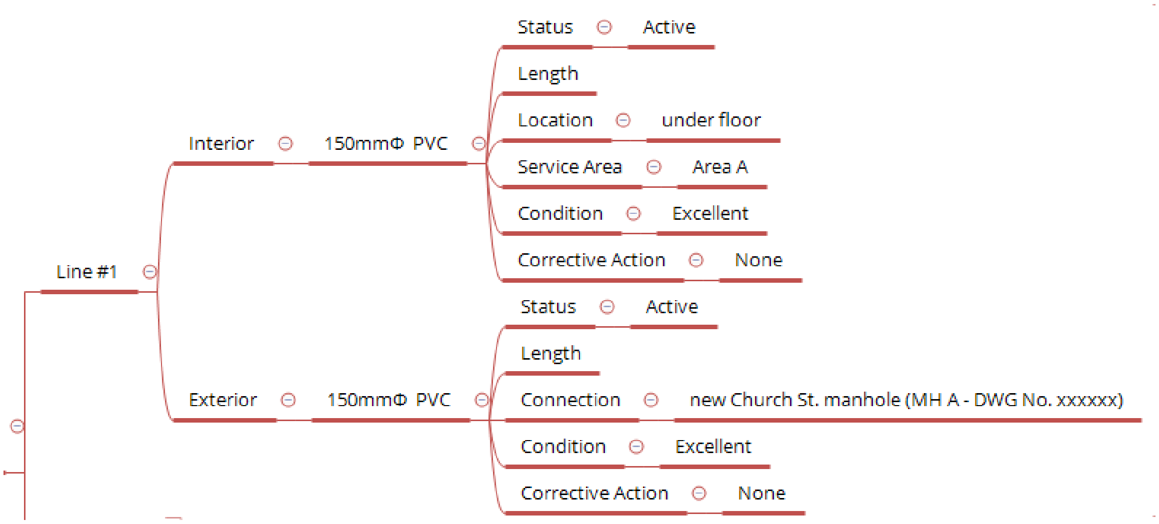
Line #1
Interior
150mmΦ PVC
Status
Active
Length
Location
under floor
Service Area
Area A
Condition
Excellent
Corrective Action
None
Exterior
150mmΦ PVC
Status
Active
Length
Connection
new Church St. manhole (MH A - DWG No. xxxxxx)
Condition
Excellent
Corrective Action
None

Figure C.1g

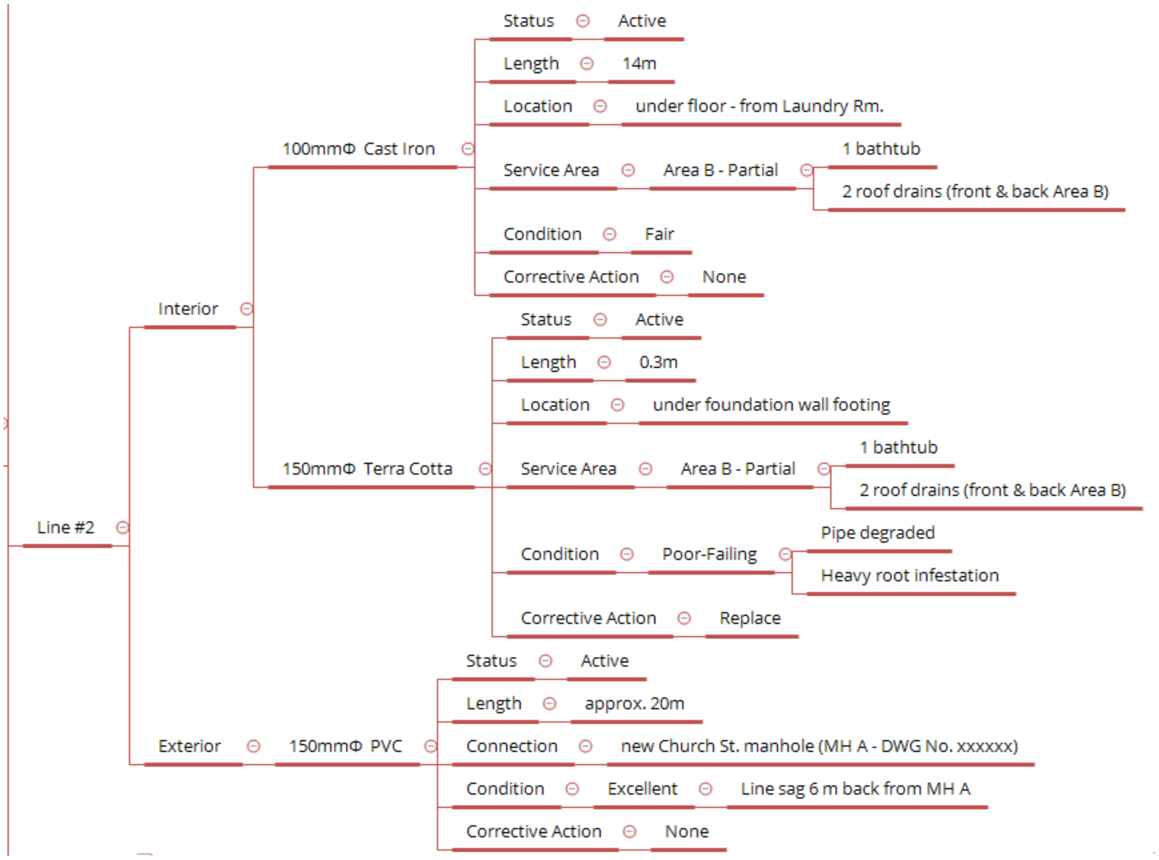

Figure C.1h

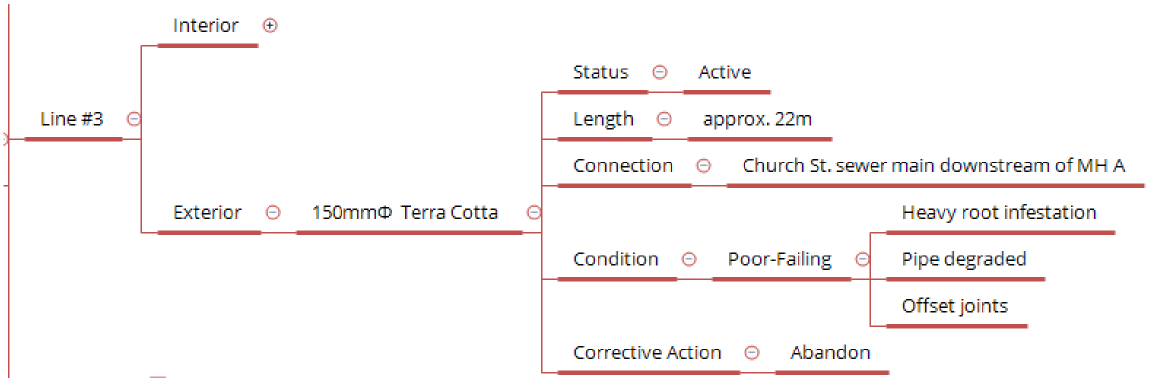

Figure C.1i

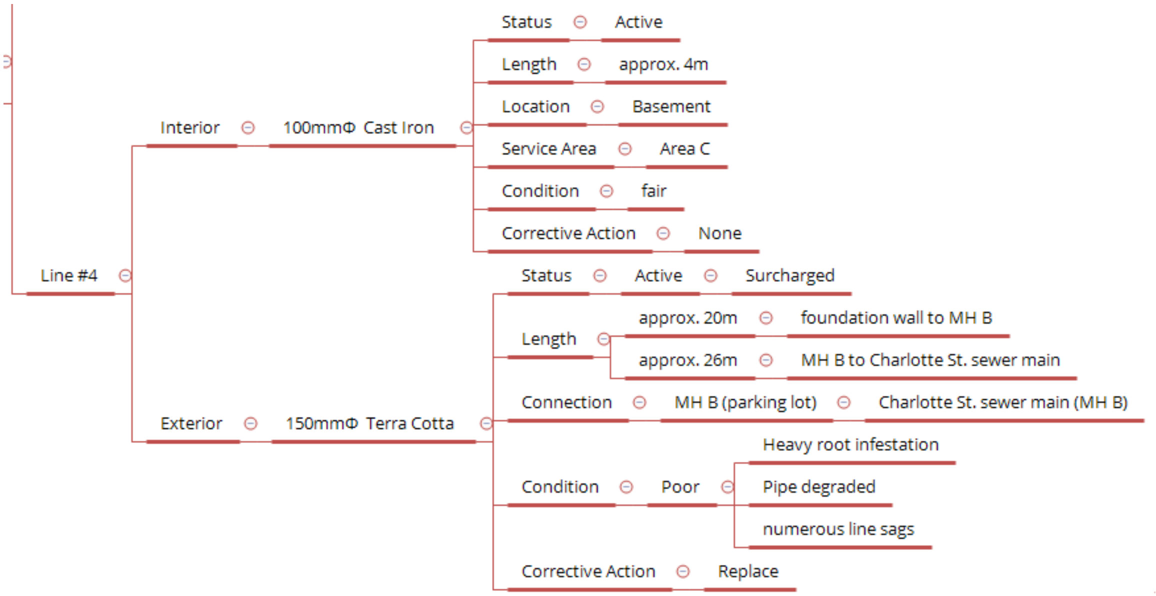
Status
Active
Length
approx. 4m
Location
Basement
Interior
100mmΦ Cast Iron
Service Area
Area C
Condition
fair
Corrective Action
None
Line #4
Status
Active
Surcharged
approx. 20m
foundation wall to MH B
Length
approx. 26m
MH B to Charlotte St. sewer main
Connection
MH B (parking lot)
Charlotte St. sewer main (MH B)
Exterior
150mmΦ Terra Cotta
Heavy root infestation
Condition
Poor
Pipe degraded
numerous line sags
Corrective Action
Replace

Figure C.1j

Curriculum Vitae

Candidate's full name: Jeremy James Bowmaster

Universities attended (with dates and degrees obtained):

University of New Brunswick, BScE, 2015

Publication(s):

E-Business in the Architecture, Engineering and Construction (AEC) Industry in Canada: An Atlantic Canada Study, International Council for Research and Innovation in Building and Construction, TG83: e-Business in Construction, Nov. 2016, ISBN: 978-90-803022-5-9

Conference Presentations: None