Measuring and Visualizing Integrated Project Interface Status

by

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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Chapter 2 of this thesis contains parts of two papers co-authored by myself, my research team colleagues Dr. Benjamin Sanchez and Seoukyoung Kang, and my supervisor Dr. Haas. I developed the methodology and research design of the paper, with input from Dr. Sanchez, Dr, Haas, and Ms. Kang.

> Eray, E., Sanchez, B., Haas, C. (2019) Usage of Interface Management System in Adaptive Reuse of Buildings, Buildings, 9(5), 105,

> Eray, E. Sanchez, B., Kang, S., Haas, C. (2019) Usage of Interface Management in Adaptive Reuse of Buildings, in Advances in Informatics and Computing in Civil and Construction Engineering, Cham: Springer International Publishing, pp. 725–731.

Chapter 2, Chapter 3, and Chapter 5 of this thesis contain parts of a paper co-authored by myself, and my supervisors Dr. Haas and Dr. Rayside. I developed the methodology for the analysis and wrote the paper based on findings, all with input from Dr. Haas and Dr. Rayside.

> Eray, E., Haas C., Rayside, D. (2019) A Model for Measuring Interface Health between Project Stakeholders in Complex Construction Projects, 7th CSCE/CRC International Construction Specialty Conference, in Laval, QC, Canada, from June 12th to June 15th, 2019z

Chapter 2, Chapter 4 and Chapter 5 of this thesis contain parts of a paper co-authored by myself, my supervisors Dr. Haas and Dr. Rayside, and Dr. Mani Golparvar-Fard from University of Illinois at Urbana-Champaign. I wrote the paper based on the literature review and research on Track design, all with the input from Dr. Haas, Dr. Rayside, and Dr. Golparvar-Fard.

> Eray E., Haas C., Rayside, D., Golparvar-Fard, M. (2018) A conceptual framework for tracking design completeness of the Track Line discipline in Mass Rapid Transit projects, 35th International Symposium on Automation and Robotics in Construction (ISARC 2018), in Berlin, Germany, from July 20th to July 25th, 2018

Chapter 2 and Chapter 5 of this thesis contains parts of a paper co-authored by myself, my supervisors Dr. Haas and Dr. Rayside, and my research team colleague Dr. Behrooz Golzarpoor. I developed the methodology for the analysis and wrote the paper based on the findings, all with input from Dr. Haas, and Dr. Rayside, and Dr. Golzarpoor.

> Eray E., Golzarpoor B., Rayside D., Haas C. (2017) An Overview on Integrating Interface Management and Building Information Management Systems, 6th CSCE/CRC International Construction Specialty Conference, in Vancouver, BC, Canada, from May 31st to June 3rd, 2017

Chapter 3 and Chapter 5 of this thesis contains parts of a paper in progress co-authored by myself, my supervisors Dr. Haas and Dr. Rayside. I developed the methodology for the analysis and wrote the paper based on the findings, all with input from Dr. Haas, and Dr. Rayside.

> Eray, E., Haas, C., Rayside, D., An Integrated Approach for Analyzing Interface Workload and Interface Health Between Stakeholders Involved in Complex Construction Projects, to be submitted to Journal of Construction Engineering and Management

Abstract

The overall goal of this thesis is to develop and validate ways to effectively measure and visualize integrated project interface status in terms of interface health, workload, and engineering progress. Collaboration, communication, and interactions between project stakeholders have a high impact on the overall success of complex capital projects. Managing interactions between stakeholders, tracking deliverables, measuring workload, and measuring engineering progress is particularly important in the early phases of complex capital projects. Early phases include: (a) project definition, (b) conceptual plan and preliminary design, (c) detailed design, and (d) procurement. Due to the iterative nature of design and the cyclic nature of the communications and deliverables between project stakeholders, any decision made in those phases or any health problem between project stakeholders, such as misalignment or miscommunications, has a critical effect on the remainder of the project. These complexities are beyond the capabilities of traditional project management methods such as CPM (critical path method) scheduling and Earned Value Analysis. To manage these projects and their complex nature, new methods that can detect overloaded interfaces, identify unhealthy relationships between stakeholders and measure engineering progress are needed in addition to the existing traditional project management methods in the construction industry.

Consistent with the overall goal of this thesis, the objectives of this thesis are to (1) develop methods to measure and visualize health and workload between project stakeholders, and (2) develop methods to measure and visualize engineering progress by using BIM (Building Information Model) and IMS (Interface Management System) related data.

To address the first objective, a project monitoring method named Integrated Project Monitoring Method (Contribution-1, C1) that visualizes interface health and workload measurements within the stakeholder interface network is introduced. To populate this visualization for a given project, both quantitative (C2: Framework-A) and qualitative (C3: Framework-B) measurements of early-phase project health and workload are developed. The quantitative analysis receives its inputs from project electronic information management systems, including: Interface Management Systems, Project Schedules, Change Management systems, Document Management systems, and related information technology (IT), as well as workflow management systems. The qualitative analyses receives its inputs using a novel, simplified qualitative point system developed as part of this thesis.

To address the second objective, a novel connection between Interface Management Systems (IMS) and Building Information Management (BIM) data (C4: BIM+IMS Connector) is proposed and Model Maturity Index (MMI) definitions for Mass Rapid Transit domain (C5: MRT-MMI), as well as corresponding assessment and visualization tools (C6: MRT-MMI-AT) are developed.

The methodological contributions (C1-C4) of this thesis combine to form a holistic approach to measuring and visualizing project health and workload in the early phases of project progress, with the potential to give owners and managers early indications about where additional efforts might be best applied to support project success.

The validation of this thesis was done across several different projects in different domains. The two primary domains of validation were Mass Rapid Transit (MRT) and Nuclear Power Generation (NPG), with various subdomains in each being considered. It is concluded that measuring interface health and workload between project stakeholders in complex projects, such as MRT and NPG projects, and measuring engineering progress during the early phases of the MRT projects is feasible by using the tools and frameworks developed and presented in this thesis.

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Dedication

This thesis is dedicated to my parents Şayide Işık and Muhammet Metin Eray, and my brother Anıl Kıvılcım Eray, whose unconditional love and support made this a possibility.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background and Motivation

Defining complexity in construction projects is a challenge. Mass rapid transit systems, refineries, nuclear power plants, and port facilities, are often considered complex because they involve large numbers of project stakeholders with different backgrounds and locations, employ new technologies, have logically intricate activity relationships, involve multiple contract types within a sophisticated delivery and governance structure, and have a high cost as well as exposure to risk (Shokri, 2014; Shokri, Haas, et al., 2016; Shokri et al., 2011). Typically, these projects end up completed late, and occasionally, billions of dollars over budget, though they can be managed successfully.

Effective communication amongst all of the stakeholders is one of the most critical success factors in project management. Often, miscommunication between stakeholders leads to inefficient processes and project delays. According to the Project Management Institute's (PMI) Pulse Report' (2013) findings, on average, two-in-five projects do not meet the original project goals, and one-in-five projects are unsuccessful due to ineffective communication (PMI, 2013). That shows how crucial it is to manage communication and connections across stakeholders for meeting project goals.

Management of stakeholder relationships, workloads, deliverables, and measurement of engineering progress are particularly important in the early phases of a project which are accepted as *project definition, conceptual plan and preliminary design, detailed design, and procurement phases* in this thesis. Even though any decision made in those phases has a significant effect on the remainder of the project, limited attention has been given to those phases (Austin et al., 2002). Traditional project management methods, such as CPM, do not completely cope with these complexities, nor do they explicitly handle the iterative nature of design or the cyclic nature of communication and deliverables among stakeholders in the early phases of complex capital projects (Austin et al., 2002; Lawrence & Scanlan, 2007; Srour et al., 2013). In order to manage such projects and achieve project goals, new methods that can detect overloaded interfaces or unhealthy relationships between stakeholders, and measure engineering progress are crucial in the construction industry.

Several promising practices, tools and systems are emerging for management of complex projects in the early project definition, design and procurement phases. They include various electronic information management systems such as: Interface Management (IM), automated Change Management (CM), Request for Information (RFI), Contract Management, Deliverables Management, Building Information Modeling (BIM), Document Management Systems (DMS), Collaboration Management Systems (CMS), Workflow Management Systems (WfMS), as well as processes and practices, such as Front End Engineering Design (FEED), Project Definition Rating Index (PDRI), etc (El-Gohary & El-Diraby, 2010). However, while each of these systems solve some aspect of the management problems posed, they are not well integrated in theory and practice.

Conventional project management approaches such as CPM scheduling and Earned Value Analysis remain the backbone of modern project management; however, today's projects rely on more sophisticated systems that employ iterative methodologies. In this thesis, the question of how to measure engineering progress and project health during the early phases of complex capital projects is explored. *Progress measurement* is defined as a quantitative assessment of the state of development of a project between conception and delivery for use. *State of development* can be defined for example by the level of detail in 3D design (e.g. BIM), process models, risk registers, public consultations, permits, right-of-way, project delivery method, procurement specifications, and other project definition and design elements. *Health measurement* is defined as a quantitative and qualitative assessment of the state of functionality of stakeholder collaboration in the project. Quantitative assessment includes, for example, the percent of stakeholder interface agreement deliverables submitted on-time, or the response time distribution for requests for information. Qualitative assessment includes, for example, perception of alignment amongst stakeholders, confidence in project leadership, participant satisfaction, stress levels, and other factors. Methods exist for progress and health measurement, and those methods are explained in Chapter 2 of this thesis; however, they are poorly developed for the early phases of complex projects.

Improved measurement of project health and engineering progress at the early phases of complex capital projects is required in order to improve their performance. To improve and measure project health and engineering processes, relations among currently dominant collaboration and management systems used for the early phases of complex projects must be developed. Such systems include Interface Management Systems (IMS) which is used for managing communications and deliverables between project stakeholders with a process oriented approach, Building Information Modeling (BIM) systems (as well as their industrial and infrastructure equivalents) which is used for creating an intelligent model of a project with an object oriented approach, and conventional CPM-based project management systems. More detailed explanation of IMS and BIM are given in Chapter 2.

1.2 Research Objectives

The overall goal of the proposed research is to develop and validate methods for measuring and visualizing integrated project interface status between project stakeholders in terms of health, workload, and engineering progress. Consistent with the overall goal, the objectives and the sub-objectives that need to be covered in this thesis include:

1. Develop and validate methods to measure and visualize *health* and *workload* between project stakeholders involving:
    - Definition of quantitative interface health indicators that can be calculated automatically by actual project data
    - Definition of qualitative interface health and workload indicators that need human analysis and input for the calculation
    - Development of models based on both qualitative and quantitative indicators to measure interface health between project stakeholders
    - Development of models to visualize present project health between project participants in semantically rich and useful forms.
2. Develop and validate methods to measure and visualize *engineering progress* by using BIM and IMS related data involving:
    - Development of a framework for database-level integration of BIM and IMS
    - Definition of design progress measurement criteria and attributes
    - Development of a model to assess design maturity

1.3 Research Premises

The two key premises of this research are;

1. Measuring and visualizing health and workload between project stakeholders will facilitate early detection and more effective diagnosis of overall project health problems in complex capital projects.

2. Project design progress can be tracked more accurately with integrated BIM and Project Information Management systems, such as IMS.

1.4 Research Scope

This research study was conducted within the following scope:

- Complex Capital Projects with the focus on large scale Mass Rapid Transit (MRT) projects, totaling hundreds of billions of dollars annual activity globally, and Nuclear Power Plant Refurbishment projects which have an average capital cost of approximately $2 billion (CAD) per Station Unit in Canada (CME, 2010; Fernandez, 2019),
- Early phases of the projects include project definition, conceptual planning, preliminary design, detailed design, and procurement phases.

1.5 Research Methodology

The proposed methodology is illustrated as a flowchart in Figure 1. Overall, the research methodology has five main sections: preliminary stage, design and implementation, data collection, visualization and validation, and documentation.

Detailed descriptions of the required steps associated with the above approach and objectives are as follows:

1- **Literature review:** Conduct a comprehensive literature review on 3D information modeling; project information management systems; interface management systems; project tracking, control, and monitoring; building information modeling; level of development; model maturity index; project health indicators; and social network analysis.

2- **Health and Workload Measurement:** Select interface health and workload indicators from the literature and define metrics and methods to calculate them by the structured and unstructured data.

3- **Dashboard Development:** Generate qualitative and quantitative, interrogatable, data-based dashboards to show interface health conditions between project stakeholders.

4- **Integration:** Establish links and ways to manage them between IM and BIM systems by connecting interface points to related 3D BIM components. The links can be established by connecting common features in the 3D BIM and IMS such as; project specifications, location and dimensions of the elements, and Industry Foundation Classes (IFCs).

5- **Formalization:** Develop new engineering progress measurement definitions for Mass Rapid Transit Projects.

6- **Data collection:** Conduct research meetings with industry partners and collect data for health and engineering progress measurements from one or more sample projects.

7- **Model Development:** Review several Mass Rapid Transit projects, and create a synthesized 3D BIM model and IM network systems. Define interface points between project participants on both the 3D BIM and the IM network. Generalize the models.

8- **Monitoring:** Measure interface health and workload between project stakeholders and assess project engineering progress according to data obtained from the IM system and 3D BIM model. Develop a panel that shows results.

9- **Validation:** Validate the proposed methods on sample data collected via functional demonstration and feedback from industry experts.

10- **Documentation and dissemination:** Document and present the findings of this research via periodic reports, conference and journal papers and PhD thesis.

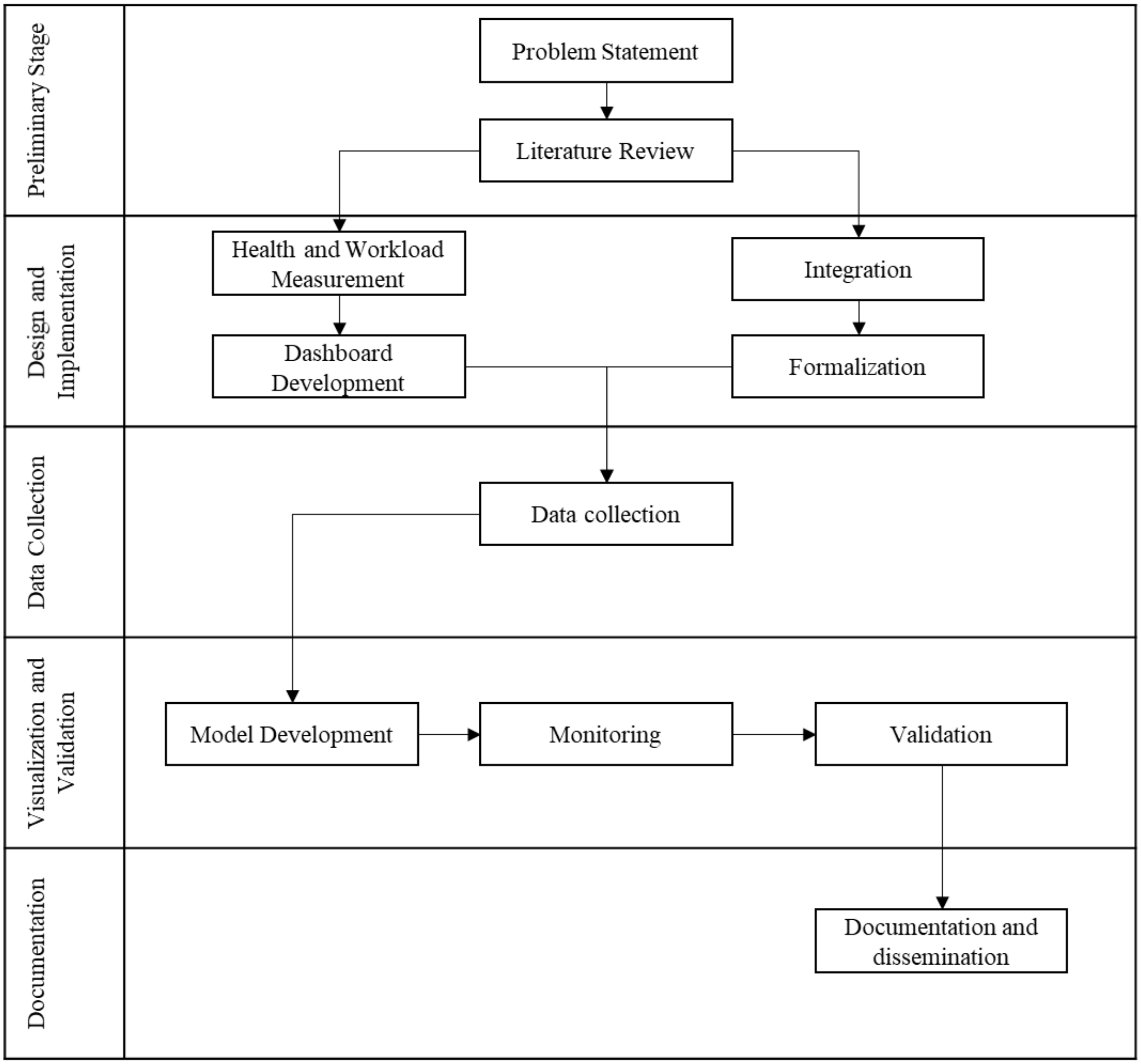


Figure 1 Research Methodology Flowchart

1.6 Thesis Structure

This thesis is organized into six chapters. In Chapter One, an overview of the background and motivation of the project, research objectives, scope, and methodology is provided.

In Chapter Two, the literature review and background information about Interface Management (IM) system and its elements, Building Information Modelling (BIM) and its components, project health and interface health, engineering progress measurement methods, and Social Network Analysis are presented.

In Chapter Three, stakeholder interface networks and the methodology of how to measure interface health and workload between project stakeholders is explained.

In Chapter Four, a framework overview of database-level integration of BIM and IMS and conceptual engineering progress measurement definitions and corresponding assessment tools for Mass Rapid Transit Systems are presented.

In Chapter Five, validation of the proposed framework and models are presented. The proposed Integrated Project Monitoring Method is validated through applications on six complex construction projects from two major industry segments: Mass Rapid Transit (MRT) and Nuclear Power Generation (NPG). In order to validate the BIM and IM system integration and engineering progress measurement definitions and assessment tools, a hypothetical railway model is created. Functional validation of the proposed model is presented through a railway project created.

In Chapter Six, a summary of this research, contributions, limitations, and recommendations for future work is provided.

Chapter 2

Literature Review

2.1 Introduction to Project Management Information Systems

Managing and controlling information and document exchange between project participants is one of the most important elements to successfully accomplish projects. There are several project management techniques in literature and software on the market today. Some of the most known project management systems are Change Management, Deliverables Management, Request for Information, and Interface Management Systems (IMSs). In this proposal, all of these systems are covered under the Project Management Information Systems (PMIS) definition. In the PMBOK Guide 5th Edition, PMIS is defined as “An information system consisting of the tools and techniques used to gather, integrate, and disseminate the outputs of project management processes (Rose, 2013). It is used to support all aspects of the project from initiating through closing, and can include both manual and automated systems.” Among the aforementioned systems, the main focus of this research is on the IMS. Therefore, detailed explanations for other systems are not provided in this Chapter.

2.2 Introduction to Interface Management Systems (IMS)

The concept of Interface Management (IM) was first introduced as a subset of systems engineering in the 1960s, and the first applications of IM were in the aerospace industry (Construction Industry Institute, 2014). Today, there are several different definitions and classifications of the term “interface” in literature. One of the initial definitions, based on a systems approach, was given by Wren (1967) as “the contact point between relatively autonomous organizations which are interdependent and interacting as they seek to cooperate to achieve some larger system objectives” (Wren, 1967). Over the years, various researchers proposed more definitions for the term “interface”. Today many researchers consider an interface as “a common boundary or interconnection between independent but interacting systems, organizations, stakeholders, project phases and scopes, and construction elements” (Chen et al., 2007; Healy, 1997; Lin, 2013, 2009; Morris, 1997; Stuckenbruck, 2008; Wren, 1967).

Interface management (IM) can be defined as the process of managing project-related communications, project stakeholders’ responsibilities, project phases and physical entities (Shokri, Ahn, et al., 2016; Weshah et al., 2013; Wren, 1967). In general, IM is used in complex projects and executed by a large number of stakeholders who have different specializations, with many overlapping activities. In 2014, Construction Industry Institute (CII) introduced the IM implementation guide where definitions of IMS elements, and effective IM practices that can be applied broadly on different types of construction projects, are explained (Construction Industry Institute, 2014). According to the guideline, IMS is defined as “the management of communications, relationships, and deliverables among two or more interface stakeholders” (Construction Industry Institute, 2014). Interface Management Systems (IMS), which focus on managing the communications, relationships, and deliverables between project stakeholders, are a potential solution for managing complex projects, through defining better ways to identify, record, monitor, and track the project interfaces (Eray, Sanchez, et al., 2019).

Interfaces are generated when projects are divided into several sub-projects undertaken by different organizations (Chua & Godinot, 2006; Shokri, 2014; Stuckenbruck, 2008), and can be classified as soft or hard in a project. In the literature, information exchanges between project participants such as design criteria, clearance requirements, and specifications related interactions between engineering delivery teams or between a delivery team and an external party are accepted as examples of soft interface deliverables. Examples of hard interfaces include physical connections between two or more components or systems such as structural steel connections, pipe terminations, or cable connections. Also, interfaces can be external or internal depending on how the work related to the interface is done. An interface within a single contract or scope of work can be considered internal, whereas if it occurs between contracts or scopes of work, then it can be considered external. Moreover, more detailed classification of interfaces such as time interfaces, geographical interface, technical interface, and organizational interface can be found in literature too (Chua & Godinot, 2006; Eray, Sanchez, et al., 2019; Shokri, 2014).

2.2.1 Elements of IMS

A typical Interface Management System (IMS) would consist of six main components: Interface Stakeholders, Interface Points (IPs), Interface Agreements (IAs), Interface Action Items (IAIs), Interface Agreement Deliverables (IADs), and Interface Control Document/Drawings (ICDs). The definitions of these typical elements are as follows:

- **Interface Stakeholder:** An organization that participated in a formal Interface Agreement which is within an IM plan of the project.

- **Interface Points (IPs):** "An IP is a soft and/or hard contact point between two interdependent interface stakeholders" (Shokri 2014).
- **Interface Agreements (IAs):** A document that presents the communication and agreements between two Interface Stakeholders over an IP. It includes descriptions of interface deliverables, need dates, and required actions for that specific IP.
- **Interface Action Items (IAIs):** A document that shows the tasks and activities completed to provide the IA deliverables that are defined in the related IA.
- **Interface Control Document/Drawing (ICDs):** A document that presents the information related to the IP and its approved interface change requests.
- **Interface Agreement Deliverables (IADs):** In order to generalize these terms, from this point on IAIs and ICDs will be mentioned as Interface Agreement Deliverables (IADs) in this proposal.

Generally, an IMS may include dozens if not hundreds of IPs, each IP may include multiple IAs, and each IA may include various types of IADs. Therefore, there could be numerous IADs in a system (Shokri, 2014; Shokri, Haas, et al., 2016). A simplified IMS hierarchy can be seen on Figure 2.

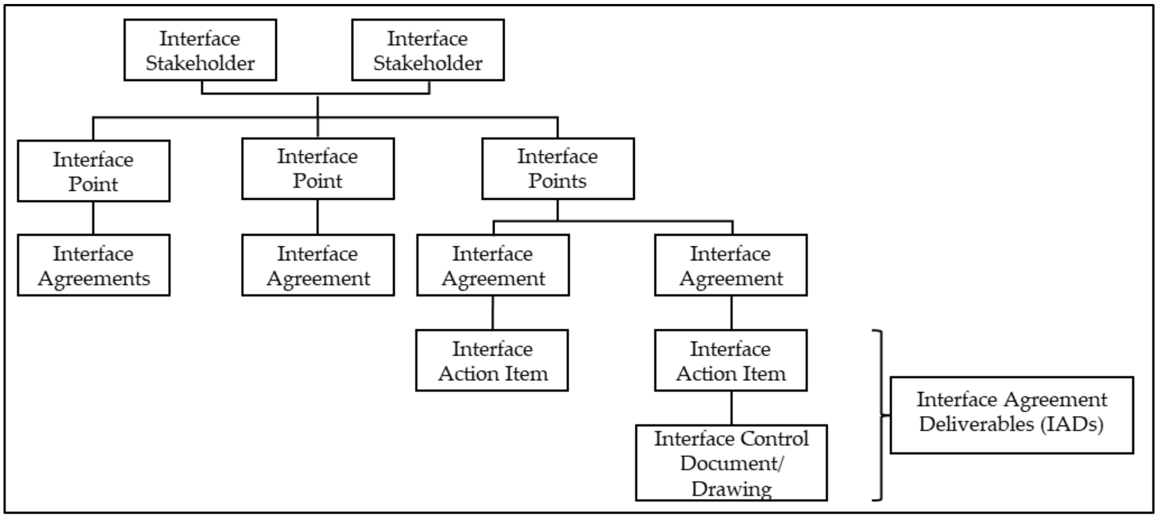


Figure 2 Simplified IMS Hierarchy (Source: Eray, Sanchez, & Haas, 2019)

Recording and managing Interface Points (IPs), Interface Agreements (IAs), and Interface Agreement Deliverables (IADs) make up the core structure of an Interface Management System (IMS). The fundamental data of an IP that should be recorded include the reference number, title, description, category, involved stakeholders and their responsibilities, creation and approval dates, and the status of the IP. As illustrated in Figure 2, there can be several IAs related to an IP. Therefore, it is also recommended to register and track IAs by recording a description of IAD, creation date, need date, forecasted date, delivery date, and closing date of IA (Construction Industry Institute, 2014; Shokri, 2014). These are the examples of metadata required.

2.2.2 Applications of IMS in the Construction Industry

In the literature, an increasing number of studies on the Interface Management System (IMS) definition, interface problems, and web-based IMS platforms, can be found. Interface problems in construction projects have been studied under varying constraints such as limiting the study to only two parties involved in a project such as owners and contractors, or designers and contractors, or contractors and subcontractors, etc. (Al-Hammad, 1990, 1995, 2000; Al-Hammad & Al-Hammad, 1996; Al-Hammad, 1993), or limiting the project type to a specific construction category (Al-Hammad & Assaf, 1992; Chen et al., 2008; Yeh et al., 2017), or to a specific phase in the project lifecycle such as design or construction (Arain & Assaf, 2007; Yeganeh et al., 2019), or to a country/region (Al-Hammad & Assaf, 1992; Sha'ar et al., 2016), or to a specific interface type.

Several scholars proposed IMS for various type of complex projects which are executed by a large number of stakeholders who have different specializations, with many overlapping activities. Pavitt and Gibb published one of the early works on the need for IMS in building projects and introduced a system to manage cladding interfaces (Pavitt & Gibb, 2003). In 2004, Harrison and Hamilton provided an overview of an IMS for railroad and rail transit systems. They also explained interface problems that can occur on different types of contracts in railway projects, interface control process illustrations, and risks of IMS on rail transit projects (Harrison & Hamilton, 2004). In 2006, Chua and Godinot introduced the Work Breakdown Structure (WBS) matrix concept to improve IMS in construction projects with a case study on Mass Rapid Transit projects (Chua & Godinot, 2006). Another IMS platform was proposed by Lin (2013) to connect project participants for managing interface problems during the construction phase (Lin, 2013).

In 2015, two different web-based IMS are introduced. Ju and Ding (2015) proposed an integrated interface model for metro equipment engineering to improve an IMS by changing it from traditional methods to a more standardized and structured web-based IM format (Ju & Ding, 2015). Lin (2015) also developed a web-based IMS that integrates three-dimensional interface maps to a BIM approach for engineers to improve physical interface information sharing and tracking during the construction phase for building projects (Lin, 2015).

In recent years, usage of IMS has been investigated in various types of construction projects such as Mass Rapid Transit (MRT) projects, adaptive reuse projects, offshore projects, etc. For example, Yeh et al. (2017) focused on interface problems on design-build and design-bid-build type MRT projects and provided a four-step solution which includes using WBS to identify key interface correlations and manage engineering interface problems in these projects (Yeh et al., 2017). Following that research, in 2020 Yeh et al. proposed preventive IM for Mass Rapid Transit projects and suggested series of interface design criteria for MRT projects to prevent interface problems related failures (Yeh et al., 2020). In 2019, Eray et al explored barriers and interface problems occur in adaptive reuse projects and investigated usage of IMS in adaptive reuse projects (Eray, Sanchez, et al., 2019). Yassari and Bahai (2019) investigated the IM process and strategies to manage interfaces between various subsystems during the design, fabrication, and installation phases on a case study from the oil and gas industry (Yasseri & Bahai, 2019).

The usage of IMS is growing in the construction industry lately. Although IMS was introduced in the 1960s, it was not used in engineering and construction projects extensively, because of the lack of necessary technological infrastructure and lack of common understanding of IM. Today, with the developments in information and communication technologies, more engineering and construction projects have adopted IM in different forms in their projects using in-house and commercial systems (Shokri, 2014; Shokri, Ahn, et al., 2016; Shokri, Haas, et al., 2016; Shokri et al., 2011, 2012).

2.3 Introduction to Building Information Modelling (BIM)

Building Information Modelling (BIM) technology, which was introduced almost thirty years ago, is one of the most promising developments in the architecture, engineering and construction (AEC) industry today (Eastman et al., 2008). Although the term “BIM” is very popular today, there is still no single or widely accepted definition for BIM technology. The definition provided by The National Building Information Model Standard (NBIMS) as “a digital representation of physical and functional characteristics of a facility and it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward”, will be accepted as the BIM definition for this research (NBIMS, 2016).

The main idea behind BIM is creating an intelligent model of the project which includes not only graphical details, but also engineering information of the system such as material data, wind force, cost, schedule, and facility management information, etc. (Shan & Goodrum, 2014). Basically, BIM can be explained as a philosophy that many project management software can interoperable with each other and reveal a 3D model that includes project related information on the model elements itself. In other words, BIM is not a ready-to-go software package that companies can purchase and use, but there are many different software packages on the market today that are interoperable with each other and can create more accurate models together.

In traditional 3D modeling, elements were created as lines, squares, circles, etc. With new modeling techniques, elements can be modeled with data included. For example, when a model on Autodesk AutoCAD (or another equivalent software) is created, the elements would be presented as lines that only include information related elements' dimensions and locations. It wouldn't provide the information about the modeled element itself. However, when a model is created on Autodesk Revit (or equivalent), the elements would be created in 3D including not only its geometric information, but also non-geometric such as schedule, cost, identity, location, manufacturer, owner, etc. related information too (Ahn et al., 2010; Azhar, 2011; Ding et al., 2012; Lin, 2015; Zeng & Tan, 2007). Therefore, the evaluation of the BIM system changed the 3D modeling concept from its roots.

2.3.1 Evaluation of BIM

Improvements on computer science and developments on the software platforms helped BIM technology to extend traditional 2D and 3D technical drawings into more intelligent visual modeling. Today, schedule and cost data of the project can be connected to a BIM model as the 4th and 5th dimensions and can be tracked visually. Also, improvements in cloud computing technology helped BIM systems move forward on access, update, and sharing model information (Shan & Goodrum, 2014).

Today, a BIM system can be considered as a group of tools that enables users to generate, store, manage, exchange, and share building information in an interoperable and reusable way during the project lifecycle (Vanlande et al., 2008). A BIM system can be used in each stage of a project for different purposes. During the conceptual design stage, it can be used for design, sustainability analysis, site and logistics management, and cost estimation. At the design and pre-construction stage, it is mainly used for multi-trade coordination, design visualization, and evaluation of the constructability of the project. The advantage of the BIM System usage in this phase is to coordinate design between stakeholders, to conduct clash detection analysis, and to create walkthrough animations of the project. Using a BIM System during the construction phase would help project participants reduce requests for information and change orders, do less rework, solve design problems before the actual construction through visualization, and improve productivity by having more effective construction management and easier information exchange. Project participants could save time and money with these benefits during the construction phase. At turnover and facility management stages, a BIM system can be used as a centralized information database of the project (Leite et al., 2011; Shan & Goodrum, 2014). Hence, usage of a BIM system in all the phases of the project would facilitate control of the lifecycle cost and project data in a systematic way and help to manage the project on rapid, accurate and interoperable platforms (Leite et al., 2011).

Interoperability is a concept that is highly important for BIM systems since it is one of the root ideas behind it. Therefore, software vendors working in the BIM area are also focusing on providing interoperable solutions for all phases of the project such as the Industry Foundation Classes (IFC) Standard. Since BIM systems software works with structured data, which can be easily ordered and processed, connections between BIM and other systems can be easily created in theory. According to SmartMarket Report published by McGraw Hill Construction in 2014, almost 28% percent of the construction industry in North America was using BIM System or related tools in 2007, while it increased to 71% in 2012 (McGraw Hill Construction, 2014).

In the literature, there are numerous studies that deal with different application areas of BIM technology on construction projects, such as; using BIM models for improving collaboration between project participants, reducing material waste, detecting clashes, creating energy-efficient structures, controlling design changes, simulating the construction phase in terms of cost and time, etc. (Azhar et al., 2011; Meadati & Goedert, 2008; Roh et al., 2011; Singh et al., 2011; Wong & Fan, 2013). Also, there are several research projects have been done on integrating BIM models with other methods or systems such as facility management systems, building lifecycle management systems, IMS, etc. to solve specific problems on the construction projects and improve the usage of 3D modeling among different stages of the construction projects.

One of the most cited research papers on integrating a BIM system with another system was written by Goedert and Meadati in 2008. Their research was based on integrating construction process documentation with a BIM system during the construction phase. That research introduced the concept and methods of integrating a BIM model with 3D as-built data, as well as methods to capture and store construction specifications, submittals, shop drawings, change orders, and RFIs submitted during the construction phase and producing 4D as constructed model by connecting the schedule (Meadati & Goedert, 2008).

The integration of CPM and BIM system has been achieved a long time ago, and that connection opened ways to new research areas. For example; Shan and Goodrum (2014) provided a framework on integrating BIM with CPM to simulate the impact of temperature and humidity at the project level. The proposed framework only focused on structural steel erection activities since these activities are mostly done outdoors, they are mostly high priority activities and generally on the critical path in the construction projects, and there is already a BIM standard for steel. As an outcome of the project, Shan and Goodrum (2014) found that the man-hours on the structural steel erection activity differ according to the start date of the project and location data on the model (Shan & Goodrum, 2014).

Sustainability and green building construction are also two of the main research areas in the AEC industry. Therefore, the number of studies on green building concepts and BIM systems is also raised. Jrade and Jalaei (2015) explained a new concept of integrating BIM and the Canadian green building certification system (LEED) at the conceptual design stage of sustainable buildings. The proposed methodology describes how to implement an integrated platform during the conceptual design phase to create sustainable designs for buildings. In order to integrate these two systems, Jrade and Jalaei collected the lists of green products and certified materials and linked these data to a BIM tool's database. The advantages of the proposed integrated system are that the documentation process of certification becomes shorter by using the proposed methodology, and users can calculate the total soft cost related to the registration and certification process of the designed building (Jalaei & Jrade, 2015).

Although an IM system is a relatively new concept in the construction industry, there are researchers around the world working on IM in different stages of construction projects. Lin (2015) proposed a methodology to integrate IM and BIM approach to effectively manage physical interfaces in the construction projects. The proposed methodology enables users to track and manage the interface events using the 3D interface maps integrated into the BIM approach during the construction phase. A web-based framework called the ConBIM-IM system is developed for the construction phase of the small-sized construction projects as an end result of the research (Lin, 2015).

In general, BIM systems are used for building types of construction projects. However, nowadays with technological developments on BIM-related software, BIM is also being used for infrastructure projects such as highways, airports, bridges, and railway projects, too. London Crossrail project, which is the first major infrastructure project using BIM lifestyle concept, is a unique example for BIM System usage on infrastructure projects. As part of this research, 4 research meetings were conducted between August 2017 and December 2017 with Nisrine Chartouny, an industry expert from Bechtel Corporation. Bechtel Corporation was hired as Crossrail project's project delivery partner in 2009, and has been acting as lead contractor and giving project management support to the London Crossrail project to deliver the 42km of central tunnels, and eight new subsurface stations (Rogers, 2019). In these research meetings, BIM System usage in the London Crossrail project was investigated through open-ended questions (Eray, 2017).

2.3.2 Open Data Standards

Industry Foundation Classes (IFC) is an object-oriented building information model format developed by the International Alliance for Interoperability (IAI) in 1994 with the aim of describing, sharing and exchanging building data among different AEC/FM (Architecture, Engineering, Construction / Facilities Management) software applications (Azhar, 2011; Deng et al., 2016). It is an open-source format which is free and well documented (Areo, 2016; buildingSMART, 2016).

Most of the objects in a BIM model can be defined in IFC format which provides objects' actors, controls, groups, products, processes, and resources information as structured information. In other words, an IFC file of a BIM model would include both geometric and semantic information of the BIM elements, such as owner information, cost, scheduling, utility information, etc. Therefore, a BIM model based on IFC's can be used in various stages of a construction project.

The main common form of IFC is a plain text ascii file. Each line of an IFC model data would include an instance of an entity with its unique reference ID, entity name, and its list of attributes (Hamledari et al., 2017). To date, four IFC domains have been released, and the latest release, IFC4, is accepted as the ISO 16739 standard. The first releases of the IFC domain mainly included instances related to building type of projects, however, its coverage area increased with each new release. The next release, IFC5, is still under the planning phase, and it is expected to include full support for various infrastructure domains and more parametric capabilities.

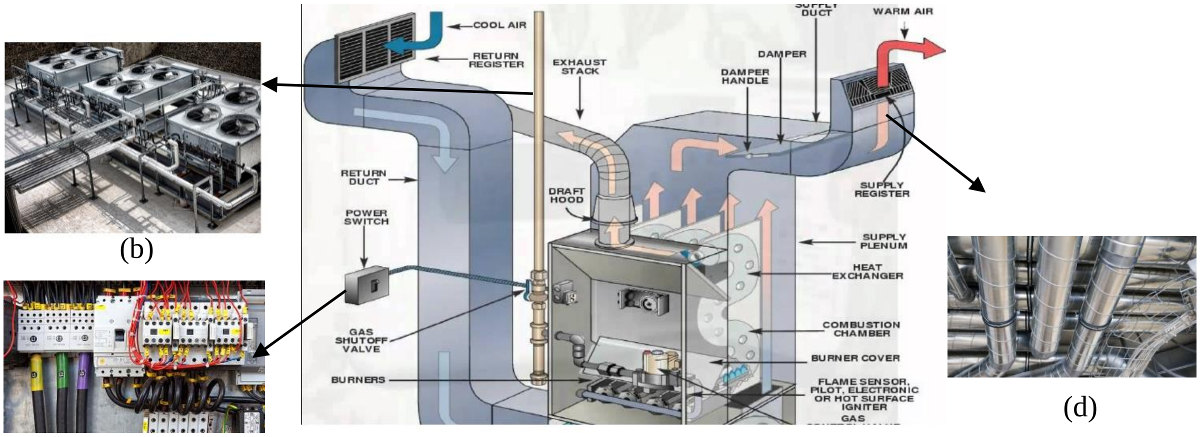
Similarly, ISO 15926 is an equivalent open data standard that developed for data integration and information exchange between computer systems during the life of a process plant. The main idea behind ISO 15926 was developing a common language between systems used by the project stakeholders such as owner, operators, engineering procurement and construction companies, suppliers, and subcontractors. Although ISO 15926 standard is originally developed for Oil and Gas industry, it can be used for any type of information exchange and integration due to its generically developed data model and reference data library (Kim et al., 2017; Leal, 2005).

Though it is not released as an IFC Standard yet, China Railways BIM Alliance prepared and submitted the first national development of IFC for the railway domain to Building Smart International (bSI) in 2015. It is published as bSI SPEC which is a document that is prepared by any organization on any topic for which they want to create a standardized best practice, but which is not yet ready to be a bSI Standard. The published bSI SPEC covers alignment, track, subgrade, bridge, tunnel, station, drainage, and geology disciplines in railway engineering, and it provides a platform for further developments in the IFC railway domain (Alliance, 2015, 2016).

The latest release of the IFC standard includes eight domains which are namely;

- IfcArchitectureDomain,
- IfcBuildingControlsDomain,
- IfcConstructionMgmtDomain,
- IfcElectricalDomain,
- IfcHvacDomain,
- IfcPlumbingFireProtectionDomain,
- IfcStructuralAnalysisDomain, and
- IfcStructuralElementsDomain.

In order to provide a better explanation of IFC format and IFC domain connections, an HVAC example is created. A typical HVAC system and some of the typical interface points between the contractors can be seen on Figure 3.



(b)

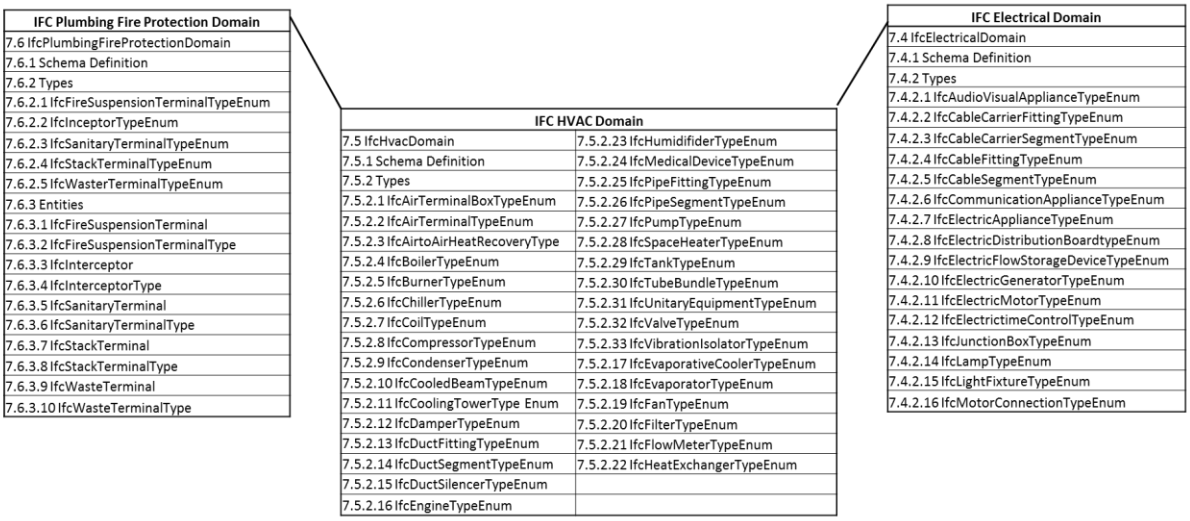
(c)

(a)

(d)

Figure 3 An HVAC system and its contractors, (a) HVAC system contractor (Source: (Stevenson & Whalen, 2012)), (b) Mechanical contractor (Source:(Air, 2017)), (c) Electrical Contractor (Source:(CIM-TEAM, 2017)), and (d) Ductwork contractor (Source:(Systems, 2017))

The connections of the HVAC domain with other system domains can be seen in Figure 4. When a BIM model that contains an HVAC system is saved in IFC format; the information related to the HVAC elements would be saved in related domains.



IFC Plumbing Fire Protection Domain
7.6 IfcPlumbingFireProtectionDomain
7.6.1 Schema Definition
7.6.2 Types
7.6.2.1 IfcFireSuspensionTerminalTypeEnum
7.6.2.2 IfcInceptorTypeEnum
7.6.2.3 IfcSanitaryTerminalTypeEnum
7.6.2.4 IfcStackTerminalTypeEnum
7.6.2.5 IfcWasterTerminalTypeEnum
7.6.3 Entities
7.6.3.1 IfcFireSuspensionTerminal
7.6.3.2 IfcFireSuspensionTerminalType
7.6.3.3 IfcInterceptor
7.6.3.4 IfcInterceptorType
7.6.3.5 IfcSanitaryTerminal
7.6.3.6 IfcSanitaryTerminalType
7.6.3.7 IfcStackTerminal
7.6.3.8 IfcStackTerminalType
7.6.3.9 IfcWasteTerminal
7.6.3.10 IfcWasteTerminalType

IFC HVAC Domain	
7.5 IfcHvacDomain	7.5.2.23 IfcHumidifiderTypeEnum
7.5.1 Schema Definition	7.5.2.24 IfcMedicalDeviceTypeEnum
7.5.2 Types	7.5.2.25 IfcPipeFittingTypeEnum
7.5.2.1 IfcAirTerminalBoxTypeEnum	7.5.2.26 IfcPipeSegmentTypeEnum
7.5.2.2 IfcAirTerminalTypeEnum	7.5.2.27 IfcPumpTypeEnum
7.5.2.3 IfcAirtoAirHeatRecoveryType	7.5.2.28 IfcSpaceHeaterTypeEnum
7.5.2.4 IfcBoilerTypeEnum	7.5.2.29 IfcTankTypeEnum
7.5.2.5 IfcBurnerTypeEnum	7.5.2.30 IfcTubeBundleTypeEnum
7.5.2.6 IfcChillerTypeEnum	7.5.2.31 IfcUnitaryEquipmentTypeEnum
7.5.2.7 IfcCoilTypeEnum	7.5.2.32 IfcValveTypeEnum
7.5.2.8 IfcCompressorTypeEnum	7.5.2.33 IfcVibrationIsolatorTypeEnum
7.5.2.9 IfcCondenserTypeEnum	7.5.2.17 IfcEvaporativeCoolerTypeEnum
7.5.2.10 IfcCooledBeamTypeEnum	7.5.2.18 IfcEvaporatorTypeEnum
7.5.2.11 IfcCoolingTowerType Enum	7.5.2.19 IfcFanTypeEnum
7.5.2.12 IfcDamperTypeEnum	7.5.2.20 IfcFilterTypeEnum
7.5.2.13 IfcDuctFittingTypeEnum	7.5.2.21 IfcFlowMeterTypeEnum
7.5.2.14 IfcDuctSegmentTypeEnum	7.5.2.22 IfcHeatExchangerTypeEnum
7.5.2.15 IfcDuctSilencerTypeEnum	
7.5.2.16 IfcEngineTypeEnum	

IFC Electrical Domain
7.4 IfcElectricalDomain
7.4.1 Schema Definition
7.4.2 Types
7.4.2.1 IfcAudioVisualApplianceTypeEnum
7.4.2.2 IfcCableCarrierFittingTypeEnum
7.4.2.3 IfcCableCarrierSegmentTypeEnum
7.4.2.4 IfcCableFittingTypeEnum
7.4.2.5 IfcCableSegmentTypeEnum
7.4.2.6 IfcCommunicationApplianceTypeEnum
7.4.2.7 IfcElectricApplianceTypeEnum
7.4.2.8 IfcElectricDistributionBoardtypeEnum
7.4.2.9 IfcElectricFlowStorageDeviceTypeEnum
7.4.2.10 IfcElectricGeneratorTypeEnum
7.4.2.11 IfcElectricMotorTypeEnum
7.4.2.12 IfcElectrictimeControlTypeEnum
7.4.2.13 IfcJunctionBoxTypeEnum
7.4.2.14 IfcLampTypeEnum
7.4.2.15 IfcLightFixtureTypeEnum
7.4.2.16 IfcMotorConnectionTypeEnum

Figure 4 HVAC IFC domain

2.4 Introduction to Project and Interface Health

Project health and human physical health have various similarities when it comes to evaluating their health conditions. There would be several symptoms that give clues about the health of a construction project, similar to symptoms of human physical health (Weippert, 2009). Humphreys et al summarized these similarities in 7 points. These similarities are namely; 1) state of health influences performance, 2) symptoms can be used as a starting point to quickly assess health, 3) symptoms of poor health are not always present or obvious, 4) state of health can be assessed by measuring key areas and comparing these areas' values to established norms, 5) health changes temporarily, 6) remedies can often be prescribed to return to good health, 7) correct and timely diagnosis can prevent small problems from becoming large (Humphreys et al., 2004; Weippert, 2009). By tracking these similarities, proactive solutions can be taken before poor health conditions occur.

Health of a construction project can be widely determined by tracking project performance against predetermined project goals, objectives, and relationships amongst the project team members. In the literature, project health and project performance measurement related studies are intertwined and correlated. For example; Tsoukas (2005) defined project health as the synonym of project performance (Tsoukas, 2005). It is expected that a project which has an unhealthy project environment, where stakeholders' communication is poor, interfaces are not being managed well, and stakeholders are not working towards the project's aim as a team, would have a poor project performance at the end of its lifecycle. Therefore, there are overlapped indicators that are used as both project health indicators and project performance indicators.

Interface health is a subset of project health since management of interfaces between project stakeholders is one of the main components that directly affect the overall project health. Interface health can be defined as the overall health of all the connections between two interface stakeholders in terms of meeting the requirements of the IAs they have, and working as a team for predetermined project goals. Therefore, in order to measure project health, first, interface health between project stakeholders should be measured (Eray, Haas, et al., 2019). In Figure 5, the connection between project health and interface health is presented as a triangle.

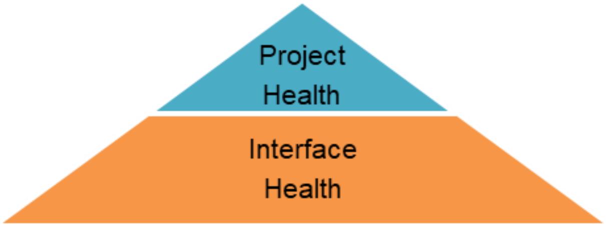


Figure 5 Triangle of Health in Project Environment

Several models that are related to measuring project health have been proposed in the literature. The most recent significant research on determining health problems in construction projects was conducted by CII in 2006. CII proposed a Project Health Indicator (PHI) tool that contains a questionnaire with 43 leading indicators. Each of these indicators has a hypothesized connection with one or more of 5 outcomes, which are project cost, schedule, quality/operability, safety, and stakeholder satisfaction. By filling out the PHI tool questionnaire with its Likert scale, the health of a project in terms of what may be expected for these 5 outcomes can be estimated (CII, 2006).

Another model for assessing construction project health was proposed by the Cooperative Research Centre (CRC) Project Diagnostics Research Team in 2002. Over the years, the model that they proposed has been converted into a toolkit named "Project Diagnostics". In this model, a circular process for investigating the health of a construction project is used. Initially, construction projects are assessed by using 30 Key Performance Indicators (KPIs) that are related to 7 Critical Success Factors (CSFs). If the outcome indicates that an assessed project is unhealthy, then the project is examined according to Contributing Factors (CFs) that are associated with each CSF, and Secondary Performance Indicators (SPIs) that are related to each CFs. At the end of these examinations, root causes of the unhealthy project are determined, and remedial activities that are associated with each root cause can be identified. This cycle should be repeated until the project's health is measured as healthy (Tsoukas, 2005).

2.5 Introduction to progress measurement in design

Measurement of the design progress is an evolving challenge in today's 3D modeling dominated design environment (Poirier et al., 2015). Improvements in the software engineering and computer science fields extended traditional 2D and 3D technical design drawings into more intelligent visual modeling processes in the construction industry. Today, Building Information Modeling (BIM) philosophy which can be defined as creating a virtual prototype of the system, is getting more and more important in the construction industry (Azhar et al., 2015).

Today, there are several 3D modeling software options on the market so that engineering design can be done on the shared design files among the project stakeholders. Although these improvements bring huge flexibility and power to the construction industry such as automatically superimposing different design files and being able to detect clashes, creating walk-through views of the design models, and estimating projects' quantity takeoff automatically, etc., it is hard to measure engineering design progress during the design phase of the projects.

The traditional design progress measurement technique was counting the completed engineering drawings and completed issued-for-construction files. However, it is hard to perform this technique on 3D models, since the 3D design is an evolving process on the same design files. Measurement of the design process becomes even harder on complex construction projects since many project participants are involved in the design of the project.

There are different approaches and tools for measuring design progress in both the literature and industry today. One of these approaches is tracking the Level of Development (LOD) of design elements in the model. Mainly LOD definitions are focusing on graphical details on the design elements. Beyond the geometric information, LOD can be used to specify what additional semantic data should be defined and shared for model components for different LOD levels. LOD definitions helps project stakeholders who receive design models, to understand the content and reliability of that content (Grani, 2016). However, design progress is not only related to the graphical details and representation, it is also related to engineering information added to the model, and documents and process records behind the design. Another approach to measuring design progress, which focuses on engineering information added to the model, is tracking Model Maturity Index (MMI) levels of the project disciplines. Both LOD and MMI level approaches are explained in the next subsections.

Also, there are various Building Information Modeling (BIM) maturity assessment tools available today that help users to measure their project performance on BIM implementation. Arup, which is a global engineering and design firm, developed one of these BIM maturity assessment tools in 2014 (Azzouz et al., 2016). The main purpose behind Arup’s BIM Maturity Measurement (BIM MM) tool is to assess the BIM implementation maturity in projects and compare it between different projects. Therefore, although the BIM MM tool provides a measurement on “maturity”, the usage area of this tool is different than measuring the design maturity of the project itself.

2.5.1 Level of Development (LOD)

Generally, 3D models of construction projects range between a conceptual drawing to a fully detailed and coordinated construction model. One way of measuring design completeness in construction projects is tracking Level of Development (LOD) level of the elements on the model. In 2008, the American Institute of Architects (AIA) released a contract document, “AIAE202-2008 BIM Protocol Exhibit,” which defines Level of Development (LOD) and LOD levels, which are related primarily to the amount of design detail in the model. According to the AIA, LOD 100 represents a conceptual drawing, while LOD 500 is the as-built model; LOD gets higher during the design phase of the project and reaches its highest level during the construction phase (AIA, 2008).

In 2011, BIMForum formed a working group to initiate the development of a LOD specification which follows CSI Uniformat 2010 organization and LOD schema developed by AIA. By following these organizations and basic LOD definitions, the working group created examples, illustrations and defined a LOD Specification. In this specification, general insight and definitions of LOD levels for the design elements specified in Uniformat 2010 was provided. BIMForum released the latest version of the LOD Specification in April 2019 (BIMForum, 2019).

LOD Specification provides consistency in communication of the design content and information reliability of design models (BIMForum, 2019; Grani, 2016). Mainly LOD level definitions are related to the graphical and geometric details on the design elements on the model. In other words, as the accuracy of the design of the elements gets higher, the LOD level of each element also gets higher in the model. Beyond the geometric information, LOD specifications can be used for specifying additional semantic data such as cost and schedule data, that should be defined and shared for model components in each LOD levels (BIMForum, 2019; Latiffi et al., 2015). There are several LOD spreadsheets available to accompany the LOD levels.

LOD levels are defined only for elements on the design model and there is no such LOD level of the complete design model. It cannot easily or consistently be aggregated to a total LOD level for a project. However, it can be used to track the design progress of specific elements in the design model over time (BIMForum, 2019; Boton et al., 2015; Yoders, 2012). LOD can be added as a shared parameter to the models created on Autodesk Revit to track the design progress of the project. During the design phase, the LOD level of the elements can be arranged manually by the design team according to the LOD definitions that they created for their project' design elements. When each element's LOD level is defined on the model, the project team can track changes on these levels to see progress in their projects.

2.5.2 Model Maturity Index (MMI)

Most of the engineering progress in the early phases of complex capital projects is not graphical-design related, and such progress must be captured as well in order to have a complete idea about the progress in the project. Examples of such engineering processes are diverse and include geotechnical studies, mechanical and control systems design, and structural systems analysis.

Similar to the AIA, the Construction Industry Institute (CII) published metrics to measure progress in model-based engineering projects in 2017. These metrics are called Model Maturity Index (MMI) and they are focusing on engineering information added to the 3D model, and documents and process records behind the design. Similar to LOD, MMI definitions have levels ranging between MMI 100 which mainly refers to conceptual design, to MMI 600 which indicates that facility management data is included in that discipline.

Until today twelve sets of MMI definitions which are Piping, Structural, Instrumentation, HVAC, Equipment, Civil, Electrical, Fire Protection, Layout, Foundations, Buildings, and P&IDs, have been established by CII. Each of these definitions is providing a clear set of modeling requirements for each MMI level in that discipline to fulfill. The MMI levels are calculated per discipline per location on the 3D model, and calculations are done by the Model Maturity Risk Index (MMRI) tool developed by CII (CII, 2017).

While LOD levels are mainly related to the design detail on the model, MMI levels are related to the amount of the information in the model. In other words, both graphical and non-graphical information associated with the project is reflected with MMI levels. Another difference between LOD and MMI levels is, LOD is mainly related with details on the design of the model elements, while MMI levels are prepared for design disciplines in the project.

2.5.3 Model Maturity Risk Index (MMRI)

As part of the Model Maturity Index research, the Construction Industry Institute also developed the Model Maturity Risk Index (MMRI) tool (CII, 2017). The tool includes questionnaires for each MMI discipline defined (Piping, Structural, Instrumentation, HVAC, Equipment, Civil, Electrical, Fire Protection, Layout, Foundations, Buildings, and P&IDs). The aim of the MMRI tool is assessing MMI level of these disciplines for a specific location in the project. It also provides a percentage of remaining work to achieve higher MMI level within the discipline for the selected specific location too.

The questionnaires in the MMRI tool have inter-disciplinary relationships between the disciplines too. Mainly, the questions on the tool are based on the information added to the model such as site plan, geotechnical investigation, design parameters, equipment data, clash detection analysis. The user of the tool needs to select an answer from the drop-down menu for each question for the selected location. The typical answers in the tool are Yes, No, Not applicable, Design Specified, Loaded, Confirmed, etc. for each question. Each of these answers would have connections with different MMI levels and also weights on MMI level calculation. As an example Foundation is a discipline in which CII provided MMI definitions and MMRI tables. The questionnaire for Foundation in the MMRI tool has questions about the size and location of the design components. While the answer of "preliminary design" to these questions has a connection with MMI 100, the answer of "design specified" has a connection with MMI 300.

The main usage area of the tool is expected to be a guide showing the current maturity of the model and required modeling efforts of specific disciplines in different locations on the project. The project team can have better communication in model reviewing meetings by filling the questionnaires and obtaining current MMI levels of the specific modeling disciplines in different locations.

2.6 Introduction to Social Network Analysis

Briefly, Social Network Analysis (SNA) extends from graph theory and is an approach for analyzing relationships and investigating interactions between dependent entities (Eteifa & El-adaway, 2018; Shokri, 2014). Networks are used in SNA to represent and analyze interactions between individuals or groups. In these networks, each individual or group is represented by a node, and the interactions between each individual or group are represented by a link between nodes (Alarcón et al., 2013; Shokri, 2014). The definition of the interactions between groups differs based on the research area and problem. In this research, an interaction can be an interface point, agreement, deliverable, report, meeting, etc. between two individuals or groups (nodes), and the volume of those interactions defines the weight of the links between nodes.

Several metrics can be obtained by conducting Social Network Analysis (SNA), such as network density, clustering coefficient, distance, average path length, degree centrality, eigenvector centrality, etc. (Kereri & Harper, 2018). These metrics make SNA a powerful tool that converts invisible information to visible and easily understandable formats (Alarcon, 2013). For example, distance gives the minimum number of links required to connect two particular nodes, as in the popular idea of "six degrees of separation".

In this thesis, degree centrality (DC) is used as part of the SNA analysis to measure each node's importance. Theoretically, in a network, a node is important if it is linked to other important nodes, and importance is based on the number of links and weight of those links. Also, when the degree centrality value gets higher, the importance of the node gets higher too. Thus, by calculating the DC value of each node in a network, important nodes can be detected. In this thesis, an open-source network visualization software named Gephi (version 0.9.2) is used for visualization.

2.7 Knowledge Gaps

Traditional project management methods often provide solutions to estimate resource profiles of the stakeholders. However, those solutions do not provide any adequate insight of the health or workload status of the stakeholder connections. Communication and collaboration between project stakeholders directly affect the overall project outcome, therefore special attention should be given to interfaces between project stakeholders. Although IMS and project health have been studied in the literature, measuring workload and health of the interfaces between project stakeholders is still a new research area.

Currently, there is a lack of a detailed study on measuring engineering progress at the design phase of complex construction projects. Methods exist: however, they are either poorly developed for the early phases of the complex projects or obsolete in the 3D design world. A 3D based engineering design evolves through levels of development, added detail, and established relations. Integrating IMS, BIM, and Critical path method based project management techniques can bring solutions to these problems. However, although IMS and BIM have been studied comprehensively in the literature, there is still a knowledge gap in integrating these systems.

The concepts of LOD, MMI and MMRI levels are relatively new in the literature. These definitions are particularly important to measure design progress in complex projects since they are considering not only the geometric data but also engineering data to measure progress. Today, MMI levels are only available for 12 disciplines (and they are not available without purchase from the CII), however, the scope of these definitions is limited with buildings or industrial projects, and there is still a knowledge gap on engineering progress tracking in transportation and infrastructure projects.

Chapter 3

Stakeholder Interface Networks and Integrated Project Monitoring Method

3.1 Usage of network analysis in construction projects

The roots of Social Network Analysis go back to studies of social relations (Moreno, 1934) and network characteristics of individuals (Lewin, 1936). Originally, networks were used as a tool to describe the relationship pattern and flow of information among individuals or groups (Paul et al., 2008). Over the last 30 years, Social Network Analysis (SNA) and network analysis gained broad attention in project management and construction management related studies. The development of several SNA tools and software accelerated this process. Gradually SNA has become one of the key methods to use in hybrid research design in management research, and it gained popularity in construction industry in the areas of construction management, transportation planning, and construction safety (Chinowsky & Taylor, 2012; Eteifa & El-adaway, 2018; Zheng et al., 2016).

In the last two decades, SNA has been used as an analytical tool in various research projects in the construction management field such as: (1) examining communication efficiency in engineering project organizations (Loosemore, 1998; Mead, 2001), (2) understanding collaboration between groups in engineering projects (Pryke, 2004, 2005), (3) recognizing knowledge sharing patterns among project teams (Paul et al., 2008; Schröpfer et al., 2017), (4) investigating correlation between communication networks and coordination in construction projects (Hossain, 2009; Hossain & Wu, 2009), (5) investigating collaboration patterns and their impacts on the profit performance (Park et al., 2011), (6) comparing knowledge integrating process in competitive and collaborative working systems (Ruan et al., 2012), (7) analyzing stakeholder-associated risks and their interactions (Yang & Zou, 2014), (8) understanding and analyzing job-site management problems (Shyh-Chyang, 2015), and (9) analyzing job-site physical health and safety problems (Eteifa & El-adaway, 2018). In this thesis, SNA is mainly employed for visualization and as a part of the analytical method for evaluating workload and health of communication and coordination between project stakeholders.

Traditionally, the chain of commands and line of authority in an organization is illustrated by using traditional hierarchical management structures. In such systems, the connections between project participants are illustrated as a tree structure. However, these structures do not illustrate all project participants and they exclude the lines of communications in many cases, as well as other types of relationships. Especially in modern management systems, such as Integrated Project Delivery (IPD), organizations are becoming more collaborative and less hierarchical (AIA, 2007; Gahassemi & Becerik-Gerber, 2011). In a typical complex project, there would be many project stakeholder pairs whose responsibilities in the project are directly interdependent; in other words, there would be interface points between those project stakeholders (Chua & Godinot, 2006). In order to evaluate interfaces between project stakeholders, it is important to visualize the communication and collaboration patterns between these groups in an organization.

Interfaces between project stakeholders can be visualized by using networks where nodes represent stakeholders and edges represent interfaces between stakeholders (Shokri, 2014). In this thesis, these networks are referred as stakeholder interface networks. In order to provide an illustration, an example stakeholder interface network is presented in Figure 6. In this illustration, all nodes are accepted as equally important and the weight of the edges is assumed to be the same for all edges.

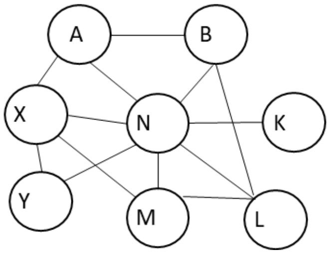
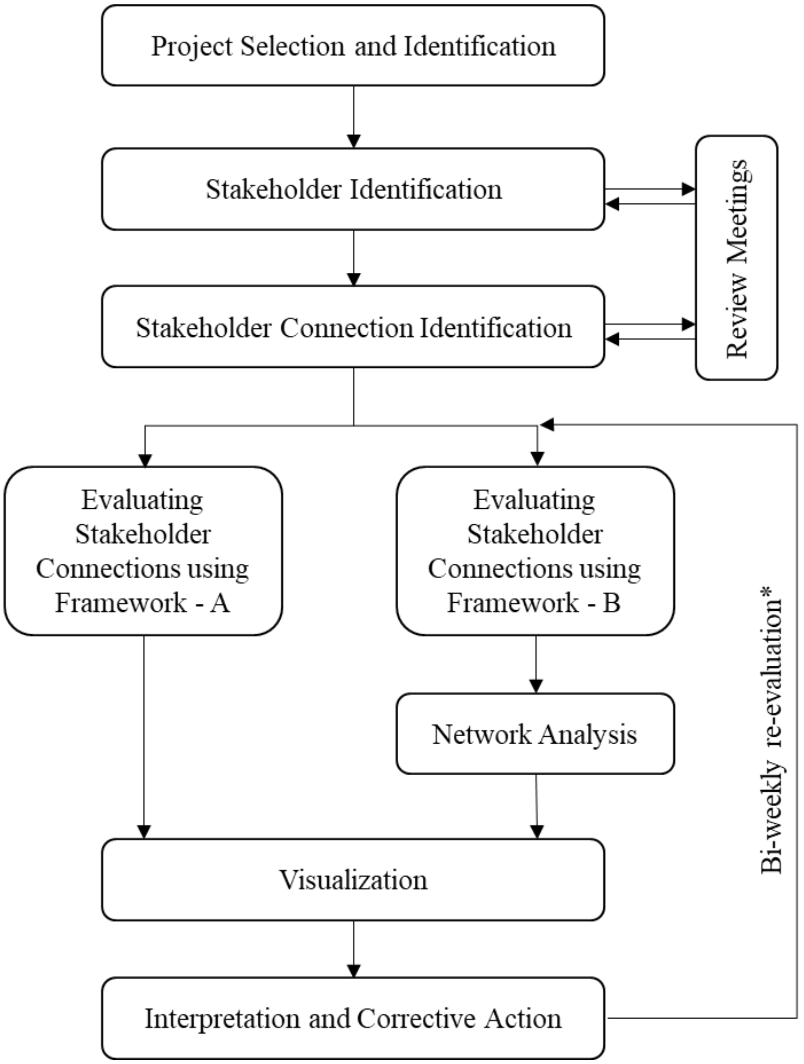


Figure 6 Example Stakeholder Interface Network

Stakeholder interface networks are useful for illustrating collaboration between project stakeholders. In this thesis, these networks are used as a base for visualizing the health and workload condition of the interfaces between project stakeholders.

3.2 Methodology – Integrated Project Monitoring Method

In this research, methods to measure and visualize interface health and workload between project stakeholders are investigated and the Integrated Project Monitoring Method is developed. Integrated Project Monitoring Method contains two frameworks (Framework-A and Framework-B) to evaluate stakeholders' connections. Stakeholder Interface Networks are used for visualization of the results. Figure 7 presents the methodology of how to measure interface health and workload between project stakeholders, as well as how to establish Stakeholder Interface Networks by using the Integrated Project Monitoring Method. Details of each step are provided in the following subsections.



*Suggested re-evaluation cycle

Figure 7 Methodology of Integrated Project Monitoring Method

3.2.1 Project Selection and Identification

The first step is selecting a project to conduct interface health analysis and gather general information about the project such as problem definition, location, timeline, contact point, etc. Construction projects might follow different project phases throughout their lifecycle, or name the phases differently, depending on the project delivery method used. Therefore, the project lifecycle map where names of each project phase and their orders should be gathered in this step too.

3.2.2 Stakeholder Identification

After selecting a project and gathering general information about the project lifecycle, the next step is identifying project stakeholders in each project phase. It is expected that any construction project would have a dynamic environment where stakeholders involved in the project change throughout the project lifecycle. Therefore, in order to create stakeholder interface networks for a project throughout its project lifecycle, the first step is identifying a master stakeholder list that shows all the stakeholders involved in the project. While preparing this list, the project phases when these stakeholders are actively involved in the project should be clarified. This way stakeholder list for each project phase can be created.

Typically, stakeholder list data would be stored in project information management systems adopted in the project and can be reached by writing specific queries. In case when such a system is not available, or the data acquisition process is time consuming, project stakeholders should be defined by having meetings with the project team. In those meetings name of stakeholders, the timeline of when each stakeholder actively involved in the project and their status in the project (internal stakeholder/external stakeholder) should be clarified.

3.2.3 Stakeholder Connection Identification

After creating stakeholder lists for each project phase, the next step is investigating interfaces between stakeholders. If a pair of stakeholders have interface points in the project that require them to have meetings, and/or sharing reports in between, and/or sending requests to each other, and/or have common deliverables that they need to agree, then it is accepted that these stakeholders have a connection.

If an Interface Management System (IMS) is already established in the project, then data for interface points between stakeholders can be obtained by creating related queries. In case there is no available IMS data for the project, the format presented in Table 1 can be used for gathering interfacing stakeholders list data from construction organizations. Typically, project managers or team leaders can identify interfacing stakeholders. As it is addressed in Section 3.2.1, construction projects might follow different project phases throughout their lifecycle. Therefore, instead of naming project phases as “Design”, “Execution”, or “Closeout”, generic names such as Phase A, Phase B, etc. are used for project phases in Table 1.

Having face to face review meetings with Project Managers (PMs) or team leaders to fill Table 1 would speed up the process in this step. PMs or team leaders can identify interactions between project stakeholders for each phase during review meetings. At the end of this exercise, adjacency matrixes for each project phase that shows interfacing stakeholders would be obtained. Examples of filled version of Table 1 can be found in Appendix D, Appendix E, and Appendix F.

Table 1 Data collection format for defining interfacing stakeholders in each project phase

	Interactions with other stakeholders in			
Name	**Phase A**	**Phase B**	**Phase C**	**etc.**

In this research, two different approaches are investigated for evaluating interface health between project stakeholders. The first framework which will be referred as Framework-A hereafter is defined for measuring interface health by using actual project data from various project information management systems such as Change Management, Interface Management, Document Management, Request For Information systems, and project schedule. However, although Framework-A provides objective results based on actual project data without human interpretation, it is found that Framework-A is hard to implement as a general model for every organization due to the complexity of data required and differences in IT systems. After having several meetings with five different organizations, namely Ontario Power Generation, Stantec, Arup, Toronto Transit Commission, and Waterloo Region on various construction projects they undertake, it is concluded that either it would take a very long time to establish Framework-A in their organization, or it was impossible because the required data was not available in the organization's database. Nonetheless, this approach is partially validated through functional demonstration later in Section 5.1, to substantiate the conclusions made concerning its feasibility and efficacy. In order to overcome these problems and create a simpler model that can be adopted in any project without having a complex project information management system, a second framework (Framework–B) which is based on a novel qualitative point system is established. Details of each framework are provided in the related subsections below.

3.2.3.1 Evaluating Stakeholder Connections using Framework-A

In typical complex construction projects, there would be several project stakeholders involved, and the number of stakeholders would change in different project phases. Theoretically, if there are "*n*" number of project stakeholders involved in a project, the number of paired combinations between these project stakeholders can be found with the formula given in Equation 1, where n is the number of project stakeholders.

$$C(n,2) = \frac{n!}{(n-2)!2!} \qquad [1]$$

However, since interface health can be measured bi-directionally, the order or the combination of the project stakeholders would matter in this research. Therefore, the maximum number of calculations between pairs would be double of the result reached by using Equation 1. In other words, since the order of the pairs is important in this framework, instead of combination formulas, the permutation formula which is given in Equation 2 where again n is the number of the project stakeholders, should be used.

$$P(n,2) = \frac{n!}{(n-2)!} \qquad [2]$$

For example, if a project involves 10 project stakeholders, the theoretical maximum number of links that can be created would be 45, and in that network, the maximum number of interface health measurement calculations that need to be conducted would be 90. Manually collecting data and conducting these calculations for a project that has a large number of stakeholders would be time-consuming. One way of overcoming this problem is using project information management systems data to measure interface health.

The main assumption behind Framework-A is that project information management systems are used in complex construction projects in order to manage communication and collaboration between project stakeholders, and data from those systems are stored in project database. Therefore, Framework-A is based on the idea of using actual project data to measure interface health. The overall methodology that is followed in Framework-A is presented in Figure 8.

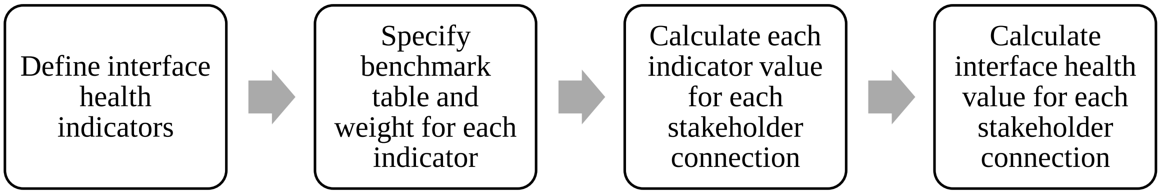


Figure 8 Methodology of Framework-A

As presented in Figure 8, the first step of Framework-A is defining interface health indicators. Therefore, a literature review on health indicators is conducted, and interface health indicators are defined. In 2006, CII released a tool to estimate project health in construction projects in terms of project cost, schedule, quality/operability, safety, and stakeholder satisfaction by using a Likert scale (CII, 2006). The tool included a questionnaire with 43 leading project health indicators. Initially, among these 43 health indicators, 10 of them are selected as health indicators that can be calculated automatically using actual project data instead of using a Likert scale. Then, these health indicators are used as a guide to define 14 interface health indicators that can be measured by actual project data from various project information management systems. The defined interface health indicators and expected data resource for those indicators are presented in Table 2.

Table 2 Defined Interface Health Indicators

No	Description	Data Source
I_1	Number of RFIs	Request For Information System
I_2	Average response duration of RFIs	
I_3	Percentage of RFIs that have time-overruns	
I_4	Amount of Change requests	Change Management System Interface Management System
I_5	Percentage of cost effect of the change requests/scope changes	
I_6	Average response duration of change requests	
I_7	Average approval duration of the change requests	
I_8	The average number of revisions on the documents	Document Management System Interface Management System
I_9	Number of rejections	
I_{10}	Total design rework hours	Schedule
I_{11}	Design rework hours vs targeted design hours	
I_{12}	Cost effect (percentage) of design rework hours	
I_{13}	Number of milestones that are missed	
I_{14}	Delay effect on actual vs planned schedule	

The second step of the methodology is specifying benchmark values and weights for each interface health indicators defined. However, these values would be project specific and should be determined by the project team. Therefore, defining a general weight and benchmark table for each indicator is beyond the scope of this thesis.

The third step is calculating each interface health indicator for each edge on the stakeholder interface network using actual project data. As explained previously, interface health between two stakeholders is bi-directional, therefore, interface health indicators should be calculated bi-directionally too. After calculating each indicator for both directions on the edge between two stakeholders, benchmark tables should be used for selecting related indicator values. However, it is worth repeating that these benchmark tables would be project-specific, and the project team should define the values according to project goals and expectations.

After finding each indicator value between two project stakeholders, the fourth step is calculating interface health (H) value for each edge on the stakeholder interface network by using Equation 3 below.

$$\mathrm{Health}_{ij}^{A} = (\mathrm{w}_1 \mathrm{x} \mathrm{I}_1) + (w_2 \mathrm{x} I_2) + (w_3 \mathrm{x} I_3) + (w_4 \mathrm{x} I_4) + (w_5 \mathrm{x} I_5) + \cdots + (w_{14} \mathrm{x} I_{14}) \qquad [3]$$

where *w* represents the weight of each indicator defined by the project team, and *I* represents the calculated values of each interface health indicator.

Interface health (H) value between two stakeholders varies between 1 and 0, where the higher value would mean better project health. After calculating the H value between two stakeholders, the interface health condition can be determined by using a final benchmark table that is defined by the project team. Then, interface health condition results for each stakeholder connection can be presented on the stakeholder interface network by using color codes.

Interface health between two stakeholders is bi-directional, and each direction can have a different interface health result. In other words, interface health value between stakeholder A and stakeholder B can be different for each stakeholder since they may experience the health of the relationship differently. In Figure 9, an example of different interface health measurement between two stakeholders are presented with the color codes.

Figure 9 Bi-directional interface health representation

However, although Framework-A can provide an objective and quantitative data based interface health value for each stakeholder connection in a complex project, it is hard to collect data required for defined interface health indicators. In order to validate Framework-A, several research meetings were conducted with five different construction organizations (Ontario Power Generation, Stantec, Arup, Toronto Transit Commission, and Waterloo Region) undertaking multiple complex construction projects simultaneously. However, after several meetings with these organizations, it was found that either these organizations were not using all of the systems listed above in their projects, or they were not storing required data in a reachable database. Therefore, it can be concluded that Framework-A is ideal for construction organizations where required project information management systems and their data are available.

3.2.3.2 Evaluating Stakeholder Connections using Framework-B

In the previous section, a novel system to measure interface health between project stakeholders in the early phases of construction projects using actual project data is introduced. The limitations faced during data collection to apply Framework-A showed that a simpler approach is needed to measure interface health between project stakeholders where actual project data is not readily available. Following this idea, a simpler yet powerful methodology that can be applied throughout the project lifecycle is developed through a series of discussions and an iterative process with the industry partners in this research project.

Framework-B is based on a qualitative assessment of interface health and interface workload between project stakeholders. Although interface health condition of stakeholders' connections in the current project phase can be a leading indicator for project performance, health measurement is considered feasible only for past and current phases of the project by the research partners, whereas workload estimation is considered feasible throughout project lifecycle by the research partners. Estimating future workload may be useful for resource-leveling in a portfolio of projects and it is one of the future research subject recommended in Section 6.4 of this thesis. The key indicators behind workload estimation is checking the number of shared interfaces, amount of interface agreements, amount of interface agreement deliverables, and communication frequency between project stakeholders. Since the evaluation is based on qualitative assessment, even though there is no sophisticated Project Information Management System being used, or the data of those systems are not available, users would still be able to evaluate the workload between project stakeholders based on their observations. In this analysis, the high number of shared interfaces, agreements, deliverables, and frequent communications would indicate a high workload between two stakeholders. Thus, the main idea behind interface health measurement between two interface stakeholders is evaluating their responsiveness of their communication, punctuality on the project schedule, their alignment on overall project goals, and the number of revisions that occur on the deliverables sent and received between those stakeholders.

Starting from this idea, a novel qualitative point system to estimate workload and interface health between stakeholders is defined. In this system, project managers are expected to evaluate each stakeholder connection in their project for a time period such as per project phase by using a 3-point scale where "3" indicates high workload on the connection and indicates potential poor health conditions, and “1” indicates low workload in the connection and potential good health conditions. 3-point scale equates to high-medium-low (HML) scale which is used in risk management (Baccarini et al., 2004; Díaz-López et al., 2016). By evaluating each stakeholder connection using this qualitative point system, project managers can quickly diagnose overloaded, unhealthy stakeholder connections. In Table 3 and Table 4, criteria and scale descriptions for both workload and health estimation point systems are presented respectively. It is important to note that while this qualitative point systems were developed for the research partners’ relatively broad joint portfolio of project types (complex, but small nuclear maintenance projects, and large complex transportation projects), it is possible that they may need to be recalibrated for different industry sectors or other categories of projects, such as mega oil and gas projects.

Table 3 Point System for Workload Estimation Between Each Pair of Stakeholders per Project Phase

Code	Main Criteria	Scale description	Value
W1	Interfaces	High Number of interfaces (physical, organizational, contractual) (>15)	3
		Medium Number of interfaces (physical, organizational, contractual) (>5 and ≤15)	2
		Low Number of interfaces (physical, organizational, contractual) (≤5)	1
W2	Communication Frequency	Daily or 2-3 times per week	3
		Weekly	2
		Bi-weekly or less	1
W3	Agreements	High number of agreements per shared interface (>4)	3
		Medium Number of agreements per shared interface (>2 and ≤4)	2
		Low number of agreements per shared interface (≤2)	1
W4	Deliverables	High Number of deliverables (reports, design files, specifications, etc.) (>10)	3
		Medium Number of deliverables (reports, design files, specifications, etc.) (>4 and ≤10)	2
		Low Number of deliverables (reports, design files, specifications, etc.) (≤4)	1

Table 4 Point System for Health Estimation Between Each Pair of Stakeholders per Project Phase

Code	Main Criteria	Scale description	Value
H1	Responsiveness	High degree of ambiguity and reluctance	3
		Fuzzy responses that require multiple revisions	2
		Well defined and smooth process/responses	1
H2	Punctuality	Constant delays on requests and deliverables that affect milestones and critical path	3
		There are time overruns on requests and deliverables but didn’t affect critical path	2

Code	Main Criteria	Scale description	Value
		No missed milestones and no time-overruns on requests and deliverables	1
H3	Alignment	Stakeholders are experiencing poor relationship and misalignment on project goals	3
		Stakeholders have disagreements on project goals and deliverables, but are solution oriented.	2
		Stakeholders are well aligned on project goals	1
H4	Revisions	High amount of revisions (≥50) due to miscommunications and/or change requests (CR)	3
		Medium number of revisions on reports/design files/deliverables (≥5 and <50) due to miscommunications and/or CR	2
		Low or no revisions on reports/design files/deliverables (<5) due to miscommunications and/or CR	1

It is worth mentioning again that the values on the scale column of both Table 3 and Table 4 were defined by considering complex construction project environments of the research partners of this thesis. However, these can be recalibrated according to the expectations of any project team before starting evaluation. After evaluating each stakeholder connection on the stakeholder interface network using Table 3 and Table 4, the overall workload and health value of each stakeholder connection can be calculated by using Equation 4 and Equation 5 respectively.

$$Workload_{ij}^{B} = W1_{ij} + W2_{ij} + W3_{ij} + W4_{ij} \qquad [4]$$

$$Health_{ij}^{B} = H1_{ij} + H2_{ij} + H3_{ij} + H4_{ij} \qquad [5]$$

where W1, W2, W3, and W4 are main criteria for workload, H1, H2, H3, and H4 are main criteria for health, and *ij* represents the connection between stakeholder *i* and *j*.

In order to eliminate biases, health and workload evaluation of the stakeholders' connections should be done by multiple people from the same group. In such cases, group decision can be achieved by using average mean or geometric mean of all the inputs from different decision makers from the same group. Also, different stakeholder groups should be involved in the evaluation process. Interface health and workload conditions might be experienced differently among two interfacing stakeholders, and by collecting data from both parties, different perspectives can be analyzed. Thus it is important to collect health and workload data from various stakeholders to have a broader view on the project.

3.2.4 Network Analysis

There are several metrics that can be obtained by conducting SNA including density and distance (Lee et al., 2018). These metrics make SNA a powerful tool that converts invisible information to visible and easily understandable format (Alarcón et al., 2013). For example, distance gives the minimum number of edges required to connect two particular nodes, as in the popular idea of "six degrees of separation". However, most of those metrics are defined for binary situations where edges between nodes are just present or absent and doesn't have any weight (Opsahl et al., 2010).

In Framework-B, weighted networks where edges between nodes have weights (workload value) are analyzed. In such networks, node centrality is not solely related to the number of the edges a node has, but the weight of those edges has an impact on node centrality too. Therefore, in order to identify each node's importance in weighted networks, the methodology proposed by Opsahl et al (2010) is followed.

Opsahl et. al (2010) discussed that the centrality of a node, in other words, the importance of a node, would be impacted by both the number of edges the focal node has and the weight of those edges in a weighted network. In order to measure node centrality in a weighted network, they proposed a 3-step methodology that combines node degree and node strength by using a tuning parameter. The first step is calculating the degree of each node. According to Freeman (1978), degree of a focal node is the number of nodes that the focal node connected to (Freeman, 1978). This measure can be calculated by using Equation 6 below.

$$k_i = \sum_j^N x_{ij} \qquad [6]$$

where *k* is the node degree, *i* is the focal node, *j* represents all other nodes, *N* is the total number of nodes, and *x* is the adjacency matrix of the network where x_{ij} is equal to 1 if node *i* is connected to node *j*, otherwise it equals to 0 (Opsahl et al., 2010).

The second step is calculating node strength which is the sum of edge weights the focal node has. This measure can be calculated by using Equation 7 below.

$$s_i = \sum_j^N w_{ij} \qquad [7]$$

where *w* is the weighted adjacency matrix of the network, in which the cell w_{ij} corresponds to the weight of the edge between node *i* and node *j*.

The third and last step is calculating degree centrality (DC) measure which shows the node centrality in weighted networks by using Equation 8 below.

$$DC_i = k_i^{1-\alpha} . s_i^{\alpha} \qquad [8]$$

where α is a positive tuning parameter that should be set according to the research setting and data collected. If α value is selected between 0 and 1, then the higher DC value would show higher importance, while if α value selected a higher value than 1, then low DC value would show higher importance in the studied network (Opsahl et al., 2010). In this research, α value is assumed to be equal to 0.5 in all case projects presented in Chapter 5.

Most of the network metrics are focused on static networks whose topology does not evolve with time. In recent years, new studies on dynamic networks that change within time by the addition or removal of new nodes and edges have been added to literature (Ghanem et al., 2018). In this research, a snapshot method is used for dynamic network analysis, and static networks are obtained for different time frames in the project lifecycle. In other words, dynamic networks that evolve and change throughout the project lifecycle are divided into several static networks for different time frames. Then DC value of nodes is calculated for each individual static network.

As introduced in Section 3.2.4.2, in this research workload value between project stakeholders is used as the weight of the edges. Thus, while DC value point outs the importance of the nodes, it also indicates the workload of the nodes based on the number of the connection it has and the workload of those connections.

3.2.5 Network Visualization

Nodes and edges are two main elements of any network system, therefore in order to establish a stakeholder interface network, nodes and edges should be defined. In this step, data collected in the previous steps are processed and converted into nodes and edges tables.

First, data collected in the stakeholder identification phase are converted into nodes table by giving a unique ID and Label to each stakeholder and converting phase involvement data into Time-set values. Time-set values can be actual start and end dates of the phases when each stakeholder is involved in the project. If this data is not available, then interval values can be used. For example, if a stakeholder stays active for only the first three phases of the project, then the Time-set value for that stakeholder would be [0,3] where 0 is the start point of the first phase and 3 is the endpoint of the third phase. If Framework-B is used then, the degree centrality of the nodes should be added as the fourth column.

Second, data collected in the stakeholder connection identification phase and evaluating stakeholders' connections phase are converted into edges tables. Each edges table consists of six columns namely: (1) Source, (2) Target, (3) Type, (4) Interval, (5) Weight, and (6) Health. “Source” and “Target” columns contain node IDs of connecting stakeholders. Depending on the network created, the type of each connection would be entered as either “undirected” or “directed. The “Interval” column contains the Time-set data of each stakeholder connection. Since workload between stakeholders is only analyzed in Framework-B, if Framework-A is used for evaluating stakeholder’s connection, then the weight of each connection would be accepted as equal and would be “1” for each edge. If Framework-B is used, then the “Weight” column would contain dynamic workload values between project stakeholders. Lastly, the “Health” column contains dynamic health values between project stakeholders.

After creating nodes and edges table for the selected project, the stakeholder interface network is established and visualized using a network visualization software. If Framework-B is used, the thickness of the links would represent the workload between stakeholders and the color of the links would represent the interface health of stakeholder connections. Workload and health value between each stakeholder range between 4 to 12. Higher values represent a high workload and poorer health. Also, both workload and health values are transferred to the edges table without using a benchmark table. Therefore, edge thicknesses on the stakeholder interface networks also range between 4-12. Interface health of stakeholder connections is represented by a color spectrum where lower health values are represented by a lighter color and higher health values are represented by a darker color on the links between nodes. The color spectrum used for health value visualization in Framework-B is presented in Figure 10. Health value “0” is added to the spectrum for the projects where health data is not available.

Health	0	4	5	6	7	8	9	10	11	12

Figure 10 Color spectrum for Interface Health Values

In Equation-4 and Equation-5, the weight of each criterion is accepted as equal to “1”. However, different weights are assigned to each criterion based on project expectations. Similarly, defining a standard array for poor, good, and average health conditions is beyond the scope of this research, since the weight of the health criteria and expectations on the health of stakeholder collaboration can differ in each project. In order to provide an example of how the health scale can differ from project to project, two different health scales are presented in Figure 11. Before adopting this methodology in any organization, the scoring system explained in this research should be reviewed by the task force, and health definitions should be set for their project types.

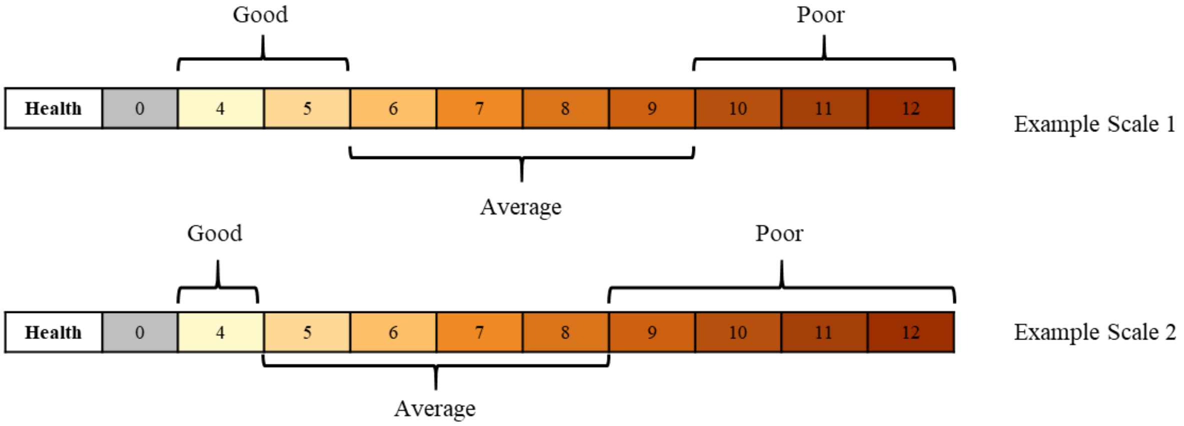


Figure 11 Example health scales

Lastly, Degree Centrality (DC) values are represented by node sizes in stakeholder interface networks where higher DC values are represented with bigger nodes. In this research, node sizes are scaled relatively. For each stakeholder interface network, the node which has the lowest DC value would have the size of 10, while the node which has the highest DC value would have the size of 30. The size of the remaining nodes would be arranged automatically in between. A sample stakeholder interface network which is used for visualizing interface health and workload values on the edges and DC values on the nodes is presented in Figure 12.

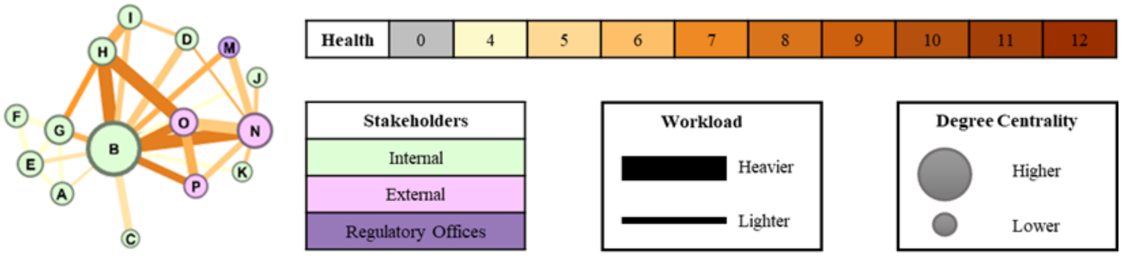


Figure 12 A sample Stakeholder Interface Network

There are several network visualization software available in the market today. In this research, two different tools are used for visualization of the stakeholder interface networks. The first one is an open-source data visualization tool named Gephi (version 0.9.2) which requires nodes and edges tables imported in CVS file format. The second one is also an open-source tool created for this research. Gephi is used as the main visualization tool in this thesis to create stakeholder interface networks and visualize the interface health and workload results. The stakeholder interface networks created using Gephi are presented in Chapter 5 and the stakeholder interface networks created using the second tool is attached to Appendix H as a second visualization option.

3.2.6 Interpretation and Corrective Action

The last step is the interpretation and corrective action on the networks created. In this step, critical stakeholder connection with high workload and poor health condition can be detected on the established networks. It is important to have review meetings with PMs and/or Team Leaders in this step to discuss the results presented on the established networks. PMs and Team Leaders of the project can review the established networks and provide their feedback and make corrections on their evaluation files if needed. Ideally, stakeholder’s connections should be evaluated regularly. In this research, a bi-weekly re-evaluation is recommended.

3.3 Summary

Workload and health of stakeholder interactions in complex projects have been ignored or underappreciated in the past, however, stakeholder connections are the core elements that affect overall project success at the end. Especially in the dynamic environment of complex construction projects where there are several project stakeholders working together to achieve overall project goals together, it is important to track the workload and health of the interactions between stakeholders. Traditional project management methods often provide solutions to estimate the resource profile of the stakeholders. However, those solutions do not provide any insight about the workload between stakeholders or interface health between stakeholders.

In this section, Integrated Project Monitoring Method which is the first methodological contribution of this thesis, is introduced. Integrated Project Monitoring method is developed for measuring and visualizing interface health and workload between project stakeholders in complex construction projects. Integrated Project Monitoring Method contains two new frameworks which are the second and third methodological contributions of this thesis. The contribution of the first framework, Framework-A, is that it focuses on interface health measurement between project stakeholders by using project data obtained from Interface Management Systems, Project Schedules, Change Management systems, Document Management systems, and related information technology (IT) and workflow management systems directly. Therefore, it promises an objective data-based methodology to measure interface health between project stakeholders. However, since Framework-A is based on those systems' availability, data acquisition is the main limitation of Framework-A.

The contribution of the second framework, Framework-B, is that it focuses on both workload and health measurement between project stakeholders by using a novel qualitative point system. Framework-B promises a simple, yet powerful tool which provides results quickly without any complicated data acquisition process.

Ideally, Integrated Project Monitoring Method should be adopted at the beginning of any project, and evaluation of stakeholder connections should be done every couple of weeks. In this research, a bi-weekly re-evaluation of the stakeholder connections is recommended. By doing so, there would be more and constant workload and health data so that overloaded or poor health conditions on the stakeholder connections can be identified before it affects the overall project health.

Chapter 4

Methodology for Engineering Progress Measurement and Visualization using Project Information

The second objective of this thesis is developing methods to measure and visualize engineering progress in complex capital projects. As part of this objective, a methodology (BIM+IM Connector) for a novel connection between Interface Management Systems (IMS) and Building Information Modeling (BIM) data using database level integration is proposed (BIM+IMS Connector). The fundamental idea behind BIM-IMS integration is to obtain more accurate project data for better control during the design phase of complex construction projects. This thesis does not cover illustration of an IMS on a design model by adding Interface Points (IPs) and Interface Agreements (IAs) on the 3D model. Only database integration to obtain detailed data is investigated.

In this Chapter, the scope is limited to the Mass Rapid Transit (MRT) domain. MRT project activity is rapidly growing internationally, and they represent hundreds of billions of dollars of investment annually (Fernandez, 2019). In literature there are models and frameworks for measuring design progress of superstructure projects, therefore specific attention is given to MRT projects that don't have specific design maturity definitions. Developing methods to fill the knowledge gap on design progress measurement for mass rapid transit projects is the novelty of this research.

In order to measure engineering progress in Mass Rapid Transit (MRT) projects, new Model Maturity Index (MMI) definitions are created for the Track Line, Overhead Contact Systems (OCS), and Station disciplines. These new MMI definitions are named as MRT-MMI definitions. Furthermore, based on the MRT-MMI definitions, semi-automated tools to assess and visualize the engineering progress of the Track Line, OCS, and Station disciplines per location in an MRT project are also developed. These engineering progress assessment and visualization tools are named as MRT-MMI-AT. In these tools, visualization of the engineering progress is provided by using spider web graphs.

4.1 Integration of BIM and Interface Management System (IMS)

Integration of IMS and BIM data is a vital need for both improved project monitoring and control, and for more informed real-time decision making in large-scale complex projects. Although both BIM and IMS are used for managing complex construction projects and have common features, they require different project data. BIM systems generally consist of design, schedule, and cost data related to the project, while IMS contains information related to the engineering progress of the project. Therefore, by integrating these two systems, data for tracking engineering progress can be obtained more accurately.

Today, in many complex construction projects, IMS and BIM systems are used and managed separately. Connecting BIM systems' deterministic product management perspective and object-oriented approach with IMS' process-oriented approach would provide a better understanding of managing the complexities associated with project uncertainties and risk in organizational structure, coordination, collaboration, and communication. Also, integration of BIM and IMS would provide more accurate data to track engineering progress during the design phase, since data feeding these steps would be complemented by two systems.

Generally, in complex construction projects, the project team starts creating the BIM model of the project before establishing the IMS. In the early stages of the design phase, a conceptual 3D BIM model would be generated and would become more detailed during the project lifecycle, while an IMS would be adopted when work packages of the project are defined in the design phase. In this thesis, the definition of work packages is accepted as the well-defined manageable pieces of a project that can be executed and managed by different stakeholders. In 2015, Lin proposed a web based 3D interface map model which is based on integration of BIM and IMS. According to Lin (2015), the steps of integration of BIM and IMS start with creating a BIM model, and it is difficult to implement IMS within a BIM environment if the model is not created for construction management purposes (Lin, 2015).

BIM and IMS are dynamic systems since their elements can change, evolve, and are sometimes removed from the system. Especially in the design phases of construction projects, many new elements are added to the BIM, while many of the existing elements could be edited or deleted in order to achieve a more detailed design. Likewise, the number of project participants and Interface Points (IPs) change in the IMS during the project lifecycle. As it is explained in Section 3, generally, there are few project participants at the beginning of the project, while the number increases during the construction phase, and then it decreases at the end of the project. Also, IPs do not stay the same; they appear and disappear during the project particularly during the design phase. Therefore, the IMS expands and shrinks with changes in the number of project participants and number of interface points during the project lifecycle.

Creating the link between BIM and IM systems would help project participants to better coordinate over the course of the project and have better communication on interface related problems. Although implementing an IMS in the early phases of complex projects should generally result in better management in terms of cost, schedule, and scope, in practice, not all IMS implementations have concluded successfully. Some reasons given for specific interface management problems were “Lack of communication and coordination between project parties”, “Incomplete design or project plan”, “Poor definition of project interfaces”, “Mismanagement of responsibilities”, “Misunderstanding of integration and fusion between project parties as a system components”, and “Unclear details in the drawings”, etc. (Shokri 2014).

Many of these listed problems are related to communication, and coordination problems that can be solved by connecting an IMS with a BIM system in the early design phases of the project. The result is expected to improve communication and alignment along with reduced requests for information, change requests, and rework.

4.1.1 Methodology – BIM+IMS Connector

Connections can be created by using common features in BIM and IMS such as the schedule, specifications, location, and dimensions of the elements. In this research, mainly 3D BIM models are investigated. One way of establishing the link between BIM and IMS is using the IFC (industry foundation class) database of a BIM system. The properties of many objects in a BIM model are reachable using IFC files and can be used for connecting BIM elements with associated Interface Points (IPs) in the IMS (Eray et al., 2017).

Many objects in a BIM model can be defined in IFC format which provides objects’ actors, controls, groups, products, processes, and resources information as structured information. Although the first releases of IFC format were related to building projects, BuildingSMART concentrated on creating common resources for infrastructure projects such as bridge, tunnel, road, and rail construction. Although the IFC domain does not contain all elements on a complex construction project today, by using IFC infrastructure work extensions, some IPs could be connected to related BIM elements on the BIM model. This proposed idea is presented in Figure 13 with internal connections in both BIM and IMS.

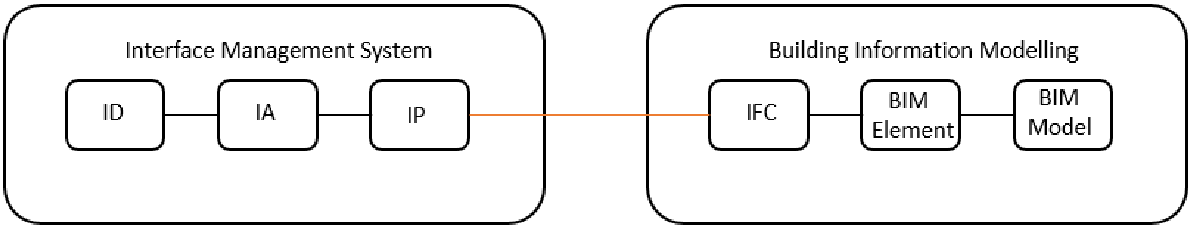


Figure 13 Proposed idea for connecting BIM and IMS

Establishing an IMS for a complex construction project needs a detailed effort at the beginning of the project. Initially, the project needs to be divided into work packages, disciplines, and areas. Then, each stakeholder needs to be linked to the related work packages. Also, the project manager, interface manager, and technical manager information should be provided to each stakeholder, so they can be informed of any new action on the IMS related to their work package. When the setup phase of the IMS is finished, then IPs and Interface Agreements (IAs) of the project can be defined.

Theoretically, in order to define an IP between two interface stakeholders using a sophisticated IMS available on the market today or an in-house model, users are required to define mandatory metadata and generate a unique ID. Metadata for defining an IP between two interface stakeholders could include but not be limited to the title of the IP, and project phase, discipline, area (location), leading work package, interfacing work package, etc. An example database connection behind an IP form can be seen in Figure 14.

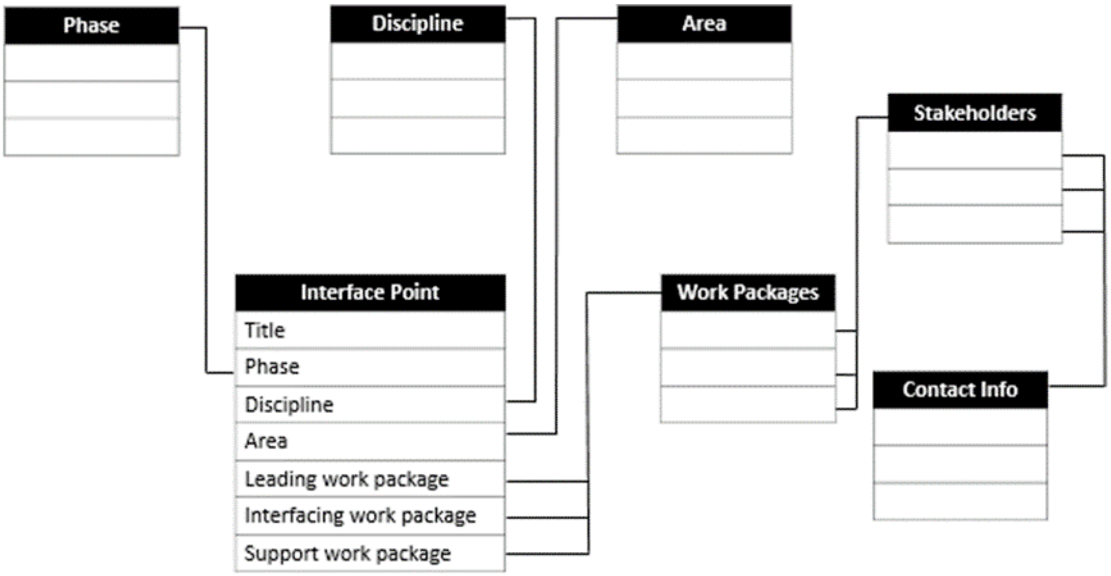


Figure 14 Example database connection behind Interface Point forms

Initial connections between BIM and IMS using the proposed framework would be area (location) data since that information is commensurate and consistent in both systems. In future implementations, facility systems, and model layer may also be useful relations. Each element on the BIM model would have a unique ID and area (location) data on the system that can be reachable by IFC format. By defining an area on an IMS, related BIM elements would be filtered and become reachable over the database. The hypothetical database based connection can be seen in Figure 15.

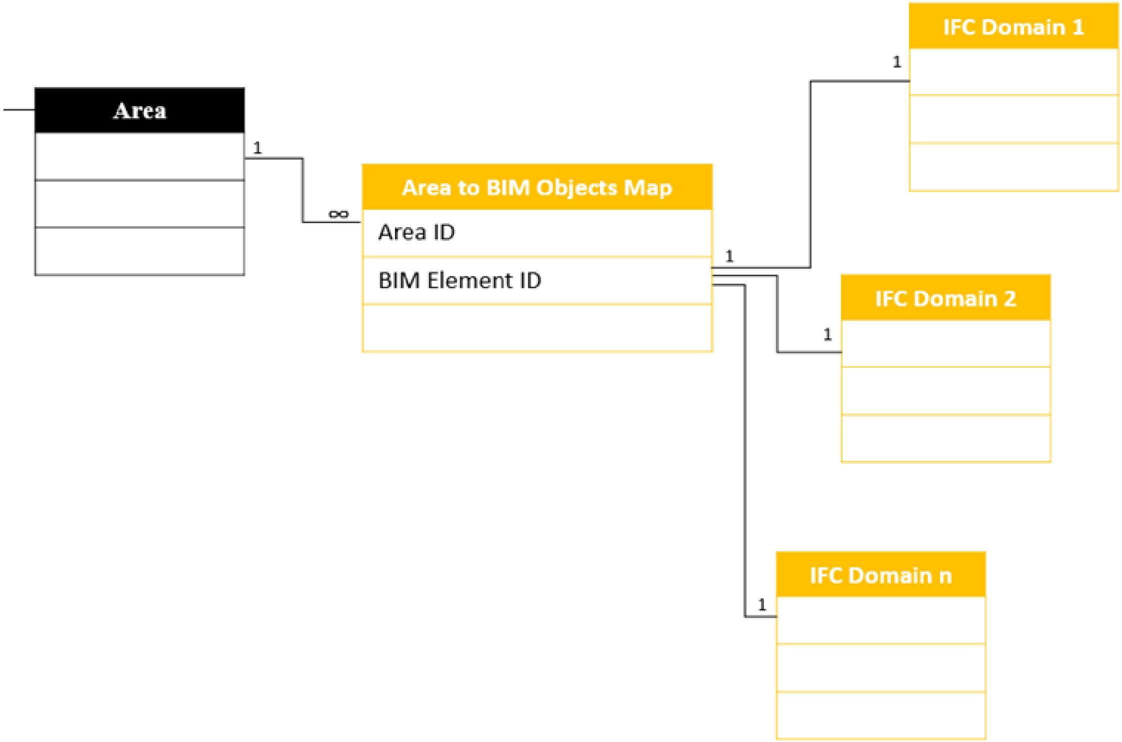


Figure 15 Hypothetical Database Level Connection

A crucial aspect of this connection is that each element would have one area, while each area would have many BIM elements. Therefore, some of the connections on the database would be one to many, while some of them would be one to one. When a database connection of a BIM model and a related IMS is established, links between BIM elements and related IPs would be created on the IP form. The flowchart of creating an IP between two interface stakeholders with explained database integration is presented in Figure 16. A sample of the IP and IA forms that are available today can be found in the Appendix A.

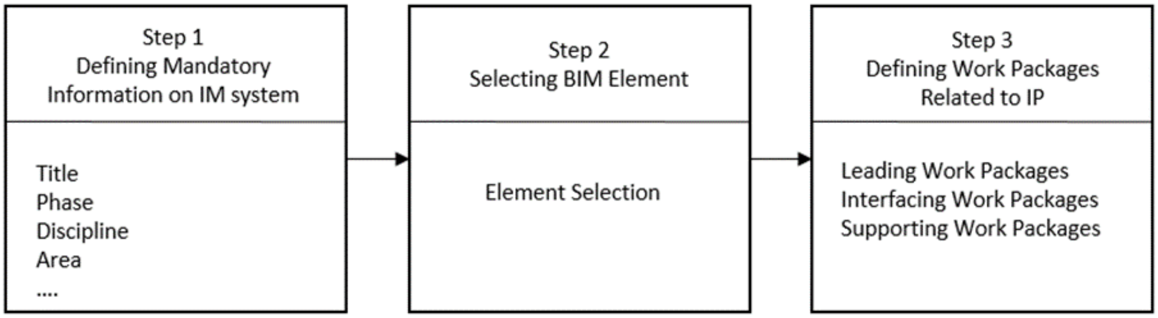


Figure 16 Flow chart of creating IP on integrated IM-BIM system

4.2 Model Maturity Index Definitions for Mass Rapid Transit Projects (MRT-MMI)

Mass Rapid Transit (MRT) systems such as Light Rail Transit (LRT), Bus Rapid Transit (BRT), and subways are important for solving traffic congestion and mobility of the people in the world's crowded cities. These MRT projects are generally considered complex projects due to their size, "brownfield" nature, engineering design and construction complexity, financial approach, contract type, and delivery method.

Although the project environment varies constantly, these projects can be considered as linear projects where many identical units are repeated. However, the graphical details and engineering information added to the model would change location-to-location on the design file. According to expert opinion from the railway industry, it is hard to track design progress in MRT projects since design details and engineering information added to the models are not always similar throughout the project. In other words, there would be locations such as stations or areas between stations, where the design model is close to the as-built version, while other locations are still in the conceptual design phase.

In order to gain industry expert views, numerous research meetings (face to face, teleconference, and skype meetings) were conducted with industry experts from various organizations such as Stantec, Toronto Transit Commission (TTC), Arup, and the Region of Waterloo (Eray, 2018a, 2018d, 2018c, 2018b). These organizations typically undertake mass rapid transit projects such as LRTs, subways projects, and freight rail projects. The names of the contact points and projects are kept confidential in this thesis. In those research meetings, general comments obtained from industry experts on how to track engineering progress during design phase were:

- "*Depending on the project requirements, either 2D drawings or 3D design models were created for each project." –Senior Structural Engineer, Arup – June 2018*
- *"Engineering progress is tracked by counting lists of drawings, lists of specifications, reports, and design briefs. So many things can get left behind, if progress is only tracked in a 3D model, but it does have some value as an indicator."- Rail Sector Lead, Stantec – September 2018*
- *"The most important element in railway projects is Track Line, because Track design and track alignment influences everything. If anything on the Track Line changes, everything in the project changes, and it would create months of work."-Rail Sector Lead, Stantec – January 2019*
- *"Design progress can be measured by tracking number of the design files for each component, tracking volume of comments from stakeholders, and volume of feedbacks on the design file of each component. For example, if there are 600 comment on the design file of a component then it can be accepted as design is now 10%. When design is getting more detailed, number of the comments should decrease, if it does not decrease than it would indicate there is a problem." - Project Lead, TTC – April 2018*
- *"Progress measurement can be done by number of hours based on effort wise." – Director Project Controls, TTC- May 2018*
- *"Design progress is based on the expert's opinion."- Project Manager, Waterloo Region- February 2018*

In this research, MRT projects specific conceptual model maturity index (MMI) definitions (MRT-MMI) and corresponding assessment tools (MRT-MMI-AT) are defined for the Track Line, Overhead Contact System (OCS), and station disciplines. Among various types of MRT projects, the main focus is given to LRT projects in this thesis and LRT projects are used to provide specific examples related to the MRT-MMI definitions and assessment tools.

LRT projects are a subdivision of MRT systems and according to the American Public Transportation Association (APTA), the definition of LRT system is "an electric railway system characterized by its ability to operate single or multiple car trains along exclusive rights-of-way at ground level, on aerial structures, in subways or in streets, able to board and discharge passengers at station platforms or at street, track, or car-floor level and normally powered by overhead electrical wires" (Furmaniak &

Schumann, 2014). According to the report published by the International Association of Public Transport (UITP) in 2015, LRT and tramway systems are operated in 388 cities around the world. Europe is the richest region in terms of the number of LRT projects. A total of 206 cities in Europe has LRT or Tramway system in-service. Eurasia follows Europe with 93 cities having LRTs (UITP, 2015).

4.2.1 MRT-MMI Definitions for Track Line discipline

Track lines on LRT projects are different than on other types of MRT projects' track lines since the main difference of the LRT projects is that the light rail vehicle (LRV) would have the ability to operate in mixed traffic on the street when necessary (Eray et al., 2018; P.C. & Consultants, 2012). Therefore, track line types used in LRT projects are generally thinner. In LRT projects, different types of tracks such as ballasted track, direct fixation track, embedded track, etc. are used (P.C. & Consultants, 2012). In this thesis, a generalized definition for measuring design completeness of the track line discipline that can be used for various types of MRT projects is created.

In order to create MRT-MMI definitions for the Track Line disciple, MII definitions provided by Construction Industry Institute (CII) are studied (CII, 2017). In addition to CII documents, the literature on Track Line design and available project agreement documents for LRT projects are reviewed (Bonnett, 2005; METRO, 2010; Region of Waterloo, 2013). After this process, key design components that can be used for tracking track line design are selected and the first version of MRT-MMI definitions for the Track Line discipline is created. Then, these definitions are shared with a rail industry expert and the validity of these definitions are established through consultation. At the end, the second and final version of MRT-MMI definitions are created conceptually for the Track Line discipline. These definitions are presented in Table 5.

Table 5 Conceptual Model Maturity Index Level Definition for Track Line Discipline (MRT-MMI)

Level	Definition
100	A generic model of the site plan, route, and topographic maps is created. Existing conditions have been quantified and graphically represented.
200	The preliminary geotechnical and hydro-technical investigation reports have been received. The engineering team decided the type of track to be utilized.

Level	Definition
	Track line components graphically modelled with preliminary size and configuration, as follows; - Site plan, topographic maps, and surveys - Horizontal and vertical layout design - The route of the project - Track components - Track ballast/bed design - At-grade crossings - Grade separations - Roadways Design performance parameters, as defined by the project, are associated with model design components as graphic or non-graphic information.
300	The geotechnical and hydro-technical investigation reports have been received and confirmed. Project-specific layout and track line specifications are attached to the related components. Track line components are graphically modelled with design-specified size and configuration, as follows; - Site plan, topographic maps, and surveys - Horizontal and vertical layout design - The route of the project - Track components - Track ballast/bed design - At-grade crossings - Grade separations - Roadways Project plans and permits have been submitted to AHJ (Authority Having Jurisdiction). Environmental and remediation requirements have been submitted to AHJ.
350	Track line components are graphically modelled with confirmed size and configuration, as follows; - Site plan, topographic maps, and geotechnical investigation - Horizontal and vertical layout design

Level	Definition
	- The route of the project - Track components - Track ballast/bed design - At-grade crossings - Grade separations - Roadways Project plans and permits have been confirmed by AHJ Environmental and remediation requirements have been confirmed by AHJ.
400	Track line components are graphically modelled with approved size and configuration, as follows; - Site plan, topographic maps, and geotechnical investigation - Horizontal and vertical layout design - The route of the project - Track components - Track ballast/bed design - At-grade crossings - Grade separations - Roadways The Issued for Construction (IFC) drawing package and specifications have been submitted. Project plans and permits have been approved by AHJ. Environmental and remediation requirements have been approved by the AHJ.
500	As-built: as-built conditions are graphically represented in the model
600	FM-enabled: as-built models are supplied with facility management information as outlined by project scope

4.2.2 MRT-MMI Definitions for Overhead Contact System (OCS)

The second discipline selected for this research is the Overhead Contact System (OCS). In order to create MMI definitions for the OCS disciple, MII definitions provided by CII, OCS design literature, and project agreement documents for various LRT projects are reviewed in detail (Bonnett, 2005; CII, 2017; METRO, 2010; Region of Waterloo, 2013; Weiss & Dupont, 1989). After this process, the key design components that can be used for tracking design are selected. The conceptual MRT-MMI definitions created for the OCS discipline can be seen in Table 6.

Table 6 Conceptual MRT-MMI Level Definition for the OCS Discipline

Level	Definition
100	A generic model of the site plan, route, and topographic maps is created. Existing conditions have been quantified and graphically represented.
200	The location of any underground and overhead utilities have been detected and graphically represented. Overhead Contact System components are graphically modelled with preliminary size and configuration, as follows; - Site plan, topographic maps, and surveys - Curb and property lines - Horizontal and vertical layout design of track line - Intersection layouts - Vehicle envelope - Pantograph envelope - Pole locations - Pole loadings - Guying network - Tension calculations
300	Overhead Contact System components are graphically modelled with design-specified size and configuration, as follows; - Site plan, topographic maps, and surveys - Curb and property lines - Horizontal and vertical layout design of track line - Intersection layouts - Vehicle envelope - Pantograph envelope - Pole locations - Pole loadings - Guying network

Level	Definition
	- Tension calculations
350	Overhead Contact System components are graphically modelled with confirmed size and configuration, as follows; - Site plan, topographic maps, and surveys - Curb and property lines - Horizontal and vertical layout design of track line - Intersection layouts - Vehicle envelope - Pantograph envelope - Pole locations - Pole loadings - Guying network - Tension calculations
400	Overhead Contact System components are graphically modelled with approved size and configuration, as follows; - Site plan, topographic maps, and surveys - Curb and property lines - Horizontal and vertical layout design of track line - Intersection layouts - Vehicle envelope - Pantograph envelope - Pole locations - Pole loadings - Guying network - Tension calculations The IFC drawing package and specifications have been submitted.
500	As-built: as-built conditions are graphically represented in the model
600	FM-enabled: as-built models are supplied with facility management information as outlined by project scope

4.2.3 MRT-MMI Definitions for Stations

The last design discipline selected for this research is the Stations. In order to create MMI definitions for the Stations discipline, design specifications and agreements from various LRT projects across Canada are studied. Additionally, currently available MII definitions provided by CII, station design literature, and key design components for tracking Station design are studied. Conceptual MRT-MMI definitions created for the Station discipline can be seen in Table 7.

Table 7 Conceptual MRT-MMI Level Definition for Station Discipline

Level	Definition
100	A generic model of the site plan, route, and topographic maps are created. Existing conditions have been quantified and graphically represented.
200	The preliminary geotechnical investigation report has been received. The utility conflict matrix is prepared. Public infrastructure works are planned. The civil plan of the station area and profile have been quantified and graphically represented. The engineering team decided the type of foundation to be utilized. Station components are graphically modelled with preliminary size and configuration, as follows; - Subsurface foundation elements - Station platform - Station fixed objects - Station equipment - Station access routes and emergency exit routes Station equipment data, as defined by the project are associated with model design components as graphic or non-graphic information.
300	The geotechnical investigation report has been received and confirmed. The locations of major equipment and structures are decided and graphically modelled. Station components are graphically modelled with design-specified size and configuration, as follows; - Subsurface foundation elements - Station platform

Level	Definition
	- Station fixed objects - Station equipment - Station access routes and emergency exit routes Clash detection analysis has been conducted.
350	Station components are graphically modelled with confirmed size and configuration, as follows; - Subsurface foundation elements - Station platform - Station fixed objects - Station equipment - Station access routes and emergency exit routes
400	Station components are graphically modelled with approved size and configuration, as follows; - Subsurface foundation elements - Station platform - Station fixed objects - Station equipment - Station access routes and emergency exit routes The IFC drawing package and specifications have been submitted.
500	As-built: as-built conditions are graphically represented in the model
600	FM-enabled: as-built models are supplied with facility management information as outlined by project scope

4.3 Engineering Progress Assessment and Visualization Tools for Mass Rapid Transit Projects (MRT-MMI-AT)

Although MRT projects specific MRT-MMI definitions for the Track line, Overhead Contact System, and Station disciplines are conceptual currently, conceptual engineering progress assessment and visualization tools (MRT-MMI-AT) for those disciplines are developed. Explanation of each tool and explanation of how the design progress of each discipline can be assessed with this method is provided in the next sub-sections.

4.3.1 Engineering Progress Assessment and Visualization Tool (MRT-MMI-AT) for the Track Line Discipline

In order to create the engineering progress assessment tool for the Track Line discipline, first, currently available tools and definitions are reviewed in detail and then six main categories that are used in Track Line design are defined. The categories are Preliminary Work, Design components, Interdisciplinary Work, Specifications, Permits, and Submittals. Based on the MRT-MMI definitions explained and presented in Section 4.2.1, twenty-one criteria are created under the six categories. The developed conceptual engineering progress assessment tool for Track Line discipline is presented in Table 8.

In order to obtain the MRT-MMI level of Track Line discipline for a specific location on the project by using the criteria presented in Table 8, the applicability of each criterion for that location should be obtained. Therefore, a fourth column, named Applicability, is added to the right end of the presented table. The options in the applicability column belong to Set A and is presented as Equation 9 below.

$$\begin{aligned} A = \{ & Not\ Applicable, Yes, No, Preliminary, Generic, Loaded, Confirmed, \ldots \\ & \ldots, Received, Design\ Specified, Approved, Submitted\ to\ AHJ, \ldots \\ & \ldots, Confirmed\ by\ AHJ, Approved\ by\ AHJ, IFC\} \end{aligned} \qquad [9]$$

By filling the applicability column for each criterion on the table for a specific location on the project, the MRT-MMI level of Track Line discipline in that location on the model can be obtained.

Table 8 MRT-MMI-AT for the Track Line Discipline

Categories	**Code**	**Criteria**	**Applicability**
Preliminary Work	C1	The geotechnical investigation has the status	$S \mid S \in A$
	C2	The hydro-technical investigation has the status	$S \mid S \in A$
	C3	The site plan, topographic maps, and surveys have the status	$S \mid S \in A$
	C4	Existing conditions have been quantified and graphically represented.	$S \mid S \in A$
Design components	C5	The track alignment (horizontal and vertical layout design) has the status	$S \mid S \in A$
	C6	The track ballast/bed design has the status	$S \mid S \in A$
	C7	The at-grade crossings have the status	$S \mid S \in A$
	C8	The grade separations have the status	$S \mid S \in A$
	C9	The roadways have the status	$S \mid S \in A$
	C10	The track line components are created with approximate size, material, and location, and have the status	$S \mid S \in A$
	C11	Design performance parameters have status	$S \mid S \in A$

Categories	Code	Criteria	Applicability
Interdisciplinary Work	C12	The Overhead Contact System design has the status	S | S ∈ A
	C13	The signal design has the status	S | S ∈ A
	C14	The grading and drainage/stormwater sewer design has the status	S | S ∈ A
Specifications	C15	Project-specific layout specifications have the status	S | S ∈ A
	C16	Project-specific track line specifications have the status	S | S ∈ A
Permits	C17	Regulator permits have the status	S | S ∈ A
	C18	Permits from Municipalities/Highways have the status	S | S ∈ A
	C19	Permits from Utilities have the status	S | S ∈ A
	C20	Environmental and remediation requirements have the status	S | S ∈ A
Submittals	C21	The IFC drawing package and specifications has been submitted	S | S ∈ A

According to the MRT-MMI definitions for the Track Line discipline, minimum applicability response for each criterion in Table 8 is defined. In Table 9, suggested minimum applicability responses to obtain each Model Maturity Index level are presented. When applying proposed engineering progress assessment tool to any MRT project, suggested responses for each MRT-MMI level should be reviewed by the project design team and adjusted according to their project definitions and requirements.

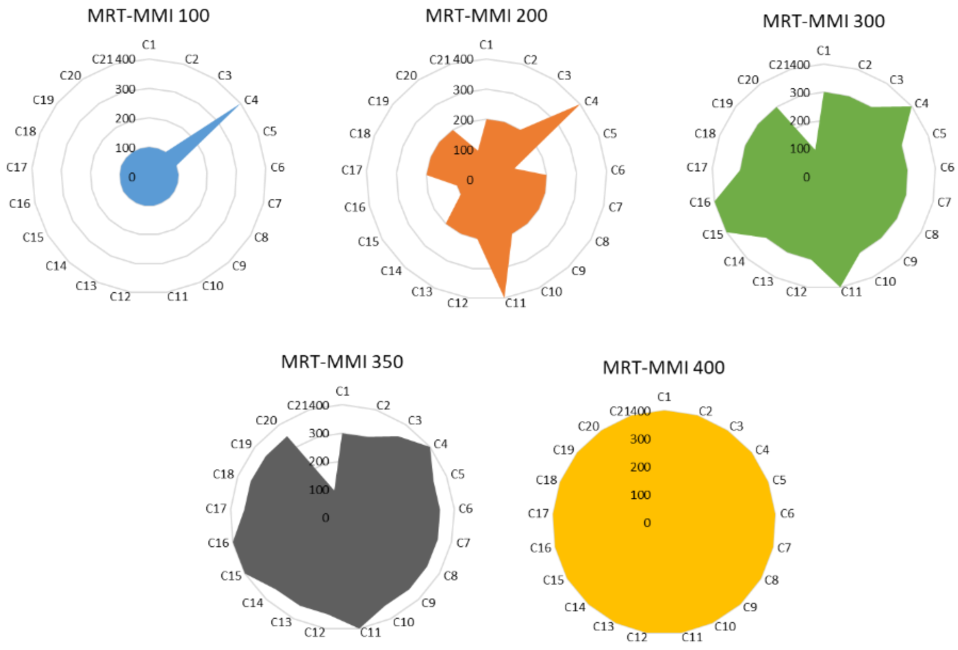
Table 9 Suggested minimum applicability responses for each criterion for each MRT-MMI Level of the Track Line discipline

Code	100	200	300	350	400
C1	Not modeled	Received	Confirmed	Confirmed	Approved
C2	Not modeled	Received	Confirmed	Confirmed	Approved
C3	Generic	Preliminary	Design Specified	Confirmed	Approved
C4	Yes	Yes	Yes	Yes	Yes
C5	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C6	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C7	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C8	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C9	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C10	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C11	Not modeled	Loaded	Loaded	Loaded	Loaded
C12	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C13	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C14	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C15	Not modeled	Not modeled	Loaded	Loaded	Loaded
C16	Not modeled	Not modeled	Loaded	Loaded	Loaded
C17	Not modeled	Not modeled	Submitted to AHJ	Confirmed by AHJ	Approved by AHJ
C18	Not modeled	Not modeled	Submitted to AHJ	Confirmed by AHJ	Approved by AHJ
C19	Not modeled	Not modeled	Submitted to AHJ	Confirmed by AHJ	Approved by AHJ

Code	100	200	300	350	400
C20	Not modeled	Not modeled	Submitted to AHJ	Confirmed by AHJ	Approved by AHJ
C21	Not modeled	Not modeled	Not modeled	Not Modeled	Yes

Measurement of engineering progress of the Track Line discipline for a selected location in the design model is done by comparing availability response of each criterion with the suggested minimum required answers presented in Table 9. By doing so, maturity level reached by each criterion is obtained. At the end, the highest maturity level met by all criteria shows the MRT-MMI level of the Track Line discipline for the selected location.

Visualization of engineering progress assessment is obtained by using Spider web graphs. Spider web graphs which are also known as radar charts, are used for presenting multidimensional metrics and comparing data (Thaker et al., 2016). These graphs provide simple and practical visualization of multiple metrics together (Rankin et al., 2008; Thaker et al., 2016). As it is presented in Table 8, developed MRT-MMI-AT tool for Track Line discipline contains 21 assessment criteria. Spider web graphs can provide simple and practical visualization for those metrics altogether. The information presented in Table 9 is converted into spider web graphs for each MRT-MMI level and presented in Figure 17. These graphs are also used as dashboards to visualize the progress of each criterion by comparing it to following MRT-MMI level.



MRT-MMI 100

MRT-MMI 200

MRT-MMI 300

MRT-MMI 350

MRT-MMI 400

Figure 17 Spider web graphs for each MRT-MMI Level for Track Line Discipline

An example filled-out MRT-MMI-AT for the Track Line discipline in a hypothetical LRT project station area is presented in Table 10. In this example, even though most criterion in the "Design components" category are modeled as "Design Specified" level, some criteria are still in the "Preliminary" level of design. In other words, although some criteria are ready for higher maturity levels, not all of them are in the same level. In the last column of Table 10, the maturity level reached by each criterion is presented. According to the applicability response of the criteria, the max maturity level reached by all criteria is Level 200. Therefore, even though some criteria have higher maturity level, the engineering progress result for that specific area is measured as MRT-MMI 200.

Table 10 An example filled engineering progress assessment tool for Track Line discipline

Categories	**Criteria Code**	**Applicability**	**Level**
Preliminary Work	C1	Received	200
	C2	Received	200
	C3	Design Specified	300
Design components	C4	Yes	400
	C5	Design Specified	300
	C6	Design Specified	300
	C7	Design Specified	300
	C8	Design Specified	300
	C9	Design Specified	300
	C10	Design Specified	300
	C11	Loaded	400
Interdisciplinary Work	C12	Preliminary	200
	C13	Preliminary	200
	C14	Preliminary	200
Specifications	C15	Not modeled	200
	C16	Not modeled	200
Permits	C17	Not modeled	200
	C18	Not modeled	200
	C19	Not modeled	200
	C20	Not modeled	200
Submittals	C21	Not modeled	200
MRT-MMI Level		**200**	

In Figure 18, an example dashboard containing a spider web graph for this example is presented. In this chart, graphs corresponding to MRT-MMI 300, MRT-MMI 200, and responses in Table 10 are overlaid to present progress on each design criterion for the example station. In this way progress of each criterion can be seen and any criterion that needs attention to obtain following MRT-MMI levels can be detected.

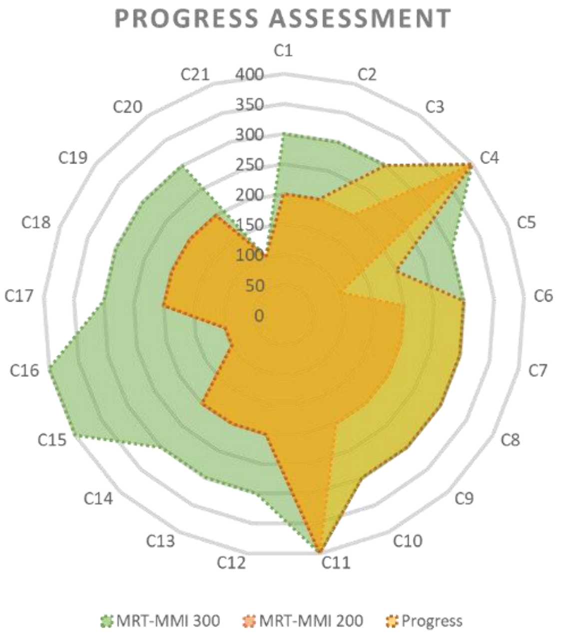


Figure 18 Example dashboard for MRT-MMI-AT Results

4.3.2 Engineering Progress Assessment and Visualization Tool (MRT-MMI-AT) for Overhead Contact System (OCS)

Similar to the proposed MRT-MMI-AT for the Track line discipline, an MRT-MMI-AT for the Overhead Contact System (OCS) is created after reviewing the literature on OCS. Two main categories are defined for tracking the design of OCS. The categories are Preliminary Work and Design Components. Based on the MRT-MMI definitions explained and presented in Section 4.2.2, twelve criteria are defined under selected categories. The developed conceptual MRT-MMI-AT for the OCS discipline is presented in Table 11.

Similar to the MRT-MMI-AT developed for the Track Line discipline, in order to obtain the MRT-MMI level of Overhead Contact System discipline for a specific location on the project, the applicability of each criterion should be obtained. The options in the applicability column also belong to Set A which is presented as Equation 9 in Section 4.3.1. After filling the applicability column for each criterion on Table 11 for a specific location on the project, the MRT-MMI level of OCS in that location on the model can be obtained.

Table 11 Engineering Progress Assessment Tool (MRT-MMI-AT) for Overhead Contact System

Categories	Code	Criteria	Applicability*
Preliminary Work	C1	The site plan, topographic maps, and surveys have the status	S | S ∈ A
	C2	Existing conditions have been quantified and graphically represented.	S | S ∈ A
Design Components	C3	Intersection layouts have the status	S | S ∈ A
	C4	Curb and property lines have the status	S | S ∈ A
	C5	Location of any underground and overhead utilities have been detected and graphical represented	S | S ∈ A
	C6	Vertical and horizontal layout of tracks has the status	S | S ∈ A
	C7	Vehicle envelope has the status	S | S ∈ A
	C8	Pantograph envelope has the status	S | S ∈ A
	C9	Pole locations have the status	S | S ∈ A
	C10	Pole loadings have the status	S | S ∈ A
	C11	Guying network has the status	S | S ∈ A
	C12	Tension calculations have the status	S | S ∈ A

Based on the OCS MRT-MMI definitions, the suggested minimum applicability response of each criterion in Table 11 for each MRT-MMI level is presented in Table 12 below.

Table 12 Suggested minimum applicability of each criterion for each MRT-MMI Level of OCS

Code	100	200	300	350	400
C1	Generic	Preliminary	Design Specified	Confirmed	Approved
C2	Yes	Yes	Yes	Yes	Yes
C3	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C4	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C5	Not modeled	Yes	Yes	Yes	Yes
C6	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C7	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C8	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C9	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C10	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C11	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C12	Not modeled	Preliminary	Design Specified	Confirmed	Approved

It is worth mentioning again that the information presented in Table 12 is suggested responses for each criterion. It is important that before applying these tools and definitions to any railway project, the design team should review these suggestions and adjust them according to their needs and project requirements.

4.3.3 Engineering Progress Assessment and Visualization Tool (MRT-MMI-AT) for the Station discipline

Lastly, an MRT-MMI-AT for the Station discipline is created after reviewing the literature on Station design. Four main categories are defined for tracking Station design in MRT projects. The categories are Preliminary Work, Design Components, Analysis, and Submittals. Based on the MRT-MMI definitions explained and presented in Section 4.2.3, sixteen criteria are created under selected categories. The developed conceptual MRT-MMI-AT for the Station discipline is presented in Table 13.

Similar to the MRT-MMI-AT proposed for the Track line and Overhead Contact System disciplines, in order to obtain MRT-MMI level of Station discipline for a specific location on the project by using the criteria presented in Table 13, the applicability of each criterion should be obtained. The options in the applicability column belong to Set A which is presented as Equation 9 in Section 4.3.1. After filling the applicability column for each criterion in Table 13 for a specific location on the project, MRT-MMI level of Station discipline in that location on the model can be obtained.

Table 13 Engineering Progress Assessment Tool (MRT-MMI-AT) for the Station Discipline

Categories	Code	Criteria	Applicability*
Preliminary Work	C1	The geotechnical investigation has the status	$S \mid S \in A$
	C2	The site plan, topographic maps, and surveys have the status	$S \mid S \in A$
	C3	Existing conditions of the track route have been quantified and graphically represented	$S \mid S \in A$
	C4	Civil plan of the station area and profile have been quantified and graphically represented	$S \mid S \in A$
	C5	Utility Conflict plans are prepared.	$S \mid S \in A$
	C6	Public Infrastructure works are planned.	$S \mid S \in A$
Design Components	C7	The locations of major equipment and structures have the status	$S \mid S \in A$
	C8	The engineering team has determined the types of foundations to be utilized	$S \mid S \in A$
	C9	Subsurface foundation elements are graphically modeled with size, material, location, and elevation, and have the status	$S \mid S \in A$
	C10	Station platform has the status	$S \mid S \in A$
	C11	Station fixed objects (furniture, signage, shelters) have the status	$S \mid S \in A$
	C12	Station access routes and emergency exit routes have the status	$S \mid S \in A$

Categories	Code	Criteria	Applicability*
	C13	Station equipment (ticket vending machines, communication equipment) have the status	S | S ∈ A
Analysis	C14	The equipment data have the status	S | S ∈ A
	C15	Clash detection is conducted.	S | S ∈ A
Submittals	C16	The Issue for Construction (IFC) drawing package and specifications has been submitted	S | S ∈ A

Based on the Station system MRT-MMI definitions, suggested minimum applicability response of each criterion in Table 13 for each Model Maturity Index level is presented in Table 14 below. Similar to Table 9 for the Track Line discipline and Table 12 for the OCS discipline, the information presented in Table 14 is suggested responses for each criterion. It is important that before applying these tools and definitions to any railway project, the design team should review these suggestions and adjust them according to their needs and project requirements.

Table 14 Suggested applicability of each criterion for each MRT-MMI Level of Station discipline

Code	100	200	300	350	400
C1	Not modeled	Received	Confirmed	Confirmed	Approved
C2	Generic	Preliminary	Design Specified	Confirmed	Approved
C3	Yes	Yes	Yes	Yes	Yes
C4	Not modeled	Yes	Yes	Yes	Yes
C5	Not modeled	Yes	Yes	Yes	Yes
C6	Not modeled	Yes	Yes	Yes	Yes
C7	Generic	Preliminary	Design Specified	Confirmed	Approved
C8	Not modeled	Yes	Yes	Yes	Yes
C9	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C10	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C11	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C12	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C13	Not modeled	Preliminary	Design Specified	Confirmed	Approved
C14	Not modeled	Loaded	Loaded	Loaded	Loaded
C15	No	No	Yes	Yes	Yes
C16	Not modeled	Not modeled	Not modeled	Not Modeled	Yes

4.4 Summary

In this Chapter, the creation of a novel connection between BIM and Interface Management System (BIM+IMS Connector) is described and new MMI level definitions and their corresponding assessment and visualization tools for the MRT domain are introduced. While BIM+IMS Connector is the fourth methodological contribution of this thesis, MRT-MMI definitions and corresponding assessment and visualization tools (MRT-MMI-AT) are the domain contributions of this thesis.

Currently, the MRT-MMI-AT that were developed with expert engineering guidance, can be filled with semi-automated assistance by using BIM and IMS data per location. As described in Section 4.1.1. of this thesis, location data can be used as the main integration point for these two systems. When full integration of BIM and IMS is developed, some automated assistance to fill engineering progress assessment and visualization tools would be available as well. As a general example; geotechnical investigation reports can be tracked using IMS by checking interface agreements, and the request for information system data between civil works and infrastructure stakeholders of the LRT project since they would share that information with each other over these systems. Similarly, track line layout design related criterion or track ballast/bed design-related criterion can be answered by using LOD levels of the related elements on the BIM file.

Chapter 5

Validation of Proposed Models: Demonstration of Functionality

As explained in Chapter 3, two frameworks are developed in this research as part of the Integrated Project Monitoring Method. Among them, Framework-A requires actual project data, and after several aborted attempts for data acquisition from different construction organizations undertaking multiple complex construction projects, it was found that either required information management systems were not available in their organization, or the required data was not stored in an accessible database. Therefore, in this Chapter, Framework-A is validated only to the extent allowed through the grounded theory methodology used to develop the metrics and presented in Section 5.1 below.

The second Framework developed, Framework-B, focuses on both workload and health measurement between project stakeholders by using a novel qualitative point system developed as part of this thesis. In this Chapter, Framework-B is validated empirically through implementing the point system in 6 projects from two different industries. Details of each project investigated and analyzed using Framework-B are provided in the related subsections below.

In Chapter 4, a methodology for database-level integration of Building Information Modeling (BIM) and Interface Management Systems (IMS), BIM+IM Connector, was explained. In order to validate the proposed methodology, a representative Light Rail Transit project is designed by using Autodesk Revit and Coreworx IMS. BIM+IM Connector is validated through a functional demonstration on the designed LRT project. Moreover, the Engineering Progress Assessment Tools for Track Line and Station disciplines are validated on the representative Light Rail Transit (LRT) project. Details of the validation process are explained in Section 5.4.

5.1 Partial Validation of Integrated Project Monitoring Method – Framework A

As presented in Figure 7, the first three steps of the Integrated Project Monitoring Method are “Project Selection and Identification”, “Stakeholder Identification”, and “Stakeholder Connection Identification”. In order to create a functional demonstration of Framework-A, the sample project presented in Figure 6 is selected. The project stakeholders and their connections are summarized in Table 15.

Table 15 Project Stakeholders and their connections

Node ID	Label	Connections
1	A	2,6,7
2	B	1,4,6
3	K	6
4	L	2,5,6
5	M	4,6,7
6	N	1,2,3,4,5,7,8
7	X	1,5,6,8
8	Y	6,7

After defining stakeholders and stakeholder connections, the next step is specifying benchmark tables and weights of each interface health indicator. As it is explained in Section 3.2.3.1, both benchmark values and indicator weights are project-specific. In this example project, all indicators have equal importance, therefore indicator weights are the same for all indicators. In order to provide example benchmark values, the benchmark table used for I_3 (Percentage of RFI time overrun) in this example is presented in Table 16. It is worth repeating that these benchmark tables are project specific and will change according to project goals and expectations. Therefore, the project teams should define the values according to their specific project.

Table 16 Example benchmark table for RFI time overrun

Time overrun (%)	Indicator value
0.0% - 20%	1.0
21% - 40%	0.7
41% - 60%	0.5
61 % - 80 %	0.3
81 % -100 %	0.1

After defining benchmark values and weights of each indicator, the next step is to "Calculate each indicator value for each stakeholder connection". An example calculation for an interface health indicator value is prepared for the third indicator, the "Percentage of RFI that has time overrun (I_3)". To calculate the value of this indicator, RFI log data (create date, need date, and completed date) between two project stakeholders needed to be collected. For the functional demonstration, RFI workflow data from a construction project of cabin gas plants in British Columbia is used in this example. For fifteen RFI workflow instances, log data between two stakeholders is shown in Table 17. The last two columns of the table show the duration of the workflow instances and the difference between need date and closed date (time overrun).

Table 17 RFI workflow log data between two project stakeholders

Create date	Need date	Closed date	Duration (days)	Time overrun (days)
8/11/2010	8/11/2010	8/13/2010	2.00	2.00
8/11/2010	8/11/2010	8/12/2010	1.00	1.00
8/20/2010	8/24/2010	8/23/2010	3.00	none
8/11/2010	8/12/2010	8/12/2010	1.00	none
8/11/2010	8/12/2010	8/12/2010	1.00	none
8/11/2010	8/12/2010	8/16/2010	5.00	4.00
8/11/2010	8/16/2010	8/12/2010	1.00	none
8/11/2010	8/17/2010	8/17/2010	6.00	none
8/11/2010	8/12/2010	8/13/2010	2.00	1.00
8/18/2010	8/24/2010	8/20/2010	2.00	none
8/18/2010	8/24/2010	8/23/2010	5.00	none
8/18/2010	8/24/2010	8/18/2010	0.00	none
8/18/2010	8/24/2010	8/20/2010	2.00	none
8/18/2010	8/20/2010	8/20/2010	2.00	none
8/26/2010	8/26/2010	8/27/2010	1.00	1.00

In this sample data, the average duration of the RFI workflow instances was 2.27 days, and 33% of the workflow instances experienced time overruns. Also, the average duration of time overruns was 0.6 days. After calculating these values, the benchmark table presented in Table 16 would be used to determine the appropriate indicator value. According to the example benchmark values in Table 16, the value of the I_3 would be 0.7. The remaining 13 interface health indicators can be calculated by following similar steps.

After calculating each indicator value between two project stakeholders, the next step is to "Calculate interface health value (H) for each stakeholder connection". For this step, interface health value between project stakeholders can be calculated by using Equation 3 presented in Section 3.2.3.1. An example H value table that summarizes interface health values between project stakeholders in the example project is presented in Table 18.

Table 18 Example Interface Health (H) Values between project stakeholders shown in Figure 6

Name	Value	Name	Value	Name	Value	Name	Value
H_{AB}	0.46	H_{NX}	0.85	H_{YN}	0.82	H_{LM}	0.88
H_{BA}	0.82	H_{XY}	0.80	H_{NY}	0.76	H_{NK}	0.86
H_{AX}	0.40	H_{YX}	0.88	H_{NM}	0.86	H_{KN}	0.81
H_{XA}	0.42	H_{XM}	0.65	H_{MN}	0.83	H_{BL}	0.92
H_{AN}	0.65	H_{MX}	0.72	H_{NL}	0.84	H_{LB}	0.89
H_{NA}	0.72	H_{BN}	0.40	H_{LN}	0.81		
H_{XN}	0.82	H_{NB}	0.42	H_{ML}	0.90		

After calculating the H values between project stakeholders, interface health condition between stakeholders can be determined by using a final benchmark table. The final benchmark table would be also project-specific and should be defined by the project team. For this example, interface health condition for H values between “0.8” and “1” are accepted as “Good Interface Health”, while the values between “0.5” and “0.79” are accepted as “Average Interface Health”, and the values below “0.5” are accepted as “Poor Interface Health”. According to these benchmark values, interface health conditions between these eight project stakeholders are presented on the stakeholder interface network by using color-codes in Figure 19.

As it is explained in Section 3.2.3.1, interface health between two stakeholders is bi-directional, and each stakeholder might experience the health of the relationship differently. In this example project, both the pair of Stakeholder A and Stakeholder B, and Stakeholder Y and Stakeholder N experienced the health of their relationships differently. In such case, on the overall network representation of the interface health condition, the color of the link between those stakeholders would be the associated color of the lower H value calculated. However, knowing each H value and seeing the actual colors of the links as it is shown in the lookouts in Figure 19, would help upper-level managers to diagnose any health problem that arises from those connections.

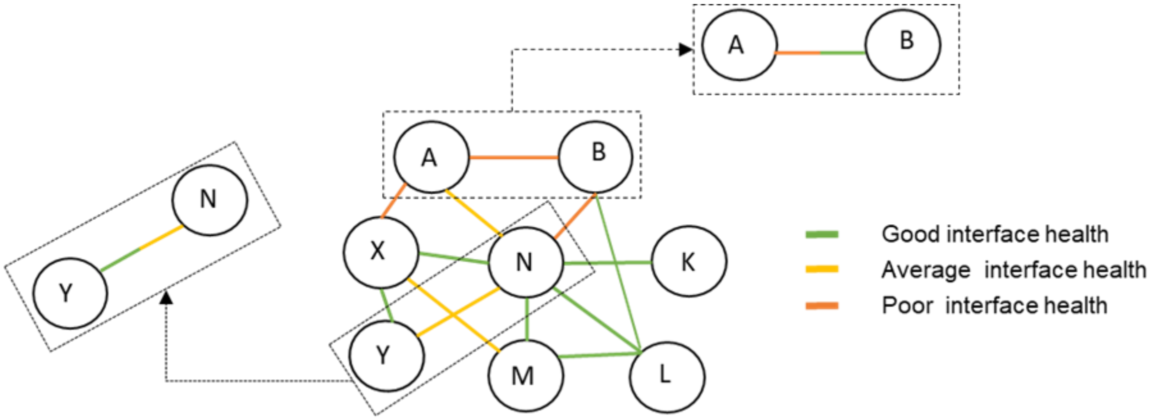


Figure 19 Interface health condition presentation on the stakeholder interface network

These network representations of interface health condition between project stakeholders can be used as a dashboard for upper-level managers in complex construction projects. Diagnosing any interface health problem between project stakeholders before it affects overall project health can be achieved by using the explained model.

5.2 Validation of Integrated Project Monitoring Method – Framework B

Integrated Project Monitoring Method using Framework-B is validated through using data from six ongoing projects from two different industries. Throughout the validation phase, a total of 37 research meetings have been conducted with two industry partners. Among those 37 research meetings, 15 of them were with the construction organization in railway industry, and 22 of them were with the organization in the nuclear industry. In these research meetings, first, this research project and its objectives were introduced. Then, example projects among these organizations' portfolio of projects were selected and data from those projects was collected. Details of each project investigated and analyzed are given in the related subsections below.

5.2.1 Project 1- Rail Line Project

The first project where Framework-B was applied to an ongoing design-build (DB) type industrial rail line project located in North America. The construction organization that provided the data was working on various rail line projects with different size and scope all around the globe. The planned length of the selected industrial rail line project was approximately 38 kilometers, the estimated construction cost of the project was $110,000,000, and the anticipated duration of the design phase was 19 months. The Project Manager of the consultant team was involved as a decision-maker in this case study. Thus, interface health and workload between stakeholders were analyzed from the consultant's point of view. During the interviews and data collection, the project was still under design. Therefore, the proposed framework was only applied to the design phase of the project.

5.2.1.1 Stakeholder Identification and Stakeholder Connections Identification

In order to identify project stakeholders and interfaces between those stakeholders, 6 review meetings were held with the Rail Sector Manager and Project Manager (PM) of Project Consultant. During these meetings, first, the methodology of the Project Health Measurement Model presented in Figure 7 was briefly introduced to the decision maker. Then, the list of project stakeholders and their hierarchical order were defined by asking open-ended questions. It was found that there were 4 main stakeholders; Owner, Contractor, Consultant, and Regulatory offices during the design phase. After defining sub-groups of Owner, Contractor, and Regulatory Offices, a total of 14 stakeholders were defined for the design phase. Then, the PM (JJ in Table 15) identified interfacing stakeholders during the design phase of the project. In Table 19, the stakeholder list and their connections with each other are summarized. The names of the companies were omitted for confidentiality purposes.

Table 19 Stakeholder List and Stakeholders' Connections List of the Rail Line project

Node ID	Label	Name	Group	Connections
1	AA	Owner – Project Manager	1	2,3,10,5,4,6
2	BB	Owners Engineer	1	1,3,10,5,4,6
3	CC	Contractor - Project Manager	2	11,10,12,3,1,13,14
4	DD	Regulatory Office 1	4	2,1
5	EE	Regulatory Office 2	4	1,2
6	FF	Regulatory Office 3	4	2,1
7	GG	Regulatory Office 4	4	18,10,17
8	HH	Regulatory Office 5	4	2,1
9	II	Regulatory Office 6	4	18,10,17
10	JJ	Consultant - PM Team	3	3,2, 1
11	KK	Contractor - Surveyors	2	10,12,13,3,2,1
12	LL	Contractor - Geotechnical/Pavement	2	10, 3,2,1
13	MM	Contractor - Bridge	2	110, 3,2,1
14	NN	Contractor - Rail	2	10,3,7,9,2,1

By the end of this step, it was found that interfaces between defined stakeholders created a total of 25 undirected connections.

5.2.1.2 Evaluating stakeholders' connections

As presented in Figure 7 in Chapter 3, after defining stakeholders and their connections, the next step in the Integrated Project Monitoring Method is to evaluate the project stakeholder's connections. Therefore, the decision-maker was asked to fill out the point system tools explained in Table 3 and Table 4 for each stakeholder connection. In the case of larger projects, it could be a project leadership team that fills out the tool. Later in this thesis, the potential impact and value of visualizing discrepancies between different assessors' (or stakeholders') perspectives on the project are explained. In Table 20, responses of the decision-maker and calculated "Workload" and "Health" values of each stakeholder connection according to those responses are presented.

Table 20 Workload and Health evaluation of each stakeholder connection in Rail Line Project

Source	Target	W1	W2	W3	W4	Workload	H1	H2	H3	H4	Health
AA	BB	3	3	2	2	10	2	2	1	2	7
AA	CC	3	1	1	1	6	2	3	2	2	9
AA	DD	2	1	2	2	7	2	2	2	2	8
AA	EE	2	1	2	2	7	2	2	2	2	8
AA	FF	2	1	2	2	7	2	2	2	2	8
AA	HH	2	1	2	2	7	2	2	2	2	8
AA	JJ	2	1	2	1	6	2	2	2	1	7

Source	Target	W1	W2	W3	W4	Workload	H1	H2	H3	H4	Health
BB	CC	3	3	2	2	10	2	2	2	1	7
BB	DD	2	1	2	2	7	2	2	2	2	8
BB	EE	2	1	2	2	7	2	2	2	2	8
BB	FF	2	1	2	2	7	2	2	2	2	8
BB	HH	2	1	2	2	7	2	2	2	2	8
BB	JJ	3	3	3	2	11	2	2	2	1	7
CC	JJ	3	3	3	2	11	2	2	1	1	6
CC	KK	3	3	3	3	12	2	3	1	1	7
CC	LL	3	3	3	2	11	2	2	1	1	6
CC	MM	3	3	3	2	11	2	2	1	1	6
CC	NN	3	3	3	2	11	2	2	1	1	6
GG	JJ	1	1	3	1	6	1	1	1	1	4
HH	JJ	1	1	3	1	6	1	1	1	1	4
II	JJ	1	1	3	1	6	1	1	1	1	4
JJ	KK	3	1	3	2	9	2	2	1	1	6
JJ	LL	2	1	3	2	8	2	2	1	1	6
JJ	MM	2	1	3	2	8	2	2	1	1	6
JJ	NN	2	1	3	1	7	2	2	1	1	6

5.2.1.3 Network Analysis

In order to determine the stakeholder that has the highest workload in this rail line project, the Degree Centrality (DC) value of each node was calculated. As explained in Chapter 3, the importance of the nodes in a network is based on both the quantity and weight of connections for each node. In this research, the weights of the connections are based on the workload values between stakeholders. Therefore, higher Degree Centrality (DC) values show a higher workload on the nodes. In Table 21, DC value of each stakeholder in this industrial rail line project is presented.

Table 21 DC value of the nodes in of Rail Line Project

ID	DC
AA	18.71
BB	20.32
CC	22.45
DD	5.29
EE	5.29
FF	5.29
GG	2.45
HH	7.75
II	2.45
JJ	27.93
KK	6.48
LL	6.16
MM	6.16
NN	6.0

Based on the network analysis conducted, the consultant (JJ) of the Rail Line Project had the highest workload among all project stakeholders, followed by the contractor (CC) and the Owner's Engineers (BB).

5.2.1.4 Visualization

As discussed in Chapter 3, nodes and edges table should be created to establish and visualize stakeholder interface networks. In the previous steps, required data for these nodes and edges tables were collected and analyzed. Nodes table may contain, Code, ID, Label, Type, Interval, and Degree Centrality (DC) data. In Table 22, the nodes table for the Rail Line project is presented as an example.

Table 22 Nodes table – Rail Line Project

Code	ID	Label	Type	Interval	DC
1	AA	Owner – Project Manager	1	[0,1]	18.71
2	BB	Owners Engineer	1	[0,1]	20.32
3	CC	Contractor - Project Manager	2	[0,1]	22.45
4	DD	Regulatory Office 1	4	[0,1]	5.29
5	EE	Regulatory Office 2	4	[0,1]	5.29
6	FF	Regulatory Office 3	4	[0,1]	5.29
7	GG	Regulatory Office 4	4	[0,1]	2.45
8	HH	Regulatory Office 5	4	[0,1]	7.75
9	II	Regulatory Office 6	4	[0,1]	2.45
10	JJ	Consultant - PM Team	3	[0,1]	27.93
11	KK	Contractor - Surveyors	2	[0,1]	6.48
12	LL	Contractor - Geotechnical/Pavement	2	[0,1]	6.16
13	MM	Contractor - Bridge	2	[0,1]	6.16
14	NN	Contractor - Rail	2	[0,1]	6.0

The data required for the edges table were collected and analyzed in Section 5.1.1.2. Based on those analyses, edges table for the Rail Line project is presented in Table 23.

Table 23 Edges Table - Rail Line Project

Source	Target	Interval	Workload	Health
AA	BB	[0,1]	10	7
AA	CC	[0,1]	6	9
AA	DD	[0,1]	7	8
AA	EE	[0,1]	7	8
AA	FF	[0,1]	7	8
AA	HH	[0,1]	7	8
AA	JJ	[0,1]	6	7
BB	CC	[0,1]	10	7
BB	DD	[0,1]	7	8

Source	Target	Interval	Workload	Health
BB	EE	[0,1]	7	8
BB	FF	[0,1]	7	8
BB	HH	[0,1]	7	8
BB	JJ	[0,1]	11	7
CC	JJ	[0,1]	11	6
CC	KK	[0,1]	12	7
CC	LL	[0,1]	11	6
CC	MM	[0,1]	11	6
CC	NN	[0,1]	11	6
GG	JJ	[0,1]	6	4
II	JJ	[0,1]	6	4
JJ	KK	[0,1]	6	4
JJ	LL	[0,1]	9	6
JJ	MM	[0,1]	8	6
JJ	NN	[0,1]	8	6

The stakeholder interface network was established according to the data presented in Table 22 and Table 23 and is visualized in Figure 19. In order to specify stakeholder groups on the network representation, color codes were used. In the graph, grey-colored nodes represent Owner, blue-colored nodes represent Contractor, pink colored nodes represent consultant, and green colored nodes represent regulatory agencies. Moreover, as introduced earlier, the workload value between project stakeholders is presented with the line thickness of the connections, and health values are presented with color codes. In Figure 20, higher workload value between project stakeholders are represented by thicker edges between nodes. Since higher health value indicates poor health condition according to the point system used, higher health value between stakeholders are represented with darker colors on the edges. Lastly, the degree centrality of each stakeholder is represented with node size such that a higher workload (higher DC) corresponds to a larger node. A legend for these representations is included in Figure 20.

As it is explained earlier in Section 3.2.3, interface health and workload conditions might be experienced differently among two interfacing stakeholders. Therefore, in order to include perspectives of different project stakeholders, health and workload evaluation of the stakeholders' connections should be done by multiple decision makers from different stakeholder groups. Ideally, in order to eliminate biases, these evaluations should also be done by multiple people from the same group. Ultimately, by collecting data from various parties in the same project, different perspectives can be analyzed and a broader view on the health and workload condition of the stakeholder connections can be achieved.

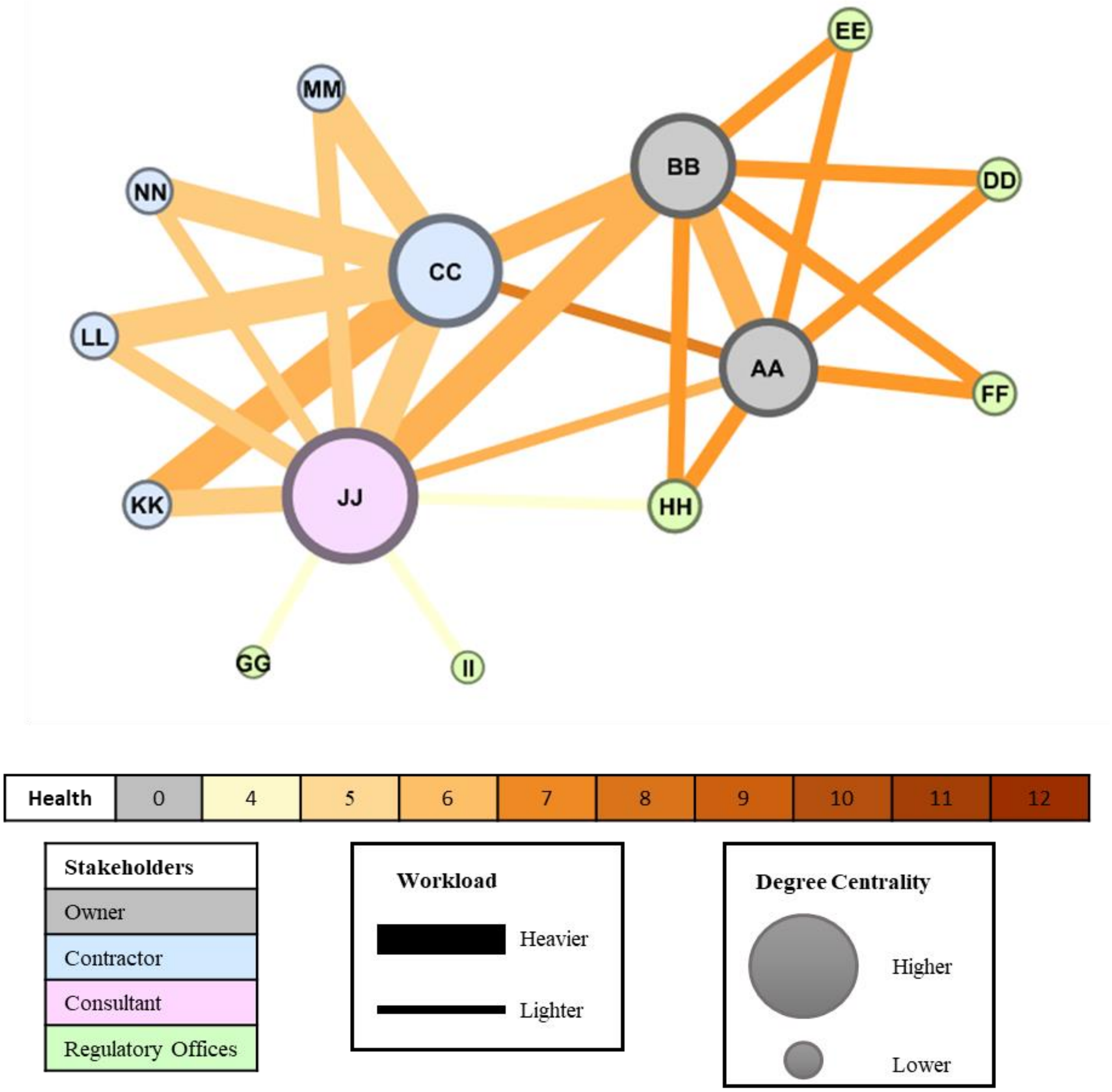


Figure 20 Stakeholder interface network of the Rail Line Project

In order to illustrate the perspective differences that different project stakeholders might have on the interface health and workload conditions of stakeholders' connections, two hypothetical versions of the stakeholder interface network of the Rail Line project are created and presented in Figure 21. The aim of creating these hypothetical networks is showing that it is possible that Contractor (a) or Owner (b) might have different opinions on the condition of the stakeholder connections in Rail Line project. By collecting data from different project stakeholders, such differences can be detected, analyzed, and reported.

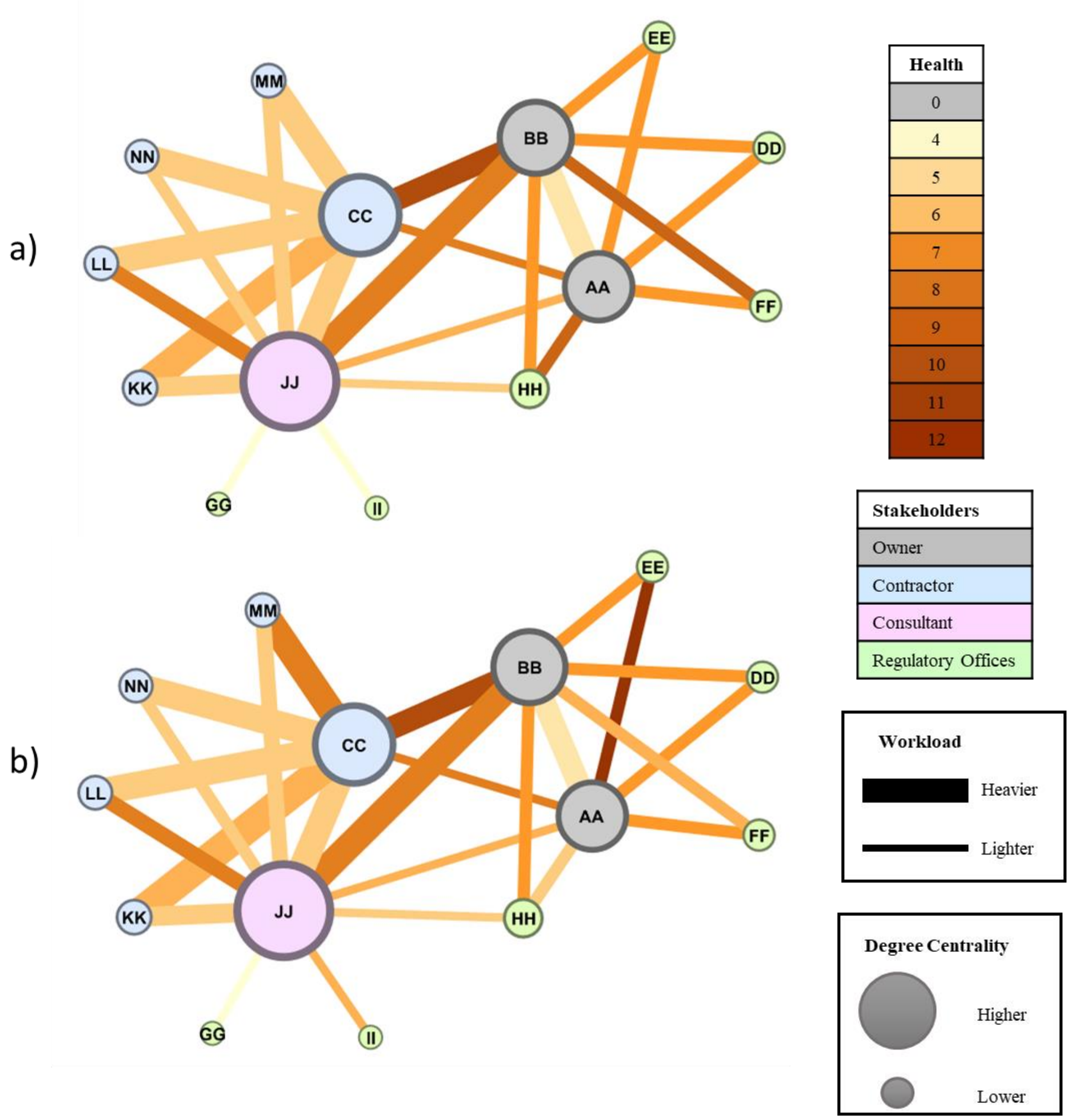


Figure 21 Two hypothetical examples (a, b) of different perspectives on Evaluation of Stakeholders' connections

5.2.1.5 Interpretation and Corrective Action

According to the analysis results presented in Table 23 and Figure 20, the workload value between stakeholder CC and KK was found the highest in this project. Moreover, it is found that the stakeholder connection between AA-CC had the poorest health condition. On the other hand, the connections between JJ-II and JJ-GG had the lowest workload and the healthiest relationship in this project.

After analyzing workload and health data and establishing a stakeholder interface network for the Rail Line project, review meetings with PM of the project were conducted. Although data were limited for the Rail Line project, since it only had two project phases and was in the first phase during the data collection, results were deemed accurate by the PM of the project. The presented example project had been facing problems related to budget, land acquisition, and limited interactions between project owner and contractor. In the results presented in Figure 20, connections between Owner, Contractor, and Regulatory Agencies shows low workload and poor health condition, which aligns with the problems the project had encountered. On the other hand, results for the connections between Consultant (JJ) and Regulatory agencies (GG, HH, II) showed low workload and good health conditions for those connections. These results were also found accurate and realistic by the PM since Consultant (JJ) has been working on submissions to those agencies and meetings between these stakeholders always had a friendly environment so far. Also, since JJ had not submitted the documents yet, the workload between those stakeholders was not high. However, the PM stated that these connections should be evaluated once more when JJ submits the documents, then the workload and health condition of these connections might change. Overall, the results presented in Figure 20 were found valid for the design phase of the project.

5.2.1.6 Re-evaluation

It is important to re-evaluate stakeholder connections regularly to detect any health problems or overloaded connections before those affect overall project health. Therefore, after conducting interpretation and corrective action on the first results, re-evaluation data was requested from the PM team after 1.5 months. Typically, the same stakeholder list and stakeholder connection list would be used for this step in the methodology. But an exception was made for this case project to gather more detailed data.

For this round, after having meetings with PM and Rail Sector Lead of the company, sub-stakeholders of the consultant's team were also added to workload and health evaluation and a more detailed stakeholder list and stakeholders' connection list were created. The stakeholder list created for re-evaluation is presented in Table 24 below.

Table 24 Stakeholder list including sub-stakeholders of Consultant's team

Id	Label	Name	Group	Interactions
1	AA	Owner – Project Manager	1	2,3,10,5,4,6
2	BB	Owners Engineer	1	1,3,10,5,4,6
3	CC	Contractor - Project Manager	2	11,10,12,3,1,17,18,13,14
4	DD	Regulatory Office 1	4	2,1
5	EE	Regulatory Office 2	4	1,2
6	FF	Regulatory Office 3	4	2,1
7	GG	Regulatory Office 4	4	18,10,17
8	HH	Regulatory Office 5	4	2,1
9	II	Regulatory Office 6	4	18,10,17
10	JJ	Consultant - PM Team	3	16,17,18,15,3,2,19,1
11	KK	Contractor - Surveyors	2	3,10,16,
12	LL	Contractor - Geotechnical/Pavement	2	3,10,15,19
13	MM	Contractor - Bridge	2	3,15,10
14	NN	Contractor - Rail	2	3,10
15	OO	Consultant - Bridge Design	3	10,12,13,16,18,19,3,2,1
16	PP	Consultant – Track Design	3	17,10,19,18,15,3,2,1
17	RR	Consultant – Drainage Design	3	16,10,18,15,19,3,2,1
18	SS	Consultant – Environmental	3	10,3,16,15,17,19,7,9,2,1
19	TT	Consultant – Roadway Design	3	16,17,10,18,15,3,2,8,7,9,1

By the end of this step, it was found that interfaces between defined stakeholders created a total of 64 undirected connections. The PM of the Rail Line project provided a new set of stakeholders' connections evaluation data for this project 1.5 months after than initial evaluation. Data collected in this step is attached in Appendix B, and the workload (W) and health (H) evaluation result of each stakeholder connection is in Table 25.

Table 25 Workload and Health evaluation result of each stakeholder connection in Rail Line Project

Source	Target	W	H	Source	Target	W	H	Source	Target	W	H
AA	BB	10	7	BB	TT	6	6	JJ	MM	8	6
AA	CC	6	9	CC	JJ	6	5	JJ	NN	7	6
AA	DD	7	8	CC	KK	12	7	JJ	OO	11	6
AA	EE	7	8	CC	LL	11	6	JJ	PP	11	6
AA	FF	7	8	CC	MM	11	6	JJ	RR	11	6
AA	HH	7	8	CC	NN	11	6	JJ	SS	11	6
AA	JJ	6	7	CC	OO	9	6	JJ	TT	11	6
AA	OO	6	7	CC	PP	8	6	KK	PP	10	6
AA	PP	6	6	CC	RR	9	6	LL	OO	9	6
AA	RR	6	11	CC	SS	9	6	LL	TT	6	6
AA	SS	6	6	CC	TT	8	6	MM	OO	9	8
AA	TT	6	5	GG	JJ	6	4	OO	PP	9	5
BB	CC	10	7	GG	RR	6	6	OO	RR	11	5

Source	Target	W	H	Source	Target	W	H	Source	Target	W	H
BB	DD	7	8	GG	SS	6	6	OO	SS	9	5
BB	EE	7	8	GG	TT	6	6	OO	TT	8	7
BB	FF	7	8	HH	JJ	6	6	PP	RR	12	6
BB	HH	7	8	HH	TT	6	6	PP	SS	8	6
BB	JJ	11	7	II	JJ	6	4	PP	TT	9	7
BB	OO	6	7	II	SS	6	6	RR	SS	9	6
BB	PP	6	7	II	RR	6	6	RR	TT	9	6
BB	RR	6	6	JJ	KK	9	6	SS	TT	8	5
BB	SS	6	11	JJ	LL	8	6	10	MM	8	6

By using the new data set obtained, Degree Centrality (DC) of the nodes was recalculated and the stakeholder interface network was recreated. The new DC value of each stakeholder is presented in Table 26, and the new stakeholder interface network is illustrated in Figure 22.

Table 26 Re-evaluated Degree Centrality values for Rail Line Project

ID	Label	DC	ID	Label	DC
1	AA	30.98	11	KK	9.64
2	BB	32.68	12	LL	11.66
3	CC	36.33	13	MM	9.17
4	DD	5.29	14	NN	6.00
5	EE	5.29	15	OO	29.50
6	FF	5.29	16	PP	26.66
7	GG	9.80	17	RR	29.15
8	HH	10.20	18	SS	27.93
9	II	7.35	19	TT	30.22
10	JJ	43.82			

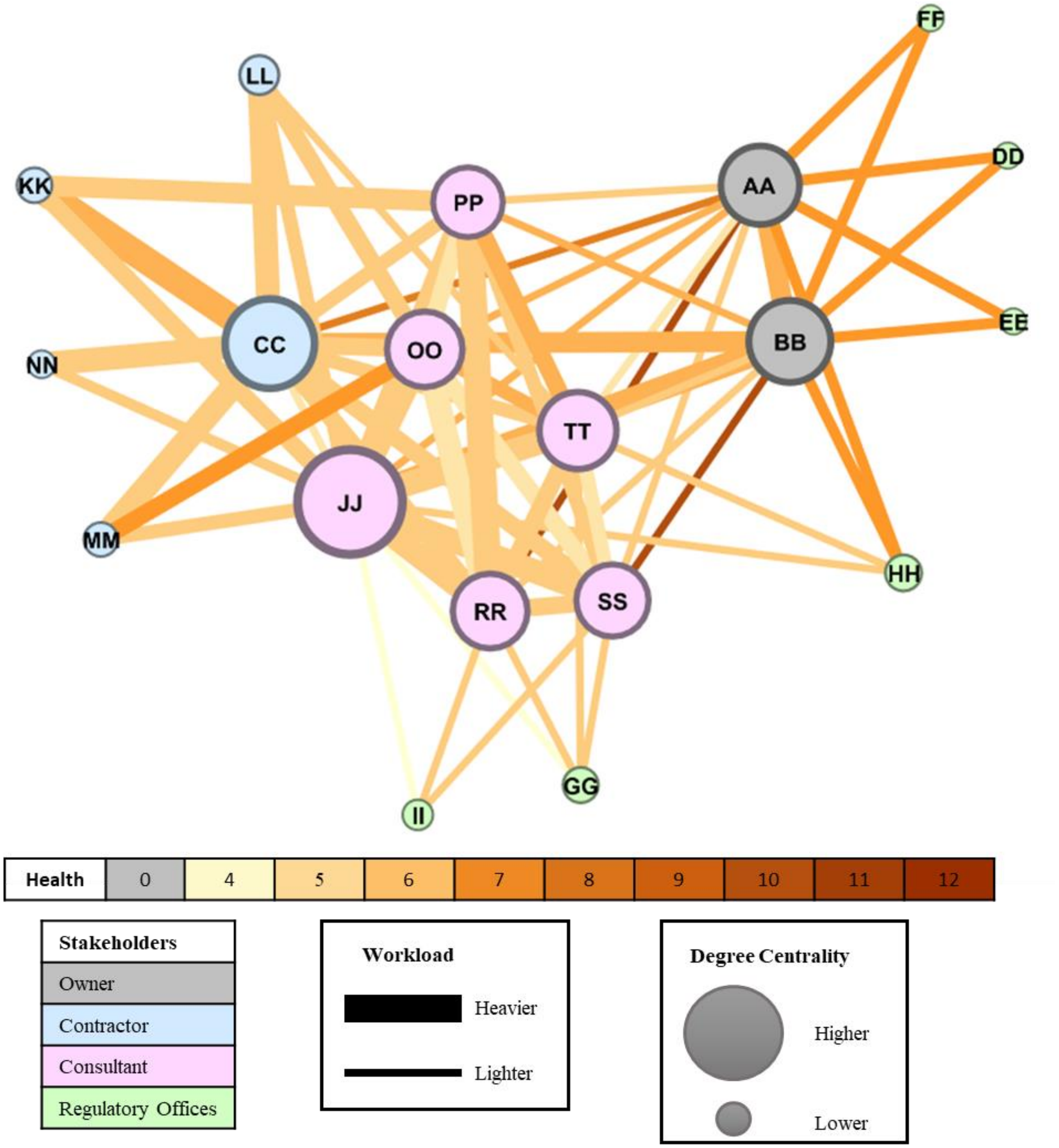


Figure 22 Stakeholder Interface network of the Rail Line Project

According to the new data set obtained, it was found that connections between CC-KK and PP-RR have the highest workload, followed by BB-JJ, CC-LL, CC-MM, CC-NN, JJ-OO, JJ-PP, JJ-RR, JJ-SS, JJ- TT, and OO-RR. Also, according to the new data set, it was found that connections between AA-RR and BB-SS had the poorest health condition followed by PR-LPM.

As the last step, initial results and re-evaluation results were compared and presented in Figure 23 and Figure 24 below. It was found that workload and health value of most of the stakeholder connections remained the same except CC-JJ (3-10). It was found that the workload between these two stakeholders dropped drastically and the health of the connection improved.

After obtaining new results and establishing the second stakeholder interface network for the Rail line Project, a face-to-face review meeting with the Rail Lead of the company was conducted. In this meeting new results were discussed with the Rail Lead. As presented in Figure 23, the interface health condition between AA-RR and BB-SS was very poor. During the review meeting, it was learned that, there was a river on the route of the Rail Line Project analyzed. Therefore, the consultant of the project had been designing a bridge for the Rail Line. However, there were problems with the Drainage design and the Environmental permits for the bridge. By the time the new set of data was collected, the collaboration between AA-RR and BB-SS was in a poor state. According to the Rail Lead of the company, that was also the reason why workload value between CC-JJ (3-10) dropped drastically (Figure 23). Therefore, these results were found accurate by Rail Lead of the company.

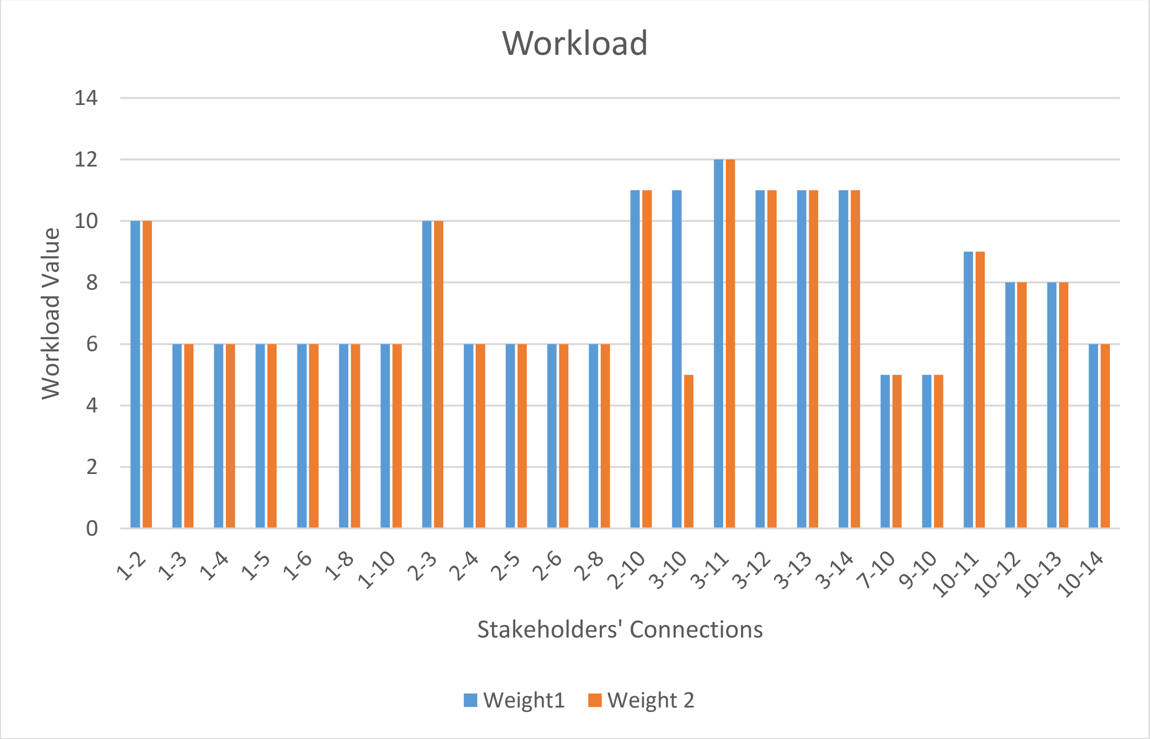


Figure 23 Workload value comparison of the initial and re-evaluation results

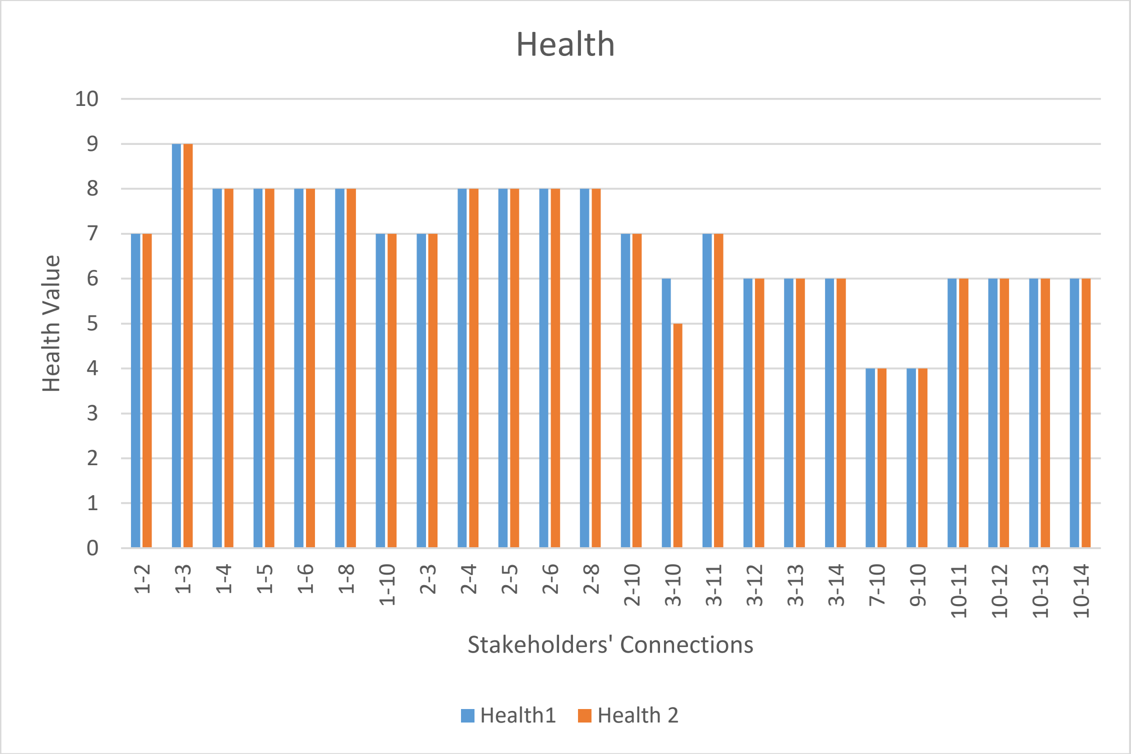


Figure 24 Health value comparison of the initial and re-evaluation results

5.2.2 Project 2 – Chemical Equipment Replacement Project

Integrated Project Monitoring Method using Framework-B was also applied to five ongoing replacement projects in a Nuclear power plant located in North America. As part of the initial meetings with the Projects Control team, organizational guidelines and procedures of nuclear projects were reviewed. According to the organizational guidelines, typical project lifecycle in this Nuclear Power plant consisted of seven project phases, which were: Identification (0-1), Initiation (1-2), Development (2-3), Definition (3-4), Execution (4-5), Closeout (5-6), and PIR (6-7). In Figure 25, the typical project timeline is illustrated. In order to generalize the lifecycle, numbers are given as the start-end date for each phase as it is presented in Figure 25.

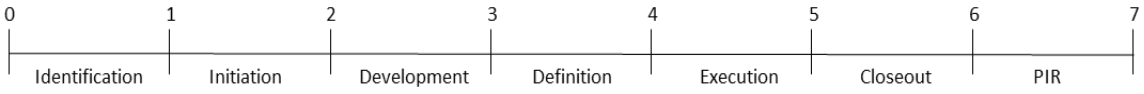


Figure 25 Typical Project Lifecycle of the Projects in the Nuclear Power Plant

Among five projects, the first one was a replacement project named Chemical Equipment Replacement (CER) Project. Briefly, the project scope was the procurement of a particulate filtration skid and the installation of interfacing piping on each unit in the plant, to re-route a portion of the condensate recirculation system flow through the filtration skid to remove corrosion product. CER was also following the same project life-cycle, and the anticipated project duration was 101 months including application in all reactors in the power plant.

During the project selection and identification step, CER project was in the Execution phase. However, it was learned that the same project was applied to another reactor in the same nuclear power plant before. Thus, the Project Manager had know-how from the previous application and was able to fill the workload and health tool for the whole project lifecycle. Project Manager of the owner's team involved as decision-maker in this case study. Therefore, in this example, interface health and workload between stakeholders were analyzed form the owner's point of view.

5.2.2.1 Stakeholder Identification and Stakeholder Connections Identification

One face to face and two teleconference meetings were held to identify project stakeholders and interfaces between those stakeholders with the PM of the CER project. During these meetings, first, background information about the CER project was collected, and then the PM provided the list of stakeholders for each project phase and explained stakeholder connections in each phase. In Table 27, the list of stakeholders, their groups (internal, external, regulatory offices) and phases when these stakeholders were active (Time set), are presented.

Table 27 Stakeholder List of Chemical Equipment Replacement Project

ID	**Name**	**Group***	**Time set**
A	Project Sponsor	1	[0,7]
B	Project and Modifications	1	[0,6]
C	Finance	1	[1,6]
D	Supply Chain	1	[2,6]
E	Operations	1	[2,6]
F	Maintenance	1	[2,6]
G	Performance Engineering	1	[2,6]
H	Projects Design Engineering	1	[2,6]
I	Procurement Engineering	1	[2,5]
N	Contractor	2	[2,6]
O	Subcontractor - Design	2	[2,6]
P	Sub vendor	2	[2,5]
M	TSSA-Pressure Boundary	3	[3,5]
J	Field Engineering	1	[3,5]

ID	Name	Group*	Time set
K	Contract Management Office	1	[3,5]
L	Drawing Office	1	[5,6]
Q	Subcontractor	2	[4,5]

* 1: Internal Stakeholder, 2: External Stakeholder, and 3: Regulatory Offices

The time set value of each stakeholder in Table 23 shows when each stakeholder was active in this project. For example, the Time set value of stakeholder E is [2,6], which means that Stakeholder E was active between the beginning of the Development phase until the end of the Closeout phase of this project. Due to having a dynamic stakeholder list, stakeholder connections were also dynamic and changing throughout the project lifecycle in this case study.

5.2.2.2 Evaluating Stakeholder Connections

In order to evaluate stakeholders' connections, the Project Manager (PM) was asked to fill the point system tool explained in Chapter 3, for all stakeholder connections in each project phase. CER project was applied in the same nuclear power plant with the same stakeholders recently. Therefore, even though the current CER project was in the Execution phase, the PM of the project was able to fill the point system tool for Closeout and PIR phases based on the first application of the CER project in the other reactor. In other words, the PM filled point system tool for the first 5 phases based on the current project, and responses for the Closeout and PIR phases were expected results based on the first application of the same project on the previous reactor. In Appendix C, data collected in the stakeholder connection evaluation step of Chemical Equipment Replacement project is provided.

Project stakeholders and stakeholder connections existed in multiple project phases of the CER project. Therefore, dynamic value sets were used for representing and evaluating point system tool results. First, Workload and Health value of each stakeholder connection were calculated for all the phases that a connection existed using Equation-4 and Equation-5. Then, dynamic value sets were created for each stakeholder connections. In Table 28, dynamic workload and health values of the stakeholder connections are presented. For example, stakeholder connection between stakeholder ID 1 and 2 has dynamic workload value of "[0,1,6];[1,2,7];[2,3,5];[3,4,5];[4,5,7];[5,6,6]". In this representation, the first two numbers inside each bracket indicate the project phase, and the third value is the workload value for this stakeholder connection in that phase. In this example, "[0,1,6]" means workload value for this connection in the Identification phase (0,1) was 6.

Table 28 Dynamic Workload and Health values in CER project

Source	Target	Workload- Dynamic	Health - Dynamic
A	B	[0,1,6.0];[1,2,7.0];[2,3,5];[3,4,5];[4,5,7];[5,6,7]	[0,1,7.0];[1,2,4.0];[2,3,5];[3,4,5];[4,5,7];[5,6,4]
B	C	[1,2,7.0];[2,3,8];[3,4,8];[4,5,8];[5,6,8]	[1,2,8.0];[2,3,5];[3,4,5];[4,5,4];[5,6,4]
A	G	[2,3,6];[3,4,6];[4,5,6];[5,6,6]	[2,3,4];[3,4,4];[4,5,4];[5,6,4]
A	E	[2,3,6];[3,4,6];[4,5,6];[5,6,6]	[2,3,4];[3,4,4];[4,5,4];[5,6,4]
B	D	[2,3,8];[3,4,8];[4,5,9];[5,6,8]	[2,3,6];[3,4,6];[4,5,5];[5,6,5]
B	E	[2,3,5];[3,4,6];[4,5,7];[5,6,7]	[2,3,5];[3,4,5];[4,5,8];[5,6,4]
B	F	[2,3,5];[3,4,6];[4,5,7];[5,6,7]	[2,3,5];[3,4,5];[4,5,8];[5,6,4]
B	G	[2,3,5];[3,4,7];[4,5,7];[5,6,7]	[2,3,5];[3,4,7];[4,5,8];[5,6,5]
B	H	[2,3,10];[3,4,11];[4,5,8];[5,6,9]	[2,3,8];[3,4,9];[4,5,6];[5,6,4]
B	I	[2,3,5];[3,4,7];[4,5,6]	[2,3,5];[3,4,6];[4,5,5]
B	N	[2,3,11];[3,4,11];[4,5,11];[5,6,9]	[2,3,8];[3,4,9];[4,5,7];[5,6,5]
B	O	[2,3,10];[3,4,10];[4,5,8];[5,6,9]	[2,3,8];[3,4,9];[4,5,7];[5,6,5]
B	P	[2,3,7];[3,4,8];[4,5,6]	[2,3,8];[3,4,9];[4,5,4]
D	I	[2,3,6];[3,4,6];[4,5,6]	[2,3,4];[3,4,6];[4,5,6]
D	N	[2,3,6];[3,4,5];[4,5,6];[5,6,7]	[2,3,7];[3,4,7];[4,5,7];[5,6,4]
E	F	[2,3,6];[3,4,7];[4,5,10];[5,6,6]	[2,3,4];[3,4,4];[4,5,6];[5,6,4]
E	G	[2,3,6];[3,4,7];[4,5,7];[5,6,6]	[2,3,4];[3,4,4];[4,5,5];[5,6,4]
F	G	[2,3,6];[3,4,7];[4,5,7];[5,6,6]	[2,3,4];[3,4,4];[4,5,5];[5,6,4]
G	H	[2,3,7];[3,4,7];[4,5,7];[5,6,7]	[2,3,8];[3,4,8];[4,5,5];[5,6,5]
H	I	[2,3,7];[3,4,9];[4,5,6]	[2,3,7];[3,4,7];[4,5,4]
H	O	[2,3,11];[3,4,11];[4,5,8];[5,6,9]	[2,3,8];[3,4,9];[4,5,5];[5,6,6]
N	O	[2,3,10];[3,4,10];[4,5,11];[5,6,10]	[2,3,6];[3,4,6];[4,5,7];[5,6,6]
N	P	[2,3,7];[3,4,7];[4,5,8]	[2,3,6];[3,4,6];[4,5,5]
O	P	[2,3,7];[3,4,9];[4,5,8]	[2,3,6];[3,4,7];[4,5,4]
B	M	[3,4,7];[4,5,7]	[3,4,7];[4,5,7]
B	J	[3,4,6];[4,5,10]	[3,4,4];[4,5,6]
B	K	[3,4,6];[4,5,10]	[3,4,4];[4,5,4]
N	M	[3,4,8];[4,5,9]	[3,4,6];[4,5,6]
N	J	[3,4,6];[4,5,10]	[3,4,6];[4,5,7]
N	K	[3,4,6];[4,5,10]	[3,4,6];[4,5,7]
N	Q	[4,5,12]	[4,5,4]
B	L	[5,6,8]	[5,6,5]
H	L	[5,6,9]	[5,6,6]

5.2.2.3 Network Analysis

In order to determine the stakeholder that has the highest workload in the Chemical Equipment Replacement project, the Degree Centrality (DC) value of each stakeholder was calculated for each project phase. In Table 29, DC values of project stakeholders for each project phase when they were active in the Chemical Equipment Replacement project are presented.

Table 29 DC values of project stakeholders in CER project

ID	DC values
A	[0,1,2.45];[1,2,2.65];[2,3,7.14];[3,4,7.14];[4,5,7.55];[5,6,7.55]
B	[0,1,2.45];[1,2,5.29];[2,3,29.48];[3,4,38.52];[4,5,39.42];[5,6,28.11]
C	[1,2,2.65];[2,3,2.83];[3,4,2.83];[4,5,2.83];[5,6,2.83]
D	[2,3,7.75];[3,4,7.55];[4,5,7.94];[5,6,5.48]
E	[2,3,9.59];[3,4,10.2];[4,5,10.95];[5,6,10.0]
F	[2,3,7.14];[3,4,7.75];[4,5,8.49];[5,6,7.55]
G	[2,3,12.25];[3,4,13.04];[4,5,13.04];[5,6,12.65]
H	[2,3,11.83];[3,4,12.33];[4,5,10.77];[5,6,11.66]
I	[2,3,7.35];[3,4,8.12];[4,5,7.35]
N	[2,3,11.66];[3,4,19.26];[4,5,24.82];[5,6,8.83]
O	[2,3,12.33];[3,4,12.65];[4,5,11.83];[5,6,9.17]
P	[2,3,7.94];[3,4,8.49];[4,5,8.12]
M	[3,4,5.48];[4,5,5.66]
J	[3,4,4.9];[4,5,6.32]
K	[3,4,4.9];[4,5,6.32]
Q	[4,5,3.46]
L	[5,6,5.83]

5.2.2.4 Visualization

Snapshots from stakeholder interface network established for Chemical Equipment Replacement project for each project phase where workload and health analysis results (Table 28) and DC values (Table 29) were used are presented in Figure 26.

As the CER project had a dynamic network and each stakeholder has different DC values in each project phase, the stakeholder who had the highest workload changes phase to phase. In order to specify stakeholder groups, color codes are given to stakeholders. In the networks below, green-colored nodes represent internal stakeholders, pink-colored nodes represent external stakeholders, and purple-colored node represents regulatory offices. Similar to the stakeholder interface network created for Rail Line Project, workload values between project stakeholders are presented with thickness and health values are presented with color codes on the edges. In other words, the stakeholder connections with higher workload value is represented with a thicker edge, and higher health value is represented with a darker color on the edges. Also, the degree centrality of each stakeholder is presented with node size in the networks below. Legends are included in Figure 26 for these representations.

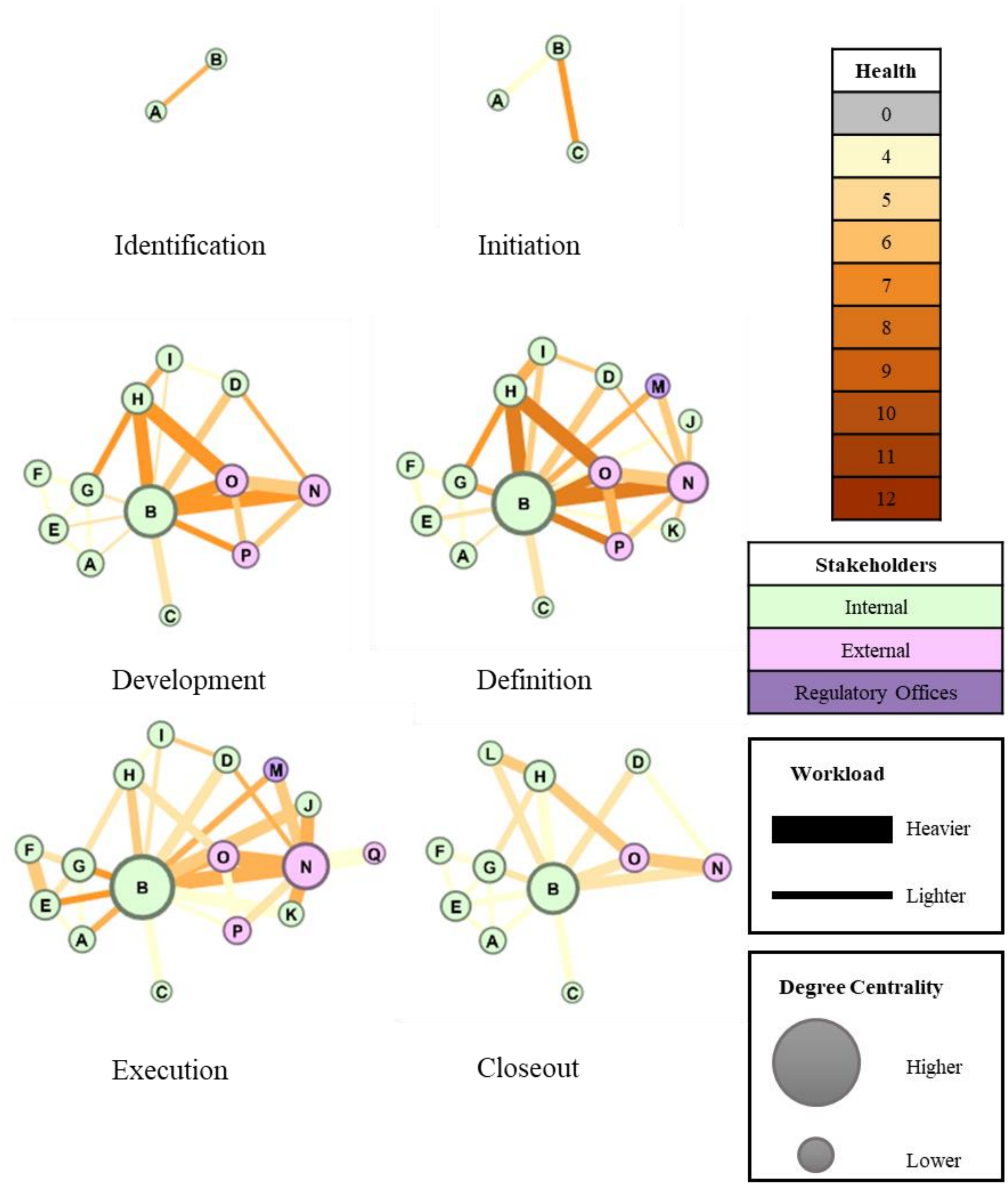


Figure 26 Stakeholder interface networks of Chemical Equipment Replacement project

5.2.2.5 Interpretation and Corrective Action

According to the results presented in Table 28, the highest workload value was calculated between stakeholder N and Q in the Execution phase [3,4]. Besides having the highest workload, the health value of the connection shows that it was one of the healthiest connections too. On the other hand, the poorest health condition through the project lifecycle was calculated between B-H, B-O, B-N, and B-P at the definition phase. It was also seen that these connections had poor health conditions during the development phase too.

After analyzing collected data and establishing stakeholder interface networks for Chemical Equipment Replacement Project, results were shared with PM of the project. Analysis results were found to correspond with the actual project conditions and were validated by PM of the project during review meetings.

5.2.3 Project 3 – Detector Assemblies Replacement Project

The second project selected in the Nuclear Power Plant to apply Framework-B was another ongoing replacement project named Detector Assemblies Replacement project. These detectors were the secondary safety Shut Down System (SDS2) for the reactor units at the Nuclear Power Plant and were responsible for providing the main control room with an indication of the state of SDS2, specifically whether the tanks are full or not. This information is essential for operators to monitor real-time and guarantee control over the reactor units. There were eight detector assemblies and sixteen power supplies in each of the four reactor units. However, these detector components and power supplies have reached the end of life and were obsolete. There was an increasing burden on operators due to false alarms, and an increasing burden on maintenance due to lack of spare parts.

Briefly, the project scope was replacing the detector assemblies and power supplies with new equipment in all four units that target the same functionality as the existing system and procure sufficient spares. Detector Assemblies Replacement project was also following the same project lifecycle presented in Figure 25, and the anticipated project duration was approximately 118 months including application in all reactors in the power plant. Project Manager of the owner's team involved as decision-maker and provided data for this project, thus, interface health and workload between stakeholders were analyzed form the owner's point of view.

5.2.3.1 Stakeholder Identification and Stakeholder Connections Identification

Multiple meetings were held to identify project stakeholders and interfaces between those stakeholders with the PM of Detector Assemblies Replacement project. During these meetings, first, background information about the Detector Assemblies Replacement project was collected, and then the PM provided the list of stakeholders for each project phase and identified interfacing stakeholders in each phase by following the format presented in Table 1. In Table 30, the list of stakeholders, their groups (internal, external, regulatory offices) and phases when these stakeholders were active (Time set), are presented. The stakeholders' connection list for the Detector Assemblies Replacement project is attached to Appendix D.

Table 30 Stakeholder List of Detector Assemblies Replacement Project

ID	Label	Name	Group*	Time-set
1	SRE	System Responsible Engineer	1	[1,7]
2	PRO	Projects	1	[1,7]
3	DGG	Design	1	[1,6]
4	MNT	Control Maintenance	1	[2,6]
5	OPS	Operations	1	[2,6]
6	VEN	Equipment Vendor	2	[3,5]
7	SC	Supply Chain	1	[2,5]
8	HF	Human Factors	1	[2,4]
9	RS	Reactor Safety	1	[2,4]
10	SSC	Seismic	1	[2,4]
11	CS	Conventional Safety	1	[3,5]
12	RP	Radiation Protection	1	[3,5]
13	WC	Work Control	1	[3,5]
14	WA	Work Assessing	1	[3,5]
15	OUT	Outage	1	[3,5]

*1=internal Stakeholder, 2= External Stakeholder

5.2.3.2 Evaluating Stakeholder Connections

After obtaining the Stakeholder List and Stakeholders connection list, the stakeholder connection evaluation tool was prepared for the Detector Assemblies Replacement project. During the review meetings, how to fill the tool by using the point system presented in Table 3 and Table 4 was explained to PM of the project. During the review meetings, the Detector Assemblies Replacement project was at the beginning of the Execution phase. Therefore, the PM of the project provided workload and health data only for Initiation, Development, Definition, and Execution phases. At the end of this step, dynamic weight and dynamic health value of each stakeholder connection when they were active in the project were collected. In Table 31, stakeholder connections and their dynamic health and weight values are presented.

Table 31 Dynamic Workload and Health values in Detector Assemblies Replacement project

Source	Target	Weight Dynamic	Health Dynamic
1	2	[1,2,5];[2,3,6];[3,4,7];[4,5,8]	[1,2,5];[2,3,7];[3,4,4];[4,5,4]
1	3	[1,2,4];[2,3,9];[3,4,7]	[1,2,5];[2,3,7];[3,4,6]

Source	Target	Weight Dynamic	Health Dynamic
2	3	[1,2,6];[2,3,10];[3,4,10];[4,5,9]	[1,2,6];[2,3,7];[3,4,7];[4,5,4]
2	4	[2,3,6];[3,4,6];[4,5,10]	[2,3,5];[3,4,4];[4,5,6]
2	5	[2,3,6];[3,4,6];[4,5,8]	[2,3,5];[3,4,4];[4,5,6]
2	7	[2,3,8];[3,4,6];[4,5,6]	[2,3,8];[3,4,6];[4,5,6]
3	4	[2,3,5];[3,4,5]	[2,3,5];[3,4,6]
3	5	[2,3,5];[3,4,5]	[2,3,5];[3,4,4]
3	7	[2,3,5];[3,4,7]	[2,3,5];[3,4,5]
3	8	[2,3,5];[3,4,5]	[2,3,7];[3,4,6]
3	9	[2,3,5];[3,4,5]	[2,3,6];[3,4,4]
3	10	[2,3,5];[3,4,5]	[2,3,6];[3,4,5]
2	6	[3,4,9];[4,5,9]	[3,4,8];[4,5,4]
2	8	[3,4,6]	[3,4,5]
2	11	[3,4,6];[4,5,6]	[3,4,4];[4,5,4]
2	12	[3,4,6];[4,5,6]	[3,4,4];[4,5,4]
2	13	[3,4,7];[4,5,8]	[3,4,4];[4,5,4]
2	14	[3,4,6];[4,5,6]	[3,4,6];[4,5,4]
2	15	[3,4,8];[4,5,9]	[3,4,9];[4,5,7]
3	6	[3,4,11];[4,5,10]	[3,4,8];[4,5,4]
6	7	[3,4,5];[4,5,6]	[3,4,6];[4,5,5]
13	15	[3,4,7];[4,5,9]	[3,4,5];[4,5,4]
4	5	[4,5,9]	[4,5,4]
4	13	[4,5,9]	[4,5,4]
4	15	[4,5,9]	[4,5,4]
5	13	[4,5,9]	[4,5,4]
5	15	[4,5,9]	[4,5,4]
12	13	[4,5,9]	[4,5,4]
12	15	[4,5,9]	[4,5,4]

5.2.3.3 Network Analysis

After collecting dynamic health and workload values of each stakeholder connection, network analysis was conducted for the Detector Assemblies Replacement project. The details of the network analysis conducted is given in Section 3.2.4 earlier. At the end of this analysis, dynamic Degree Centrality (DC) values of each stakeholder for all the phases they were active in the project were calculated. Since workload and health data for the last two phases were not available, DC values of the stakeholders in Closeout and PIR phases were 0. Calculated DC values are presented in Table 32 below.

Table 32 DC values of project stakeholders in Detector Assemblies Replacement Project

ID	DC values
SRE	[1,2,4.24];[2,3,5.48];[3,4,5.29];[4,5,2.83];[5,6,0.0];[6,7,0.0]
PRO	[1,2,4.69];[2,3,13.42];[3,4,31.56];[4,5,30.58];[5,6,0.0];[6,7,0.0]
DGG	[1,2,4.47];[2,3,19.8];[3,4,23.24];[4,5,6.16];[5,6,0.0]
MNT	[2,3,4.69];[3,4,4.69];[4,5,12.17];[5,6,0.0]

ID	DC values
OPS	[2,3,4.69];[3,4,4.69];[4,5,11.83];[5,6,0.0]
SC	[2,3,5.1];[3,4,7.35];[4,5,4.9]
HF	[2,3,2.24];[3,4,4.69]
RS	[2,3,2.24];[3,4,2.24]
SSC	[2,3,2.24];[3,4,2.24]
VEN	[3,4,8.66];[4,5,8.66]
CS	[3,4,2.45];[4,5,2.45]
RP	[3,4,2.45];[4,5,8.49]
WC	[3,4,5.29];[4,5,14.83]
WA	[3,4,2.45];[4,5,2.45]
OUT	[3,4,5.48];[4,5,15.0]

As it is explained in Section 3.2.4, DC values are showing the importance of each stakeholder. Since workload values are used as the weight values of each edge in this analysis, DC value indicates the workload of each stakeholder in this research.

5.2.3.4 Visualization

A dynamic Stakeholder Interface Network was established for the Detector Assemblies Replacement project by using the nodes and edges data presented in Table 30, Table 31, and Table 32. Snapshots from the dynamic network for each project phase in the Detector Assemblies Replacement project is presented in Figure 27. Similar to the Rail Line project and Chemical Equipment Replacement project, workload value of each stakeholder connection is represented with line thickness on the edges, health values are represented with color codes on the edges, and the DC value of each stakeholder is represented with the node sizes. Detailed legend is also included in Figure 27 for these representations. In order to specify stakeholder groups, color codes are given to stakeholders. In the networks presented in Figure 27, green-colored nodes represent internal stakeholders, pink-colored nodes represent external stakeholders. Although workload and health data of the stakeholder connections in Closeout and PIR phases were not available, stakeholder connections were known. Thus, networks in those phases are also created and presented in Figure 27, to show the evaluation of the stakeholder interface network over time.

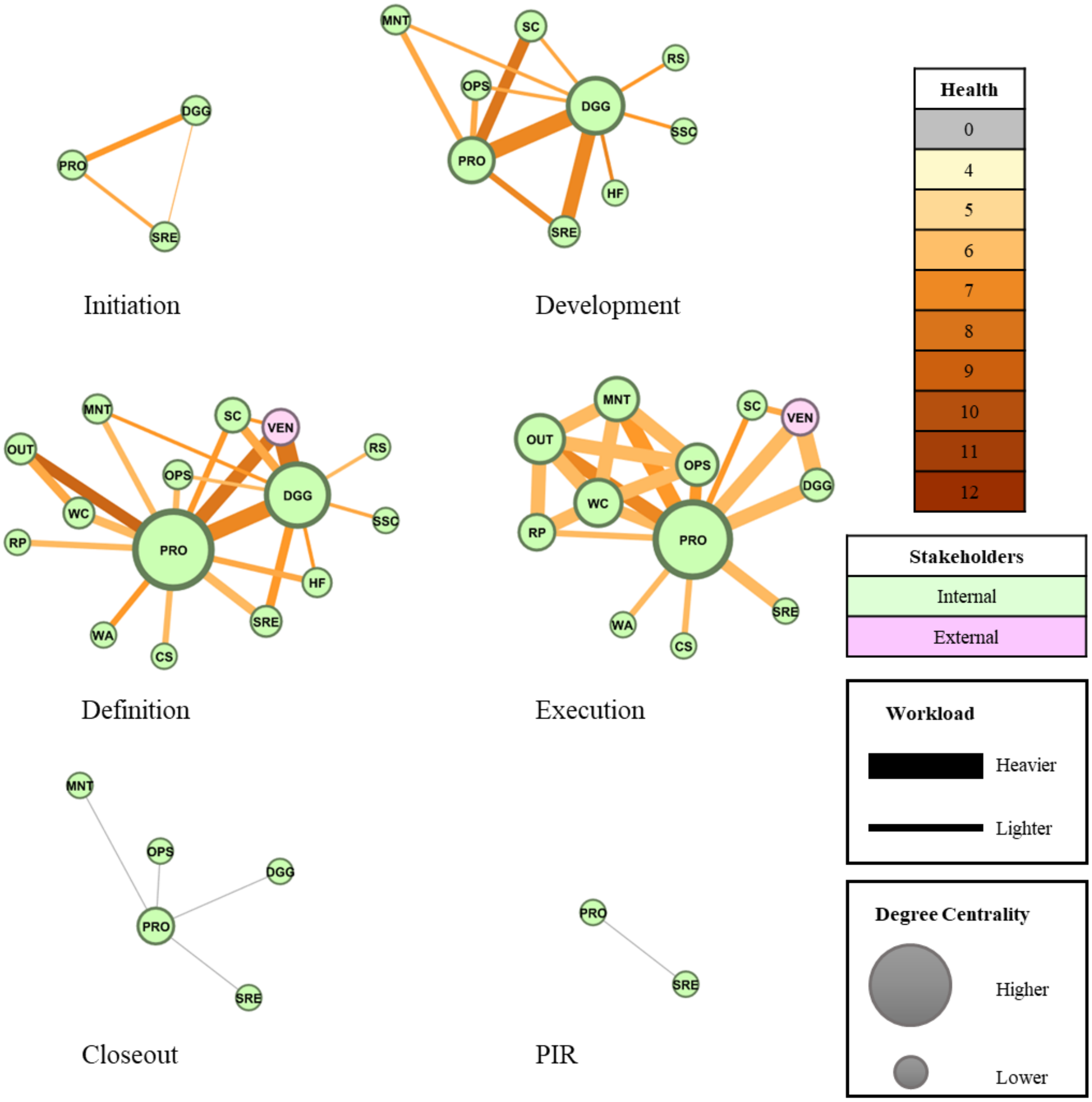


Figure 27 Stakeholder Interface Networks of Detector Assemblies Replacement Project

5.2.3.5 Interpretation and Corrective Action

According to the results presented in Table 31, the highest workload value was calculated between stakeholder Design (DGG) and Vendor (VEN) in Definition phase [3,4], and poorest health condition through project lifecycle was calculated between Projects (PRO) and Outage (OUT) during Definition phase [3,4].

After analyzing collected data and establishing stakeholder interface networks for Detector Assemblies Replacement project, results were shared and reviewed with the PM of the project. During these last reviewing meetings, open-ended questions were asked the PM to reveal the root causes of the high workload and poor health conditions between project stakeholders, and it comes to light that the Detector Assemblies Replacement project started late at the beginning and all milestones were missed along the way. Besides, internal stakeholders were undertaking various other projects and had their own internal milestones that have a higher priority for the nuclear power plant. This was also the main reason why PRO and OUT had the poorest health condition during the Definition phase. Since all the milestones missed during the project before OUT was active, the project was late, and when the Definition phase started OUT already had internal milestones that had a higher priority that affects the overall plant. That crated poor health conditions between PRO and OUT. At the end of these review meetings, analysis results were found to correspond with the actual project conditions and were validated by the PM of the project.

5.2.4 Project 4 – Control Positioners Replacement Project

The third project selected in the Nuclear Power Plant to apply Integrated Project Monitoring Method using Framework-B was another ongoing replacement project named Control Positioners Replacement project. The existing analog positioners in this nuclear power plant were degraded and it was a heavy burden on maintenance crews to get these calibrated and operating within performance tolerance. Each of the units in the Nuclear Power Plant had 14 valves and associated positioners, which control the flow of water through the reactor. Briefly, the project scope was replacing these analog positioners with digital smart positioners.

The anticipated project duration of the Control Positioners Replacement project was approximately 142 months including application in all reactors in the power plant. This project was also following the same project lifecycle presented in Figure 25, as other ongoing projects in the same Nuclear Power Plant and had seven project phases. The Project Manager (PM) of the owner’s team involved as the decision-maker and provided data for this project, thus, interface health and workload between stakeholders were analyzed form the owner’s point of view.

5.2.4.1 Stakeholder Identification and Stakeholder Connections Identification

After project selection, the PM of the project was asked to provide the stakeholder list and stakeholder’ connections list for all project phases following the data collection format presented in Table 1. The master stakeholder list for the Control Positioners Replacement project is presented in Table 33 and the stakeholder connection list for each project phase is attached in Appendix E. At the end of this step, stakeholders and stakeholder connections for each project phase of the Control Positioners Replacement project were collected.

Table 33 Stakeholder List of Control Positioners Replacement project

Id	Label	Name	Group	Time-set
1	ENG	Engineering	1	[0,7]
2	PM	Project Manager	1	[1,7]
3	CM	Control Maintenance	1	[0,1];[2,5]
4	OPS	Operations (Project SPOC)	1	[0,1];[2,5];[6,7]
5	OPSO	Operations (Authorized Operator)	1	[4,5]
6	DES	Design	1	[2,7]
7	CG	Computers Group	1	[3,4]
8	CS	Conventional Safety	1	[2,4]
9	RP	Radiation Protection	1	[3,5]
10	WC	Work Control	1	[4,5]
11	EPM	EPC PM	2	[3,6]
12	ECPM	EPC Construction PM	2	[3,6]
13	EC	EPC Coordinator	2	[3,6]
14	EDDL	EPC Design Discipline Lead	2	[3,4]
15	EDE	EPC Design Engineering	2	[3,4]
16	ES	EPC Software	2	[3,4]
17	EDTL	EPC Design Team Lead	2	[3,6]
18	SC	Supply Chain	1	[3,5]

*1=internal Stakeholder, 2= External Stakeholder

5.2.4.2 Evaluating Stakeholder Connections

Based on the stakeholders' connections list provided by PM of the project, the workload and health evaluation tool for the Control Positioners Replacement project was created and shared with PM during the review meetings. After explaining the tool and point system for workload and health evaluation of stakeholder connections, PM provided data for each connection between stakeholders in the project. Data collected for this step is attached to Appendix E.

During the data collection for stakeholder connections evaluation, Control Positioners Replacement project was at the beginning of the Execution phase. Therefore, the PM of the project provided workload and health data for the first 4 phases. For the last three phases (Execution, Closeout, and PIR), the PM only provided stakeholders' connections list and expected workload values between project stakeholders. Dynamic workload and health values of stakeholder connections in the Control Positioners Replacement project are attached in Appendix E.

5.2.4.3 Network Analysis

After collecting dynamic health and workload values of each stakeholder connection, network analysis was conducted for Control Positioners Replacement Project. The details of the network analysis conducted is given in Chapter 3 earlier. At the end of this analysis, dynamic Degree Centrality (DC) values of each stakeholder for all the phases they were active in the project were calculated. Calculated DC values are presented in Table 34 below.

Table 34 DC values of project stakeholders in Control Positioners Replacement Project

ID	DC values
ENG	[0,1,4.0];[1,2,2.0];[2,3,4.24];[3,4,4.9];[4,5,4.9];[5,6,8.66];[6,7,6.71]
CM	[0,1,2.0];[2,3,2.0];[3,4,11.62];[4,5,16.94];[6,7,2.24]
OPS	[0,1,2.0];[2,3,2.0];[3,4,12.04];[4,5,16.61];[6,7,2.24]
PM	[1,2,2.0];[2,3,4.24];[3,4,36.28];[4,5,32.83];[5,6,16.79];[6,7,4.47]
DES	[2,3,10.49];[3,4,35.33];[4,5,18.14];[5,6,11.66];[6,7,2.24]
CS	[2,3,2.0];[3,4,10.0]
CG	[3,4,4.47]
RP	[3,4,10.0];[4,5,7.14]
EPM	[3,4,23.43];[4,5,22.27];[5,6,12.0]
ECPM	[3,4,23.81];[4,5,30.0];[5,6,17.32]
EC	[3,4,23.81];[4,5,30.0];[5,6,11.66]
EDDL	[3,4,12.65]
EDE	[3,4,16.61]
ES	[3,4,4.24]
EDTL	[3,4,19.8];[4,5,14.32];[5,6,14.14]
SC	[3,4,4.47];[4,5,4.0]
OPSO	[4,5,13.96]
WC	[4,5,12.81]

5.2.4.4 Visualization

A dynamic Stakeholder Interface Network was established for the Control Positioners Replacement project by using the nodes and edges data presented in Table 33, Table 34 and Appendix E. Snapshots from the dynamic network for each project phase in the Control Positioners Replacement project is presented in Figure 28. Similar to the previous projects presented, the workload value of each stakeholder connection was represented with line thickness on the edges, health values were represented with color codes on the edges, and the workload of each stakeholder was represented with the node sizes. Detailed legends are also provided on Figure 28. Although health data of the stakeholder connections in Execution, Closeout and PIR phases were not available, stakeholder connections and expected workload values of those connections were known. Thus, networks in those phases are also created and presented in Figure 28, to show the evaluation of the stakeholder interface network over time.

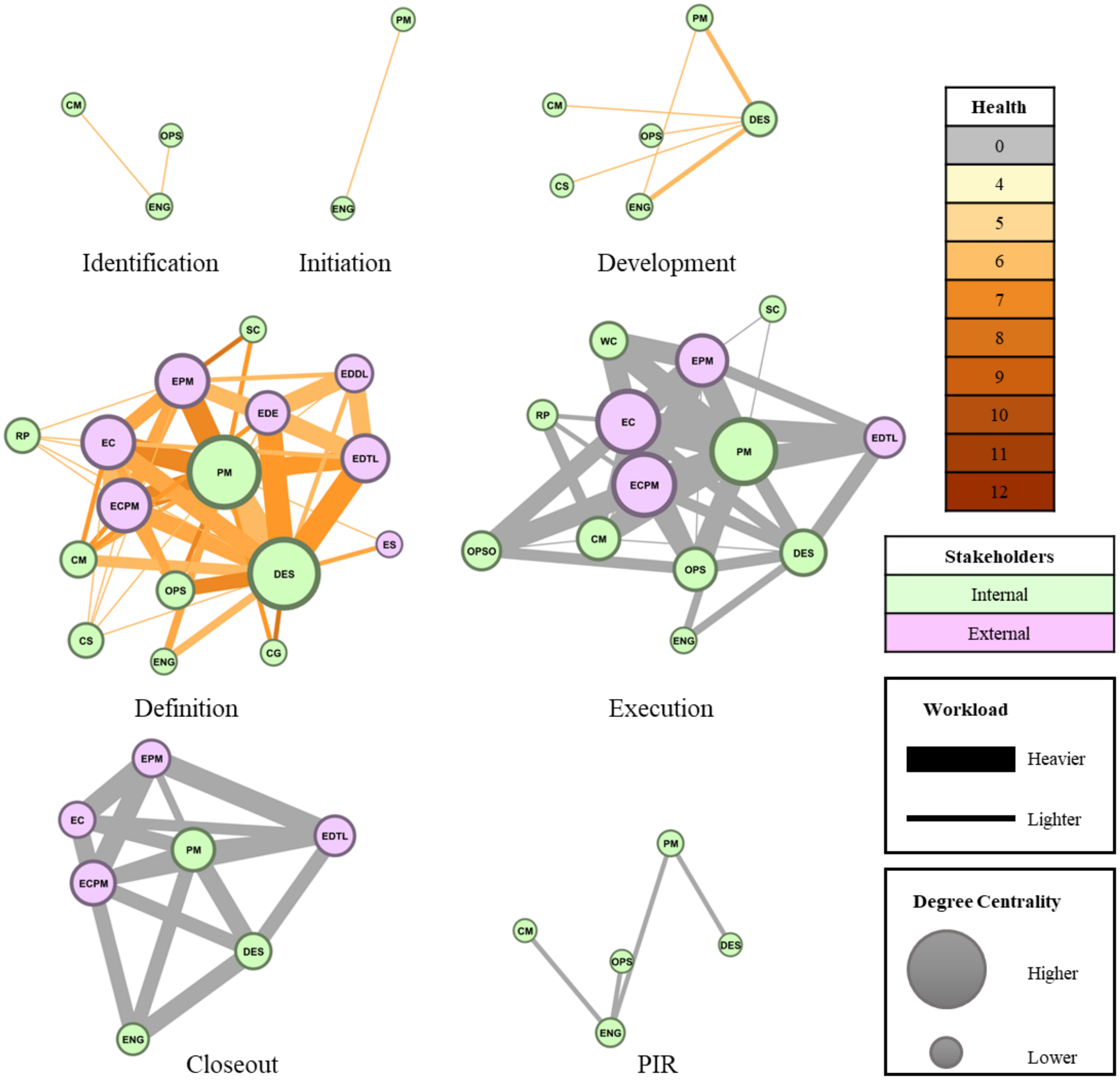


Figure 28 Stakeholder Interface Networks of Control Positioners Replacement project

5.2.4.5 Interpretation and Corrective Action

In the Control Positioners Replacement project, the highest workload values were calculated between stakeholders PM and Design in the Definition phase [3,4], and between stakeholders ECPM and EC in Definition [3,4] and Execution [4,5] phases. On the other hand, the poorest health condition through the project lifecycle was calculated between Design (DES) and Computers group (CG) during the Definition phase [2,3].

After analyzing collected data and establishing stakeholder interface networks for the Control Positioners Replacement project, results were shared and reviewed with the PM of the project. PM explained that rework between the Design and Computers group was high during the Definition phase because there were inconsistencies in the reports. That created poor health conditions among these project stakeholders. By the end of these review meetings, analysis results were found to correspond with the actual project conditions and were validated by the PM of the project.

5.2.5 Project 5 – Air Conditioning Unit Replacement Project 1 (ACU-1)

The fourth project selected in the Nuclear Power Plant to apply the proposed Integrated Project Monitoring Method using Framework-B was another ongoing replacement project named Air Conditioning Unit Replacement (ACU-1) project. Briefly, the project scope was taking on essentially a like-for-like replacement of 90 Air Cooling Units (ACUs) across the station. These were simple water-cooled ACUs that provide cooling and steam protection to nearby critical equipment, and they were degraded with either leaking coils or spraying water. Thus a replacement project was initiated.

ACU-1 project was also following the same project lifecycle illustrated in Figure 25, as other ongoing projects in the same Nuclear Power Plant and had seven project phases. The Project Manager (PM) of the owner's team involved as decision-maker and provided data for this project, thus, interface health and workload between stakeholders were analyzed form the owner's point of view.

5.2.5.1 Stakeholder Identification and Stakeholder Connections Identification

After project selection, the PM of the project was asked to provide the stakeholder list and stakeholder' connections list for all project phases by filling the data collection table presented in Table 1. The obtained master stakeholder list for the ACU -1 project is presented in Table 35. At the end of this step, the stakeholder list and stakeholders' connections list for each project phase of the ACU-1 project were collected. ACU-1 project' stakeholders' connection list is attached to Appendix F.

Table 35 Stakeholder List of ACU-1 Project

Id	Label	Name	Group	Time-set
1	ENG	Engineering	1	[0,7]
2	PM	Project Manager	1	[1,7]
3	CM	Control Maintenance	1	[0,1];[2,5]
4	OPS	Operations (Project SPOC)	1	[0,1];[2,5];[6,7]

Id	Label	Name	Group	Time-set
5	OPSO	Operations (Authorized Operator)	1	[4,5]
6	DES	Design	1	[2,7]
8	CS	Conventional Safety	1	[2,4]
9	RP	Radiation Protection	1	[3,5]
10	WC	Work Control	1	[4,5]
12	ECPM	EPC Construction PM	2	[3,6]
13	ECC	EPC Construction Coordinator	2	[3,6]
17	EDTL	EPC Design Team Lead	2	[3,6]
18	SC	Supply Chain	1	[3,4]

*1=internal Stakeholder, 2= External Stakeholder

5.2.5.2 Evaluating Stakeholder Connections

Based on the stakeholders’ connections list provided by the PM of the project, the workload and health evaluation tool for the ACU-1 project was created and shared with the PM during the review meetings. After explaining the tool and point system for workload and health evaluation of stakeholder connections, the PM provided data for each stakeholder connection in the project.

During the data collection for stakeholder connections evaluation, ACU-1 project was in the Execution phase. Therefore, the PM of the project provided workload and health evaluation for the first 5 phases. For the last two phases (Closeout, and PIR), the PM only provided expected workload values between project stakeholders. Collected data is presented in Appendix F.

5.2.5.3 Network Analysis

After collecting dynamic health and workload values of each stakeholder connection, network analysis was conducted for ACU-1 project. The details of the network analysis conducted is given in Chapter 3 earlier. At the end of this analysis, dynamic Degree Centrality (DC) values of each stakeholder for all the phases they were active in the project were calculated. Calculated DC values are presented in Table 36 below.

Table 36 DC values of project stakeholders in ACU-1 project

ID	DC values
ENG	[0,1,4.0];[1,2,2.0];[2,3,4.24];[3,4,6.0];[4,5,4.9];[5,6,8.66];[6,7,6.71]
CM	[0,1,2.0];[2,3,2.0];[3,4,10.49];[4,5,15.3];[6,7,2.24]
OPS	[0,1,2.0];[2,3,2.0];[3,4,13.04];[4,5,14.49];[6,7,2.24]
PM	[1,2,2.0];[2,3,4.24];[3,4,24.7];[4,5,27.33];[5,6,14.32];[6,7,4.47]
DES	[2,3,10.49];[3,4,25.28];[4,5,18.52];[5,6,11.66];[6,7,2.24]
CS	[2,3,2.0];[3,4,8.0]
RP	[3,4,8.0];[4,5,7.14]

ID	DC values
ECPM	[3,4,20.59];[4,5,26.66];[5,6,14.14]
ECC	[3,4,20.4];[4,5,26.66];[5,6,8.49]
EDTL	[3,4,15.1];[4,5,11.66];[5,6,10.95]
SC	[3,4,2.24]
OPSO	[4,5,13.96]
WC	[4,5,9.64]

5.2.5.4 Visualization

A dynamic Stakeholder Interface Network was established for ACU-1 project. Snapshots from the dynamic network for each project phase in is presented in Figure 29 with detailed legends. Although health data of the stakeholder connections in Closeout and PIR phases were not available, stakeholder connections and expected workload values of those connections were known. Thus, networks in those phases are also created and presented in Figure 29, to show the evaluation of the stakeholder interface network over time.

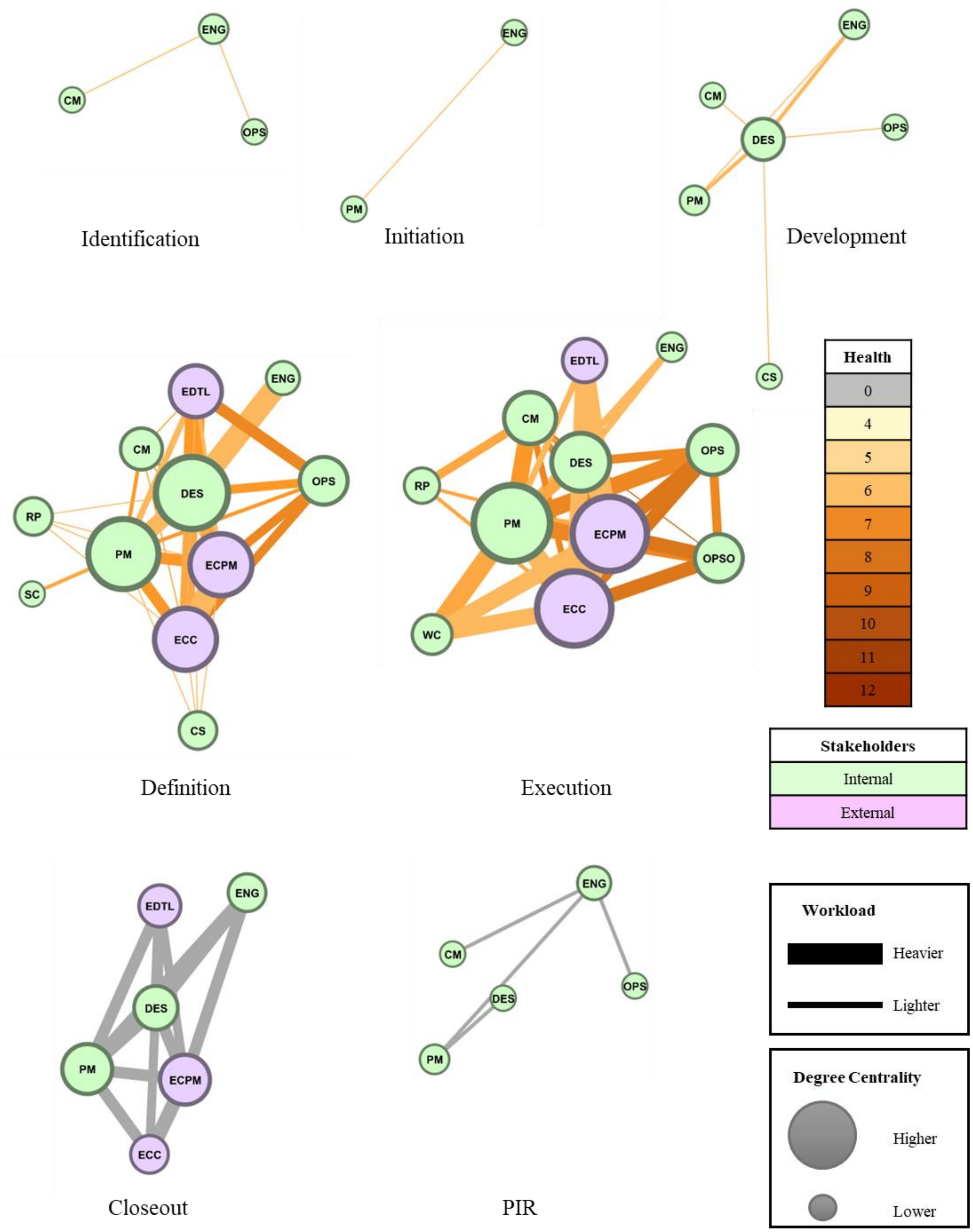


Figure 29 Stakeholder Interface Networks of ACU-1 project

5.2.5.5 Interpretation and Corrective Action

According to the results presented in Appendix F and on Figure 29, the highest workload values were calculated between external stakeholders EPC Construction PM (ECPM) and EPC Construction Coordinator (ECC) in Execution phase [4,5], followed by connections between the Project Manager (PM) and those external stakeholders in the same project phase. On the other hand, the poorest health condition through the project lifecycle was calculated between Operations (OPSO) and Control Maintenance (CM) during the Execution phase [4,5]. After analyzing collected data and establishing stakeholder interface networks for the ACU-1 project, results were shared and reviewed with the PM of the project. The PM explained that internal priorities were affecting health conditions between project stakeholders. For example, the reason behind the relatively poor health condition between CM and OPSO was the misalignment of the stakeholder priorities. These stakeholders had other ongoing projects that had higher priorities that affected the health of the connection. By the end of these review meetings, analysis results found to correspond with the actual project conditions and were validated by the PM of the project.

5.2.6 Project 6 –Air Conditioning Unit Replacement Project 2 (ACU-2)

The fifth project selected in the Nuclear Power Plant to apply the proposed Integrated Project Monitoring Method using Framework-B was another ongoing Air Conditioning Unit (ACU) replacement project. The Scope of Work for this project was to replace the two ACUs which reached the end of life and were in a state of disrepair.

ACU-2 project was also following the same project lifecycle which is presented in Figure 25, as other ongoing projects in the same Nuclear Power Plant, and had seven project phases. The Project Manager (PM) of the owner's team involved as decision-maker and provided data for this project, thus, interface health and workload between stakeholders were analyzed form the owner's point of view.

5.2.6.1 Stakeholder Identification and Stakeholder Connections Identification

After project selection, the PM of the project was asked to provide the stakeholder list and stakeholder' connections list for all project phases. The master stakeholder list for the ACU-2 project is presented in Table 37. At the end of this step, stakeholders and stakeholder connections for each project phase of the ACU-2 project were collected. The data collected for ACU-2 project is presented in Appendix G.

Table 37 Stakeholder List of ACU-2 project

Id	Label	Name	Group	Time-set
1	SRE	SRE	1	[0,6]
3	DRE	Director Engineering	1	[0,3]
5	HFE	Human Factors Engineering	1	[3,5]
7	OPS	Operations	1	[0,1];[2,6]
8	MTN	Maintenance	1	[0,1];[2,6]
11	RE	Radiation Protection	1	[2,4]
12	CS	Conventional Safety	1	[2,4]
13	CE	Chemistry and Environment	1	[2,4]
14	FE	Field Engineering	1	[2,5]
15	ERO	Emergency Response Organization	1	[3,5]
17	TRN	Training	1	[5,6]
18	PSC	Plant Status Control	1	[4,6]
19	PRC	Procedures	1	[5,6]
23	PRO	Projects	1	[1,6]
24	DSG	Design	1	[2,6]
28	CMO	Contract Management Office	1	[2,5]
30	WC	Work Control	1	[3,5]
31	WA	Work Assessing	1	[3,5]
32	FNC	Finance	1	[1,6]
33	SC	Supply Chain	1	[2,6]
35	QLT	Quality	1	[3,4]
36	BM	Contractor	2	[2,6]
46	RCPL	Subcontractor	3	[2,6]

*1=internal Stakeholder, 2= External Stakeholder, 3=Subcontractor

5.2.6.2 Evaluating Stakeholder Connections

Based on the stakeholders' connections list provided by the PM of the project, the workload and health evaluation tool for the ACU-2 project was created and shared with the PM during the review meetings. After explaining the tool and point system for workload and health evaluation of stakeholder connections, the PM provided data for each stakeholder connections in the project.

During the data collection for stakeholder connections evaluation, ACU-2 Project was at the beginning of the Execution phase. Although ACU-2 project hasn't started the Execution phase, the PM of the project provided both health and workload data for Execution and Closeout phases too based on experience. Thus, data for the first 4 phases are real project data for the ACU-2 project, and data for the last 2 phases are based on the PM's expectations based on the experience.

As it is presented in Table 37, a total of 23 stakeholders were involved in the ACU-2 project throughout its project lifecycle. During stakeholders' connection evaluation step, it was found that

ACU-2 project was a well-connected project which had in total of 113 stakeholder connection throughout its project lifecycle. The workload and health data of these connections are attached to Appendix G.

5.2.6.3 Network Analysis

After collecting dynamic health and workload values of each stakeholder connection, network analysis was conducted for the ACU-2 Project. By the end of this analysis, dynamic Degree Centrality (DC) values of each stakeholder for all the phases they were active in the project were calculated. Calculated DC values are presented in Table 38 below.

Table 38 DC values in ACU-2 project

Label	DC
SRE	[0,1,8.66];[1,2,5.1];[2,3,23.66];[3,4,23.62];[4,5,20.78];[5,6,9.38]
DRE	[0,1,7.55];[1,2,6.0];[2,3,28.0]
HFE	[3,4,6.0];[4,5,14.0]
OPS	[0,1,7.35];[2,3,15.43];[3,4,18.52];[4,5,31.11];[5,6,14.73]
MTN	[0,1,6.93];[2,3,11.83];[3,4,20.59];[4,5,30.98];[5,6,16.25]
RE	[2,3,10.0];[3,4,10.0]
CS	[2,3,10.0];[3,4,12.0];[5,6,4.0]
CE	[2,3,10.0];[3,4,8.0]
FE	[2,3,6.0];[3,4,4.0];[4,5,22.63]
ERO	[3,4,2.0];[4,5,15.49]
TRN	[5,6,10.0]
PSC	[4,5,5.66];[5,6,6.0]
PRC	[5,6,8.0]
PRO	[1,2,8.66];[2,3,30.4];[3,4,40.6];[4,5,42.43];[5,6,25.88]
DSG	[2,3,17.35];[3,4,19.08];[4,5,21.91];[5,6,7.55]
CMO	[2,3,5.48];[3,4,5.66];[4,5,18.33]
WC	[3,4,6.0];[4,5,16.25]
WA	[3,4,6.0];[4,5,14.7]
FNC	[1,2,5.66];[2,3,6.71];[3,4,5.29];[4,5,14.14];[5,6,2.0]
SC	[2,3,7.55];[3,4,6.63];[4,5,12.65];[5,6,3.46]
QLT	[3,4,6.0]
BM	[2,3,2.0];[3,4,25.04];[4,5,46.96];[5,6,11.31]
RCPL	[2,3,2.0];[3,4,8.0];[4,5,41.27];[5,6,5.66]

5.2.6.4 Visualization

A dynamic Stakeholder Interface Network was established for the ACU-2 project. Snapshots from the dynamic network for each project phase in the ACU-2 project are presented in Figure 30 with detailed legends.

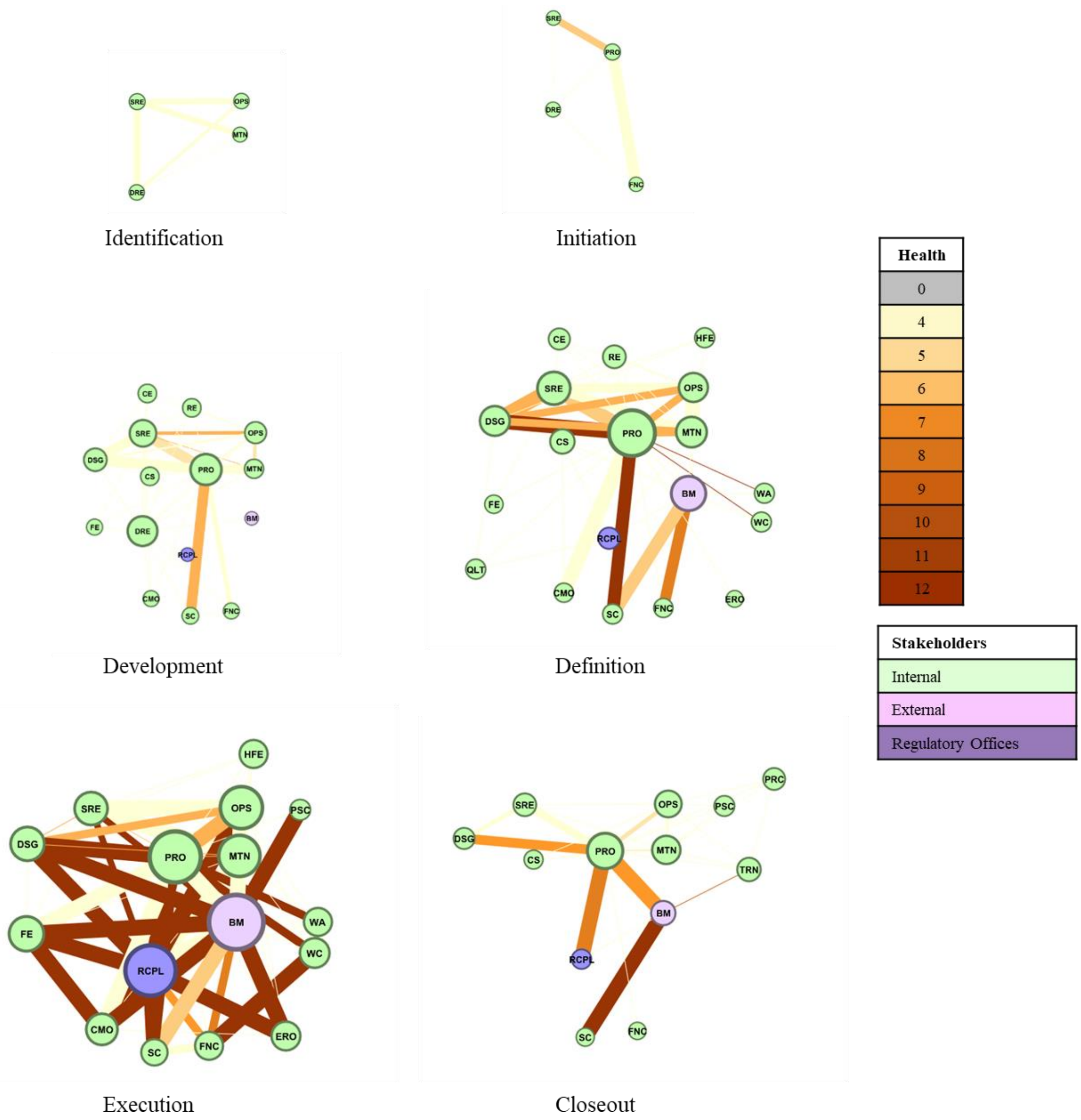


Figure 30 Stakeholder Interface Networks of ACU-2 project

5.2.6.5 Interpretation and Corrective Action

According to the workload and interface health analysis results presented in Appendix G and on Figure 30, the highest workload values in the first four phases of ACU-2 project were calculated between stakeholders Operations (OPS) and Maintenance (MTN), Projects (PRO) and Systems Responsible Engineer (SRE), PRO and Design (DSG), SRE and DSG, and PRO and Contract Management Office

(CMO) in Definition phase [3,4]. Meanwhile, the poorest health condition the first four phases of the ACU-2 project was calculated between stakeholders PRO and Supply Chain (SC), PRO and Work Assessment (WA), and PRO and Work Control (WC) at the Definition phase [3,4].

After analyzing collected data and establishing stakeholder interface networks for the ACU-2 project, results were shared with PM of the project at the review meetings. During these meetings, PM explained that the turnover rate was high in the internal and external stakeholders. Due to the time new employees required for training and learning, high workload and poor health condition between project stakeholder occurred. For example, the main reason for the poor health condition between Projects (PRO) and Supply Chain (SC) groups was related to both high turnover rate in Supply Chain and outdated software usage. Over time, procedures followed in the ACU-2 project changed, thus the software used become outdated. That also created extra work between project stakeholders.

Internal stakeholders in the project were also responsible for many other ongoing projects in the same nuclear power plant. For example, Operations (OPS) and Maintenance (MNT) were responsible for other projects primarily which created a high workload for stakeholders that needed to collaborate with them. Moreover, it is learned that documentation of initial ACU project implemented in the 1970s were printed on paper, and external stakeholders were having hard time to reach those documentations. That was also another reason for the high workload between internal and external stakeholders. By the end of these review meetings, analysis results were found to correspond with the actual project conditions and were validated by the PM of the project.

5.3 Partial Functional Validation of the BIM and IMS Integration

The proposed methodology for Building Information Modeling and Interface Management System (IMS) can be further explained and partially validated through an example Light Rail Transit (LRT) project. LRT projects are a subdivision of Mass Rapid Transit systems. Today, many LRT projects all around the world face problems that can be solved by establishing proper IM and BIM systems. Some of the common problems LRT projects face are; designing the platform lower than it should be, or designing train door heights that are different than the platform design, or building platforms shorter than the train length, or constructing stations narrower than trains can fit. Solving these types of problems at the late phases of the project result in substantial extra costs and schedule problems (Board, 1995; Flanagan, 2016).

Generally, BIM or equivalent 3D tools are used for LRT design to manage project complexity and perhaps more importantly to communicate design details and interfaces. In addition to BIM, IMS should also be used in LRT projects to manage communications and deliverables between project stakeholders in design and construction phases. In order to demonstrate the functionality and efficacy of the IMS and BIM integration, a model LRT system was developed for this thesis. A good model would abstract key network morphology and elements of actual LRT projects allow for scenario and sensitivity tests, would be useful for illustrating concepts being studied and developed, would be realistic enough to convince practitioners of its representativeness, and be simple enough that it can be managed and manipulated by a single researcher. The development of such a model is described in the following sections.

5.3.1 A Model Interface Management System of a Light Rail Transit (LRT) Project at its Early Phases

Generally, Light Rail Transit (LRT) projects are built by consortiums which contain several project stakeholders who have different specializations. In such organizations, many interface points between project stakeholders would be created. For instance, station platforms would be subject to many interface points in an LRT project. Dimensions of the platforms are important for designing other systems in the project, therefore project participants need to agree on the dimensions of station platforms, and these agreements should be controlled properly. For example, the height of the platform would be an interface point between project stakeholders who undertake Rolling Stock and Civil Works since it would affect the design of the train and door locations and vice versa. Similarly, the wideness of the stations would be another interface point between project stakeholders who undertake the design of Civil Works, Rolling Stock, and Track Works.

Yeh et al. (2017) defined a breakdown structure of a typical Mass Rapid Transit (MRT) project to manage interfaces in urban MRT projects. In this thesis, the breakdown structure that is defined by Yeh et al. (2017) was taken into consideration while creating the 3D model and the IM system of a model project. The main branches of the aforementioned breakdown structure can be seen in Figure 31.

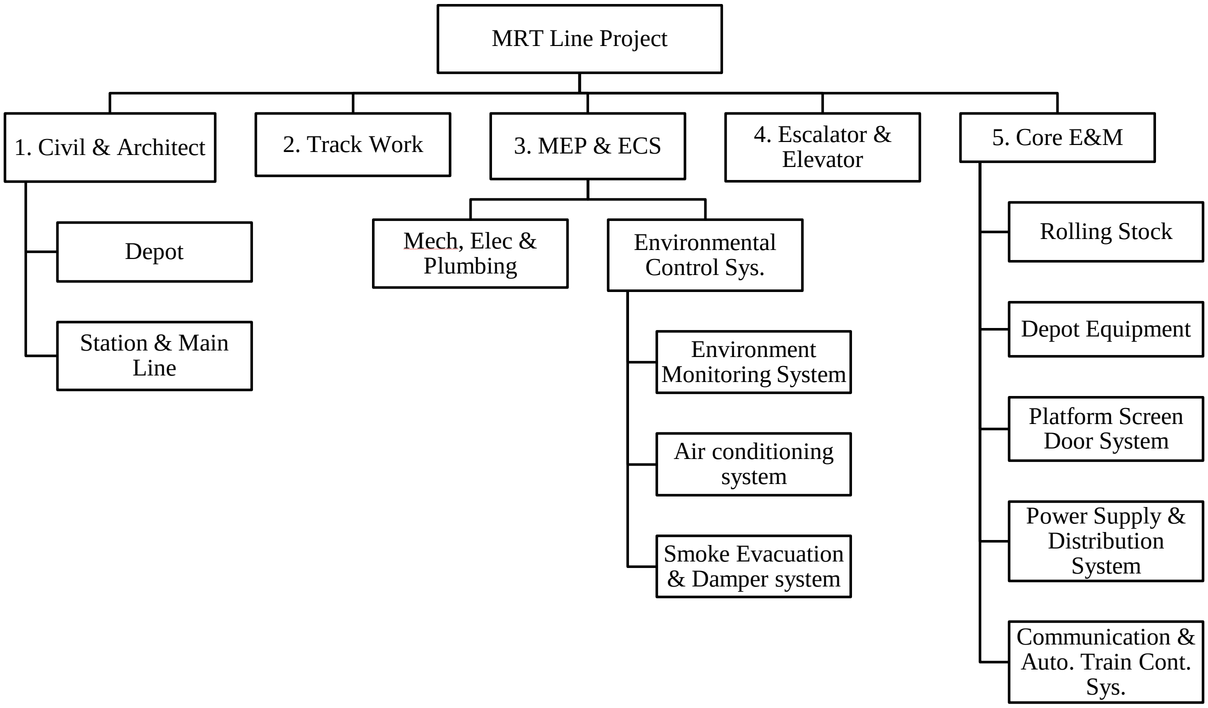


Figure 31 Breakdown structure of a typical MRT line project. Source: (Yeh et al., 2017)

In the 3D model and IMS developed after reviewing many existing LRT projects, an LRT project built by a consortium was hypothesized. To set up its IMS, a fundamental database structure which is explained in Section 4.1 was followed. The first step of setting up an IMS for a project is defining its scope packages, scope IDs, contractors of these packages, and contractor IDs. Therefore, five engineering work packages including Civil Works, Rolling Stock, Track Works, Signaling, and Infrastructure were defined for this LRT model with the assumption that each project stakeholder would be responsible for only one work package. The project setup table with randomly created contractor names and related database codes is summarized in Table 39.

Table 39 IM System Project Setup Table

Scope Package Name	Scope Package Code	Contractor Name	Contractor Code
Owner	OWN	ICA	ICA
Rolling Stock	RLS	Alton	ALT
Signaling	SGN	MTN Rail Works	MTN
Infrastructure	INF	Sose Infrastructure	SOS
Civil Works	CVW	Enk	ENK
Track Works	TRW	YRRail	YRR

The second step of setting up an IMS for a project is defining the Project Manager of the project, and Interface Managers and Technical Contacts of contractors. For this LRT model, an interface manager and two technical contacts for each contractor (stakeholder) were defined with randomly created names. In Table 40, the main contact points of each stakeholder can be seen.

Table 40 Contact points of each stakeholder in model IM system

Contracting Party	Package	Name	Role
ICA	Owner	Ekin Eray	Project Manager
ICA	Owner	Ekin Eray	Interface Manager
ALT	Rolling Stock	Jacob Brown	Interface Manager
ALT	Rolling Stock	Harry Taylor	Technical Contact
MTN	Signaling	Thomas Lewis	Interface Manager
MTN	Signaling	Daniel Morgan	Technical Contact
MTN	Signaling	Erin Richards	Technical Contact
SOS	Infrastructure	Grace Foster	Interface Manager
SOS	Infrastructure	Jack Mason	Technical Contact
SOS	Infrastructure	Adam West	Technical Contact
ENK	Civil Work	David Murray	Interface Manager
ENK	Civil Work	Luke Palmer	Technical Contact
ENK	Civil Work	Mark Lucas	Technical Contact
YRR	Track Works	Amy Moore	Interface Manager
YRR	Track Works	Lisa Lloyd	Technical Contact
YRR	Track Works	Paul Lavender	Technical Contact

The third step of setting up an IMS for a project is dividing the model project into Phases, Disciplines, and Areas. Since LRT projects are linear projects, each station and sections between stations were accepted as an area for this project. Also, the phase was assumed as the design phase for each interface point and agreement. Discipline and Area data of the project can be seen in Table 41.

Table 41 Discipline and Areas of the Model

Discipline	Code	Area	Code
Administration	ADM	Conestoga	CNS
Procurement	PRO	Northfield	NRF
Earthwork	ERW	R&T Park	RTP
Track line	TRC	UW	UWS
Structural	STR	Seagram	SGR
Operations/ Maintenance	OPR	Central Control Center	CCC
Mechanical	MEC	Between CNS-UWS	Btw CNS-UWS
Signaling	SIG	Between CNS-NRF	Btw CNS-NRF
Civil	CVL	Between NRF-RTP	Btw NRF-RTP
Electrical	ELE	Between RTP-SGR	Btw RTP-SGR
Telecommunication	TEL		
Multidiscipline	MLT		

After defining all the mandatory tables presented in Figure 13 earlier, IPs and IAs between contractors can be created. Some IP examples between defined work packages are shown in Table 42.

Table 42 Examples for Interface points on LRT projects

Leader	Partner	Title of Interface	Interface Description
RLS	CVW	Platform Level	Details of cant and platform levels
RLS	TRW	Vehicle Data	Vehicle data for dimensioning other systems
SGN	CVW	Signals	Requirements for implementation
RLS	TRW	Insulated Rail Joints	Location and Quantity of Insulated Rail Joints
OWN	RLS	Design restrictions	Height restrictions for dimensioning vehicles

5.3.2 Conceptual 3D Design

In order to create a conceptual 3D design for the model LRT project, project agreements, route and station designs of several projects such as Waterloo LRT, Eglington Crosstown LRT, Valley metro were studied. After reviewing project documents from different LRT projects, a conceptual 3D design for the model LRT project was created by using Autodesk Revit 2017. The families and objects available on Autodesk Revit 2017, and objects freely available on the internet were used while creating the LRT project model. As explained in the previous sections, in complex construction projects, generally a project team starts creating a 3D model of the project before establishing its IM system. According to the assumptions that have been made for this research, there would be a conceptual 3D BIM model of the LRT project in the early stages of the design phase, and each element on the model could be defined by IFC format. Thus, the model LRT project represents the early phases of the design stage of such a project. A partial route of the modeled LRT project is presented in Figure 32 and example stations are presented in Figure 33.

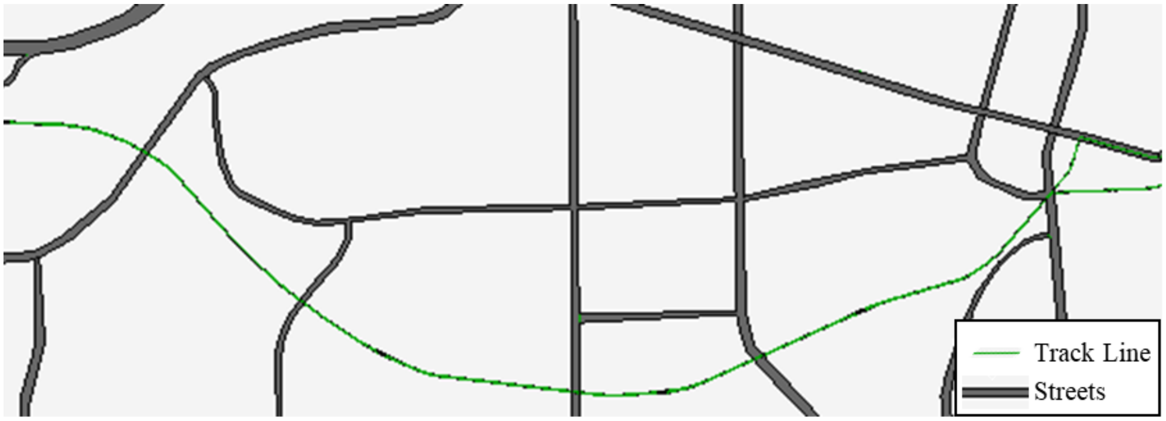


Figure 32 Partial Route of the LRT model

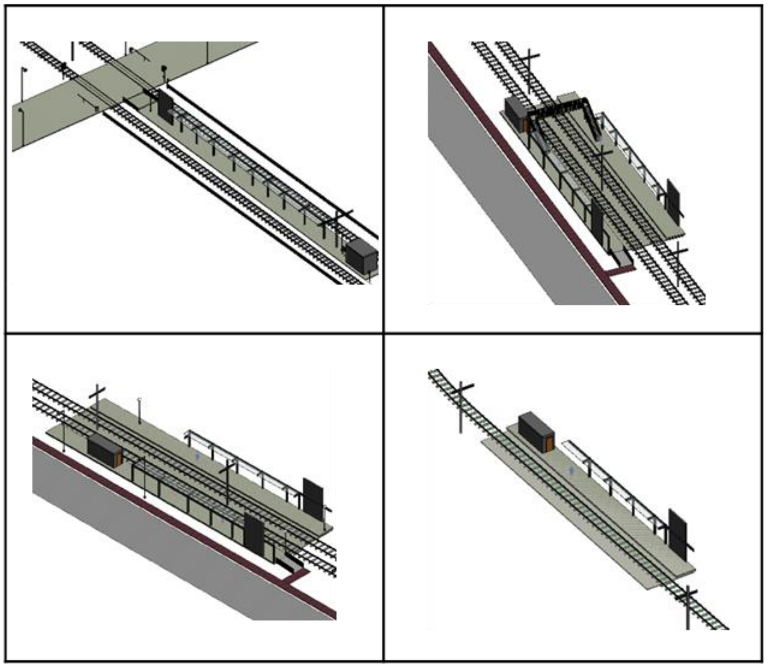


Figure 33 Example stations on the model

Three different types of LRT stations were modeled: (1) island type, (2) one-side type, and (3) double side type. A total of 14 stations were added to the 12-km long hypothetical LRT line. A typical number of design objects for an LRT platform would be over 1000 in real projects. In this research, a limited number of design objects which would be subject to interface points and interface agreements between project participants were added to the model. Objects that are placed in the station models were: concrete platform, concrete base, steel platform columns, beams, glass platform roof, concrete platform wall, electric poles, technical room, connection ramp between platform and road, stoppers, fences, traffic lights, signals for the train, platform lights, electrical boxes, and pipe lines. Objects on the island type platform can be seen on Figure 34.

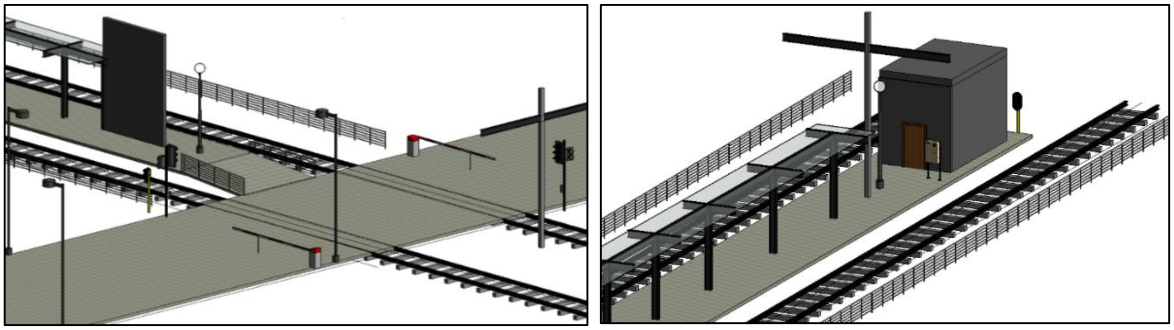
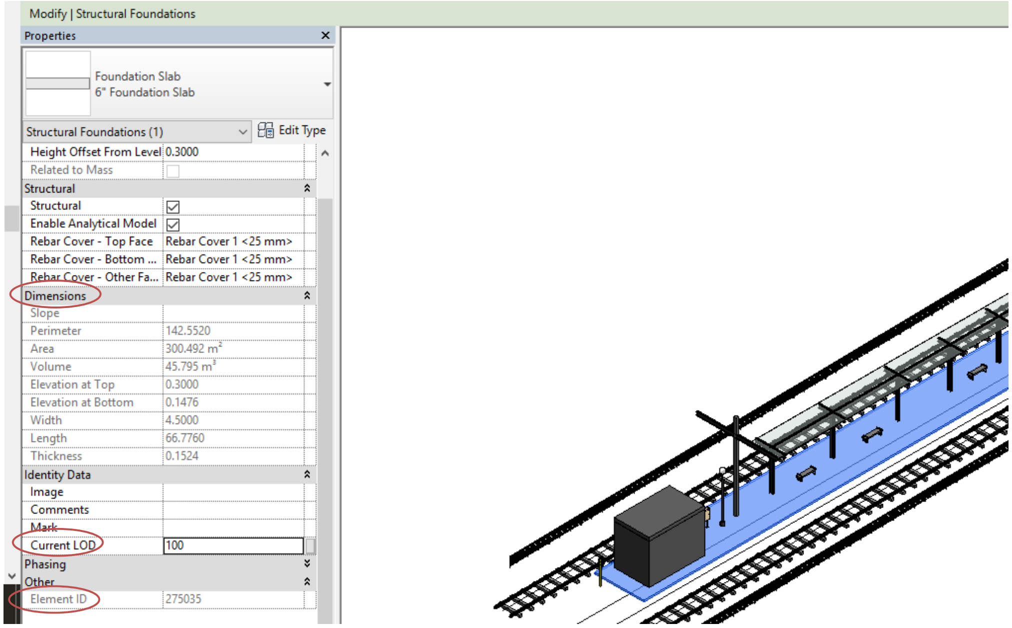


Figure 34 Island type LRT station (part – 1 and part -2)

Each object in this model contained its own properties such as material type, dimensions, constraints, identity data, LOD, etc. Properties of the elements can be accessed with the database of the software. For example, properties screen of a Platform object on an island type of station is shown in Figure 35.



Height Offset From Level	0.3000
Related to Mass	☐
Structural	
Structural	☑
Enable Analytical Model	☑
Rebar Cover - Top Face	Rebar Cover 1 <25 mm>
Rebar Cover - Bottom ...	Rebar Cover 1 <25 mm>
Rebar Cover - Other Fa...	Rebar Cover 1 <25 mm>
Dimensions	
Slope	
Perimeter	142.5520
Area	300.492 m^2
Volume	45.795 m^3
Elevation at Top	0.3000
Elevation at Bottom	0.1476
Width	4.5000
Length	66.7760
Thickness	0.1524
Identity Data	
Image	
Comments	
Mark	
Current LOD	100
Phasing	
Other	
Element ID	275035

Figure 35 Properties of a Platform object

5.3.3 Proposed Database Level Integration of BIM and IMS (BIM+IMS Connector)

In Chapter 4, a framework for database-level integration of Interface Management System (IMS) and BIM is proposed. As it is explained in Chapter 4, integration between these two systems can be done by connecting Interface Points to related objects on the BIM model, and the IP forms in the IMS can be used for setting this integration. For example, in order to create the first interface point for the model project shown in Table 42, the IM manager of the Rolling Stock would follow the framework shown in Figure 14. As a first step, the IM manager would define the IP title, which would be “Platform level” in this example, then choose the phase, discipline, and area of the interface point from dropdown menus which shows the information presented in Table 41. Depending on the complexity of the project, discipline data can be divided into Systems too.

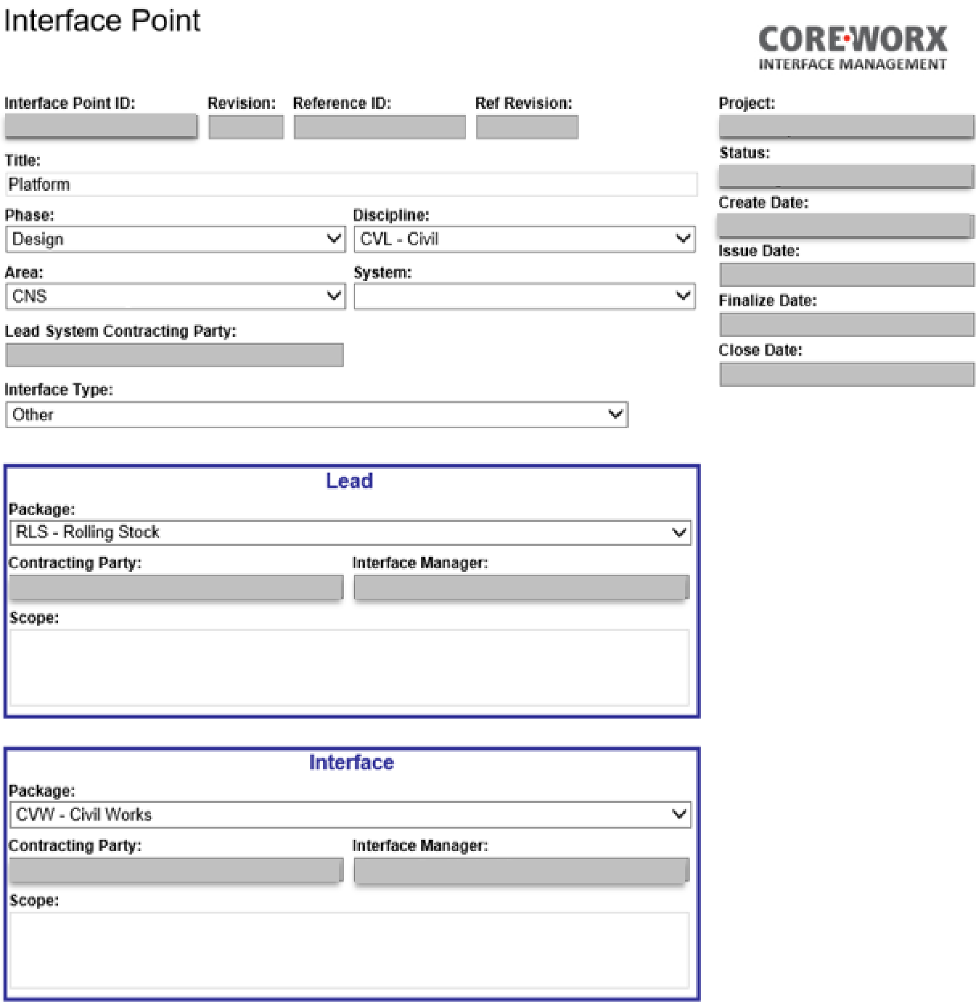
When the Area option is selected from the dropdown menu, BIM elements in that specific area on the model would be listed. In this example, the user needs to select the platform element which has the unique ID as “2604785” from the BIM element section. After selecting related BIM element, the user would require to define work packages related to this IP. In this example, the leading work package would be Rolling Stock, while the interfacing work package is Civil Works. When the IP form is submitted, it would get a unique ID such as “IP-CNS-CVL-0001” and all parties involved in this IP would be notified. When Rolling Stock and Civil Works create Interface Agreements (IAs) for this specific IP, it would be automatically connected to IP and BIM element too. In Table 43, Interface Point (IP), Interface Agreement (IA), and BIM element connection of the first two examples summarized in Table 42 is shown.

Table 43 Example IP - IA - BIM Element relationship table

Leader	Partner	Title of IP	IP-ID	IA-ID	BIM-element ID
RLS	CVW	Platform Level	IP-CNS-CVL-0001	IA-ALT-ENK-CVL-00001	2604785
TRW	CVW	Platform Level	IP-CNS-CVL-0002	IA-YRR-ENK-CVL-00002	2604785

Several IMS software available on the market today. In this research, Coreworx IMS Software was used for creating the IM System for the case study. Coreworx is a project management information software that is used for engineering and construction projects. It offers several web-based software products that create solutions for different management problems, such as; project information control, interface management, change management, contract management, deliverables management, and requests for information. All of these mentioned products are sharing the same database in the main system. Therefore, these products are connected via a shared database and queries for different products can be done.

In Figure 36, the filled IP form on the Coreworx IMS for the case study can be seen. Grey rows on IP forms on Figure 36 would be automatically filled by the system when the form is saved. Details of the BIM element selection can be seen in Figure 37. The part shown in Figure 37 would be added on the current IP form prior to selecting leading and interfacing work packages, when BIM and IM systems are fully integrated over the database.



Interface Point

Interface Point ID:
Revision:
Reference ID:
Ref Revision:
Project:
Status:
Create Date:
Issue Date:
Finalize Date:
Close Date:
Title: Platform
Phase: Design
Discipline: CVL - Civil
Area: CNS
System:
Lead System Contracting Party:
Interface Type: Other

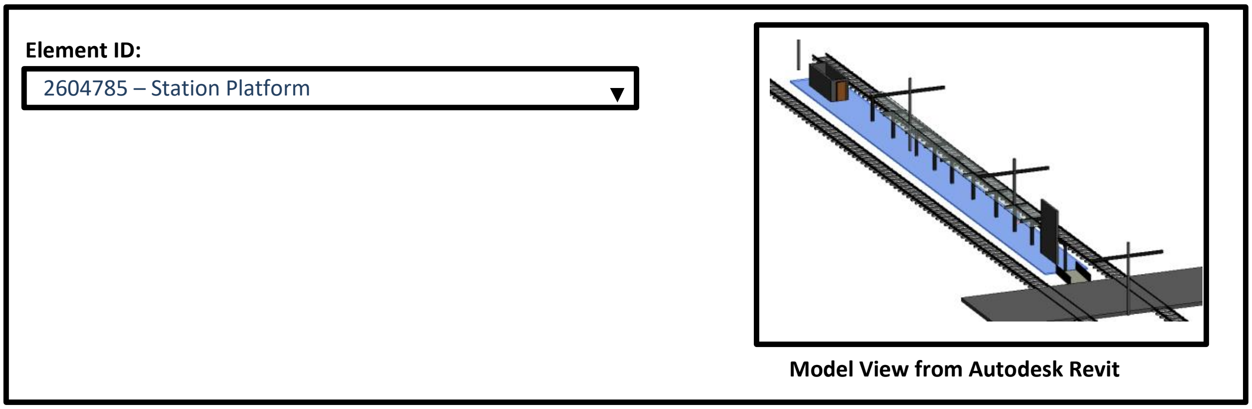
Lead

Package: RLS - Rolling Stock
Contracting Party:
Interface Manager:
Scope:

Interface

Package: CVW - Civil Works
Contracting Party:
Interface Manager:
Scope:

Figure 36 Creating IP form on Coreworx IMS



Element ID:
2604785 – Station Platform

Model View from Autodesk Revit

Figure 37 BIM element selection on IP form

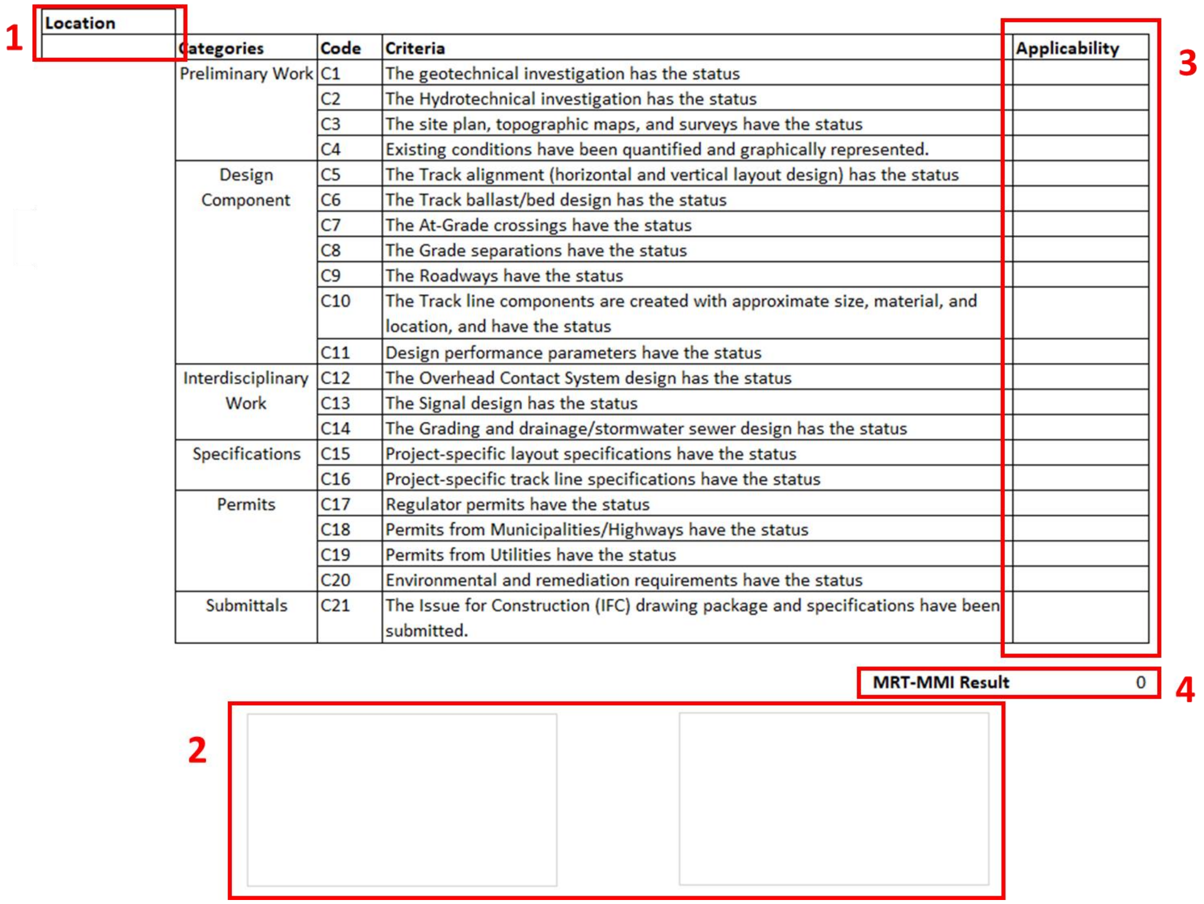
5.4 Validation of Engineering Progress Assessment Tools (MRT-MMI-AT)

In Chapter 4, new model maturity index definitions (MRT-MMI) and corresponding assessment and visualization tools (MRT-MMI-AT) for Track Line, Overhead Contact System, and Station disciplines are presented. In order to validate proposed MRT-MMI definitions and MRT-MMI-ATs, Microsoft Excel-based semi-automated tools for Track Line, Overhead Contact System, and Station discipline were created.

The functionality of the proposed engineering progress tracking framework is demonstrated through the LRT model created and presented in Section 5.3.2. As it is introduced, a 12-km long hypothetical LRT line which includes 14 stations was modeled in Autodesk Revit 2017 as part of this thesis. In order to use the engineering progress tracking tools created, details of the LRT project were introduced to the tool by adding location names and visuals of these locations from the latest 3D model created. Among these locations, three of them were used for demonstration.

5.4.1 Measuring engineering progress of Track Line discipline between two stations

A screenshot from the engineering progress assessment tool (MRT-MMI-AT) for Track Line discipline is presented in Figure 38 below. The structure of the tool is same for the Overhead Contact system and Station disciplines. In order to use the Microsoft Excel based-tool created, first, the project location should be selected from the dropdown menu highlighted as Number 1 in Figure 38. Based on the selected location, pictures from the model will appear in the boxes highlighted as Number 2 in Figure 38. Then applicability of each criterion should be answered by selecting the answer from the dropdown menu highlighted as Number 3. By the end of this step, MRT-MMI level of the Track Line discipline in the selected location will calculated and will appeared in the box highlighted as Number 4. In section 4, minimum required answers for each MRT-MMI level for each discipline are provided.



Location

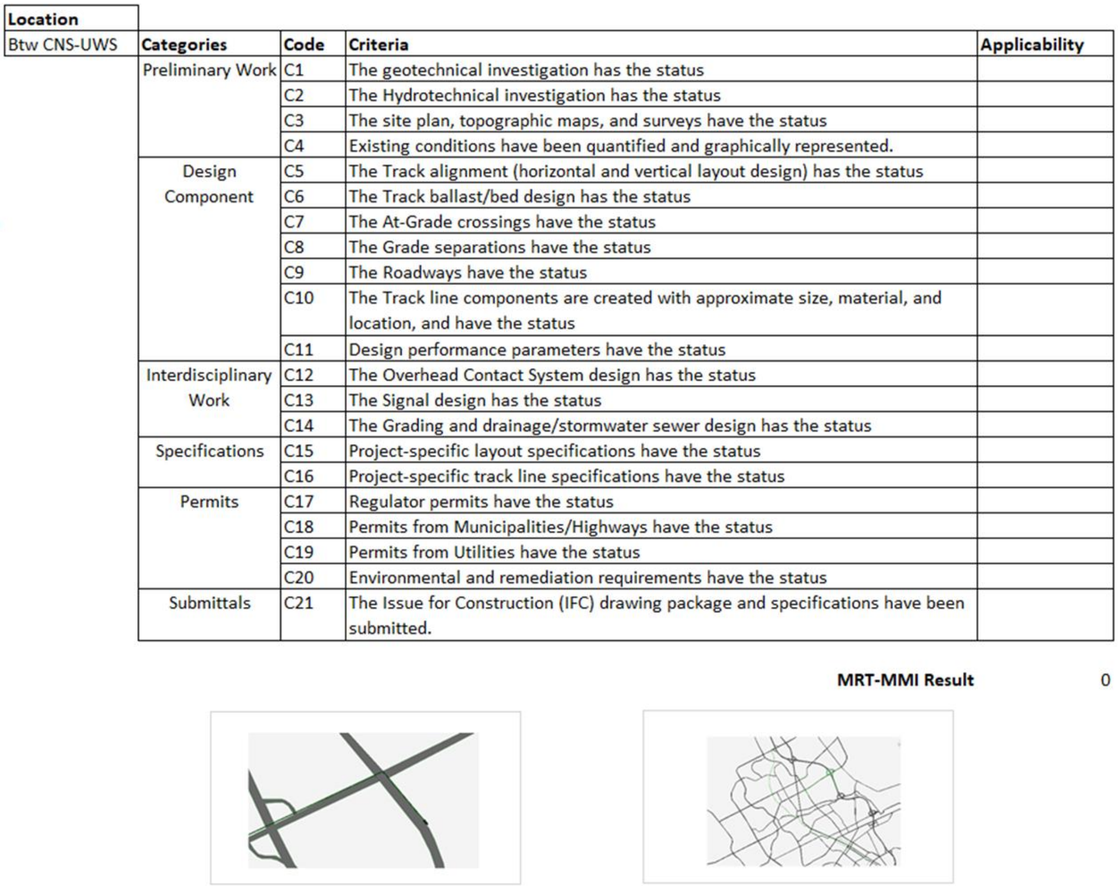
Categories	Code	Criteria	Applicability
Preliminary Work	C1	The geotechnical investigation has the status	
	C2	The Hydrotechnical investigation has the status	
	C3	The site plan, topographic maps, and surveys have the status	
	C4	Existing conditions have been quantified and graphically represented.	
Design Component	C5	The Track alignment (horizontal and vertical layout design) has the status	
	C6	The Track ballast/bed design has the status	
	C7	The At-Grade crossings have the status	
	C8	The Grade separations have the status	
	C9	The Roadways have the status	
	C10	The Track line components are created with approximate size, material, and location, and have the status	
	C11	Design performance parameters have the status	
Interdisciplinary Work	C12	The Overhead Contact System design has the status	
	C13	The Signal design has the status	
	C14	The Grading and drainage/stormwater sewer design has the status	
Specifications	C15	Project-specific layout specifications have the status	
	C16	Project-specific track line specifications have the status	
Permits	C17	Regulator permits have the status	
	C18	Permits from Municipalities/Highways have the status	
	C19	Permits from Utilities have the status	
	C20	Environmental and remediation requirements have the status	
Submittals	C21	The Issue for Construction (IFC) drawing package and specifications have been submitted.	

MRT-MMI Result 0

Figure 38 Engineering Progress Assessment tool for Track Line Discipline

In order to demonstrate the functionality of the tool created, the section between CNS and UWS stations in the 3D model created was used. First, the location was selected on the tool, and pictures of the selected location from the 3D model appeared as it is presented in Figure 39.

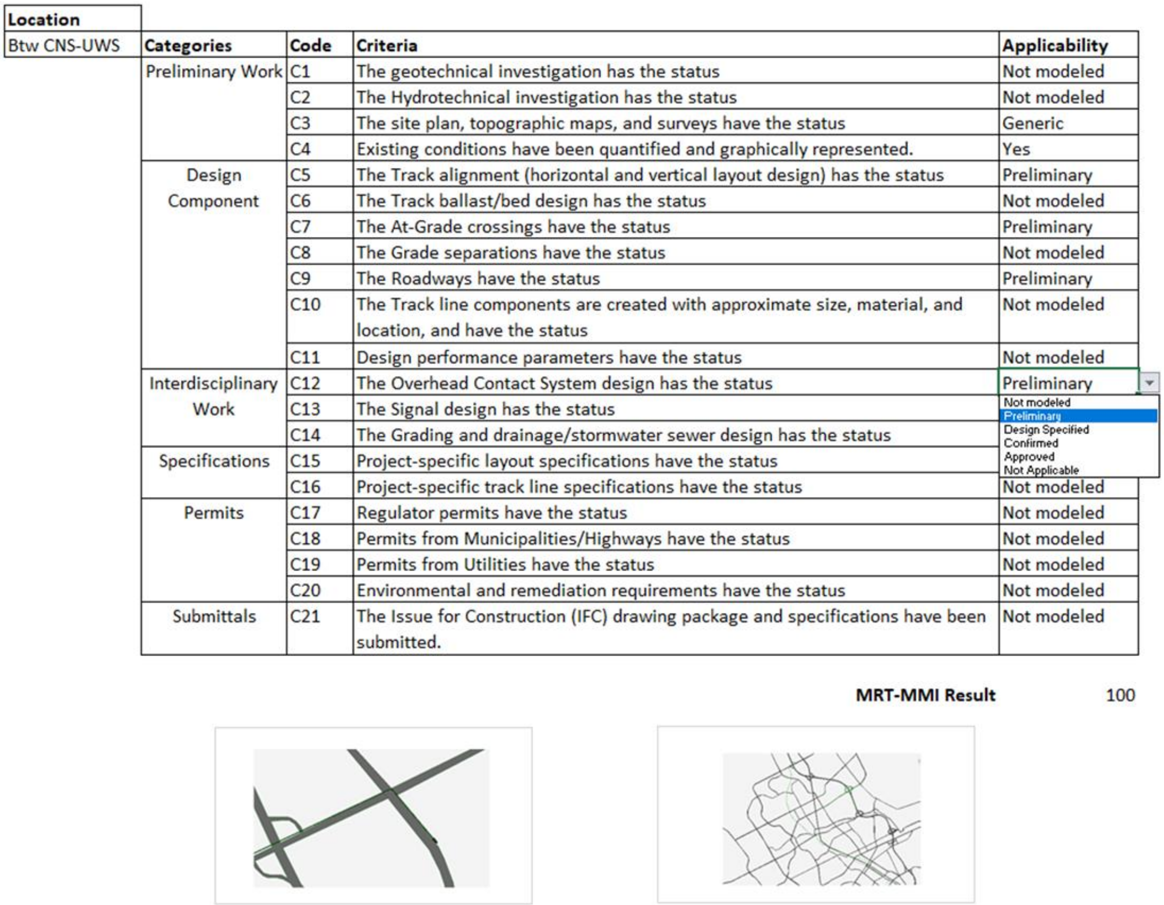
Then, the applicability of each criterion on the table was answered for the selected location accordingly. The latest version of the 3D model created for this research included the generic site plan and maps of the area where existing conditions were graphically represented. Also as can be seen in Figure 39, track alignment, at grade crossings, roadways, and OCS were modeled preliminary in the selected location. A screenshot from the model while answering the applicability of each criterion for the selected location is presented in Figure 40.



Location				
Btw CNS-UWS	**Categories**	**Code**	**Criteria**	**Applicability**
	Preliminary Work	C1	The geotechnical investigation has the status	
		C2	The Hydrotechnical investigation has the status	
		C3	The site plan, topographic maps, and surveys have the status	
		C4	Existing conditions have been quantified and graphically represented.	
	Design Component	C5	The Track alignment (horizontal and vertical layout design) has the status	
		C6	The Track ballast/bed design has the status	
		C7	The At-Grade crossings have the status	
		C8	The Grade separations have the status	
		C9	The Roadways have the status	
		C10	The Track line components are created with approximate size, material, and location, and have the status	
		C11	Design performance parameters have the status	
	Interdisciplinary Work	C12	The Overhead Contact System design has the status	
		C13	The Signal design has the status	
		C14	The Grading and drainage/stormwater sewer design has the status	
	Specifications	C15	Project-specific layout specifications have the status	
		C16	Project-specific track line specifications have the status	
	Permits	C17	Regulator permits have the status	
		C18	Permits from Municipalities/Highways have the status	
		C19	Permits from Utilities have the status	
		C20	Environmental and remediation requirements have the status	
	Submittals	C21	The Issue for Construction (IFC) drawing package and specifications have been submitted.	

MRT-MMI Result 0

Figure 39 Selection of location on the engineering progress tracking tool



Location				
Btw CNS-UWS	**Categories**	**Code**	**Criteria**	**Applicability**
	Preliminary Work	C1	The geotechnical investigation has the status	Not modeled
		C2	The Hydrotechnical investigation has the status	Not modeled
		C3	The site plan, topographic maps, and surveys have the status	Generic
		C4	Existing conditions have been quantified and graphically represented.	Yes
	Design Component	C5	The Track alignment (horizontal and vertical layout design) has the status	Preliminary
		C6	The Track ballast/bed design has the status	Not modeled
		C7	The At-Grade crossings have the status	Preliminary
		C8	The Grade separations have the status	Not modeled
		C9	The Roadways have the status	Preliminary
		C10	The Track line components are created with approximate size, material, and location, and have the status	Not modeled
		C11	Design performance parameters have the status	Not modeled
	Interdisciplinary Work	C12	The Overhead Contact System design has the status	Preliminary
		C13	The Signal design has the status	
		C14	The Grading and drainage/stormwater sewer design has the status	
	Specifications	C15	Project-specific layout specifications have the status	
		C16	Project-specific track line specifications have the status	Not modeled
	Permits	C17	Regulator permits have the status	Not modeled
		C18	Permits from Municipalities/Highways have the status	Not modeled
		C19	Permits from Utilities have the status	Not modeled
		C20	Environmental and remediation requirements have the status	Not modeled
	Submittals	C21	The Issue for Construction (IFC) drawing package and specifications have been submitted.	Not modeled

MRT-MMI Result 100

Figure 40 Selecting applicability of each criterion

Based on the answers entered in the model, the engineering progress of Track Line discipline for the selected location on the 3D model was found as MRT-MMI 100. In order to compare results with minimum required responses for MRT-MMI 100 and MRT-MMI 200, a spider web chart was created. As presented in Figure 41, progress on C7, C9, and C12 were already in MMI 200 level and C4 was already in MMI 400 level but the rest of the criteria were still in the MRT-MMI 100 level. By having such graphs, it is expected that designers can detect the missing elements on the model and focus on those to achieve more mature models.

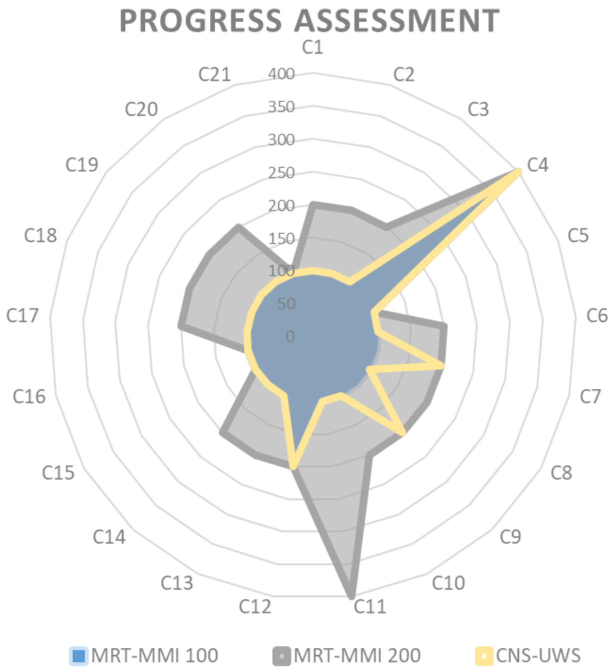
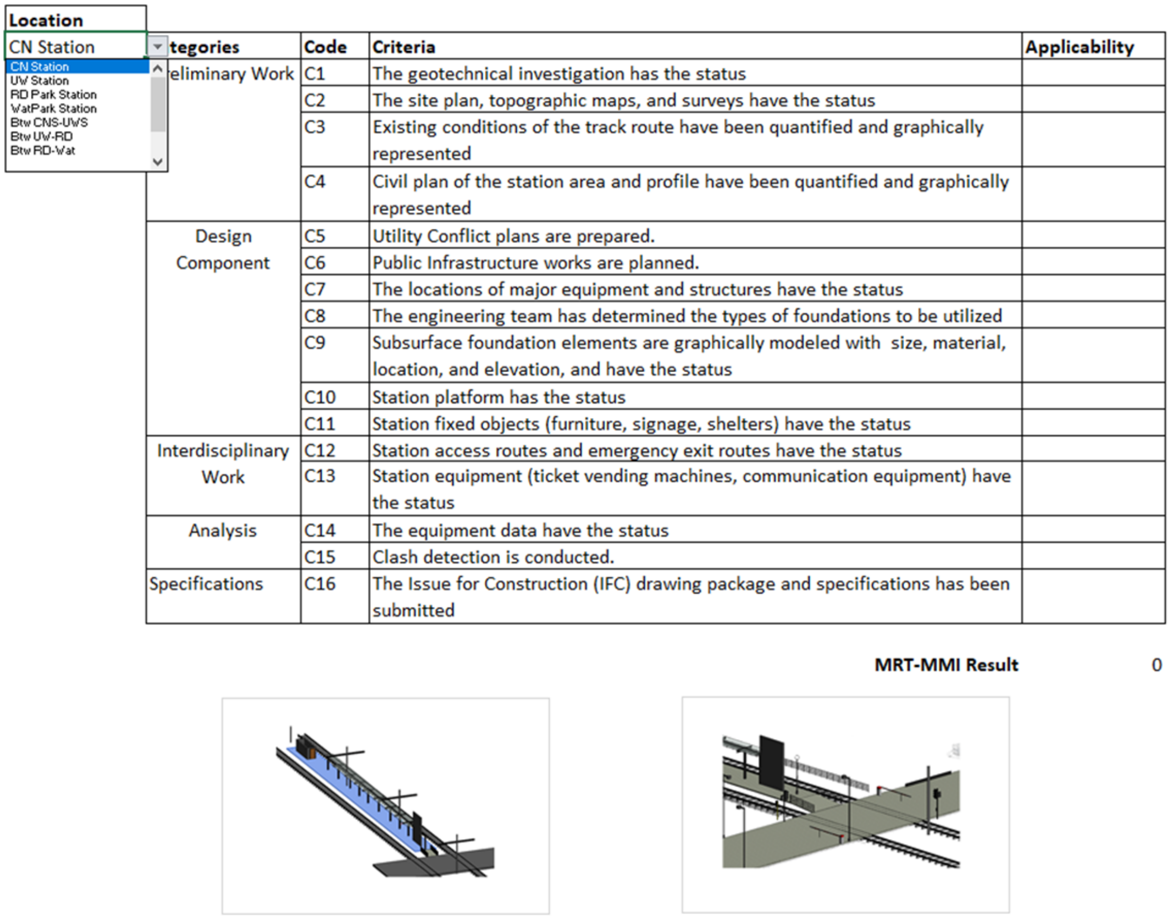


Figure 41 Engineering Progress Assessment result for the example project

5.4.2 Measuring engineering progress of the Station discipline of an LRT station

In Section 4.2.3 and 4.3.3 new model maturity index definitions and corresponding assessment and visualization tool are proposed for the Station discipline. Based on the proposed definitions, a Microsoft Excel based tool was created. The structure of the tool was the same as the tool presented for the Track Line discipline in Section 5.4.1. The functionality of the tool is demonstrated through the 3D LRT model created for this thesis. Among 14 stations modeled, CNS station was selected for the demonstration.

First, CNS Station was selected from drop-down menu created and pictures of the CNS Station from the 3D model were appeared on the tool as presented in Figure 42.



Location

CN Station

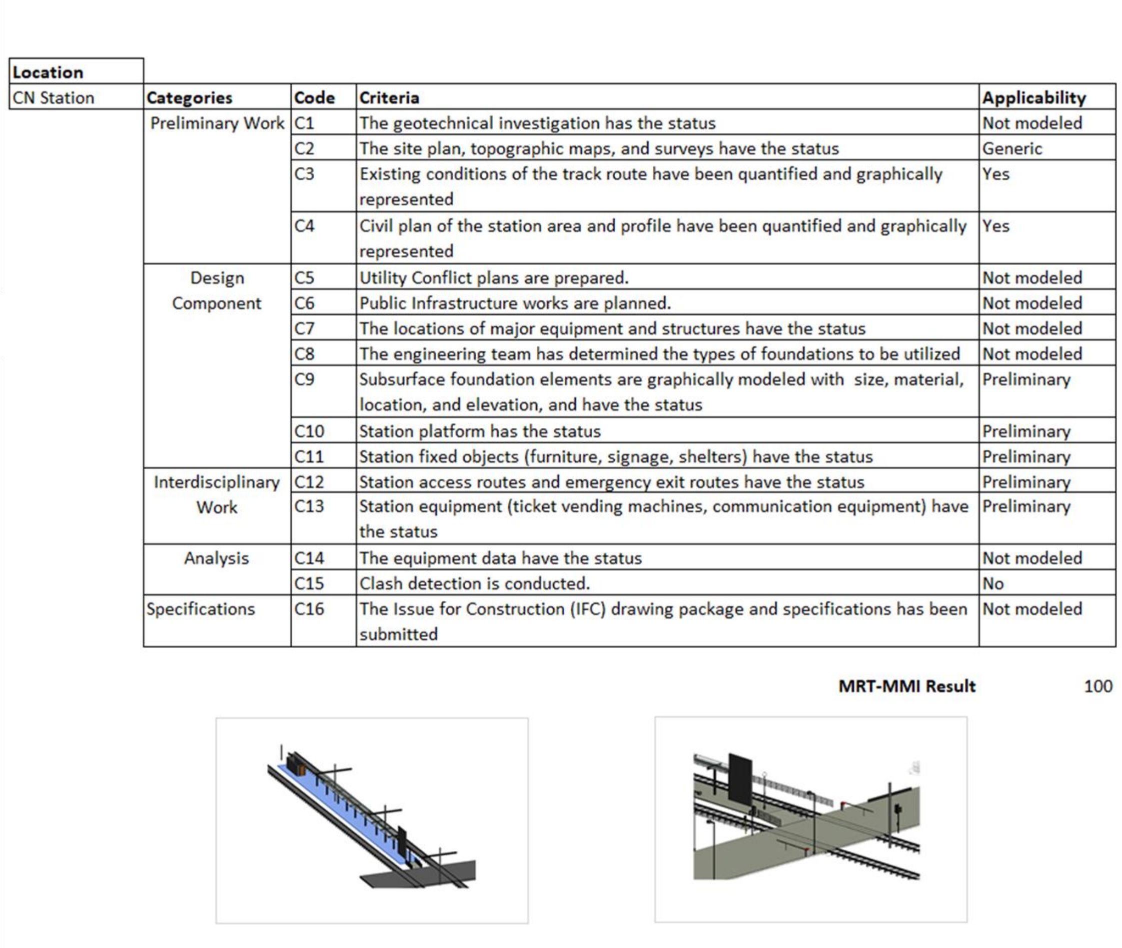
CN Station
UW Station
RD Park Station
WatPark Station
Btw CNS-UWS
Btw UW-RD
Btw RD-Wat

tegories	Code	Criteria	Applicability
eliminary Work	C1	The geotechnical investigation has the status	
	C2	The site plan, topographic maps, and surveys have the status	
	C3	Existing conditions of the track route have been quantified and graphically represented	
	C4	Civil plan of the station area and profile have been quantified and graphically represented	
Design Component	C5	Utility Conflict plans are prepared.	
	C6	Public Infrastructure works are planned.	
	C7	The locations of major equipment and structures have the status	
	C8	The engineering team has determined the types of foundations to be utilized	
	C9	Subsurface foundation elements are graphically modeled with size, material, location, and elevation, and have the status	
	C10	Station platform has the status	
	C11	Station fixed objects (furniture, signage, shelters) have the status	
Interdisciplinary Work	C12	Station access routes and emergency exit routes have the status	
	C13	Station equipment (ticket vending machines, communication equipment) have the status	
Analysis	C14	The equipment data have the status	
	C15	Clash detection is conducted.	
Specifications	C16	The Issue for Construction (IFC) drawing package and specifications has been submitted	

MRT-MMI Result 0

Figure 42 Location selection on the tool

Second, applicability of each criterion on the table was answered for the selected location accordingly. The latest version of the CNS station on the 3D model created for this thesis included generic site plan, track route, plan of the station area, foundation elements, platform, station equipment, entrance and exit route, electric poles, technical room, fences, traffic lights, signals for the train, platform lights, electrical boxes, and pipelines. A screenshot from the tool showing the applicability of each criterion for CNS Station is presented in Figure 43. According to the suggested minimum applicability of each criterion for Station discipline presented in Table 14 , the MRT-MMI level of the CNS station was found as “100”.



Location				
CN Station	**Categories**	**Code**	**Criteria**	**Applicability**
	Preliminary Work	C1	The geotechnical investigation has the status	Not modeled
		C2	The site plan, topographic maps, and surveys have the status	Generic
		C3	Existing conditions of the track route have been quantified and graphically represented	Yes
		C4	Civil plan of the station area and profile have been quantified and graphically represented	Yes
	Design Component	C5	Utility Conflict plans are prepared.	Not modeled
		C6	Public Infrastructure works are planned.	Not modeled
		C7	The locations of major equipment and structures have the status	Not modeled
		C8	The engineering team has determined the types of foundations to be utilized	Not modeled
		C9	Subsurface foundation elements are graphically modeled with size, material, location, and elevation, and have the status	Preliminary
		C10	Station platform has the status	Preliminary
		C11	Station fixed objects (furniture, signage, shelters) have the status	Preliminary
	Interdisciplinary Work	C12	Station access routes and emergency exit routes have the status	Preliminary
		C13	Station equipment (ticket vending machines, communication equipment) have the status	Preliminary
	Analysis	C14	The equipment data have the status	Not modeled
		C15	Clash detection is conducted.	No
	Specifications	C16	The Issue for Construction (IFC) drawing package and specifications has been submitted	Not modeled

MRT-MMI Result 100

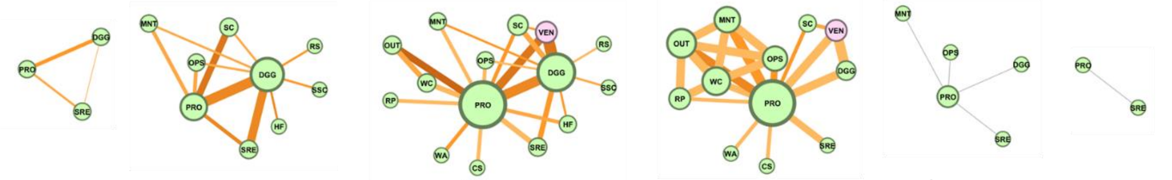
Figure 43 MMI Result screen for Station discipline

Chapter 6

Conclusions and Future Work

This thesis presented methods and frameworks to measure and visualize integrated interface status between project stakeholders in terms of health, workload, and engineering progress. Effective communication and alignment on the project goals amongst all of the project stakeholders is critical for construction projects. Any misalignment or miscommunication between project stakeholders can lead to inefficient processes and project delays. These are signs of interface health problems between project stakeholders. Although traditional project management methods often provide solutions to estimate the resource profiles of the project stakeholders, they do not provide insight into the workload and health of the interfaces between project stakeholders which can both affect overall project outcomes. Integrated Project Monitoring Method, the first methodological contribution presented in this thesis, provides solutions to detect unhealthy and overloaded interfaces between project stakeholders. Detection of such interfaces provides early indications to upper-level management where additional efforts might be best applied to overall project health and performance.

Integrated Project Monitoring Method contains two Frameworks, which are the second and third methodological contributions of this thesis, for evaluating health of the stakeholders' connections. The first framework, Framework-A, is based on the actual project data and promises an objective data driven health measurement. However, due to the complexity of the data acquisition from project information management systems, Framework-A is only ideal for construction organizations where the required data is available electronically. The second framework, Framework-B, is based on a novel point system developed as part of this thesis. This allows Framework-B to be adopted in any construction organization without any complicated data acquisition processes. Additionally, the concept of stakeholder interface network is developed as part of the Integrated Project Monitoring Method. Stakeholder interface networks are based on graph theory and social network analysis, and they are used for mapping complex and dynamic project environments by illustrating project stakeholders as nodes, and stakeholders' connections (interfaces) as edges. The interface health and workload evaluation results obtained from Framework-A and Framework-B are presented on these networks via thickness and colors on the edges and size on the nodes. Example stakeholder interface networks of the Detector Assemblies Replacement project studied in Chapter 5 are presented in Figure 44 below. In this thesis, partial validation of the Framework-A is presented, while Framework-B is applied to 6 complex construction projects from railway and nuclear industries, and validated through experts' judgements in these case studies.



Initiation Development Definition Execution Closeout PIR

Figure 44 Stakeholder Interface Networks of Detector Assemblies Replacement project

Engineering progress measurement during the early phases of construction projects is an essential management task. While most of the engineering progress in the early phases of complex capital projects is not graphical-design related, this progress must be captured in order to have a comprehensive understanding about the projects' progress. Despite its importance, there is a lack of detailed studies in this area. Although engineering progress measurement methods exist, they are either specific for a class of projects or poorly developed for current design practices. This thesis proposed a method to integrate Building Information Modelling and Interface Management Systems (BIM+IMS Connector) to obtain accurate project data to have better control during the early phases of complex construction projects. BIM+IMS Connector is the fourth methodological contribution of this thesis. Additionally, new model maturity index definitions (MRT-MMI) and engineering progress assessment and visualization tools (MRT-MMI-AT) are created for Mass Rapid Transit (MRT) projects. Dashboards containing Spider web graphs are used for visualizing engineering progress of Track Line, Overhead Contact System, and Station disciplines in MRT projects. MRT-MMI definitions and their corresponding assessment tools (MRT-MMI-AT) are the domain contributions of this thesis.

In order to validate the methodology proposed for integrating BIM and IMS (BIM+IMS Connector), engineering progress measurement definitions (MRT-MMI), and assessment tools (MRT-MMI-AT) for Mass Rapid Transit projects, a 3D model and interface management system environment are created for a Light Rail Transit (LRT) project. The functionality of the proposed studies are demonstrated by using the LRT model created.

6.1 Conclusions

The studies presented in this thesis have demonstrated that the four methodological contributions are feasible and insightful, and that the two MRT domain contributions are usable. Feasibility of the methodological contributions is demonstrated both intellectually and empirically. Intellectually, these contributions represent novel combinations of existing ideas, such as the applications of Graph Visualization and Social Network Analysis to construction projects (Integrated Project Monitoring Method), and the novel way of connecting Building Information Management (BIM) to Interface Management Systems (IMS) (BIM+IMS Connector). Empirically, these new methods were applied on both real and simulated data from a variety of construction projects across two major industry segments: Mass Rapid Transit (MRT) and Nuclear Power Generation (NPG).

The empirical studies with industry partners demonstrated that these methodological contributions are insightful. The industry experts affirmed that the outputs of the methods corresponded to their expert judgment about the projects, and that the novel visual method of combining and presenting the information gave them new insights about the projects.

It is expected that future work will demonstrate that these insights are effective in improving project outcomes. This will require the application of these methods to a project over its duration as all of the studies here were based on data from completed projects, an important first validation step before attempting to apply these methods to active projects.

The quantitative approach to measuring project health (Framework-A) requires a high degree of IT systems integration, which may not be available on all projects. The qualitative approach (Framework-B), by contrast, involves a simple questionnaire that can be completed by people working on the project, allowing it to be deployed on any project.

Usability of the two MRT domain contributions is, again, demonstrated both intellectually and empirically. Intellectually, the structure and content of the contributions are compared to existing CII materials for other domains, and is also justified against the MRT literature. Empirically, the validation studies show how these definitions (MRT-MMI) and the corresponding assessment tool (MRT-MMI-AT) would be applied using simulated data.

Finally, it is concluded that the studies presented in this thesis have demonstrated that the measurement and visualization of integrated interface status in terms of health, workload and engineering progress, are feasible by the methods and models proposed.

6.2 Contributions

In this thesis, a new set of tools and methods for measuring health and workload between project stakeholders and measuring engineering progress in the early phases of complex construction projects are developed. The main contributions can be summarized in 6 major areas:

1. **Integrated Project Monitoring Method:**

First, definitions of Project health and Interface health for complex construction project environments are created. Then, methods to measure interface health between project stakeholders are investigated and a new method is developed. The Integrated Project Monitoring Method contains two new frameworks that are developed to measure interface health. Those frameworks are the second and third contribution of this thesis and are discussed in the following sections. In order to visualize the interface health and workload status between project stakeholders, the stakeholder interface network concept is developed as part of the Integrated Project Monitoring Method. In these networks, project stakeholders are illustrated as nodes and connections between project stakeholders are illustrated as edges. The results obtained from Framework-A are presented by color codes on the edges, while the results obtained from Framework-B are presented by thickness (workload) and color codes (health) on the edges, and size of the nodes (Degree Centrality). Ultimately, these networks can be used for reviewing project health conditions throughout the project lifecycle.

2. **Framework-A:**

Framework-A is the first method developed as part of the Integrated Project Monitoring Method. It is based on actual project data from various project information management systems currently being used in the industry. Since interface health between project stakeholders can be measured by using actual project data with this framework, it promises objective results.

3. **Framework-B:**

Framework-B is the second method developed as part of the Integrated Project Monitoring Method. It is based on a novel simplified qualitative point system developed as part of this thesis. In addition to interface health measurement, workload measurement on the stakeholder connections and Social Network Analysis are also part of Framework-B.

4. **BIM+IMS Connector**:

In order to obtain accurate project data, to have better control over the design progress, and to have better communication about interface related problems in the early phases of the complex construction projects, a framework to integrate BIM and Interface Management data is developed as part of this thesis. BIM+IMS Connector is based on connecting Interface Points between project stakeholders to corresponding BIM element in the 3D model via Industry Foundation Classes (IFCs).

5. **New Model Maturity Index Definitions for Mass Rapid Transit Projects (MRT-MMI):**

In order to measure engineering progress in the early phases of Mass Rapid Transit (MRT) projects, new Model Maturity Index definitions for disciplines specific in MRT domain are created (MRT-MMI). The selected disciplines in MRT projects to define MMI definitions are Track Line, Overhead Contact Systems, and Stations.

6. **Engineering progress assessment and visualization tools for Mass Rapid Transit Projects:**

Based on the MRT-MMI definitions, conceptual semi-automated engineering progress assessment tools (MRT-MMI-AT) are created. By using these tools, one can assess and visualize the MRT-MMI level of the Track Line, Overhead Contact System, or Stations per location in a 3D model.

6.3 Limitations

Despite the benefits of these works, this study has limitations which can be categorized in three groups:

1) Limitations of the proposed ideas that are inherent in their nature:

- Framework-A, is based on the availability of various project information management systems such as Interface Management, Request for Information, Change Management system, etc. Through a series of discussions with multiple industry partners, it was found that either these organizations were not using all the systems listed above in their projects, or they were not storing required data in a reachable database. Therefore, while Framework-A can provide an objective, quantitative data-based interface health value for each stakeholder connection in a complex project, data acquisition is its the main limitation.
- While the aforementioned health measurement and visualization contributions are promising, their effectiveness in practice has yet to be established empirically. This will take many years of implementation and dozens of documented capital projects as input for subsequent statistical

analysis. This limitation is common to most management practice innovations, yet continuous innovation is necessary for capital project performance improvements to be made possible.

2) Threats to internal validity:

- Framework-B, is based on filling a novel qualitative point system tool. Ideally, health and workload evaluations should be done by multiple stakeholders or even multiple people from the same group to eliminate individual biases. In this thesis, Framework-B is validated by applying it to six projects from two different industries. The main limitation of the validation, in each example project, is that workload and health evaluation were conducted from one party's point of view. In order to have different perspectives on the project, these evaluations should include multiple project parties' views on stakeholder interfaces.
- The proposed MRT-MMI definitions and assessment tools for Track Line, Overhead Contact System, and Station disciplines in Mass Rapid Transit projects were verified on a representative model LRT project. Validation and implementation of this model were not performed on a full-scale project given a lack of project examples due to proprietary and confidentiality considerations. However, it is anticipated that elements of the model will be implemented in practice by the industry partner involved in its development.

3) Threats to external validity:

- The qualitative point system used in Framework-B is developed for the research partners' relatively broad joint portfolio of project types, therefore, a recalibration of the values may be needed for different industry sectors or other categories of projects, such as mega oil and gas projects.

6.4 Recommendations for Future Research

Measurement of interface health and workload between project stakeholders is a new topic in the construction industry. The following recommendations for future research are proposed based on this thesis:

- In this thesis, all interface health and workload criteria are accepted as having equal weights (importance). Future research can investigate the actual importance of each criterion over these calculations and can investigate the sensitivity of the model to criteria weights.

- As explained in the limitations section, the interface health and workload evaluations of the stakeholder connections in the case projects were conducted from one party's point of view. It is recommended to conduct the same analysis from multiple project parties' perspectives.
- Expanding the Integrated Project Monitoring Method to portfolio-level research is a promising research area. It is recommended to explore the applicability of the model in multiple project environments with shared project stakeholders.
- In this thesis, interface health and workload data is collected from six different projects from two different industries. Future research can investigate the potential connections between project types and network topologies by conducting data mining techniques.
- It is recommended to verify the functionality of the engineering progress measurement model on one or more full-scale Mass Rapid Transit Projects, if the projects may provide adequate data.

6.5 Publications

The peer-refereed publications, directly related to the scope of this thesis, and authored by the candidate are listed below:

6.5.1 Peer-refereed journal articles

1. **Eray, E.,** Sanchez, B., Haas, C. (2019) Usage of Interface Management System in Adaptive Reuse of Buildings, *Buildings*, 9(5), 105, DOI: 10.3390/buildings9050105

6.5.2 Journal Articles in Progress

1. **Eray, E**., Haas, C., Rayside, D., An Integrated Approach for Analyzing Interface Workload and Interface Health Between Stakeholders Involved in Complex Construction Projects, to be submitted to Journal of Construction Engineering and Management
2. **Eray, E.**, Haas, C., Rayside, D., Analyzing stakeholder interfaces in a portfolio of engineering projects, to be submitted by Summer 2020
3. **Eray, E.,** Haas, C., Rayside D., Evaluation of interfaces between project stakeholders in a group decision environment, to be submitted by Summer 2020

6.5.3 Peer-refereed conference articles

1. **Eray, E.**, Haas, C., Rayside, D. (2019) A Model for Measuring Interface Health between Project Stakeholders in Complex Construction Projects, 7th CSCE/CRC International Construction Specialty Conference, in Laval, QC, Canada, from June 12th to June 15th, 2019

2. **Eray, E.** Sanchez, B., Kang, S., Haas, C. (2019) Usage of Interface Management in Adaptive Reuse of Buildings, in Advances in Informatics and Computing in Civil and Construction Engineering, Cham: Springer International Publishing, pp. 725–731. [DOI: 10.1007/978-3-030-00220-6_87](https://doi.org/10.1007/978-3-030-00220-6_87)
3. **Eray, E.**, Haas, C., Rayside, D., Golparvar-Fard, M. (2018) A conceptual framework for tracking design completeness of the Track Line discipline in Mass Rapid Transit projects, 35th International Symposium on Automation and Robotics in Construction (ISARC 2018), in Berlin, Germany, from July 20th to July 25th, 2018
4. **Eray, E**., Golzarpoor, B., Rayside, D., Haas, C. (2017) An Overview on Integrating Interface Management and Building Information Management Systems, 6th CSCE/CRC International Construction Specialty Conference, in Vancouver, BC, Canada, from May 31st to June 3rd, 2017

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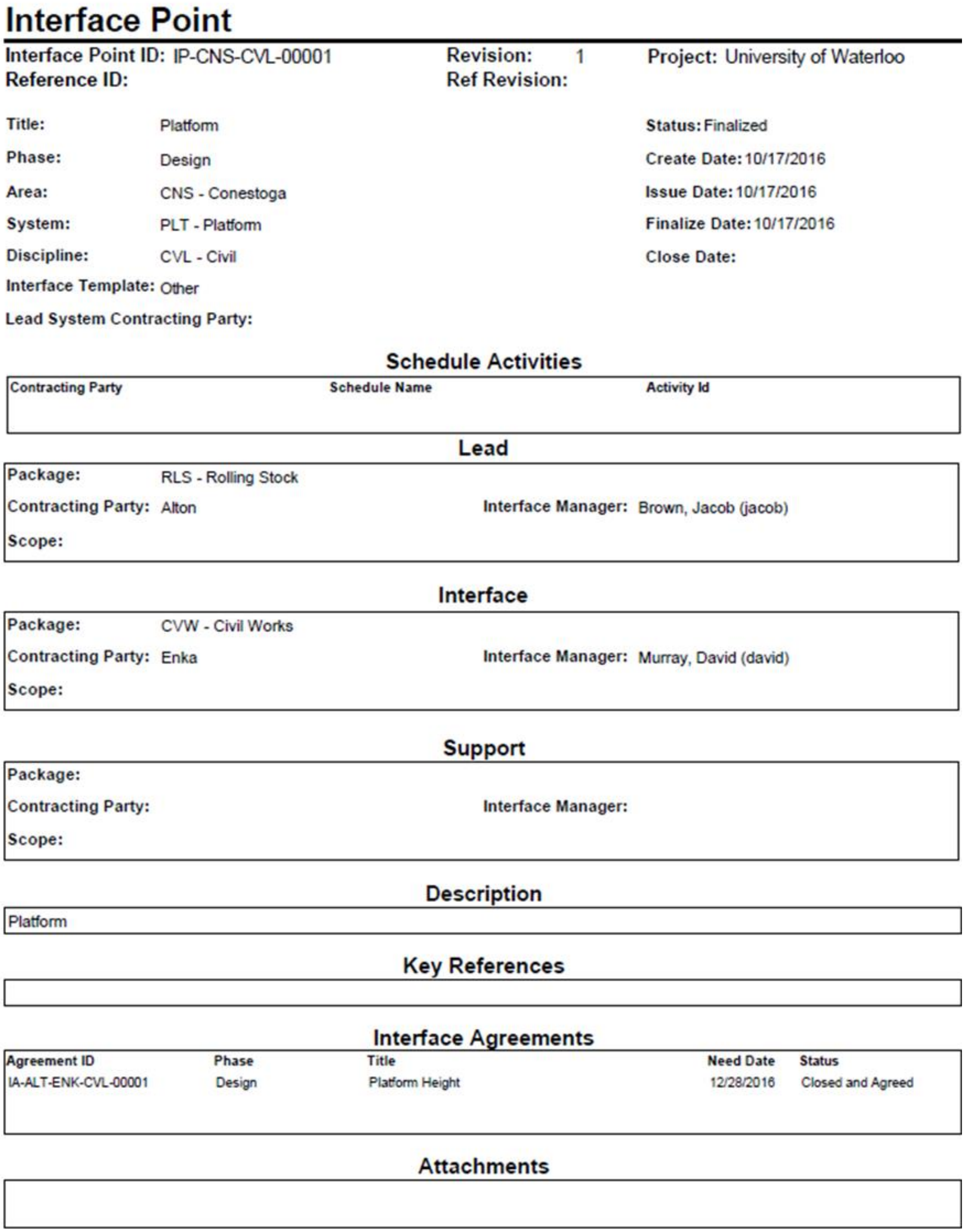
Appendix A

Sample IP and IA Forms



Interface Point

Interface Point ID: IP-CNS-CVL-00001 **Revision:** 1 **Project:** University of Waterloo

Reference ID: **Ref Revision:**

Title: Platform

Phase: Design

Area: CNS - Conestoga

System: PLT - Platform

Discipline: CVL - Civil

Interface Template: Other

Lead System Contracting Party:

Status: Finalized

Create Date: 10/17/2016

Issue Date: 10/17/2016

Finalize Date: 10/17/2016

Close Date:

Schedule Activities

Contracting Party	Schedule Name	Activity Id

Lead

Package: RLS - Rolling Stock

Contracting Party: Alton **Interface Manager:** Brown, Jacob (jacob)

Scope:

Interface

Package: CVW - Civil Works

Contracting Party: Enka **Interface Manager:** Murray, David (david)

Scope:

Support

Package:

Contracting Party: **Interface Manager:**

Scope:

Description

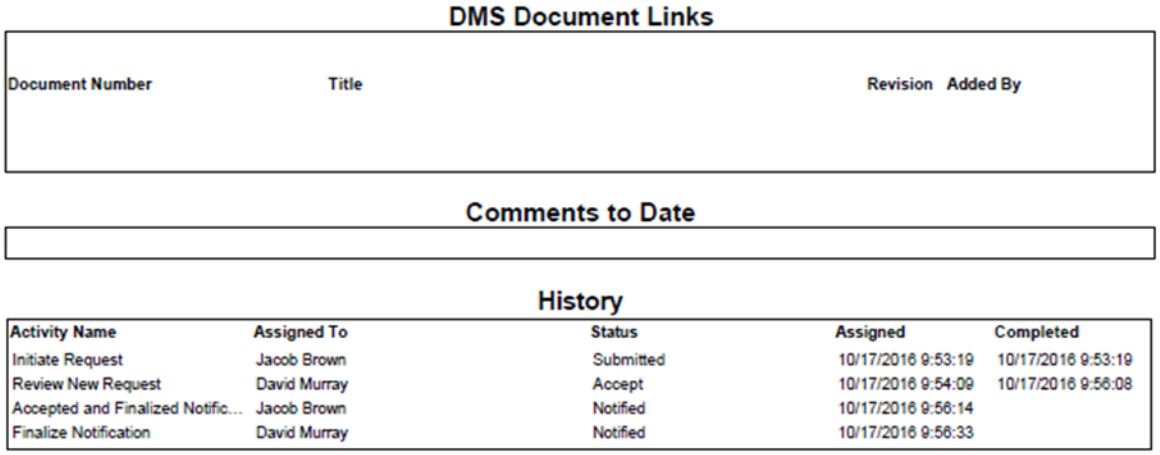
Platform

Key References

Interface Agreements

Agreement ID	Phase	Title	Need Date	Status
IA-ALT-ENK-CVL-00001	Design	Platform Height	12/28/2016	Closed and Agreed

Attachments



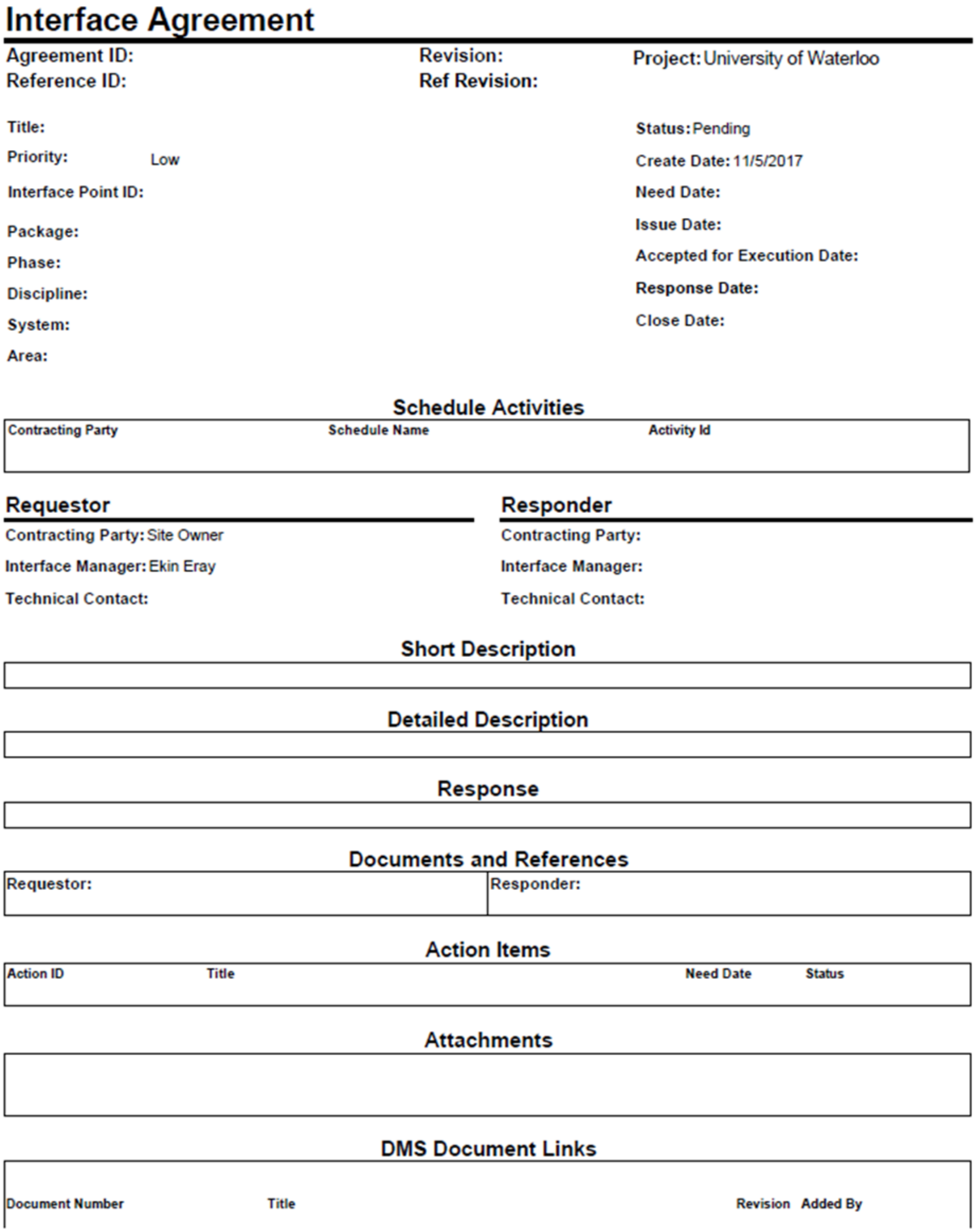
DMS Document Links

Document Number	Title	Revision	Added By

Comments to Date

History

Activity Name	Assigned To	Status	Assigned	Completed
Initiate Request	Jacob Brown	Submitted	10/17/2016 9:53:19	10/17/2016 9:53:19
Review New Request	David Murray	Accept	10/17/2016 9:54:09	10/17/2016 9:56:08
Accepted and Finalized Notific...	Jacob Brown	Notified	10/17/2016 9:56:14	
Finalize Notification	David Murray	Notified	10/17/2016 9:56:33	



Interface Agreement

Agreement ID:
Revision:
Project: University of Waterloo
Reference ID:
Ref Revision:

Title:
Status: Pending
Priority: Low
Create Date: 11/5/2017
Interface Point ID:
Need Date:
Package:
Issue Date:
Phase:
Accepted for Execution Date:
Discipline:
Response Date:
System:
Close Date:
Area:

Schedule Activities

Contracting Party	Schedule Name	Activity Id

Requestor

Contracting Party: Site Owner
Interface Manager: Ekin Eray
Technical Contact:

Responder

Contracting Party:
Interface Manager:
Technical Contact:

Short Description

Detailed Description

Response

Documents and References

Requestor:	**Responder:**

Action Items

Action ID	Title	Need Date	Status

Attachments

DMS Document Links

Document Number	Title	Revision	Added By

Comments to Date

History

Activity Name	Assigned To	Status	Assigned	Completed

Appendix B Rail Line Project

Workload and Health evaluation of each stakeholder connection in Rail Line Project (re-evaluation)

Source	**Target**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	**2**	3	3	2	2	2	2	1	2
1	**3**	3	1	1	1	2	3	2	2
1	**4**	2	1	2	2	2	2	2	2
1	**5**	2	1	2	2	2	2	2	2
1	**6**	2	1	2	2	2	2	2	2
1	**8**	2	1	2	2	2	2	2	2
1	**10**	2	1	2	1	2	2	2	1
1	**15**	1	1	2	2	2	2	1	2
1	**16**	1	1	2	2	2	2	1	1
1	**17**	2	1	1	2	3	3	3	2
1	**18**	1	1	2	2	2	2	1	1
1	**19**	1	1	2	2	1	2	1	1
2	**3**	3	3	2	2	2	2	2	1
2	**4**	2	1	2	2	2	2	2	2
2	**5**	2	1	2	2	2	2	2	2
2	**6**	2	1	2	2	2	2	2	2
2	**8**	2	1	2	2	2	2	2	2
2	**10**	3	3	3	2	2	2	2	1
2	**15**	2	1	2	1	2	2	2	1
2	**16**	1	1	2	2	2	2	1	2
2	**17**	1	1	2	2	2	2	1	1
2	**18**	2	1	1	2	3	3	3	2
2	**19**	1	1	2	2	2	2	1	1
3	**10**	1	1	2	2	1	2	1	1
3	**11**	3	3	3	3	2	3	1	1
3	**12**	3	3	3	2	2	2	1	1
3	**13**	3	3	3	2	2	2	1	1
3	**14**	3	3	3	2	2	2	1	1
3	**15**	3	1	3	2	1	2	1	2
3	**16**	2	1	3	2	1	2	1	2
3	**17**	3	1	3	2	1	2	1	2
3	**18**	3	1	3	2	1	2	1	2
3	**19**	2	1	3	2	1	2	1	2
7	**10**	1	1	3	1	1	1	1	1
7	**17**	1	1	3	1	1	1	3	1
7	**18**	1	1	3	1	1	1	3	1
7	**19**	1	1	3	1	1	1	3	1
8	**10**	1	1	3	1	1	1	3	1

Source	**Target**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
8	**19**	1	1	3	1	1	1	3	1
9	**10**	1	1	3	1	1	1	1	1
9	**18**	1	1	3	1	1	1	3	1
9	**17**	1	1	3	1	1	1	3	1
10	**11**	3	1	3	2	2	2	1	1
10	**12**	2	1	3	2	2	2	1	1
10	**13**	2	1	3	2	2	2	1	1
10	**14**	2	1	3	1	2	2	1	1
10	**15**	3	2	3	3	1	2	1	2
10	**16**	3	2	3	3	1	2	1	2
10	**17**	3	2	3	3	1	2	1	2
10	**18**	3	2	3	3	1	2	1	2
10	**19**	3	2	3	3	1	2	1	2
11	**16**	3	1	3	3	1	3	1	1
12	**15**	3	1	3	2	1	2	2	1
12	**19**	1	1	3	1	1	2	2	1
13	**15**	3	2	2	2	2	2	2	2
15	**16**	3	2	2	2	1	2	1	1
15	**17**	3	2	3	3	1	2	1	1
15	**18**	3	2	2	2	1	2	1	1
15	**19**	3	2	2	1	1	2	2	2
16	**17**	3	3	3	3	1	2	1	2
16	**18**	3	2	2	1	1	2	2	1
16	**19**	3	2	2	2	1	2	2	2
17	**18**	3	2	2	2	1	2	2	1
17	**19**	3	2	2	2	1	2	1	2
18	**19**	3	2	2	1	1	2	1	1

Appendix C

Chemical Equipment Replacement Project Data

Project Stakeholders at the Identification Phase

Nodes			
Node ID	**Label**	**Name**	**Group**
1	A	Project Sponsor	1
2	B	Project and Modifications	1

Evaluation of Stakeholder Connections at the Identification Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	1	1	2	2	2	2	2	1

Project Stakeholders at the Initiation Phase

Nodes			
Node ID	**Label**	**Name**	**Group**
1	A	Project Sponsor	1
2	B	Project and Modifications	1
3	C	Finance	1

Evaluation of Stakeholder Connections at the Initiation Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	2	1	3	1	1	1	1	1
2	3	2-3	2	1	2	2	2	2	2	2

Project Stakeholders at the Development Phase

Nodes			
Node ID	**Label**	**Name**	**Group**
1	A	Project Sponsor	1
2	B	Project and Modifications	1
3	C	Finance	1
4	D	Supply Chain	1
5	E	Operations	1
6	F	maintenance	1
7	G	Performance Engineering	1
8	H	Projects Design Engineering	1
9	I	Procurement Engineering	1

10	N	Contractor	2
11	O	Subcontractor - Design	2
12	P	Subvendor	2

Evaluation of Stakeholder Connections at the Development Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	1	1	2	1	2	1	1	1
1	7	1-7	1	1	3	1	1	1	1	1
1	5	1-5	1	1	3	1	1	1	1	1
2	3	2-3	2	1	3	2	1	2	1	1
2	4	2-4	2	2	2	2	2	2	1	1
2	5	2-5	1	1	2	1	2	1	1	1
2	6	2-6	1	1	2	1	2	1	1	1
2	7	2-7	1	1	2	1	2	1	1	1
2	8	2-8	3	2	2	3	2	2	2	2
2	9	2-9	1	1	2	1	2	1	1	1
2	10	2-10	3	3	2	3	2	2	2	2
2	11	2-11	3	2	2	3	2	2	2	2
2	12	2-12	1	1	2	3	2	2	2	2
4	9	4-9	1	1	3	1	1	1	1	1
4	10	4-10	2	1	2	1	2	2	2	1
5	6	5-6	1	1	3	1	1	1	1	1
5	7	5-7	1	1	3	1	1	1	1	1
6	7	6-7	1	1	3	1	1	1	1	1
7	8	7-8	2	1	2	2	2	2	2	2
8	9	8-9	2	1	2	2	2	2	1	2
8	11	8-11	3	3	2	3	2	2	2	2
10	11	10-11	3	3	2	2	2	1	1	2
10	12	10-12	2	1	3	1	2	1	1	2
11	12	11-12	2	1	3	1	2	1	1	2

Project Stakeholders at the Definition Phase

Nodes			
Node ID	**Label**	**Name**	**Group**
1	A	Project Sponsor	1
2	B	Project and Modifications	1
3	C	Finance	1
4	D	Supply Chain	1
5	E	Operations	1
6	F	maintenance	1
7	G	Performance Engineering	1
8	H	Projects Design Engineering	1
9	I	Procurement Engineering	1

10	N	Contractor	2
11	O	Subcontractor - Design	2
12	P	Subvendor	2
13	M	TSSA-Pressure Boundary	3
14	J	Field Engineering	1
15	K	Contract Management Office	1

Evaluation of Stakeholder Connections at the Definition Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	1	1	2	1	2	1	1	1
1	7	1-7	1	1	3	1	1	1	1	1
1	5	1-5	1	1	3	1	1	1	1	1
2	3	2-3	2	1	3	2	1	2	1	1
2	4	2-4	2	2	2	2	2	2	1	1
2	5	2-5	2	1	2	1	2	1	1	1
2	6	2-6	2	1	2	1	2	1	1	1
2	7	2-7	2	1	2	2	2	1	2	2
2	8	2-8	3	3	2	3	2	3	2	2
2	9	2-9	2	1	2	2	2	1	2	1
2	10	2-10	3	3	2	3	2	3	2	2
2	11	2-11	3	2	2	3	2	3	2	2
2	12	2-12	2	1	2	3	2	3	2	2
2	13	2-13	1	1	3	2	2	2	1	2
2	14	2-14	1	1	3	1	1	1	1	1
2	15	2-15	1	1	3	1	1	1	1	1
4	9	4-9	1	1	2	2	1	2	1	2
4	10	4-10	1	1	2	1	2	2	2	1
5	6	5-6	2	1	3	1	1	1	1	1
5	7	5-7	2	1	3	1	1	1	1	1
6	7	6-7	2	1	3	1	1	1	1	1
7	8	7-8	2	1	2	2	2	2	2	2
8	9	8-9	2	2	2	3	2	2	1	2
8	11	8-11	3	3	2	3	2	3	2	2
10	11	10-11	3	3	2	2	2	1	1	2
10	12	10-12	2	1	3	1	2	1	1	2
10	13	10-13	2	1	3	2	1	2	1	2
10	14	10-14	2	1	2	1	2	1	2	1
10	15	10-15	2	1	2	1	2	1	2	1
11	12	11-12	3	2	2	2	2	2	1	2

Project Stakeholders at the Execution Phase

Node ID	Label	Name	Group
1	A	Project Sponsor	1
2	B	Project and Modifications	1
3	C	Finance	1
4	D	Supply Chain	1
5	E	Operations	1
6	F	maintenance	1
7	G	Performance Engineering	1
8	H	Projects Design Engineering	1
9	I	Procurement Engineering	1
10	N	Contractor	2
11	O	Subcontractor - Design	2
12	P	Subvendor	2
13	M	TSSA-Pressure Boundary	3
14	J	Field Engineering	1
15	K	Contract Management Office	1
17	Q	Subcontractor - Scaffolding Support	2

Evaluation of Stakeholder Connections at the Execution Phase

Links										
			Workload				Health			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	2	1	2	2	2	2	2	1
1	7	1-7	1	1	3	1	1	1	1	1
1	5	1-5	1	1	3	1	1	1	1	1
2	3	2-3	2	1	3	2	1	1	1	1
2	4	2-4	2	2	3	2	1	2	1	1
2	5	2-5	2	1	2	2	2	2	2	2
2	6	2-6	2	1	2	2	2	2	2	2
2	7	2-7	2	1	2	2	2	2	2	2
2	8	2-8	3	2	2	1	2	2	1	1
2	9	2-9	1	1	3	1	2	1	1	1
2	10	2-10	3	3	2	3	2	2	1	2
2	11	2-11	2	2	2	2	2	2	1	2
2	12	2-12	1	1	3	1	1	1	1	1
2	13	2-13	2	1	2	2	2	2	1	2
2	14	2-14	3	2	3	2	1	1	2	2
2	15	2-15	3	2	3	2	1	1	1	1
4	9	4-9	1	1	2	2	1	2	1	2
4	10	4-10	2	1	2	1	2	2	2	1
5	6	5-6	3	2	3	2	1	2	1	2
5	7	5-7	2	1	3	1	1	2	1	1
6	7	6-7	2	1	3	1	1	2	1	1

7	8	7-8	2	1	3	1	1	2	1	1
8	9	8-9	1	1	3	1	1	1	1	1
8	11	8-11	2	1	3	2	1	1	1	2
10	11	10-11	3	3	3	2	2	2	1	2
10	12	10-12	2	1	3	2	1	2	1	1
10	13	10-13	2	2	3	2	1	2	1	2
10	14	10-14	3	3	2	2	2	2	1	2
10	15	10-15	3	3	2	2	2	2	2	1
10	17	10-17	3	3	3	3	1	1	1	1
11	12	11-12	2	1	3	2	1	1	1	1

Project Stakeholders at the Closeout Phase

Node ID	**Label**	**Name**	**Group**
1	A	Project Sponsor	1
2	B	Project and Modifications	1
3	C	Finance	1
4	D	Supply Chain	1
5	E	Operations	1
6	F	Maintenance	1
7	G	Performance Engineering	1
8	H	Projects Design Engineering	1
10	N	Contractor	2
11	O	Subcontractor - Design	2
16	L	Drawing Office	1

Evaluation of Stakeholder Connections at the Closeout Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	2	1	2	2	1	1	1	1
1	7	1-7	1	1	3	1	1	1	1	1
1	5	1-5	1	1	3	1	1	1	1	1
2	3	2-3	2	1	3	2	1	1	1	1
2	4	2-4	2	1	3	2	1	2	1	1
2	5	2-5	2	1	2	2	1	1	1	1
2	6	2-6	2	1	2	2	1	1	1	1
2	7	2-7	2	1	2	2	2	1	1	1
2	8	2-8	2	2	3	2	1	1	1	1
2	10	2-10	2	2	3	2	1	1	1	2
2	11	2-11	2	2	3	2	1	1	1	2
2	16	2-16	2	1	3	2	1	2	1	1
4	10	4-10	2	1	3	1	1	1	1	1
5	6	5-6	1	1	3	1	1	1	1	1
5	7	5-7	1	1	3	1	1	1	1	1

6	7	6-7	1	1	3	1	1	1	1	1
7	8	7-8	1	1	3	2	1	2	1	1
8	16	8-16	2	2	3	2	1	2	1	2
8	11	8-11	2	2	3	2	1	2	1	2
10	11	10-11	2	3	3	2	1	2	1	2

Appendix D

Detector Assemblies Replacement Project Data

Stakeholders' Connection List

Stakeholders		**Interactions with other Stakeholders**						
ID	**Label**	**[0-1]**	**[1-2]**	**[2-3]**	**[3-4]**	**[4-5]**	**[5-6]**	**[6-7]**
1	SRE		2,3	2,3	2,3	2	2	2
2	PRO		1,3	1,3,4,5,7	1,3,4,5,6,7,8,11,12,13,14,15	1,3,4,5,6,7,11,12,13,14,15	1,3,4,5	1
3	DGG		1,2	1,2,4,5,7,8,9,10	1,2,4,5,6,8,9,10,	2,6	2	
4	MNT			2,3	2,3	2,5,13,15	2	
5	OPS			2,3	2,3	2,4,13,15	2	
6	VEN				2,3,7	2,3,7		
7	SC			2,3	2,6	2,6		
8	HF			3	2,3			
9	RS			3	3			
10	SSC			3	3			
11	CS				2	2		
12	RP				2	2,13,15		
13	WC				2	2,4,5,12,15		
14	WA				2	2		
15	OUT				2	2,4,5,12,13		

Project Stakeholders at the Initiation Phase [1-2]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
2	PRO	Projects	1
3	DGG	Design	1

Evaluation of Stakeholder Connections at the Development Phase

			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	1	1	2	1	1	2	1	1
1	3	1-3	1	1	1	1	1	2	1	1
2	3	2-3	1	2	2	1	2	2	1	1

Project Stakeholders at the Development Phase [2-3]

Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
2	PRO	Projects	1

Node ID	Label	Name	Group
3	DGG	Design	1
4	MNT	Maintenance	1
5	OPS	Operations	1
7	SC	Supply Chain	1
8	HF	Human Factors	1
9	RS	Reactor Safety	1
10	SSC	Seismis	1

Evaluation of Stakeholder Connections at the Development Phase

Links										
			Workload				Health			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	1	1	3	1	2	2	2	1
1	3	1-3	2	3	3	1	2	2	1	2
2	3	2-3	3	3	3	1	2	3	1	1
2	4	2-4	1	1	3	1	2	1	1	1
2	5	2-5	1	1	3	1	2	1	1	1
2	7	2-7	2	3	2	1	2	3	1	2
3	4	3-4	1	1	2	1	2	1	1	1
3	5	3-5	1	1	2	1	2	1	1	1
3	7	3-7	1	1	2	1	2	1	1	1
3	8	3-8	1	1	2	1	2	2	2	1
3	9	3-9	1	1	2	1	2	2	1	1
3	10	3-10	1	1	2	1	2	2	1	1

Project Stakeholders at the Definition Phase [3-4]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
2	PRO	Projects	1
3	DGG	Design	1
4	MNT	Maintenance	1
5	OPS	Operations	1
6	VEN	Equipment Cendor (Kinectrics)	2
7	SC	Supply Chain	1
8	HF	Human Factors	1
9	RS	Reactor Safety	1
10	SSC	Seismis	1
11	CS	Conventional Safety	1
12	RP	Radiation Protection	1
13	WC	Work Control	1
14	WA	Work Assessing	1
15	OUT	Outage	1

Evaluation of Stakeholder Connections at the Definition Phase

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	2	1-2	2	1	3	1	1	1	1	1
1	3	1-3	2	1	3	1	2	2	1	1
2	3	2-3	3	3	3	1	2	2	1	2
2	4	2-4	1	1	3	1	1	1	1	1
2	5	2-5	1	1	3	1	1	1	1	1
2	6	2-6	3	3	2	1	2	3	1	2
2	7	2-7	2	1	2	1	2	2	1	1
2	8	2-8	1	1	3	1	2	1	1	1
2	11	2-11	1	1	3	1	1	1	1	1
2	12	2-12	1	1	3	1	1	1	1	1
2	13	2-13	2	1	3	1	1	1	1	1
2	14	2-14	2	1	2	1	2	2	1	1
2	15	2-15	3	2	1	2	2	3	2	2
3	4	3-4	1	1	2	1	2	2	1	1
3	5	3-5	1	1	2	1	1	1	1	1
3	6	3-6	3	3	2	3	2	3	1	2
3	7	3-7	2	1	3	1	1	2	1	1
3	8	3-8	1	1	2	1	2	2	1	1
3	9	3-9	1	1	2	1	1	1	1	1
3	10	3-10	1	1	2	1	2	1	1	1
6	7	6-7	1	1	2	1	2	2	1	1
13	15	13-15	2	1	3	1	1	2	1	1

Project Stakeholders at the Execution Phase [4-5]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
2	PRO	Projects	1
3	DGG	Design	1
4	MNT	Maintenance	1
5	OPS	Operations	1
6	VEN	Equipment Cendor (Kinectrics)	2
7	SC	Supply Chain	1
11	CS	Conventional Safety	1
12	RP	Radiation Protection	1
13	WC	Work Control	1
14	WA	Work Assessing	1
15	OUT	Outage	1

Evaluation of Stakeholder Connections at the Execution Phase

Links										
			Workload				Health			
Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	2	1-2	2	2	3	1	1	1	1	1
2	3	2-3	3	3	2	1	1	1	1	1
2	4	2-4	3	3	3	1	2	2	1	1
2	5	2-5	2	2	3	1	2	2	1	1
2	6	2-6	2	3	3	1	1	1	1	1
2	7	2-7	1	2	2	1	2	2	1	1
2	11	2-11	1	1	3	1	1	1	1	1
2	12	2-12	1	1	3	1	1	1	1	1
2	13	2-13	2	3	2	1	1	1	1	1
2	14	2-14	1	1	3	1	1	1	1	1
2	15	2-15	3	3	2	1	2	2	2	1
3	6	3-6	3	3	3	1	1	1	1	1
4	5	4-5	2	3	3	1	1	1	1	1
4	13	4-13	3	3	2	1	1	1	1	1
4	15	4-15	3	3	2	1	1	1	1	1
5	13	5-13	3	3	2	1	1	1	1	1
5	15	5-15	3	3	2	1	1	1	1	1
6	7	6-7	1	1	3	1	2	1	1	1
12	13	12-13	3	3	2	1	1	1	1	1
12	15	12-15	3	3	2	1	1	1	1	1
13	15	13-15	3	3	2	1	1	1	1	1

Project Stakeholders at the Closeout Phase [5-6]

Nodes			
Node ID	Label	Name	Group
1	SRE	SRE	1
2	PRO	Projects	1
3	DGG	Design	1
4	MNT	Maintenance	1
5	OPS	Operations	1

Evaluation of Stakeholder Connections at the Closeout Phase

Links										
			Workload				Health			
Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	2	1-2	0	0	0	0	0	0	0	0
2	3	2-3	0	0	0	0	0	0	0	0
2	4	2-4	0	0	0	0	0	0	0	0
2	5	2-5	0	0	0	0	0	0	0	0

Project Stakeholders at the PIR Phase [6-7]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
2	PRO	Projects	1

Evaluation of Stakeholder Connections at the PIR Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	0	0	0	0	0	0	0	0

Appendix E

Control Positioners Replacement Project Data

Stakeholders' Connection List

Stakeholders		Interactions with other Stakeholders						
ID	Label	[0-1]	[1-2]	[2-3]	[3-4]	[4-5]	[5-6]	[6-7]
1	ENG	3, 4	2, 3, 4	2, 6	2, 6	2, 6	2, 6	2, 3, 4
2	PM		1	1, 6, 18	1, 3, 4, 6, 8, 9, 11, 13, 15, 17, 18	1, 3, 4, 5, 6, 9, 10, 11, 13, 17, 18	1, 6, 11, 13, 17, 18	1, 6
3	CM	1	1	2, 6	2, 6, 11, 15, 17	2, 5, 6, 9, 11, 13		
4	OPS	1	1	2, 6	2, 6, 11, 15, 17	2, 5, 6, 9, 11, 13		
5	OPSO					2, 3, 4, 13		
6	DES			2, 3, 4, 6, 8, 9	2, 3, 4, 6, 7, 8, 9, 15, 17	2, 17	1, 2, 17	
7	CG				2, 6, 17			
8	CS				2, 11, 13			
9	RP				2, 11, 13	2, 11, 13		
10	WC					2, 11, 13		
11	EPM			18	2, 12, 15, 17	2, 13, 17	2, 12, 13, 17	
12	ECPM				2, 3, 4, 6, 8, 9, 11, 13, 17	2, 3, 4, 5, 6, 9, 10, 11, 13, 17	1, 2, 6, 11, 13, 17	
13	EC				2, 3, 4, 6, 8, 9, 11, 17	2, 3, 4, 5, 6, 9, 10, 11, 17		
14	EDDL				2, 6, 11, 15, 17			
15	EDE							
16	ES				2, 6			
17	EDTL				2, 6, 11, 13, 15	2, 6, 11, 13	2, 6, 11, 13	
18	SC			2, 11	2, 11	2, 11		

Stakeholder List at the Identification Phase [0-1]

Nodes			
Node ID	Label	Name	Group
1	ENG	Engineering	1
3	CM	Control Maintenance	1
4	OPS	Operations (Project SPOC)	1

Evaluation of Stakeholder Connections at the Identification Phase

			Workload				Health			
Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	3	1-3	1	1	1	1	1	1	1	1
1	4	1-4	1	1	1	1	1	1	1	1

Stakeholder List at the Initiation Phase [1-2]

Nodes		
Node ID	**Name**	**Group**
1	Engineering	1
2	Project Manager	1

Evaluation of Stakeholder Connections at the Initiation Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	1	1	1	1	1	1	1	1

Stakeholder List at the Development Phase [2-3]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	ENG	Engineering	1
2	PM	Project Manager	1
3	CM	Control Maintenance	1
4	OPS	Operations (Project SPOC)	1
6	DES	Design	1
8	CS	Conventional Safety	1

Evaluation of Stakeholder Connections at the Development Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	1	1	1	1	1	1	1	1
1	6	1-6	1	1	1	2	1	1	1	1
2	6	2-6	1	1	1	2	1	1	1	1
3	6	3-6	1	1	1	1	1	1	1	1
4	6	4-6	1	1	1	1	1	1	1	1
6	8	6-8	1	1	1	1	1	1	1	1

Stakeholder List at the Definition Phase [3-4]

Node ID	Name	Group
1	Engineering	1
2	Project Manager	1
3	Control Maintenance	1
4	Operations (Project SPOC)	1
6	Design	1
7	Computers Group	1
8	Conventional Safety	1

Node ID	Name	Group
9	Radiation Protection	1
11	EPC PM	2
12	EPC Construction PM	2
13	EPC Coordinator	2
14	EPC Design Discipline Lead	2
15	EPC Design Eng	2
16	EPC Software	2
17	EPC Design Team Lead	2
18	Supply Chain	1

Evaluation of Stakeholder Connections at the Definition Phase

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	2	1-2	2	2	1	1	1	1	2	1
1	6	1-6	2	2	1	1	1	1	1	1
2	3	2-3	1	1	2	1	2	1	1	1
2	4	2-4	1	1	2	1	2	2	2	1
2	6	2-6	3	3	3	3	1	1	1	1
2	7	2-7	1	1	2	1	2	1	1	2
2	8	2-8	1	1	1	1	1	1	1	1
2	9	2-9	1	1	1	1	1	1	1	1
2	11	2-11	3	3	3	2	1	2	2	2
2	12	2-12	2	3	3	2	1	2	2	2
2	13	2-13	2	3	3	2	1	2	2	2
2	14	2-14	1	1	1	1	1	1	1	1
2	16	2-16	1	1	1	1	1	1	1	1
2	17	2-17	2	2	2	3	1	2	2	1
2	18	2-18	1	1	2	1	2	2	1	1
3	6	3-6	2	1	2	2	1	1	1	1
3	12	3-12	1	1	2	1	2	1	2	1
3	13	3-13	1	1	2	1	2	1	2	1
3	15	3-15	1	1	2	1	2	1	2	1
4	6	4-6	2	1	2	3	2	2	2	1
4	12	4-12	1	1	2	2	2	1	1	1
4	13	4-13	1	1	2	2	2	1	1	1
4	15	4-15	1	1	1	1	1	1	2	1
6	7	6-7	1	1	2	1	2	2	2	2
6	8	6-8	1	1	1	1	1	1	1	1
6	9	6-9	1	1	1	1	1	1	1	1
6	12	6-12	2	2	2	3	1	2	1	1
6	13	6-13	2	2	2	3	1	2	1	1
6	14	6-14	1	1	1	2	1	1	1	1
6	15	6-15	3	3	2	3	1	2	2	1
6	16	6-16	1	1	2	1	1	1	1	2
6	17	6-17	3	3	2	3	1	2	2	1

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
8	11	8-11	1	1	1	1	1	1	1	1
8	12	8-12	1	1	1	1	1	1	1	1
8	13	8-13	1	1	1	1	1	1	1	1
9	11	9-11	1	1	1	1	1	1	1	1
9	12	9-12	1	1	1	1	1	1	1	1
9	13	9-13	1	1	1	1	1	1	1	1
11	12	11-12	2	2	2	2	1	2	1	1
11	13	11-13	2	2	2	2	1	2	1	1
11	14	11-14	1	1	1	2	1	1	1	1
11	15	11-15	2	2	2	2	1	1	1	1
11	17	11-17	2	2	2	2	1	1	1	1
11	18	11-18	1	1	2	1	2	2	2	2
12	13	12-13	3	3	3	3	1	1	1	1
12	17	12-17	2	1	1	1	1	1	1	1
13	17	13-17	1	1	1	2	1	1	1	1
14	15	14-15	2	3	3	1	1	1	1	1
14	17	14-17	2	3	3	1	1	1	1	1
15	17	15-17	2	3	3	1	1	1	1	1

Stakeholder List at the Execution Phase [4-5]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	ENG	Engineering	1
2	PM	Project Manager	1
3	CM	Control Maintenance	1
4	OPS	Operations (Project SPOC)	1
5	OPSO	Operations (Authorized Operator)	1
6	DES	Design	1
9	RP	Radiation Protection	1
10	WC	Work Control	1
11	EPM	EPC PM	2
12	ECPM	EPC Construction PM	2
13	EC	EPC Coordinator	2
17	EDTL	EPC Design Team Lead	2
18	SC	Supply Chain	1

Evaluation of Stakeholder Connections at the Execution Phase

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	2	1-2	2	1	2	1	0	0	0	0
1	6	1-6	1	2	2	1	0	0	0	0
2	3	2-3	2	3	3	2	0	0	0	0
2	4	2-4	2	3	3	2	0	0	0	0
2	5	2-5	2	3	3	2	0	0	0	0

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
2	6	2-6	2	2	2	2	0	0	0	0
2	10	2-10	3	3	3	2	0	0	0	0
2	11	2-11	3	3	3	2	0	0	0	0
2	12	2-12	3	3	3	2	0	0	0	0
2	13	2-13	3	3	3	2	0	0	0	0
2	17	2-17	2	1	2	1	0	0	0	0
2	18	2-18	1	1	1	1	0	0	0	0
3	5	3-5	1	1	1	1	0	0	0	0
3	6	3-6	1	1	1	1	0	0	0	0
3	9	3-9	2	3	1	1	0	0	0	0
3	11	3-11	1	1	1	1	0	0	0	0
3	12	3-12	2	2	1	1	0	0	0	0
3	13	3-13	2	2	1	1	0	0	0	0
4	5	4-5	2	3	1	1	0	0	0	0
4	6	4-6	2	2	2	1	0	0	0	0
4	11	4-11	1	1	1	1	0	0	0	0
4	12	4-12	2	3	2	2	0	0	0	0
4	13	4-13	2	3	2	2	0	0	0	0
5	12	5-12	2	3	2	2	0	0	0	0
5	13	5-13	2	3	2	2	0	0	0	0
6	12	6-12	2	2	2	1	0	0	0	0
6	13	6-13	2	2	2	1	0	0	0	0
6	17	6-17	2	2	2	2	0	0	0	0
9	12	9-12	1	2	1	1	0	0	0	0
9	13	9-13	1	2	1	1	0	0	0	0
10	11	10-11	3	3	2	2	0	0	0	0
10	12	10-12	3	3	2	2	0	0	0	0
10	13	10-13	3	3	2	2	0	0	0	0
11	12	11-12	3	3	3	2	0	0	0	0
11	13	11-13	3	3	3	2	0	0	0	0
11	17	11-17	2	3	1	1	0	0	0	0
11	18	11-18	1	1	1	1	0	0	0	0
12	13	12-13	3	3	3	3	0	0	0	0
12	17	12-17	2	3	3	2	0	0	0	0
13	17	13-17	2	3	3	2	0	0	0	0

Stakeholder List at the Closeout Phase [5-6]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	ENG	Engineering	1
2	PM	Project Manager	1
6	DES	Design	1
11	EPM	EPC PM	2
12	ECPM	EPC Construction PM	2

13	EC	EPC Coordinatior	2
17	EDTL	EPC Design Team Lead	2

Evaluation of Stakeholder Connections at the Closeout Phase

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	2	1-2	2	2	2	2	0	0	0	0
1	6	1-6	2	2	2	3	0	0	0	0
1	12	1-12	2	2	2	2	0	0	0	0
2	6	2-6	2	2	2	3	0	0	0	0
2	11	2-11	1	2	2	1	0	0	0	0
2	12	2-12	2	2	2	2	0	0	0	0
2	13	2-13	2	2	2	2	0	0	0	0
2	17	2-17	2	2	2	2	0	0	0	0
6	12	6-12	2	2	2	2	0	0	0	0
6	17	6-17	2	2	2	2	0	0	0	0
11	12	11-12	3	3	3	1	0	0	0	0
11	13	11-13	3	3	3	1	0	0	0	0
11	17	11-17	3	3	3	1	0	0	0	0
12	13	12-13	3	3	2	1	0	0	0	0
12	17	12-17	2	2	1	2	0	0	0	0
13	17	13-17	2	2	1	2	0	0	0	0

Stakeholder List at the PIR Phase [6-7]

Nodes			
Node ID	Label	Name	Group
1	ENG	Engineering	1
2	PM	Project Manager	1
3	CM	Control Maintenance	1
4	OPS	Operations (Project SPOC)	1
6	DES	Design	1

Evaluation of Stakeholder Connections at the PIR Phase

Links										
			Workload				Health			
Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	2	1-2	1	1	2	1	0	0	0	0
1	3	1-3	1	1	2	1	0	0	0	0
1	4	1-4	1	1	2	1	0	0	0	0
2	6	2-6	1	1	2	1	0	0	0	0

Dynamic Workload and Health values of Stakeholder connections in Control Positioners Replacement Project

Source	Target	Weight Dynamic	Health Dynamic
1	3	[0,1,4.0];[6,7,5.0]	[0,1,4.0];[6,7,0.0]
1	4	[0,1,4.0];[6,7,5.0]	[0,1,4.0];[6,7,0.0]
1	2	[1,2,4.0];[2,3,4];[3,4,6];[4,5,6];[5,6,8];[6,7,5.0]	[1,2,4.0];[2,3,4];[3,4,5];[4,5,0];[5,6,0];[6,7,0.0]
1	6	[2,3,5];[3,4,6];[4,5,6];[5,6,9]	[2,3,4];[3,4,4];[4,5,0];[5,6,0]
2	6	[2,3,5];[3,4,12];[4,5,8];[5,6,9];[6,7,5.0]	[2,3,4];[3,4,4];[4,5,0];[5,6,0];[6,7,0.0]
3	6	[2,3,4];[3,4,7];[4,5,4]	[2,3,4];[3,4,4];[4,5,0]
4	6	[2,3,4];[3,4,8];[4,5,7]	[2,3,4];[3,4,7];[4,5,0]
6	8	[2,3,4];[3,4,4]	[2,3,4];[3,4,4]
2	3	[3,4,5];[4,5,10]	[3,4,5];[4,5,0]
2	4	[3,4,5];[4,5,10]	[3,4,7];[4,5,0]
2	7	[3,4,5]	[3,4,6]
2	8	[3,4,4]	[3,4,4]
2	9	[3,4,4]	[3,4,4]
2	11	[3,4,11];[4,5,11];[5,6,6]	[3,4,7];[4,5,0];[5,6,0]
2	12	[3,4,10];[4,5,11];[5,6,8]	[3,4,7];[4,5,0];[5,6,0]
2	13	[3,4,10];[4,5,11];[5,6,8]	[3,4,7];[4,5,0];[5,6,0]
2	14	[3,4,4]	[3,4,4]
2	16	[3,4,4]	[3,4,4]
2	17	[3,4,9];[4,5,6];[5,6,8]	[3,4,6];[4,5,0];[5,6,0]
2	18	[3,4,5];[4,5,4]	[3,4,6];[4,5,0]
3	12	[3,4,5];[4,5,6]	[3,4,6];[4,5,0]
3	13	[3,4,5];[4,5,6]	[3,4,6];[4,5,0]
3	15	[3,4,5]	[3,4,6]
4	12	[3,4,6];[4,5,9]	[3,4,5];[4,5,0]
4	13	[3,4,6];[4,5,9]	[3,4,5];[4,5,0]
4	15	[3,4,4]	[3,4,5]
6	7	[3,4,5]	[3,4,8]
6	9	[3,4,4]	[3,4,4]
6	12	[3,4,9];[4,5,7];[5,6,8]	[3,4,5];[4,5,0];[5,6,0]
6	13	[3,4,9];[4,5,7]	[3,4,5];[4,5,0]
6	14	[3,4,5]	[3,4,4]
6	15	[3,4,11]	[3,4,6]
6	16	[3,4,5]	[3,4,5]
6	17	[3,4,11];[4,5,8];[5,6,8]	[3,4,6];[4,5,0];[5,6,0]
8	11	[3,4,4]	[3,4,4]
8	12	[3,4,4]	[3,4,4]
8	13	[3,4,4]	[3,4,4]
9	11	[3,4,4]	[3,4,4]
9	12	[3,4,4];[4,5,5]	[3,4,4];[4,5,0]
9	13	[3,4,4];[4,5,5]	[3,4,4];[4,5,0]
11	12	[3,4,8];[4,5,11];[5,6,10]	[3,4,5];[4,5,0];[5,6,0]
11	13	[3,4,8];[4,5,11];[5,6,10]	[3,4,5];[4,5,0];[5,6,0]

Source	Target	Weight Dynamic	Health Dynamic
11	14	[3,4,5]	[3,4,4]
11	15	[3,4,8]	[3,4,4]
11	17	[3,4,8];[4,5,7];[5,6,10]	[3,4,4];[4,5,0];[5,6,0]
11	18	[3,4,5];[4,5,4]	[3,4,8];[4,5,0]
12	13	[3,4,12];[4,5,12];[5,6,9]	[3,4,4];[4,5,0];[5,6,0]
12	17	[3,4,5];[4,5,10];[5,6,7]	[3,4,4];[4,5,0];[5,6,0]
13	17	[3,4,5];[4,5,10];[5,6,7]	[3,4,4];[4,5,0];[5,6,0]
14	15	[3,4,9]	[3,4,4]
14	17	[3,4,9]	[3,4,4]
15	17	[3,4,9]	[3,4,4]
2	5	[4,5,10]	[4,5,0]
2	10	[4,5,11]	[4,5,0]
3	5	[4,5,4]	[4,5,0]
3	9	[4,5,7]	[4,5,0]
3	11	[4,5,4]	[4,5,0]
4	5	[4,5,7]	[4,5,0]
4	11	[4,5,4]	[4,5,0]
5	12	[4,5,9]	[4,5,0]
5	13	[4,5,9]	[4,5,0]
10	11	[4,5,10]	[4,5,0]
10	12	[4,5,10]	[4,5,0]
10	13	[4,5,10]	[4,5,0]
1	12	[5,6,8]	[5,6,0]

Appendix F

ACU-1 Project Data

Stakeholders' Connection List

Stakeholders		Interactions with other Stakeholders						
ID	**Label**	**[0-1]**	**[1-2]**	**[2-3]**	**[3-4]**	**[4-5]**	**[5-6]**	**[6-7]**
1	ENG	3, 4	2, 3, 4	2, 6	2, 6	2, 6	2, 6	2, 3, 4
2	PM		1	1, 6, 18	1, 3, 4, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 18	1, 3, 4, 5, 6, 9, 10, 11, 12, 13, 17, 18	1, 6, 11, 12, 17, 18	1, 6
3	CM		1	2, 6	2, 6, 11,12,13, 14, 15, 16, 17	2, 5, 6, 9, 11, 12, 13		
4	OPS		1	2, 6	2, 6, 11,12, 13, 14, 15, 16, 17	2, 5, 6, 9, 11, 12, 13		
5	OPSO					2, 3, 4, 12, 13		
6	DES			2, 3, 4, 6, 8, 9	1,2, 3, 4, 6, 7, 8, 9,11,12,13 14, 15, 16, 17	1,2,3,4,12,13, 17	1, 2, 17	
7	CS				2, 6, 16, 17			
8	RP				2,6 11, 12, 13			
9	WC				2,6, 11, 12, 13	2, 3,4, 11, 12, 13		
10	ECPM					2, 11, 12, 13		
11	ECC			18	2, 3, 4,6, 8,9, 12, 13, 14, 15, 16, 17,18	2, 3, 4,9,10, 12, 13, 17,18	2, 12, 13, 17	
12	EDTL				2, 3, 4, 6, 8, 9, 11, 13, 17	2, 3, 4, 5, 6, 9, 10, 11, 13, 17	1, 2, 6, 11, 13, 17	
13	SC				2, 3, 4, 6, 8, 9, 11, 12, 17	2, 3, 4, 5, 6, 9, 10, 11, 12, 17		
14	ENG				2,3, 4, 6, 11, 15, 16, 17			
15	PM				3,4,11,17			
16	CM				2,3,4, 6, 7,11, 14,17			
17	OPS				2,3,4, 6, 7, 11, 12, 13, 14, 15, 16	2, 6, 11, 12, 13	2, 6, 11, 12, 13	
18	OPSO			2, 11	2, 11	2, 11		

Stakeholder List at the Identification Phase [0-1]

Node ID	Label	Name	Group
1	ENG	Engineering	1
3	CM	Control Maintenance	1
4	OPS	Operations (Project SPOC)	1

Evaluation of Stakeholder Connections at the Identification Phase

			Workload				Health			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	3	1-3	1	1	1	1	1	1	1	1
1	4	1-4	1	1	1	1	1	1	1	1

Stakeholder List at the Initiation Phase [1-2]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	ENG	Engineering	1
2	PM	Project Manager	1

Evaluation of Stakeholder Connections at the Initiation Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	1	1	1	1	1	1	1	1

Stakeholder List at the Development Phase [2-3]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	ENG	Engineering	1
2	PM	Project Manager	1
3	CM	Control Maintenance	1
4	OPS	Operations (Project SPOC)	1
6	DES	Design	1
8	CS	Conventional Safety	1

Evaluation of Stakeholder Connections at the Development Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	1	1	1	1	1	1	1	1
1	6	1-6	1	1	1	2	1	1	1	1
2	6	2-6	1	1	1	2	1	1	1	1
3	6	3-6	1	1	1	1	1	1	1	1
4	6	4-6	1	1	1	1	1	1	1	1
6	8	6-8	1	1	1	1	1	1	1	1

Stakeholder List at the Definition Phase [3-4]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	ENG	Engineering	1
2	PM	Project Manager	1
3	CM	Control Maintenance	1
4	OPS	Operations (Project SPOC)	1
6	DES	Design	1
8	CS	Conventional Safety	1
9	RP	Radiation Protection	1
12	ECPM	EPC Construction PM	2
13	ECC	EPC Construction Coordinator	2
17	EDTL	EPC Design Team Lead	2
18	SC	Supply Chain	1

Evaluation of Stakeholder Connections at the Definition Phase

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	2	1-2	1	2	2	1	1	1	1	1
1	6	1-6	3	3	3	3	1	2	1	1
2	3	2-3	1	1	2	1	1	2	2	1
2	4	2-4	1	1	2	1	1	2	2	1
2	6	2-6	2	3	2	3	1	1	1	1
2	8	2-8	1	1	1	1	1	1	1	1
2	9	2-9	1	1	1	1	1	1	1	1
2	12	2-12	2	2	2	2	1	2	2	1
2	13	2-13	2	2	2	2	1	2	2	1
2	17	2-17	1	1	2	2	1	1	1	1
2	18	2-18	1	1	2	1	1	2	1	1
3	6	3-6	1	1	2	1	1	2	2	1
3	12	3-12	1	1	1	1	1	2	2	1
3	13	3-13	1	1	1	1	1	2	2	1
3	17	3-17	1	1	1	1	1	2	2	1
4	6	4-6	1	2	2	2	1	2	2	1
4	12	4-12	1	2	2	2	2	2	2	1
4	13	4-13	1	2	2	2	2	2	2	1
4	17	4-17	1	2	2	3	1	2	2	2
6	8	6-8	1	1	1	1	1	1	1	1
6	9	6-9	1	1	1	1	1	1	1	1
6	12	6-12	2	2	2	3	1	2	1	1
6	13	6-13	2	2	2	3	1	2	1	1
6	17	6-17	3	3	2	3	1	2	2	1
8	12	8-12	1	1	1	1	1	1	1	1

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
8	13	8-13	1	1	1	1	1	1	1	1
9	12	9-12	1	1	1	1	1	1	1	1
9	13	9-13	1	1	1	1	1	1	1	1
12	13	12-13	3	3	3	3	1	1	1	1
12	17	12-17	2	1	1	1	1	1	1	1
13	17	13-17	1	1	1	1	1	1	1	1

Stakeholder List at the Execution Phase [4-5]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	ENG	Engineering	1
2	PM	Project Manager	1
3	CM	Control Maintenance	1
4	OPS	Operations (Project SPOC)	1
5	OPSO	Operations (Authorized Operator)	1
6	DES	Design	1
9	RP	Radiation Protection	1
10	WC	Work Control	1
12	ECPM	EPC Construction PM	2
13	ECC	EPC Construction Coordinator	2
17	EDTL	EPC Design Team Lead	2
18	SC	Supply Chain	1

Evaluation of Stakeholder Connections at the Execution Phase

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	2	1-2	2	1	2	1	1	1	1	1
1	6	1-6	1	2	2	1	1	1	1	1
2	3	2-3	2	3	3	2	2	1	2	1
2	4	2-4	2	3	3	2	2	2	2	1
2	5	2-5	2	3	3	2	2	2	2	1
2	6	2-6	2	2	2	2	2	1	1	1
2	10	2-10	3	3	3	2	1	1	2	1
2	12	2-12	3	3	3	2	1	1	1	1
2	13	2-13	3	3	3	2	1	1	1	1
2	17	2-17	2	1	2	1	1	1	1	1
3	5	3-5	1	1	1	1	2	3	2	2
3	6	3-6	1	2	1	2	1	2	2	1
3	9	3-9	2	3	1	1	1	2	1	1
3	12	3-12	2	2	1	1	2	2	2	1
3	13	3-13	2	2	1	1	2	2	2	1
4	5	4-5	2	3	1	1	1	2	2	2

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
4	6	4-6	2	2	2	1	2	2	2	1
4	12	4-12	2	3	2	2	2	2	2	2
4	13	4-13	2	3	2	2	2	2	2	2
5	12	5-12	2	3	2	2	2	2	2	2
5	13	5-13	2	3	2	2	2	2	2	2
6	12	6-12	2	2	2	1	1	1	1	1
6	13	6-13	2	2	2	1	1	1	1	1
6	17	6-17	2	2	2	2	1	1	1	1
9	12	9-12	1	2	1	1	1	2	1	1
9	13	9-13	1	2	1	1	1	2	1	1
10	12	10-12	3	3	2	2	1	1	1	1
10	13	10-13	3	3	2	2	1	1	1	1
12	13	12-13	3	3	3	3	1	1	1	1
12	17	12-17	2	3	3	2	1	1	1	1
13	17	13-17	2	3	3	2	1	1	1	1

Stakeholder List at the Closeout Phase [5-6]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	ENG	Engineering	1
2	PM	Project Manager	1
6	DES	Design	1
12	ECPM	EPC Construction PM	2
13	ECC	EPC Construction Coordinator	2
17	EDTL	EPC Design Team Lead	2

Evaluation of Stakeholder Connections at the Closeout Phase

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	2	1-2	2	2	2	2	0	0	0	0
1	6	1-6	2	2	2	3	0	0	0	0
1	12	1-12	2	2	2	2	0	0	0	0
2	6	2-6	2	2	2	3	0	0	0	0
2	12	2-12	2	2	2	2	0	0	0	0
2	13	2-13	2	2	2	2	0	0	0	0
2	17	2-17	2	2	2	2	0	0	0	0
6	12	6-12	2	2	2	2	0	0	0	0
6	17	6-17	2	2	2	2	0	0	0	0
12	13	12-13	3	3	2	1	0	0	0	0
12	17	12-17	2	2	1	2	0	0	0	0
13	17	13-17	2	2	1	2	0	0	0	0

Stakeholder List at the PIR Phase [6-7]

Nodes			
Node ID	**Label**	**Name**	**Group**
1	ENG	Engineering	1
2	PM	Project Manager	1
3	DES	Control Maintenance	1
4	OPS	Operations (Project SPOC)	1
6	DES	Design	1

Evaluation of Stakeholder Connections at the PIR Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	2	1-2	1	1	2	1	0	0	0	0
1	3	1-3	1	1	2	1	0	0	0	0
1	4	1-4	1	1	2	1	0	0	0	0
2	6	2-6	1	1	2	1	0	0	0	0

Dynamic Workload and Health values of Power ACU Project

Source	Target	Weight Dynamic	Health Dynamic
1	3	[0,1,4.0];[6,7,5.0]	[0,1,4.0];[6,7,0.0]
1	4	[0,1,4.0];[6,7,5.0]	[0,1,4.0];[6,7,0.0]
1	2	[1,2,4.0];[2,3,4];[3,4,6.0];[4,5,6];[5,6,8];[6,7,5.0]	[1,2,4.0];[2,3,4];[3,4,4.0];[4,5,4];[5,6,0];[6,7,0.0]
1	6	[2,3,5];[3,4,12.0];[4,5,6];[5,6,9]	[2,3,4];[3,4,4.0];[4,5,4];[5,6,0]
2	6	[2,3,5];[3,4,10.0];[4,5,8];[5,6,9];[6,7,5.0]	[2,3,4];[3,4,4.0];[4,5,5];[5,6,0];[6,7,0.0]
3	6	[2,3,4];[3,4,5.0];[4,5,6]	[2,3,4];[3,4,6.0];[4,5,6]
4	6	[2,3,4];[3,4,7.0];[4,5,7]	[2,3,4];[3,4,6.0];[4,5,7]
6	8	[2,3,4];[3,4,4.0]	[2,3,4];[3,4,4.0]
2	3	[3,4,5.0];[4,5,10]	[3,4,6.0];[4,5,6]
2	4	[3,4,5.0];[4,5,10]	[3,4,6.0];[4,5,7]
2	8	[3,4,4.0]	[3,4,4.0]
2	9	[3,4,4.0]	[3,4,4.0]
2	12	[3,4,8.0];[4,5,11];[5,6,8]	[3,4,6.0];[4,5,4];[5,6,0]
2	13	[3,4,8.0];[4,5,11];[5,6,8]	[3,4,6.0];[4,5,4];[5,6,0]
2	17	[3,4,6.0];[4,5,6];[5,6,8]	[3,4,4.0];[4,5,4];[5,6,0]
2	18	[3,4,5.0]	[3,4,5.0]
3	12	[3,4,4.0];[4,5,6]	[3,4,6.0];[4,5,7]
3	13	[3,4,4.0];[4,5,6]	[3,4,6.0];[4,5,7]
3	17	[3,4,4.0]	[3,4,6.0]
4	12	[3,4,7.0];[4,5,9]	[3,4,7.0];[4,5,8]
4	13	[3,4,7.0];[4,5,9]	[3,4,7.0];[4,5,8]

Source	Target	Weight Dynamic	Health Dynamic
4	17	[3,4,8.0]	[3,4,7.0]
6	9	[3,4,4.0]	[3,4,4.0]
6	12	[3,4,9.0];[4,5,7];[5,6,8]	[3,4,5.0];[4,5,4];[5,6,0]
6	13	[3,4,9.0];[4,5,7]	[3,4,5.0];[4,5,4]
6	17	[3,4,11.0];[4,5,8];[5,6,8]	[3,4,6.0];[4,5,4];[5,6,0]
8	12	[3,4,4.0]	[3,4,4.0]
8	13	[3,4,4.0]	[3,4,4.0]
9	12	[3,4,4.0];[4,5,5]	[3,4,4.0];[4,5,5]
9	13	[3,4,4.0];[4,5,5]	[3,4,4.0];[4,5,5]
12	13	[3,4,12.0];[4,5,12];[5,6,9]	[3,4,4.0];[4,5,4];[5,6,0]
12	17	[3,4,5.0];[4,5,10];[5,6,7]	[3,4,4.0];[4,5,4];[5,6,0]
13	17	[3,4,4.0];[4,5,10];[5,6,7]	[3,4,4.0];[4,5,4];[5,6,0]
2	5	[4,5,10]	[4,5,7]
2	10	[4,5,11]	[4,5,5]
3	5	[4,5,4]	[4,5,9]
3	9	[4,5,7]	[4,5,5]
4	5	[4,5,7]	[4,5,7]
5	12	[4,5,9]	[4,5,8]
5	13	[4,5,9]	[4,5,8]
10	12	[4,5,10]	[4,5,4]
10	13	[4,5,10]	[4,5,4]
1	12	[5,6,8]	[5,6,0]

Appendix G

ACU-2 Project Data

Project Stakeholders at the Identification Phase

Nodes			
Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
3	DRE	Director Engineering	1
7	OPS	Operations	1
8	MTN	Maintenance	1

Evaluation of Stakeholder Connections at the Identification Phase

Links										
			Workload				Health			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	3	1-3	3	3	2	1	1	1	1	1
1	7	1-7	3	3	1	1	1	1	1	1
1	8	1-8	3	3	1	1	1	1	1	1
3	7	3-7	1	3	1	1	1	1	1	1
3	8	3-8	1	1	1	1	1	1	1	1
7	8	7-8	1	1	1	1	1	1	1	1

Project Stakeholders at the Initiation Phase

Nodes			
Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
3	DRE	Director Engineering	1
23	PRO	Projects	1
32	FNC	Finance	1

Evaluation of Stakeholder Connections at the Initiation Phase

Links										
			Workload				Health			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	3	1-3	1	1	1	1	1	2	1	1
1	23	1-23	3	3	1	2	2	2	1	1
3	23	3-23	1	1	1	1	1	1	1	1
3	32	3-32	1	1	1	1	1	1	1	1
23	32	23-32	3	3	3	3	1	1	1	1

Project Stakeholders at the Development Phase

Nodes			
Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
3	DRE	Director Engineering	1
7	OPS	Operations	1
8	MNT	Maintenance	1
11	RE	Radiation Protection	1
12	CS	Conventional Safety	1
13	CE	Chemistry and Environment	1
14	FE	Field Engineering	1
23	PRO	Projects	1
24	DSG	Design	1
28	CMO	Contract Management Office	1
32	FNC	Finance	1
33	SC	Supply Chain	1
36	BM	Contractor	2
46	RCPL	Subcontractor	3

Evaluation of Stakeholder Connections at the Development Phase

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	3	1-3	1	1	1	1	1	1	1	1
1	7	1-7	1	1	3	1	2	2	2	1
1	8	1-8	1	1	1	1	2	2	2	1
1	11	1-11	1	1	1	1	1	1	1	1
1	12	1-12	1	1	1	1	1	1	1	1
1	13	1-13	1	1	1	1	1	1	1	1
1	14	1-14	1	1	1	1	1	1	1	1
1	23	1-23	3	3	3	2	1	2	1	1
1	24	1-24	3	3	3	2	1	1	1	1
1	28	1-28	1	1	1	1	1	1	1	1
3	7	3-7	1	1	1	1	1	1	1	1
3	8	3-8	1	1	1	1	1	1	1	1
3	11	3-11	1	1	1	1	1	1	1	1
3	12	3-12	1	1	1	1	1	1	1	1
3	13	3-13	1	1	1	1	1	1	1	1
3	14	3-14	1	1	1	1	1	1	1	1
3	23	3-23	1	1	1	1	1	1	1	1
3	24	3-24	1	1	1	1	1	1	1	1
3	28	3-28	1	1	1	1	1	1	1	1
3	32	3-32	1	1	1	1	1	1	1	1
3	33	3-33	1	1	1	1	1	1	1	1
3	36	3-36	1	1	1	1	1	1	1	1
3	46	3-46	1	1	1	1	1	1	1	1
7	8	7-8	2	2	1	1	1	2	1	1

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
7	11	7-11	1	1	1	1	1	1	1	1
7	13	7-13	1	1	1	1	1	1	1	1
7	23	7-23	1	2	1	1	1	1	1	1
7	24	7-24	1	2	1	1	1	1	1	1
8	23	8-23	3	3	2	2	1	1	1	1
8	24	8-24	1	1	1	1	1	1	1	1
11	12	11-12	1	1	1	1	1	1	1	1
11	23	11-23	1	1	1	1	1	1	1	1
12	23	12-23	1	1	1	1	1	1	1	1
12	24	12-24	1	1	1	1	1	1	1	1
13	23	13-23	1	1	1	1	1	1	1	1
13	24	13-24	1	1	1	1	1	1	1	1
14	23	14-23	1	1	1	1	1	1	1	1
23	24	23-24	3	3	2	3	1	1	1	1
23	28	23-28	1	1	1	1	1	1	1	1
23	32	23-32	2	1	2	2	1	1	1	1
23	33	23-33	3	3	3	2	3	2	1	1
32	33	32-33	1	1	1	1	1	1	1	1

Project Stakeholders at the Definition Phase

Nodes			
Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
5	HFE	Human Factors Engineering	1
7	OPS	Operations	1
8	MNT	Maintenance	1
11	RE	Radiation Protection	1
12	CS	Conventional Safety	1
13	CE	Chemistry and Environment	1
14	FE	Field Engineering	1
15	ERO	Emergency Response Organization	1
23	PRO	Projects	1
24	DSG	Design	1
28	CMO	Contract Management Office	1
30	WC	Work Control	1
31	WA	Work Assessing	1
32	FNC	Finance	1
33	SC	Supply Chain	1
35	QLT	Quality	1
36	BM	Contractor	2
46	RCPL	Subcontractor	3

Evaluation of Stakeholder Connections at the Definition Phase

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	5	1-5	1	1	1	1	1	1	1	1
1	7	1-7	3	3	2	1	2	2	1	1
1	8	1-8	3	3	2	1	2	2	2	2
1	11	1-11	1	1	1	1	1	1	1	1
1	12	1-12	1	1	1	1	1	1	1	1
1	13	1-13	1	1	1	1	1	1	1	1
1	14	1-14	1	1	1	1	1	1	1	1
1	23	1-23	3	3	3	3	2	3	2	3
1	24	1-24	3	3	3	3	1	2	1	3
5	24	5-24	1	1	1	1	1	1	1	1
5	36	5-36	1	1	1	1	1	1	1	1
7	8	7-8	3	3	3	3	3	3	3	1
7	11	7-11	1	1	1	1	1	1	1	1
7	13	7-13	1	1	1	1	1	1	1	1
7	23	7-23	2	2	2	2	2	2	2	1
7	24	7-24	2	2	2	2	2	2	2	1
7	36	7-36	1	1	1	1	1	1	1	1
8	11	8-11	1	1	1	1	1	1	1	1
8	13	8-13	1	1	1	1	1	1	1	1
8	23	8-23	2	2	2	2	2	2	2	1
8	24	8-24	2	2	2	2	2	2	2	1
8	36	8-36	1	1	1	1	1	1	1	1
8	46	8-46	1	1	1	1	1	1	1	1
11	23	11-23	1	1	1	1	1	1	1	1
11	36	11-36	1	1	1	1	1	1	1	1
12	23	12-23	1	1	1	1	1	1	1	1
12	24	12-24	1	1	1	1	1	1	1	1
12	28	12-28	1	1	1	1	1	1	1	1
12	36	12-36	1	1	1	1	1	1	1	1
12	46	12-46	1	1	1	1	1	1	1	1
13	23	13-23	1	1	1	1	1	1	1	1
14	23	14-23	1	1	1	1	1	1	1	1
15	23	15-23	1	1	1	1	1	1	1	1
23	24	23-24	3	3	3	3	3	3	3	3
23	28	23-28	3	3	3	3	1	1	1	1
23	30	23-30	1	1	1	1	3	3	3	3
23	31	23-31	1	1	1	1	3	3	3	3
23	32	23-32	1	1	1	1	1	1	1	1
23	33	23-33	3	3	3	2	3	3	3	3
23	35	23-35	1	1	1	1	1	1	1	1
23	36	23-36	1	1	1	1	1	1	1	1
24	35	24-35	1	1	1	1	1	1	1	1
30	31	30-31	1	1	1	1	1	1	1	1

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
30	36	30-36	1	1	1	1	1	1	1	1
31	36	31-36	1	1	1	1	1	1	1	1
32	36	32-36	3	3	3	1	2	2	2	3
33	36	33-36	3	3	3	2	1	1	1	3
35	46	35-46	1	1	1	1	1	1	1	1
36	46	36-46	1	1	1	1	1	1	1	1

Project Stakeholders at the Execution Phase

Nodes			
Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
5	HFE	Human Factors Engineering	1
7	OPS	Operations	1
8	MNT	Maintenance	1
14	FE	Field Engineering	1
15	ERO	Emergency Response Organization	1
18	PSC	Plant Status Control	1
23	PRO	Projects	1
24	DSG	Design	1
28	CMO	Contract Management Office	1
30	WC	Work Control	1
31	WA	Work Assessing	1
32	FNC	Finance	1
33	SC	Supply Chain	1
36	BM	Contractor	2
46	RCPL	Subcontractor	3

Evaluation of Stakeholder Connections at the Execution Phase

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
1	5	1-5	1	1	1	1	1	1	1	1
1	7	1-7	3	3	3	3	3	3	3	3
1	8	1-8	3	3	3	3	3	3	3	3
1	14	1-14	1	1	1	1	1	1	1	1
1	23	1-23	1	1	1	1	1	1	1	1
1	24	1-24	1	1	1	1	1	1	1	1
1	36	1-36	2	2	2	1	3	3	3	3
1	46	1-46	2	2	2	1	3	3	3	3
5	7	5-7	1	1	1	1	1	1	1	1
5	8	5-8	1	1	1	1	1	1	1	1
5	23	5-23	1	1	1	1	1	1	1	1
5	24	5-24	1	1	1	1	1	1	1	1
5	36	5-36	1	1	1	1	1	1	1	1
5	46	5-46	1	1	1	1	1	1	1	1

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
7	8	7-8	3	3	3	3	3	3	3	1
7	14	7-14	1	1	1	1	1	1	1	1
7	15	7-15	1	1	1	1	1	1	1	1
7	23	7-23	3	3	3	3	3	3	3	3
7	24	7-24	2	2	2	2	2	2	2	3
7	30	7-30	1	1	1	1	1	1	1	1
7	31	7-31	1	1	1	1	1	1	1	1
7	36	7-36	3	3	3	3	3	3	3	3
7	46	7-46	3	3	3	3	3	3	3	3
8	14	8-14	1	1	1	1	1	1	1	1
8	15	8-15	1	1	1	1	1	1	1	1
8	23	8-23	1	1	1	1	1	1	1	1
8	24	8-24	1	1	1	1	1	1	1	1
8	28	8-28	1	1	1	1	1	1	1	1
8	30	8-30	1	1	1	1	1	1	1	1
8	31	8-31	1	1	1	1	1	1	1	1
8	36	8-36	3	3	3	3	3	3	3	3
8	46	8-46	3	3	3	3	3	3	3	3
14	23	14-23	3	3	3	3	3	3	3	3
14	24	14-24	1	1	1	1	1	1	1	1
14	28	14-28	3	3	3	3	3	3	3	3
14	36	14-36	3	3	3	3	3	3	3	3
14	46	14-46	3	3	3	3	3	3	3	3
15	23	15-23	1	1	1	1	1	1	1	1
15	28	15-28	1	1	1	1	1	1	1	1
15	36	15-36	3	3	3	3	3	3	3	3
15	46	15-46	3	3	3	3	3	3	3	3
18	23	18-23	1	1	1	1	1	1	1	1
18	36	18-36	3	3	3	3	3	3	3	3
23	24	23-24	3	3	3	3	3	3	3	3
23	28	23-28	3	3	3	3	3	3	3	3
23	30	23-30	2	2	2	2	2	2	2	2
23	31	23-31	2	2	2	2	2	2	2	2
23	32	23-32	1	1	1	1	1	1	1	1
23	33	23-33	2	2	2	2	2	2	2	2
23	36	23-36	3	3	3	3	3	3	3	3
23	46	23-46	3	3	3	3	3	3	3	3
24	36	24-36	3	3	3	3	3	3	3	3
24	46	24-46	3	3	3	3	3	3	3	3
28	36	28-36	3	3	3	3	3	3	3	3
28	46	28-46	3	3	3	3	3	3	3	3
30	31	30-31	3	3	3	3	3	3	3	3
30	32	30-32	3	3	3	3	3	3	3	3
30	36	30-36	1	1	1	1	1	1	1	1
31	36	31-36	1	1	1	1	1	1	1	1

Source	Target	Link ID	W1	W2	W3	W4	H1	H2	H3	H4
31	46	31-46	1	1	1	1	1	1	1	1
32	33	32-33	2	2	2	2	2	2	2	2
32	36	32-36	2	2	2	2	2	2	2	2
32	46	32-46	2	2	2	2	2	2	2	2
33	36	33-36	3	3	3	3	3	3	3	3
33	46	33-46	3	3	3	3	3	3	3	3
36	46	36-46	3	3	3	3	3	3	3	3

Project Stakeholders at the Closeout Phase

Nodes			
Node ID	**Label**	**Name**	**Group**
1	SRE	SRE	1
7	OPS	Operations	1
8	MNT	Maintenance	1
17	TRN	Training	1
18	PSC	Plant Status Control	1
19	PRC	Procedures	1
23	PR	Project Manager	1
24	DSG	Design	1
32	FNC	Finance	1
33	SC	Supply Chain	1
36	BM	Contractor	2
46	RCPL	Subcontractor	3

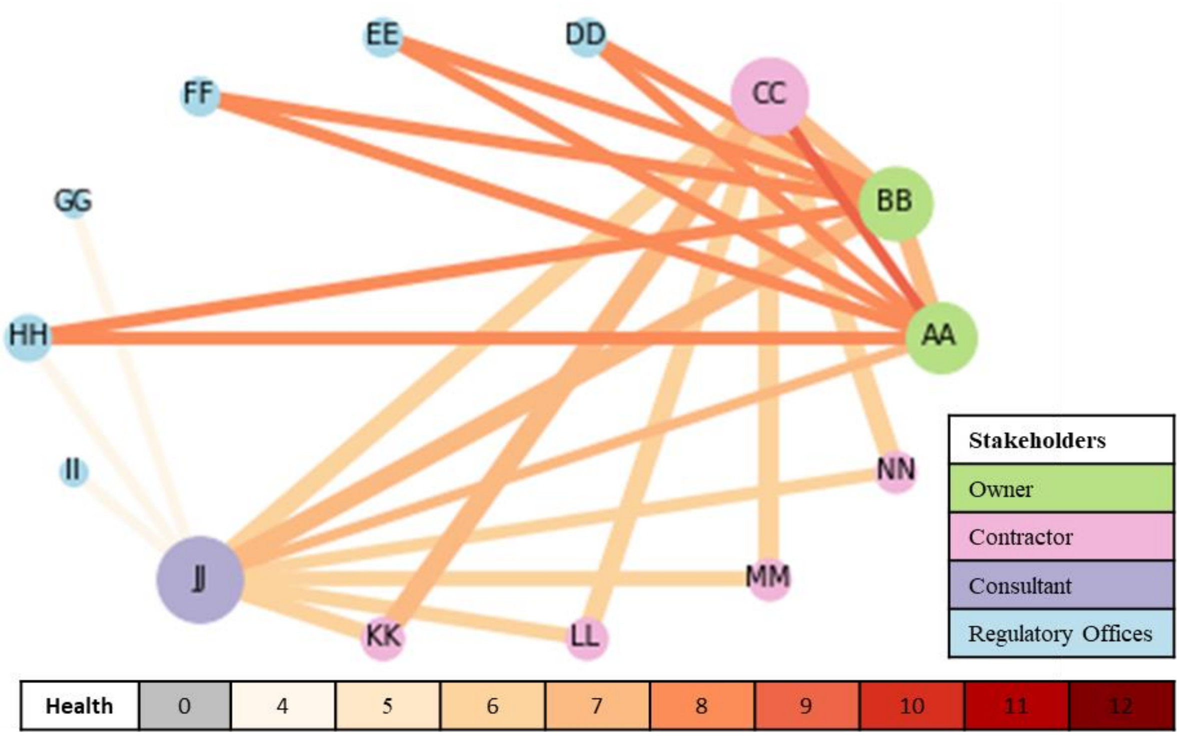
Evaluation of Stakeholder Connections at the Closeout Phase

Links										
			Workload				**Health**			
Source	**Target**	**Link ID**	**W1**	**W2**	**W3**	**W4**	**H1**	**H2**	**H3**	**H4**
1	7	1-7	1	1	1	1	1	1	1	1
1	8	1-8	1	1	1	1	1	1	1	1
1	23	1-23	1	1	3	3	1	1	1	1
1	24	1-24	1	1	1	3	1	1	1	1
7	8	7-8	1	1	1	2	1	1	1	1
7	12	7-12	1	1	1	1	1	1	1	1
7	17	7-17	1	1	1	1	1	1	1	1
7	18	7-18	1	1	1	1	1	1	1	1
7	19	7-19	1	1	1	1	1	1	1	1
7	23	7-23	1	1	1	3	1	2	1	1
8	12	8-12	1	1	1	1	1	1	1	1
8	17	8-17	1	1	1	1	1	1	1	1
8	18	8-18	1	1	1	1	1	1	1	1
8	19	8-19	1	1	1	1	1	1	1	1
8	23	8-23	1	1	1	1	1	1	1	2

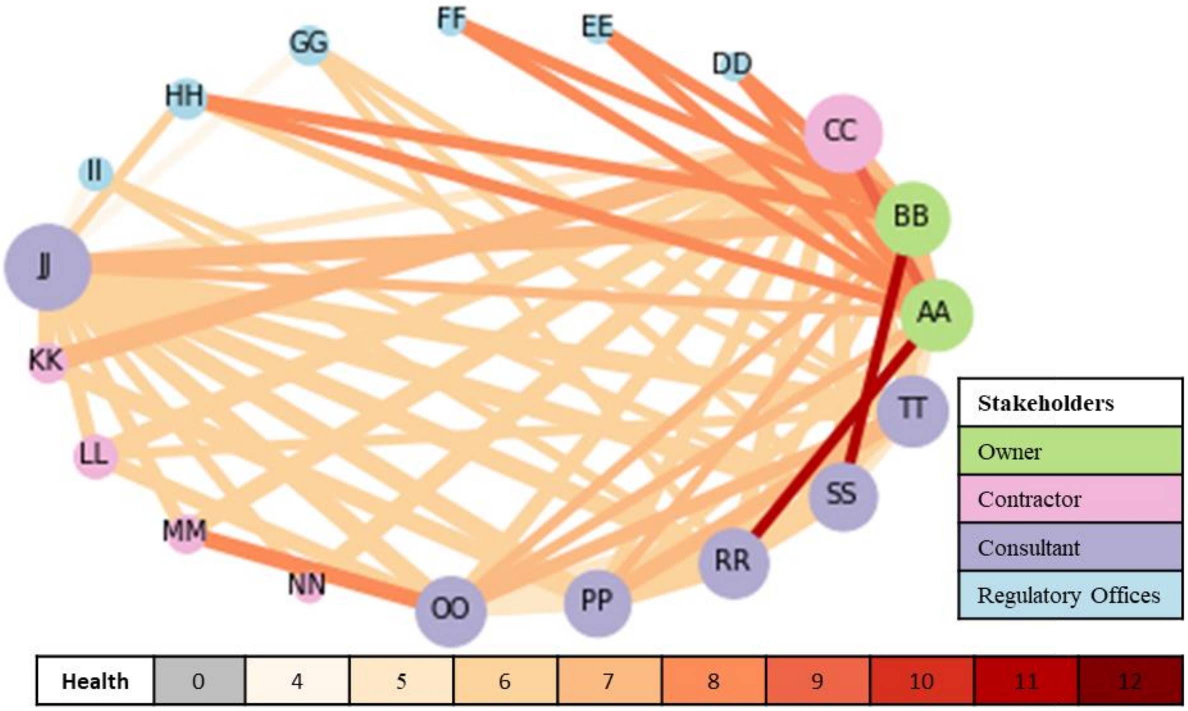
8	24	8-24	1	1	1	1	1	1	1	1
17	19	17-19	1	1	1	1	1	1	1	1
17	23	17-23	1	1	1	1	1	1	1	1
17	36	17-36	1	1	1	1	3	3	3	1
18	23	18-23	1	1	1	1	1	1	1	1
19	23	19-23	1	1	1	1	1	1	1	1
23	24	23-24	2	2	2	3	2	2	2	2
23	32	23-32	1	1	1	1	1	1	1	1
23	36	23-36	3	3	3	3	2	2	2	2
23	46	23-46	3	3	3	3	3	2	2	2
33	36	33-36	3	3	3	3	3	3	3	3
36	46	36-46	1	1	1	1	1	1	1	1

Appendix H

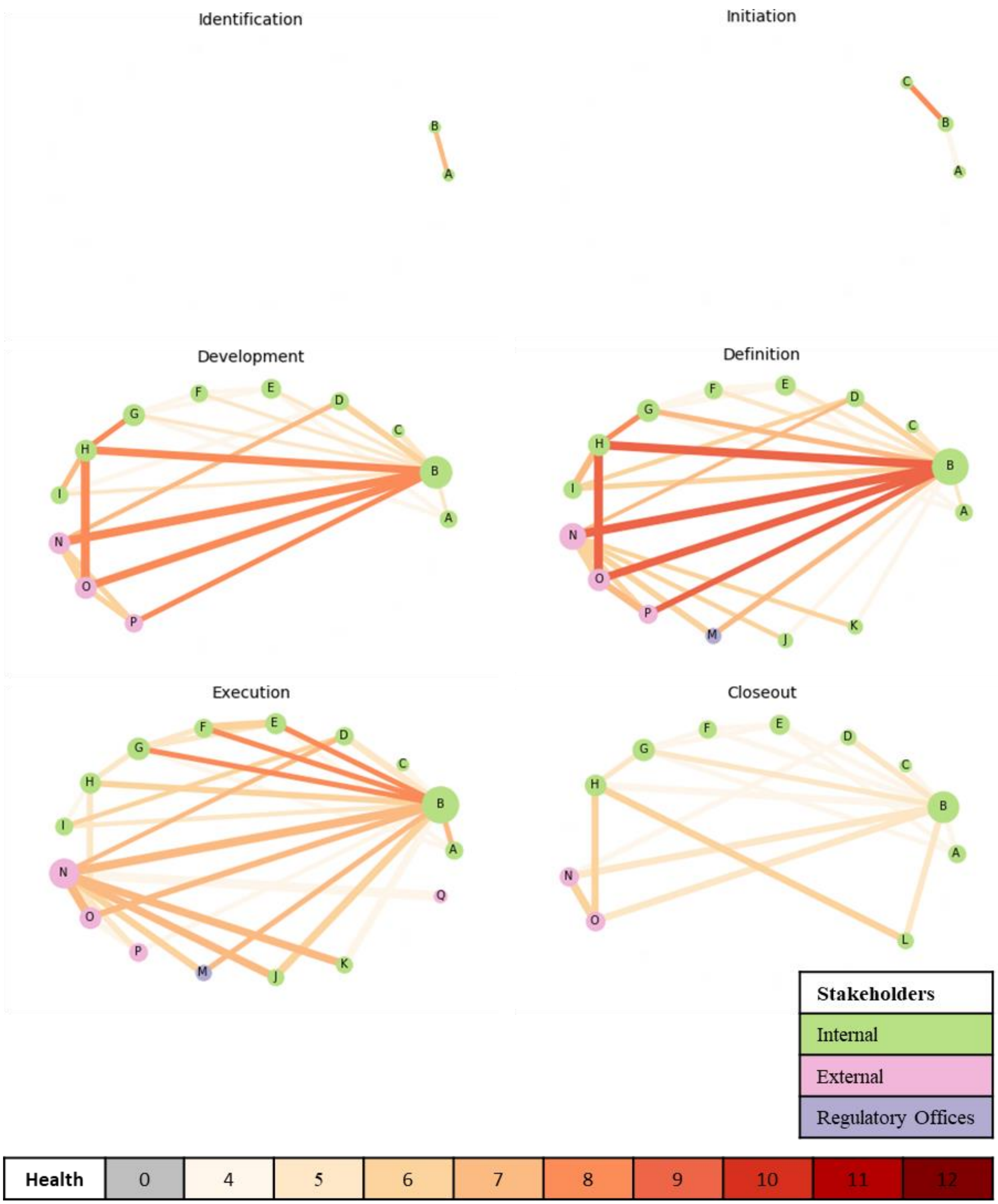
Additional Stakeholder Interface Network Representations



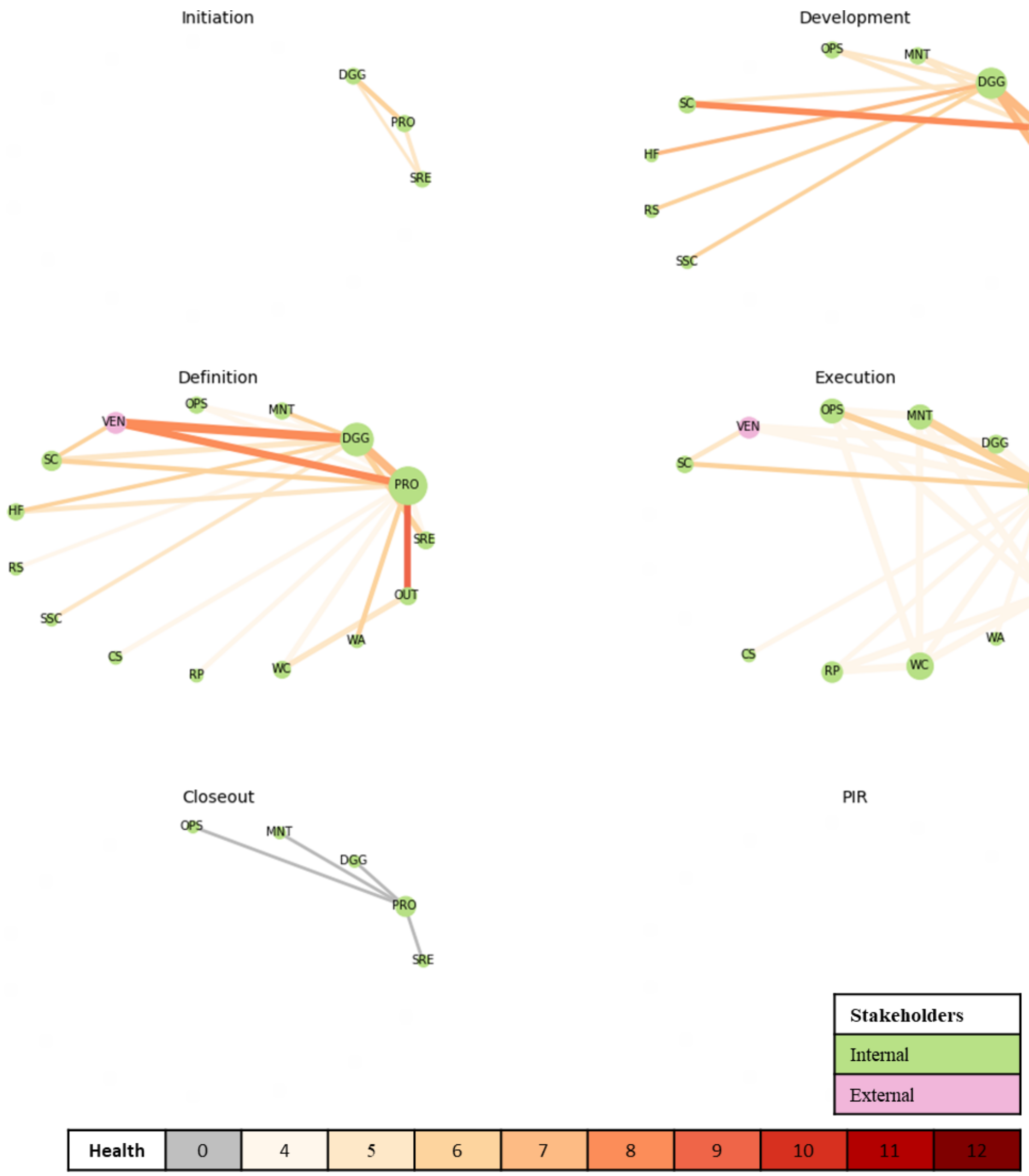
Stakeholder interface network of Rail Line Project



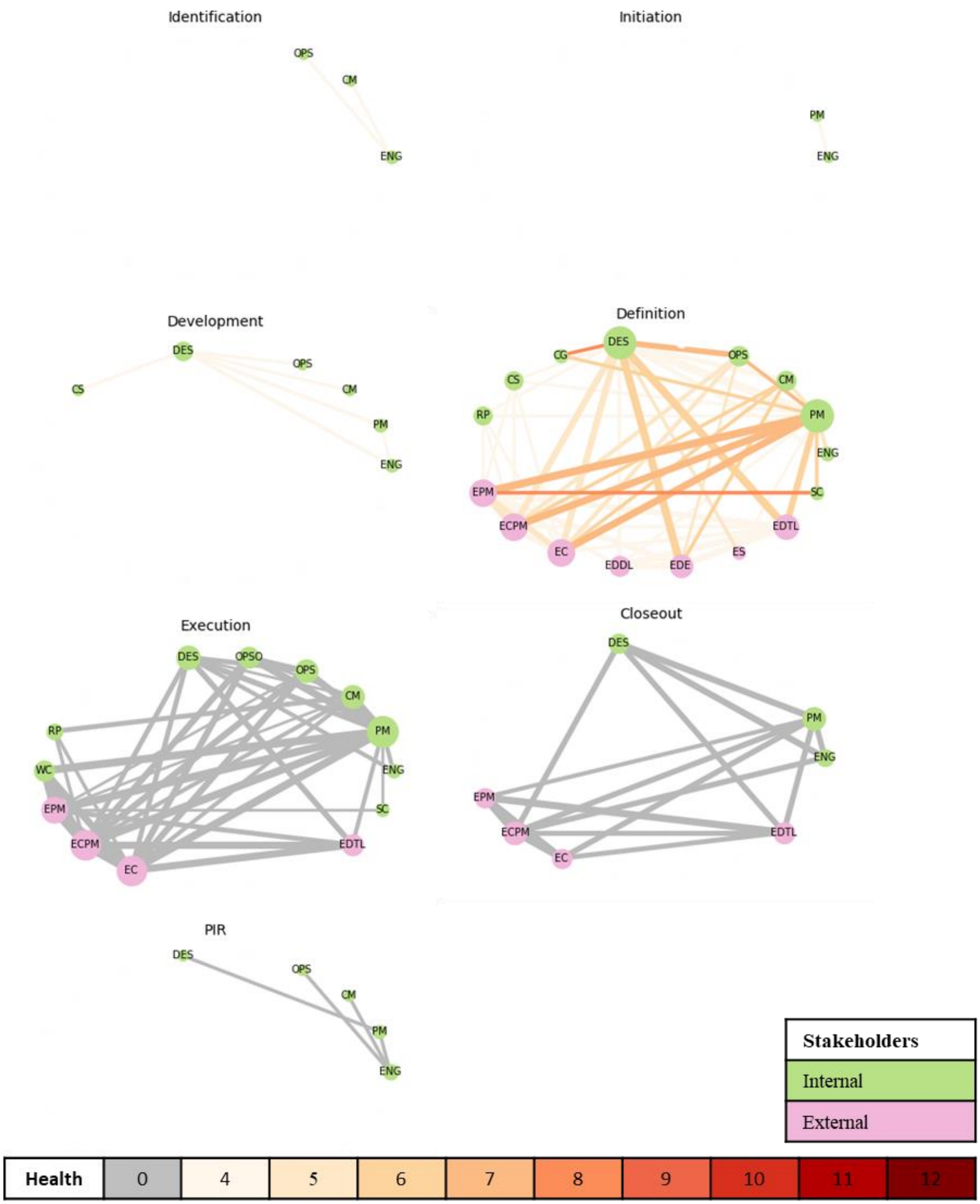
Stakeholder interface network of Rail Line Project (re-evaluation)



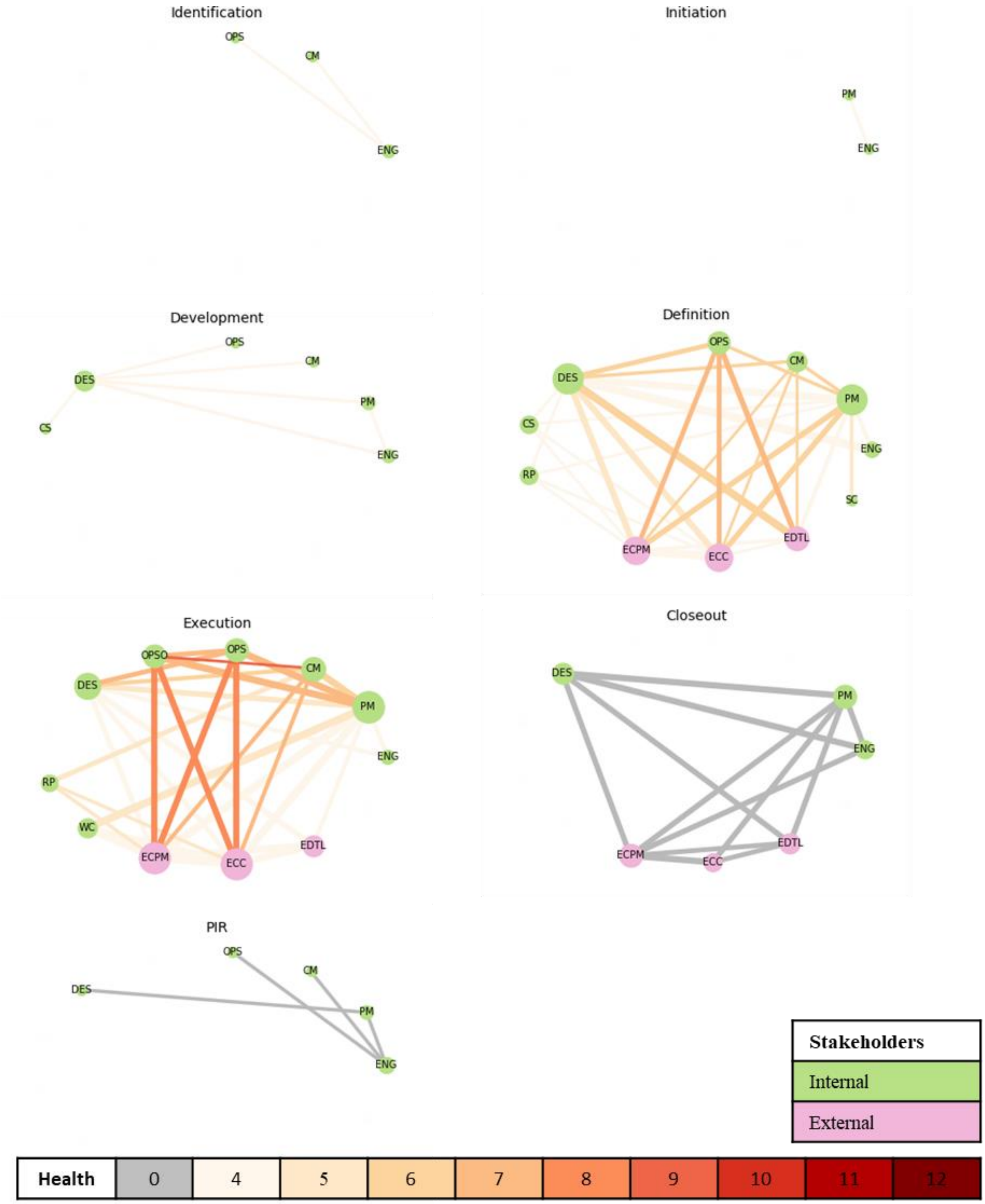
Stakeholder interface networks of Chemical Equipment Replacement project



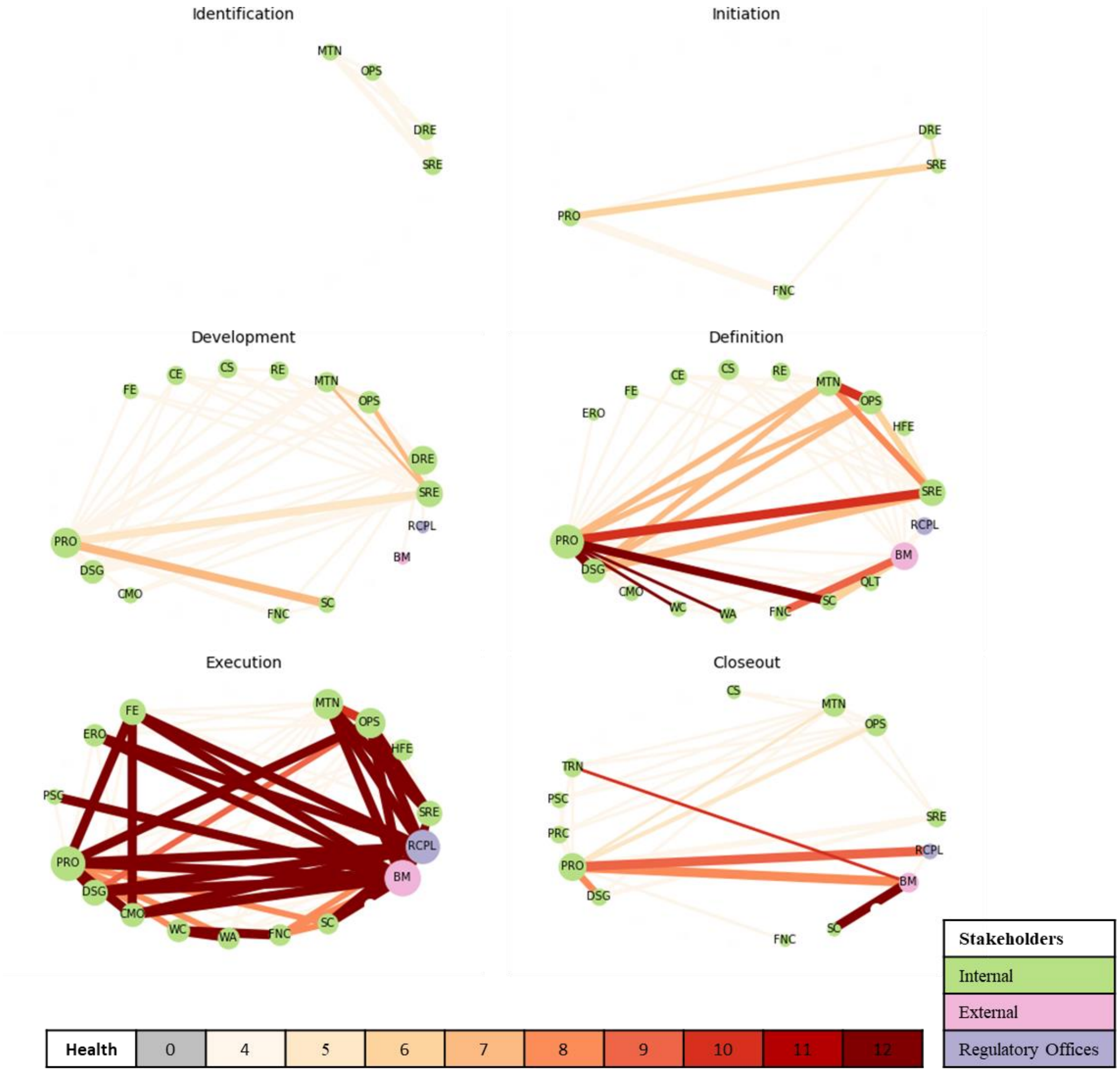
Stakeholder Interface Networks of Detector Assemblies Replacement Project



Stakeholder Interface Networks of Control Positioners Replacement project



Stakeholder Interface Networks of ACU-1 project



Stakeholder Interface Networks of ACU-2 project

Glossary

BIM (Building Information Modeling) - A digital representation of physical and functional characteristics of a facility and it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward

CII (Construction Industry Institute) - A consortium of many construction related firms from both the public and private arenas. They work together to improve business effectiveness and sustainability in construction industry.

IA (Interface Agreement) - A document that present the communication and agreements between two Interface Stakeholders over an IP.

IFC (Industry Foundation Classes) - An object-oriented building information model format used for describing, sharing, and exchanging building data among different software applications.

IM (Interface Management) – The process of managing project related communications, project stakeholders' responsibilities, project phases and physical entities.

IMS (Interface Management System) – A system that is used for management of communications, relationships, and deliverables among two or more interface stakeholders.

IP (Interface Point) - A soft and/or hard contact point between two interdependent interface stakeholders

LOD (Level of Development) - Detail level of the design elements in the BIM model. LOD definitions would change project to project.

LRT (Light Rail Transit) - Transit service using rail cars singly or in short trains, powered by electricity usually supplied by overhead wires, operated on exclusive right-of-way, on non-exclusive rights-of-way (with grade crossings), or in mixed street traffic, with stations close together.

MMI (Model Maturity Index) – Definitions that provided by CII to help measuring maturity of the model, by modeling discipline, as a function of what is modeled and the quality of the data used to create the model.

MMRI (Model Maturity Risk Index) – A toolkit that provided by CII to determine the MMI levels for each model discipline by location in the model.

MRT (Mass Rapid Transit) – A generic term for an urban public transit system using underground or elevated trains.

MRT-MMI – Model Maturity Index definitions for Mass Rapid Transit Projects.

MRT-MMI-AT- Engineering progress assessment tool to determine the MRT-MMI levels for each model discipline by location in the MRT project model.

OCS (Overhead Contact System) – A railway electrification system that supplies electric power.