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Developing an Information Modeling Framework for Tunnel Construction Projects

by

Mahsa Ghaznavi

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Abstract

A plethora of information combined with the participation of diverse disciplines during the tunneling life cycle results in fragmented information components. To address this problem, integrated information systems provide a unique environment to store project information. In this regard, consistent data structure facilitates successful information exchanges between project segments.

This thesis presents an integrated Tunnel Information Modeling (TIM) system similar to the vastly studied Building Information Modeling (BIM) concept. The proposed TIM model offers a multi-dimensional modeling procedure to develop an integrated and interoperable tunnel information model. The extension capability of the current Industry Foundation Classes (IFC) standard is utilized to define new classes for tunneling construction projects. The aim is not to develop an extension domain for the IFC data model, but to propose a step-by-step framework to achieve such an extension for tunneling projects. The resulting framework can be used as the primary component for developing an object-oriented application interface.

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List of Abbreviations

Abbreviation	Description
AEC	Architecture/Engineering/Construction
IT	Information Technology
ICT	Information and Communication Technology
AI	Artificial Intelligence
BIM	Building Information Modeling
IAI	International Alliance for Interoperability
IFC	Industry Foundation Classes
TBM	Tunnel Boring Machine
TIM	Tunnel Information Modeling
API	Application Programming Interface
JSCE	Japan Society of Civil Engineers
PMBOK	Project Mangement Body Of Knowledge
D.P.R.	Detailed Project Report
SBM	Shaft Boring Machine
EPB	Earth Pressure Balanced
CO	Change Orders
RFI	Request For Information
CBR	Case-Base Reasoning
CAD	Computer Aided Design
GIS	Geographic Information System
DAT	Decision Aid for Tunneling
CPM	Critical Path Method
3D	three-dimensional
HLA	High Level Architecture
DOD	United States Department of Defense
RTI	Run-Time Interface
SPS	Special Purpose Simulation
FOM	Federation Object Model
LOD	Level of Detailing
2D	two-dimensional
IIMIS	Integrated Inter-Organizational Management Information Systems
4D	four-dimensional
5D	five-dimensional
CVP	Construction Virtual Prototyping
CIS/2	CIMSteel Integration Standards
n-D	multi-dimensional
OOCAD	Object-Oriented CAD
VC	Virtual Construction
ISO	International Standard Organization
STEP	Standard for the Exchange of Product model data
DBB	Design-Bid-Build
ER	Exchange Requirements
MVD	Model View Definitions
O&M	Operation and Maintenance
GDL	Geometric Description Language
ODBC	Open Database Connectivity
NBIMS	National BIM Standards
NIBS	National Institute of Building Science
FIC	Facilities Information Council
WBS	Work Breakdown Structure

Chapter 1: Research Study Overview

1.1 Background

The current state of architectural/engineering/construction (AEC) industry is associated with a great amount of inefficiency and this causes less labor productivity in comparison to the manufacturing industry (Teicholz, 2001). The construction industry has dramatically transformed in recent years, with construction projects significantly increasing in complexity, specialization, and scale. Although there have been considerable technological advancements over the years, the productivity has been on a yearly decline of 0.6% since 1960's (Forbes and Ahmed, 2011). Studies conducted by the US Department of commerce, bureau of labour statistics shows that the productivity index in the construction industry has decreased drastically between the years of 1964 and 2007, whilst non-farm industries showed a 10% productivity increase (Li et al., 2008).

It is often argued that the manufacturing industry and the construction industry are not comparable. Construction projects often result in individualized, domain specific, final products, whereas manufacturing consists of repetitive products of large quantities. Manufacturing projects are often held in controlled, predictable environments aiding space planning and logistical optimization, whereas construction site locations vary, are subject to shifting and unpredictable weather conditions, and have highly variable site conditions. This is also accompanied by the need for specialized construction plant and equipment from project-to-project, while the repetitive nature of manufacturing vastly improves equipment and material consistency for automation. Finally, the construction industry is not capable of using the trial and error principle (known as *"try before build"*) to examine the quality of the final product (Li et al., 2008). There are many fundamental differences between manufacturing and construction; however manufacturing concepts can provide insight into areas of improvement for the construction industry. Eastman and Sacks (2008) specified the increasing role of manufacturing technologies as a major influence on construction efficiency among other factors. According to Babic et al. (2010), industrialization of the construction process as a key issue in the construction industry started many years ago and is necessary to achieve higher levels of productivity. Automated manufacturing and prefabrication assist to industrialize the construction processes. The introduction of computerized application tools has revolutionized the manufacturing industry and similarly, opened new horizons for the improved implementation of AEC projects.

For many years, machines and Information Technology (IT) have played a prominent role as the "sub-processes" in construction project delivery. Since the 1980's the construction industry has predominantly employed IT through the introduction of new software applications (Holt, 2009). The construction industry intends to improve the collaboration and information exchange between multiple organizations involved in a construction project by employing recent improvements in Information and Communication Technology (ICT) (Caldas et al., 2002).

The adoption of IT in the construction industry has been far less progressive than in the manufacturing industry. Moreover, the early adoption of IT usually only takes place in large-scale firms where the organization is capable of compensating the unexpected costs (Eastman et al., 2008). This is a challenge in an industry that largely consists of small firms. The hesitation to pay the high cost of implementing a new technology in a construction project is one of the factors that has limited the industry. In recent years, the application of ICT demonstrated a significant improvement in productivity and cost efficiency (Kim, 2003). With these benefits verified, it is becoming more promising for construction firms to take the advantages eventually in the later phases and during construction periods despite of higher preliminary costs of establishing a new technology in their routine. Thus, in spite of the many barriers for adopting a new information technology approach, the construction industry has employed elements of IT to support the project delivery process since 1980s (Holt, 2009).

However, according to Aouad et al. (2008), the use of IT in the AEC industry is distinguished by a high level of fragmentation, which reflects the dissociated nature of the construction industry. Different IT applications are used during multiple stages and assist in diverse processes from planning to facility management. These applications are developed by diverse vendors to satisfy the requirements for assessment, analysis, and management of the project data. In most cases, IT tools are standalone applications with no or minimum compatibility with each other because each one uses proprietary format for storing and accessing information. Therefore, the flow of information from one application to another is not directly feasible in digital form unless there is human intervention. As a result, a higher amount of errors and missing information is anticipated to occur while exchanging information from one application to another. Such separated packages of information, which are mostly interrelated as describing the same elements in the project, make it even harder to keep the integrity and consistency of project information. Consequently, a significant deal of effort was taken to connect dissociated packages of data and making an integrated system.

Throughout the years, research studies in academia have established an ongoing effort to replace the conventional view with a more integrative view of a cooperative system. This approach has been widely developed and implemented by employing different systems such as artificial intelligence (AI) and knowledge-based techniques to represent, systematize, and organize project information. Moreover, another research thread that initiated from the AI concept is focused on producing universal data models to standardize the representation of knowledge products in AEC industry (Halfawy and Froese, 2005). This standardized view has enabled the sharing and exchanging of project definitions and semantics based on a unique data format that is practical in multiple applications.

According to Kymmel (2008), the efforts to generate integrated project systems have produced significant improvements in capturing and processing project data. Therefore, specifically in the building domain, new collaborative solutions emerged such as building information modeling (BIM). The BuildingSMART alliance™, previously called Alliance for Interoperability (AIA), is the leading organization in North America seeking to explore new trends in construction industry. Its main goal is to find new tools and standards to implement BIM, and advocate it as an innovative method, which enhances productivity in construction processes and increases overall efficiency. The mainstream standard of BIM is Industry Foundation Classes (IFC). It supports the universal data structure used by different applications along a project's lifespan and utilizes interoperability among participants.

1.2 Problem Statement

Diversity of application tools and disciplines is traceable in tunnelling projects by examining a typical project, which requires the integrated results of a collection of design and analysis tools. Although the scheme of data exchanges depends on the method of procurement, the following scenario illustrates the redundancy of the conventional approach:

> The conceptual model in the preliminary stages of a tunneling project, developed in a drafting tool, is not directly applicable in the cost estimation application. The reason stems from the facts that firstly, the conceptual model is developed by a drafting tool that is based on a specific data format. The data format is not applicable in the cost estimation tool. Secondly, in a traditional project management system, the conceptual model itself basically does not include any cost-related information.

Hence, the diversity of software applications employed by different disciplines necessitates collaboration and adoptability in order to take full advantage of innovative improvements facilitated by ICT (Grilo & Jardim-Goncalves, 2010).

In tunneling studies, most of the efforts are focused on enhancing the construction and design methods in different ground conditions. However, a limited number of studies are devoted to provide solutions for inefficiencies resulting from inadequate and improper information exchange among project disciplines. Most of the studies are either dealing with a proprietary data management system or are merely dealing with a small segment of information in the process. For instance, Deulofeu et al. (2007) proposed a shared database as a resolution for information management. Although the shared database aims at providing a common repository for all the project parties, it is not capable of providing a general framework for information exchange among project segments. Another example is the study by Shen et al. (2011), which focused on developing a simplified guidance system for tunnel boring machine. The system utilizes the information collected by a robotic total station. It then employs the processed data and verifies the consistency and accuracy of the Tunnel Boring Machine (TBM) alignment during construction. However, such systems solely manage and process the information associated with a particular segment of the tunneling process.

A universal standardized system is required for successful information management, which generates tangible improvements in data exchanges and boosts the collaboration among participating applications and departments in a tunnel project. Based on Halfawy and Froese (2005), an integrated project system aims at eliminating the discrete nature of project phases and IT applications, and consequently drives the contributions from various project participants to an integrated information system that would prevent errors, inconsistencies, misunderstandings, and missing data. The most notable effort in this regard is the deployment and implementation of standard data models, particularly the IFC classes in building domain.

1.3 Methodology

Development of integrated project systems are the solution to the growing integration trends in AEC industry (Halfawy and Froese, 2005). Standard data models are the fundamental part of the integrated project systems. A standard data model assists to standardize data structures and use them as the universal medium of exchanging information in the integrated environment.

The aim of this research is to investigate the possibility of applying the integrated project system concept in tunneling projects. Although integration has been sought for the tunneling process in many research studies such as the efforts in tunneling simulation and decision making (Ruwanpura and AbouRizk, 2001 and Zhang et al., 2010), this study intends to define a general approach for such integration. The framework developed in this research explores the opportunity of describing project views and information in a universal structure that would be applicable in diverse criteria and applications to enhance the tunnel management process. In particular, it examines the potentials of applying IFC to tunneling construction projects with the incentive of obtaining a unique standard data model to standardize the description of information packages in a tunnel project. The framework in this section includes the requirements and steps to apply the already developed standard data models to the tunnelling process.

The research methodology consists of two stages; the first stage proposes a framework for generating an integrated tunnel project system. This objective is pursued by studying different products and processes in a tunnel project model and examining the similar solutions for other construction projects. The proposed framework is demonstrated by presenting tunnel components and required information to form a comprehensive tunnel information model. The tunnel project model consists of geometric and non-geometric data packages and reveals the interconnection between different segments of the tunnel information system. The proposed framework is called the Tunnel Information Modeling (TIM) project system. The TIM system is represented with an object-oriented and parametric 3D model, including tunnel physical and meta information.

The second stage focuses on interoperability and information exchange in the resulting integrated system. It intends to define a step-by-step agenda to create an exchange medium capable of communicating amongst participating disciplines and applications in the integrated environment. The existing classes in the current IFC architecture provides a platform for adding new classes and performs as a background to define the proper data structure for a tunnel project. The resulting standard data model helps to unify the data packages generated by different downstream project management disciplines. The proposed extension in this study is developed by adding new classes to the IFC 2x Edition 3 (BuildingSMART, 2011) data structure and employing property set objects.

The extended IFC classes are called "TIM-IFC classes" that refer to the tunnel information modeling classes. Moreover, "TIM project model" refers to the tunneling information modeling phenomena, as an integrated project system, similar to the BIM concept in the building segment of the AEC industry.

1.3.1 Phase A - Designing TIM Integrated project system

The research methodology to define TIM project system consists of the following divisions:

- Studying the tunneling processes, methods, and participating streams in a typical tunnel project
- Identifying the necessary blocks of information to fulfill the requirement of project management processes
- Designing different layers of TIM model and determine the information flow among disciplines

The TIM project system requires a modeling tool, which is capable of producing specific components of the tunnel project model. Since, the aim of the study is to demonstrate a general framework based on the integrated project system solutions in the market, a BIM tool will be used to present the architecture and possibilities of a TIM project system. Revit Architecture® is a non-generic proprietary tool for building structures and is used in this work. The following methodology in this phase pursues the succeeding steps:

- Creating object models in form of generic parametric families for tunnel components
- Adding supplementary data to the object models

1.3.2 Phase B - Tunnel Standard Data Model (TIM-IFC Classes)

According to the similar methodology adopted by Japan Society of Civil Engineers (JSCE) to develop the Bridge-IFC by Yabuki (2008) and the guidelines on developing IFC extension models by Hietanen (2006), the procedure for creating TIM-IFC data model for a real tunnel project is as follows:

- Studying the tunnel structure, components, and properties
- Developing a general tunnel product model
- Expanding the current IFC classes by adding new tunnel classes and eliminating similar or unnecessary classes
- Partial implementation of the TIM-IFC classes by providing the EXPRESS representation

The integrated project system is presented with a multi-dimensional tunnel model that incorporates project information. Each tunnel component can be associated with a set of TIM classes defined in the information model. The final project model is an incorporated product of physical data and non-geometric information such as cost, schedule, material, systems, methods, quality, etc. Figure 1-1 shows the methodology approach to develop TIM project system.

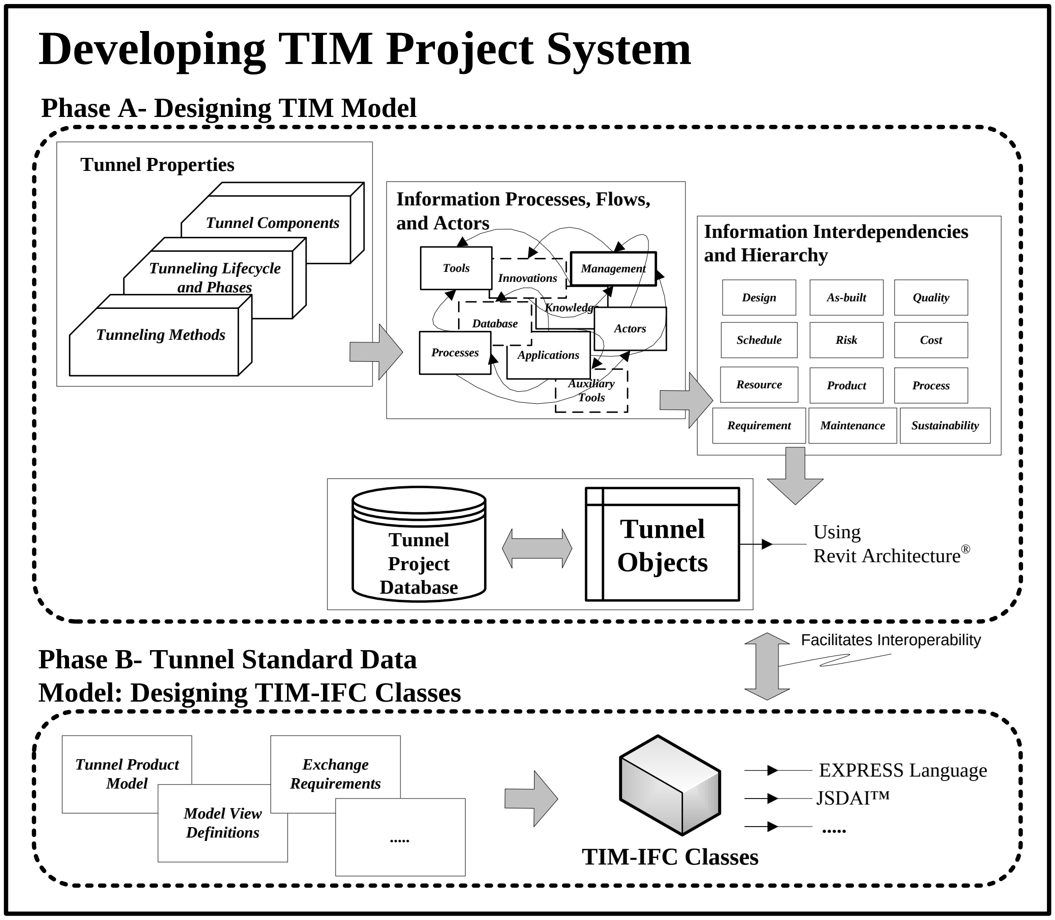


Figure 1-1 Methodology Approach to Develop TIM Project System

1.4 Research Scope

The aim of this study is to develop an integrated project system framework for tunneling construction projects. However, it is not intended to introduce a final applicable Tunnel-specific IFC data model for tunneling projects. Such development requires to be verified through a major implementation. The proposed methodology first establishes a firm background to define the incentives of developing a central data model for tunneling structures and then introduces a hierarchical framework to drive and implement a standard data model.

The scope of the TIM framework is to assist the project management processes, especially scheduling and cost estimation, during planning and construction phases of the project and to form a robust preliminary structure capable of defining an integrated project system for any tunnel project. This framework can be applied as a foundation for a more generalized tunnel project system that includes all the processes during tunnel lifecycle (i.e., design process, exploitation, facility management and maintenance, etc.).

The proposed step by step procedure to form the extended TIM-IFC classes assists to cover all tunnel information in a standard tunnel product model and avoid jeopardizing the integration process in a typical tunnel project. A typical tunnel project model, developed for a unique tunnel project, lacks the generality of a standard product model and fails to comprehend the information requirements to perform successfully in future tunnel projects. The resulting TIM framework can be used in future works to form an integrated tunnel project model that acts as the primary component for developing an object-oriented application interface. The TIM data model performs as the backbone for such development.

1.5 Research Objectives

This research study intends to accomplish the following milestones:

- Identify the tunnel components, parameters, and properties (i.e., methods, processes)
- Examine the application of integrated project system's requirements to a general tunnel project
- Form a hierarchical framework to develop the TIM project model
- Develop a framework to extend original IFC classes to represent a standard tunnel information model called TIM-IFC
- Implement the developed framework for a typical tunnel project

Through the achievement of the above milestones, this study intends to implement the following contributions to the tunnel project management process:

- The opportunity and effectiveness of the integrated project systems solution for tunneling projects
- Facilitating the flow of information amongst different parties such as stakeholders, project managers, contractors, subcontractors, via applying a uniform data model
- Enhanced consistency and integrity of project data and decreased number of errors and missing information
- Increased collaboration and integration throughout the project phases
- Saving a significant amount of time and energy in the reproduction of data in different applications
- Preserving and effectively using the historical data in future projects through the TIM database

1.6 Thesis Organization

The structure of the thesis is as follows:

Chapter 1- Research Study Overview- draws a sketch of the research backgrounds and motivations. Moreover, it indicates the scope of the work and its objectives.

Chapter 2- Literature Review- comprehensively explores the tunnel components and processes, investigates the current state of the civil infrastructures and the major origins of inefficiencies, and finally proves the necessity of a collaborative working environment and integrated project system for tunneling projects.

Chapter 3- Tunnel Information Modeling (TIM) - Research Methodology and Objectives- explains the principals of the proposed TIM system and demonstrates the methods and tools to develop it.

Chapter 4- Implementing TIM Project Model and TIM-IFC Standard Data Model Framework- describes the procedural steps to develop the TIM concept and prescribes the framework to develop TIM system and furthermore TIM-IFC classes as its interoperability medium.

Chapter 5- Summary, Conclusion, and Future Developments- devotes to the outcomes of the study and recommendations for future developments.

Chapter 2: Literature Review

2.1 Introduction

This chapter includes a summary of the background for this study that covers tunneling construction, tunneling management, integrated systems, building information modeling, and standard data models. In detail, it discusses the basis of the proposed framework, and reviews some of the previous studies in literature to support the facts that will be discussed in this dissertation.

The literature review will proceed as follows: First there will be an introduction to tunneling construction, which will explain the project lifecycle, methods, and how conventional practices are performed. This will be followed by a demonstration of the common problems in the tunneling management process, information systems, and integrated project systems. Some of the successful implementations of integrated project systems will be reviewed and an overview of standard data models will be provided. Finally, previous efforts for developing integrated systems and standard data models in underground, or other civil infrastructures will be presented. Based on this literature review, the conclusion will explain the most significant insights from the extensive research from the past, as well as the opportunities for future work.

2.2 Tunnel Construction

The congested network of routes in today's big cities makes it necessary to focus upon efficient usage of the available area and the optimized operation of free land. Therefore, underground structures, specifically tunneling projects, are vital for future developments especially when it comes to metropolitan and urban planning. Tunneling projects are high-valued construction projects that facilitate the connections in strategic and remote areas with low accessibility. Traffic tunnels, train tunnels, and sewage tunnels are among the most important types of tunneling projects in urban areas.

Innovative solutions improve design, constructability, and productivity during construction phase, which produce lower risks and costs (Mohamed and AbouRizk, 2005). Similar to other projects, in recent years the innovative construction methods and techniques have improved the efficiency of tunneling projects and have assisted in achieving higher quality and lower risks in comparison to older methods of tunneling. The new methods have facilitated the tunneling process in difficult site conditions and have empowered new opportunities that were previously impossible. These recent studies investigate various perspectives in tunneling projects such as:

- Analysis of tunnel construction methods and equipment based on risk factors, design specifications, and ground conditions (i.e., Ocak and Bilgin (2010), Palmstrome and Stille (2007), Kimura et al. (2005))
- Effects of different materials in the tunnel excavation and lining procedure (i.e., Coulter and Martin (2006))
- Control systems for specific construction methods (Shen et al. (2011))
- Evaluation of the ground and surrounding structures' behavior as a result of the tunneling process (i.e., Hisatake (2011), Solak (2009))

Despite the vast improvements in construction techniques, equipment, and materials, there is no evidence in the literature that proves any significant enhancement in tunneling project productivity as part of the AEC industry. In general, all types of construction projects are experiencing low rates of field productivity in comparison with the manufacturing industry (Li et al., 2008). Perhaps, due to the complex and unique nature of infrastructure projects (Halfawy, 2010), even more problems and weaknesses are expected in tunneling projects. These shortcomings vary from a significant amount of re-work, lost data, and inadequate visualization, to lack of interoperability between project participants. Roisin (1992) recommended applying efficient project management practices to confront with the overwhelming complexity of the tunneling projects.

In order to find a practical solution, throughout the following sections the tunneling methods, lifecycle, and components are reviewed, followed by an investigation of the major problems associated with tunneling projects.

2.3 Tunnel Construction Life Cycle

Similar to other civil infrastructures, the implementation of tunnel projects consists of different stages and phases. According to PMBOK (2008), apart from a project's complexity and magnitude, all projects experience four distinct phases: starting the project, organizing/preparing the project, carrying out the project, and closing the project. Relatively, the common stages in a tunnel project are initiation, planning, construction and finally operation/maintenance. Multiple activities form each stage of the project. Due to the unknown nature of the underground site condition, rigorous investigations are required to anticipate the soil's behavior and characteristics before and after commencing the tunneling process. These investigations vary from subsurface geotechnical and geophysical studies to site surface investigations. In particular, ground behavior evaluation is the basic step for designing tunnel projects (Solak, 2009). Geotechnical investigation is done by collecting samples from the boreholes drilled in the site. The results assist in choosing the best available alternative for the construction method, excavation equipment, and tunnel support. Based on Kolymbas (2005), the value of preconstruction investigations can make up to 3% of total project cost. However, these preliminary studies are of great benefit because more than 55% of the claims in United States result from unforeseen ground conditions. These uncertainties decrease by transferring accurate information from preliminary explorations to the other phases and parties during project lifecycle.

The feasibility studies for an underground structure refers to the process of technical and economical analysis to ensure the possibility of performing such project based on available resources and techniques. After making a final decision of whether or not to perform a project, a collection of multiple planning models composed of conceptual, engineering, and detailed studies/models are prepared (Tatiya-a, 2005). Preliminary evaluations are the most significant and effective types of investigations of the whole project lifecycle, which determines the boundaries, and enlightens further decisions during project lifecycle (Al-Bataineh, 2008). During preliminary studies different aspects such as water rights, waste disposal, and disappropriation are considered. Also, site investigation and the tendering process are completed before entering the design phase (Kolymbas, 2005). After the feasibility studies are completed, the site location is determined. An ideal project site supports the project's goal effectively and has the specific properties and facilities such as water supplies, electricity, convenient access points, and a material depot spot to advance the project operation (Zhang et al., 2010).

Tatiya-a (2005) comprehensively described the necessary activities after the preliminary studies. Based on the feasibility studies and the obtained information from economical and soil investigations, a method of construction is selected. A "conceptual model" depicting the general scheme of the components and features of the selected method is then prepared. The conceptual model explains the shape, size, location, and geometry of the general scheme of the tunnel components and is the basis for future scheduling and quantity/cost assessments. In the case of having more than one alternative, all the above exercises are undertaken for each probable choice. Finally, the best option is selected and assessed in depth during the prospected engineering and detailed studies. The "engineering model" describes the details of the design model and shows the exact access points, design methods, layout, and services along with specifications for equipment and installations. Moreover, the physical quantities and scheduling documents, based on construction, development, production, and resource requirements, is prepared and cost of the operation is assessed. In the next step, the Detailed Project Report (D.P.R.) is prepared which is composed of comprehensive drawings and specifications. Tender documents, budget forecast, and procurement schedules are also included in the D.P.R.

During the pre-construction phase, a collection of meetings and workshops are held to discuss the scope, resources, methods, and design of the project. For instance, a conventional series of such workshops in the City of Edmonton consist of concept design, value engineering, and risk analysis (Al-Bataineh, 2008). The outcome of these workshops broadens the knowledge of the participants about different aspects of the project, identifies the limitations and alternatives, which in turn assists in identifying the risks and evaluating different mitigation scenarios to eliminate or alleviate the risk factors.

The site layout designates the location of the equipment and tunnel components such as working and exit shaft, boreholes, etc. Although constant modifications and changes occur until the end of the project, the design and planning activities predominantly take place in the preconstruction phase. As the project progresses, many factors that were unknown in the preliminary stages, are being revealed and this results in major or minor changes in initial design plans.

A typical sequence of major tunneling activities consists of preparatory tasks followed by the construction of the working shaft, main tunnel, and exit shaft (Zhang et al., 2010). The tunneling process begins with constructing the working shaft. Based on the shaft shape, size, and ground specifications, the operation method may be different. After reaching the required depth, a tail tunnel is excavated to provide enough space for material and equipment handling.

An undercut is also constructed at the beginning of the tunnel alignment to further help the assembling of TBM and other equipment. Before the tunnel construction commences, based on the method of construction, suitable equipment (TBM, gantry, conveyor belts, etc.) is installed.

However, complete installation may be postponed in order to allow a minimum improvement in tunnel construction for the purpose of providing enough space for the equipment installation. Then, sequential and repetitive activities of excavation, lining, and dirt removal take place until reaching the end point of the tunnel. The survey of the tunnel alignment during excavation ensures the accuracy of the excavation direction. While the excavation in tunnel level advances, or even at the time of sinking the working shaft, the excavation of the exit shaft can begin. The major activities in the construction phase finish through the completion of the tunnel excavation and by disassembling the TBM or other equipment (Zhang et al., 2010 and Al-Bataineh, 2008).

During the construction period, minor and major installations take place on the site as well as inside the excavated parts to provide proper ventilation, illumination, power, communication, commuting, controlling, and safety. In addition, after excavation, operation devices and equipment are installed to provide the desired services for the operation and maintenance phase such as road signs, video monitors, and sensors for road tunnels. These installations take over a significant percentage of the total cost. For instance, a study on a 9.2 km tunnel in a Plabutsch western tube (road tunnel) in Austria shows that over 18 percent of the total project cost was spent on installations during construction and after the construction's completion (Kolymbas, 2005). In a road tunnel or rail tunnel, installations are for traffic control, ventilation, telecommunication, fire protection, illumination, and drainage (Kolymbas, 2005). Table 2-1 shows the typical stages and activities in a tunneling project regardless of the actual sequence of the activities, since some activities are able to take place in the same time period.

Table 2-1 Activities During Preconstruction and Construction Phases of a Tunnel Project

Phase	Activities	Details
Preconstruction (Planning & Design Phase)	Feasibility Studies and Preliminary Evaluations	Possibility of undergoing such project based on available financial and technical resources
	Meetings and Workshops	Concept design, Value engineering, Risk analysis
	Geotechnical and Geological investigation	Preliminary investigation, Main ground investigation
	Site Investigation	Exploration adits and test drifts, Field test to determine the air permeability, Tests for the applicability of slurry and earth pressure support (EPB), Tests for abraivisity of drilling equipment
	Geophysical Exploration	Exploring the subsurface texture using exploratory drillings and geophysical methods
	Selecting Construction Method	Based on the feasibility studies which considered all parameters such as economics, geology, geography and geo-mechanical
	Conceptual Studies/Model	Size, shape, location, geometry, and general scheme regarding the operation sequence
	Engineering Studies/Model	exact access points, methods design, layout, services, equipment specification, cost and scheduling
	Detailed Studies/Model	detailed drawings, specifications; tender documents, budget forecast, and procurement schedules
	Site Layout	The exact configuration of the equipment, components, materials, human resources, access points, safety equipments on the site; general arrangement drawings used.
Construction Phase	Equipment Installation	required equipment for shaft sinking, installing the
	Working Shaft Construction	varied methods based on the shape, size and soil specifications
	Tail Tunnel	Space for material handling
	Undercut	Space for equipment set up
	Equipment Installation at the Tunnel level	Boring machine, conveyor belts, muck carts, ventilation, illumination, controlling and safety devices and facilities
	Tunnel Construction and Lining	varied methods based on the shape, size and soil specifications
	Exit shaft Construction	varied methods based on the shape, size and soil specifications
	Equipment Disassembly and Removal	boring machine, conveyors, muck carts, hoisting devices, etc
	Installation Providing Serviceability after Construction	Traffic signs, ventilation, telecommunication, fire protection, illumination, and drainage
	Construction Site Cleaning and Removal	Remove all the extra materials, dirt, equipments from the site and prepare for operation and maintenance phase of the project

2.4 Tunnel Components and Construction Methods

A typical abstraction of a tunnel structure includes a working shaft, the main tunnel, and an exit shaft. Identifying the geometric dimensions, ground conditions, and design specifications of the different parts of the tunnel is essential for a tunnel product model (AbouRizk, 2010). The general basic components of any underground construction include excavation by blast or other mechanical means, followed by the initial and final ground support for the excavated cavity (US Army, 1997). The specification and construction method for the major tunnel components (shaft, tail tunnel/undercut, and tunnel) have been comprehensively reviewed as follows.

2.4.1 Shaft

Vertical excavations are classified as raises and shafts. The raise is the steeply or inclined opening in the upward direction. The reverse of the raise called the winze, which is the excavation in the opposite direction (downward). The winzes with a diameter of more than 4m are considered shafts. The process of driving a shaft is slow due to the possibility of encountering water while the drilling work is going on. However, compared to driving raises, in which the working crews have to deal with non-scaled back after blasting, driving a shaft is less hazardous for the mining crew (Tatiya-a, 2005). Even in this case, the excavated soil still needs to be lifted and hoisted to the ground level (Megaw and Bartlett, 1983). There are different types of shafts providing different functionalities. For instance, tunnel shafts assist in accessing and excavating the main tunnel, or mining shafts that provide access to the mine level for the equipment and excavation crew. Other types such as surge shafts, transformer shafts, bunker shafts, and ventilation shafts act either as a connection, ventilation, or an energy absorption path for specific applications (Singh and Goel, 2006).

Shafts are essential for the construction of underground structures. Shaft sinking is a slow and tedious work and hence the costliest excavation among the vertical opening operations for mining or civil engineering purposes. Shaft construction is commonly required for mining mineral deposits, temporary storage, and treatment of sewages, bridges, deep foundations, hydraulic lift pits, and wells. It can also be a part of a tunneling network for underground transportation or sewage systems, where it acts as a channel for a ventilation facility, escalators, and access routes for a construction and maintenance crew. Moreover, it can be a liquid conveyer, pipes and cables passage way in river crossings, or drainage and pumping channels, especially for tunnels under the waterline (Tatiya-b, 2005).

Shafts are either permanent or temporary. Temporary shafts are usually employed as an access path for the contractor use. In contrary, permanent shafts facilitate a long time function in the tunnel structure, such as ventilation and drainage, or they can even be widened to be used as stations (Jenny, 1982). Shafts are usually designed to have permanent functions so that they can be used during both the construction and operation phases (Megaw and Bartlett, 1983).

In terms of functionality during construction, the common shafts are working shafts, exit shafts, and access/service shafts. In general, the working shaft is the point of access from the ground level to the tunnel level, which facilitates labor and equipment access throughout the tunnel level. Exit shafts are used to retrieve the tunnel boring machine at the end of the excavation process. Constructing access shafts are necessary in the case of long tunnels, which are usually excavated at an equal distance from the working shaft and exit shaft.

The shape of the shaft depends on its functionality and can be circular, rectangular, or elliptical. Circular shafts are more common in soft grounds and are structurally stable in weak rocks. Elliptical shafts are rarely used. Vertical shafts are more frequent than inclined ones. The shaft function defines its proper depth. The challenges for support and excavation increase in deeper variations (Singh and Goel, 2006).

The reasonable diameter of a shaft, in order to accommodate hoisting space, equipment, and safety facilities, is 4 or 5 meters (Megaw and Bartlett, 1983). Shallow shafts are mostly large and rectangular in shape. In rectangular shafts, a 10 percent ramp is a cost effective solution for accessing the shaft bottom, if site layout allows. Tunnel shafts are usually deep - but not as much as mining shafts- and circular in shape with a relative diameter for mucking, hoisting, utility supplies, etc. The size of the shaft varies depending upon the dimensions of the special equipment such as TBM. The diameter of circular shafts is usually between 5 and 10 meters (16-33 ft.), based on the size of the largest single part of the equipment. There are some limitations for minimum and maximum size of the shafts and this depends upon the tunnel excavation method. For instance, the minimum diameter for shafts excavated by the drilling and blasting method is 3 to 3.5 meters (10-12 ft.). Hence, the maximum diameter is not limited in this shaft sinking method (US Army, 1997).

A concrete collar needs to be installed around the top of the shaft before shaft excavation starts. This ring of concrete has a top surface of at least 12 inches above the ground to avoid the entering of surface waters and falling debris into the shaft during construction period (Jenny, 1982). Leveling and preparing the surrounding area- the provisions for a crane and a curb (shaft collar), which define the perimeters of the shaft-, is necessary to consider before commencing the actual shaft sinking (Megaw and Bartlett, 1983).

There is a variety of methods for shaft excavation based on the ground conditions. Any specific ground needs a particular support as work goes on. Machine excavation is common in soft ground using a clamshell bucket to hoist the muck. Then, a crane bucket utilizes the mucking and hoisting and dumps the muck on the ground or into a hopper/truck (Jenny, 1982). Since tunnel shafts are not significantly deep, generally less than 50 meters, machine boring is not cost effective in most cases except for the deeper shafts in hard rock (Singh and Goel, 2006). In proportionally large shafts, excavation is performed using backhoes and dozers equipped with rippers to loosen the ground. Smaller shafts with stable soil and no ground water can be excavated by dry drilling methods using augers and bucket excavators mounted on a Kelly (US Army, 1997). Drilling/blasting method and raise drilling are the two methods applied to rock grounds (Zhou, 2006).

In the drilling/blasting method, which involves dividing the shaft length into sections, the sinking cycle is composed of a combination of repetitive activities in Figure 2-1.

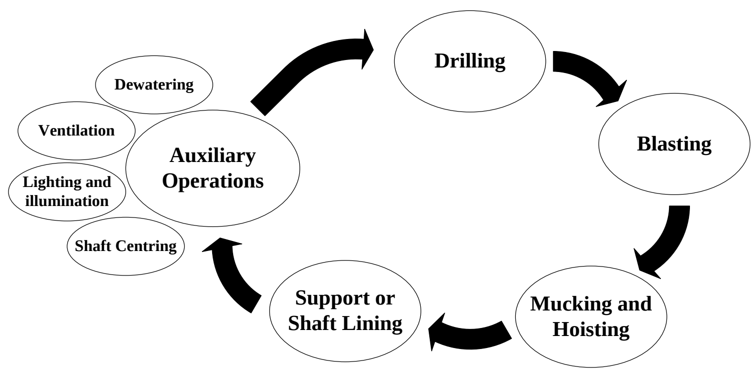


Figure 2-1 Sinking Cycle in Drill and Blast Method for Shaft Sinking

However, in case of facing unstable ground, abnormal underground water, or any combination of these situations, the ordinary excavating tools or mechanical excavators are not useful anymore. Hence, either a special method, ground consolidation, or a combined approach is required to make the sinking process feasible (Tatiya-a, 2005). The common procedures for ground improvement are dewatering, grouting, and freezing. These procedures are combined with an excavation method to sink in unstable, loose grounds with excessive amounts of ground water (US Army, 1997).

The method chosen for shaft lining depends majorly on the soil characteristics, shaft depth, underground water, and the project’s financial resources (Jenny, 1982). Shaft lining/support is one of the most time-consuming and costly activities in the shaft construction process. Shaft lining is commonly composed of initial (temporary) and final (permanent) parts. The main purpose of initial support is to stabilize and preserve the excavated shape before applying the final lining (US Army, 1997). In few cases, when the excavated cavity is temporarily stable and the working crew is safe, the initial lining is not necessary. Based on the ground condition, the length of the initial lining varies between 6 to 40 meters. In a stable soil with a moderate volume of water, the material used for the final lining can be composed of bricks, concrete blocks, or monolithic concrete, of which the latter is the common practice today. Moreover, shotcrete and cast iron tubing are the other customary materials that are used (Tatiya-a, 2005).

More than one lining method may be used for a single shaft to satisfy the site conditions since the soil strata may change throughout the depth of the shaft.

Zhou (2006) classified the lining and sinking methods that are particularly common in tunnel shafts. Tatiya-a (2005) proposed a more generalized classification that is subject to general underground supports in tunnels, shafts, or any underground cavity in the civil works. Table 2-2 includes a combination and equalized version of these two classifications.

Shotcrete lining is sometimes considered as the permanent or final support system. Even in mining shafts over a 4000 meter depth, a 40 cm thick shotcrete performs as the final support system (Singh and Goel, 2006).

Reaching to the bottom of the shaft necessitates some special considerations. Extreme care should be taken to prevent the overflowing of underground water by utilizing a pump and sump in shaft bottom. A watertight base slab at the shaft bottom provides resistance against uplifting, utilizing its weight and anchorage to the shaft lining. Moreover, provisions for the tunnel eye (tunnel entry or exit), which is a break out to the tunnel excavation, needs to be carefully taken (Megaw and Bartlett, 1983).

Table 2-2 Shaft Sinking and Lining Techniques (Based On Zhou (2006) and Tatiya-a (2005))

Lining and Excavation	Tunnel Shafts			General Underground Cavities		Supports
Initial	Sheet Piling	→	-Traditional and inexpensive -Vertical piles (timber, steel) + horizontal rib sets -Timber sheet for D<=20 feet -Steel sheet for D>20 feet	- Suitable for loose ground near the surface - Steel piles, wooden piles, or concrete piles - Driven down by heavy mallets and are placed edge to edge to form a circular lining, held in place by circular rings or curbs with 0.8-1 m interval.	←	Piling System
Initial	Soldiers pile and lagging	→	- H Piles (vertical steel elements) - Suitable for an excavation area above the static ground water or have sufficient arching to permit lagging - Hole drilled around the perimeter of the shaft , then H pile driven and concrete	↑ Different variation of piling system ~		
Initial	Liner plates	→	- Continous rings and plates to the required depth - Suitable for small shafts			
Initial	Ribs and Lagging	→	- Horrizontal ribs and vertical lagging - Applicable in cohesive soils due to the self supporting interval required			
Initial	Slurry Walls	→	- For shallow shafts in soft ground, particularly granular soil - Secondary lining is required in permenant shafts - Erosion and corrosion protection and further water proofing required	1-Sinking Drum Process (prefabricated lined shaft) 2- Forced-Drop shaft method (when drum process fails or alternate layer of loose and tough ground are envisioned) 3- Pneumatic caisson method (use of compressed air to sink through water logged in	←	Cassion Method (Drop Shaft)
Final	Concrete Segments	→	- Pre-cast or cast in place situ segmental lining - Pre-cast concrete: beneficial in wet and difficult ground since requires minimal excavation and gains full strength as soon as installment - In-situ concrete: when soil is temporarily self-support, suitable for deep shafts and any soil condition, avoids problems regarding manufacturing, delivering, and storing	Steps are: 1- Boring/drilling 2- Cementation 3- Sinking/walling - Suitable for firm and fissured ground, not for running sand type ground. Liquid cement injected through boreholes to the gullet strata to fill up cracks, and cavities. Cementation strengthen the strata and ultimately makes it waterproof.	←	Cementation
Final	Rock bolts and Wire Mesh	→	- Provides security to locally loosened blocks of rock or in predetermined spacing - Alone or in conjunction with shotcrete - Wire mesh reinforcement is a time consuming operation	Suitable for heavily watered strata including quick sand by forming a cylindar of frozen ground, following by the ordinary method of	←	Freezing Process
				Through the aquifers using rotary drills equiped with roller cutters	←	Shaft Drilling
				Using shaft borers (SBMs) includes shaft lining and equiping facilities, laser beam, mechanical direction, control device, water handling and ventilation system.	←	Shaft Boring

Based on the aforementioned review on the shaft sinking methods and properties, the shaft components include; first, all the physical parts of the shaft based on the sinking method and second, all the auxiliary equipment which is needed to excavate and operate the shaft. These components are: 1- Shaft Collar 2- Shaft initial (primary) liners 3- Shaft final (permanent) liners 4- Shaft base slab 5- Auxiliary components such as excavation (i.e., mesh segments, timber piles), hoisting, ventilation, lighting, safety, centering, dewatering, and accessing tools (i.e., tools to transfer crews, cranes, equipment). Table 2-3 represents the components of a tunnel shaft in different ground conditions, and for various excavation methods. As stated earlier, understanding the shaft properties, the designed excavation method, and the required resources will assist in modeling the whole tunnel project.

Table 2-3 Shaft Components

<table>
<tr><th>Ground Condition</th><th>Shaft Size</th><th>Excavation Method</th><th colspan="3">Lining Method</th><th colspan="2">Shaft Components</th></tr>
<tr><td rowspan="3">Soft and competent ground with no or controlled ground water</td><td rowspan="2">Small</td><td>Machine Excvation using clamshell bucket and crane</td><td rowspan="3">Pre-cast Segmental concrete by underpinning</td><td rowspan="3">In-situ Segmental concrete</td><td rowspan="3">Piling Sytem, Soldier pile and lagging, Ribs and lagging, slurry walls</td><td rowspan="3">Pre-cast or in situ concrete segments, piles (timber/steel/ concrete), H- Piles, horizontal rib and vertical lagging</td><td rowspan="5">Concrete shaft collar - Base slab - and Auxilary components such as excavation, hoisting, ventilation, lighting, safety, centering, dewatering, and accessing tools</td></tr>
<tr><td>Dry drilling methods using augers and bucket excavators mounted</td></tr>
<tr><td>Large</td><td>Backhoes and Dozers equipped with rippers</td></tr>
<tr><td>Self supporting rock</td><td>–</td><td>Drilling/Blasting or Raise Drilling/Boring Method</td><td colspan="3">Shotcrete, Rock bolts and Wire mesh, Segmental concrete</td><td>bolts, wire mesh, concrete segment</td></tr>
<tr><td>Weak soil and excessive ground water</td><td>–</td><td>Cementation, Freezing, Dewatering + Machine excavation</td><td colspan="3">Segmental shaft by caisson sinking (wet/dry caisson)</td><td>prefabricated lined shaft</td></tr>
</table>

2.4.2 Tunnel

In a tunneling project, construction of the tunnel itself is commonly the costliest part of the whole project. A significant amount of time is devoted to excavating and lining the main tunnel. Therefore, successful implementation of the tunnel element is considered as a satisfying performance for the overall tunnel project (Al-Bataineh, 2008).

The vertical depth and general location of a tunnel defines its major specifications such as support, excavation method, portal, and capping/overburden. For instance, construction below the ground water level necessitates a prefabricated support, or for tunnels in urban areas a minimum overburden is necessary to provide enough stability; otherwise the preferred method is locating the tunnel at shallow depth using the cut and cover method (Tatiya-b, 2005).

The purpose of the tunnel defines the appropriate size for the tunnel section. Important factors affecting the tunnel size are maximum dimension of the equipment and material employed during construction, as well as the tunnel's anticipated function. Moreover, a clear distance from the sides, thickness of the support, and sufficient space for pedestrian and facilities need to be considered when designing the size of the tunnel. Using tunnel borers dictates a circular or elliptical shape. Although a circular shape provides better stability, effective utilization of the space is a major challenge. Equipment selection for the tunneling method is highly dependent upon the length of the tunnel. In shorter tunnels, applying conventional methods is the common practice while in case of long tunnels, tunnel borers and innovative methods result in more technically and financially effective products (Tatiya-b, 2005).

There are different methods of tunnel construction. Some of the most conventional methods are shield tunneling and the drill/blast method (Deulofeu et al., 2007). Tatiya-b (2005) proposed a comprehensive classification for driving techniques that are commonly used in mining and civil tunnels. Figure 2-2 shows the varieties of driving methods in civil tunnels.

In the drilling and blasting method for tunnels, similar to shaft sinking, the pattern design and the number of the holes define the size, shape and orientation of the resulted cavity. This excavation method has different variations, as shown in Figure 2-2, based on the nature of the holes or cracks made in the tunnel’s face. However, the undergoing procedure in most cases is similar.

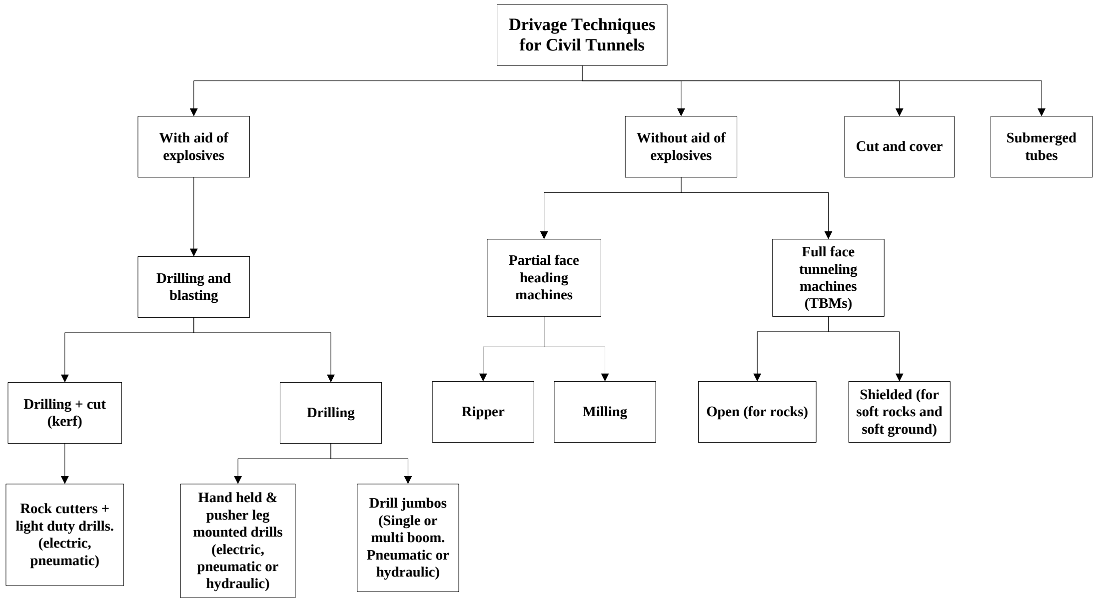


Figure 2-2 Tunneling Methods from Tatiya-b (2005)

It is composed of a repetitive cycle of activities; 1- Drilling the blast holes (parallel or angled pattern) 2- Charging the holes with explosives 3- tamping 4- blasting using electric detonators or detonating cords 5- ventilation 6- removing the blasted rock (mucking) 7-scaling the crown and walls to remove loosened pieces of rock 8- installing temporary support and finally expanding the railing, ventilation and other utilities to start the next cycle (Kolymbas, 2005). The drill and blast method is suitable for rock excavations especially where the tunnel section is a non-circular shape and thus using TBM machines is not recommended. A vast variety of lining types is applicable after excavation through drilling and blasting. The most common technique is cast-in concrete. Although most tunnels are advanced, using full-face drilling and blasting techniques, in some cases partial face advancing is inevitable because the tunnel section is too large to be drilled and blasted in one cycle. Furthermore, the weakness of the ground and unstable excavated surface limits the width of the blasted section (US Army, 1997).

In partial face heading techniques that use ripper type roadheaders, the full weight of the machine performs as a counter reaction force to actuate the cutter head.

Whereas in milling type roadheaders, a cylindrical or cone shape cutter head rotates in line with the axis of the cutter boom. Also, borers are utilized to perform partial face excavation in which a hole with a large diameter is bored from the face of the tunnel (Tatiya-b, 2005). Roadheaders are not only applicable for partial face excavation, but they are also capable of performing full-faced excavations either for small or large tunnel chambers (US Army, 1997). Excavation with hydraulic impact hammers is suitable for full-face excavations in foliated and jointed rock mass grounds. This machine excavation is utilized by a 3000 kg hydraulic hammer with impact energy of 6000 Joules (Tatiya-a, 2005). Figure 2-3 shows different types of machine excavators for tunneling purposes in different ground conditions and tunnel boring machines (TBMs).

Tunnel excavation with the aid of TBMs is suitable for any kind of soil condition. This complex equipment includes the cutter head utilized with cutting tools, and mucking buckets along with a power system, cutter head rotation, and a trust system to maintain the stability and basis for TBM movement through the tunnel direction. It is also equipped with a lining installation system, shielding to protect the working crew, and a steering system (US Army, 1997).

TBM excavation is either "open" for rock tunnels or "shielded" for weak or jointed rock/soil. Figure 2-4 shows a general classification of the TBM method. When the excavated rock mass is caving in, the shield is required to protect the TBM. In the case of excavation under the ground water level, a close face shielded TBM is required. The closed face shield maintains enough pressure to provide support against soil or water inrush through the utilization of compressed air, pressurized slurry, or an earth-pressure-balanced (EPB) shield.

Compressed air increases the hazards in the working area and imposes many difficulties when performing the excavation procedure. These difficulties are lessened by using a pressurized slurry (mostly a bentonite suspension) or by forming mud from the excavated soil (EPB shield). In the latter option, extra provisions are needed to control the excavation (Kolymbas, 2005).

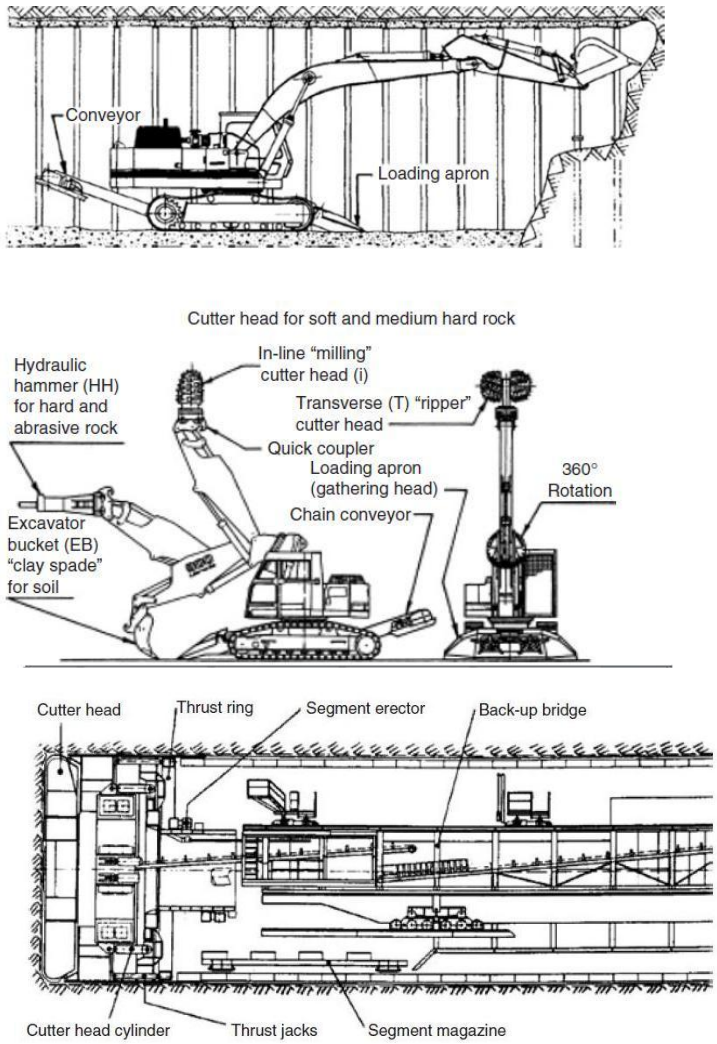


Figure 2-3 Tunnel Excavation Roadheaders, Impact Hammers and TBMs from Tatiya-a (2005)

The "Cut and Cover" method is very common for shallow tunnels especially in soft grounds. In this method, either before or after excavating the whole width of the tunnel, trench walls are constructed at the sides of the tunnel alignment using conventional methods; then the roof slab is constructed and followed by back filling and surface resuming activities (Tatiya-b, 2005).

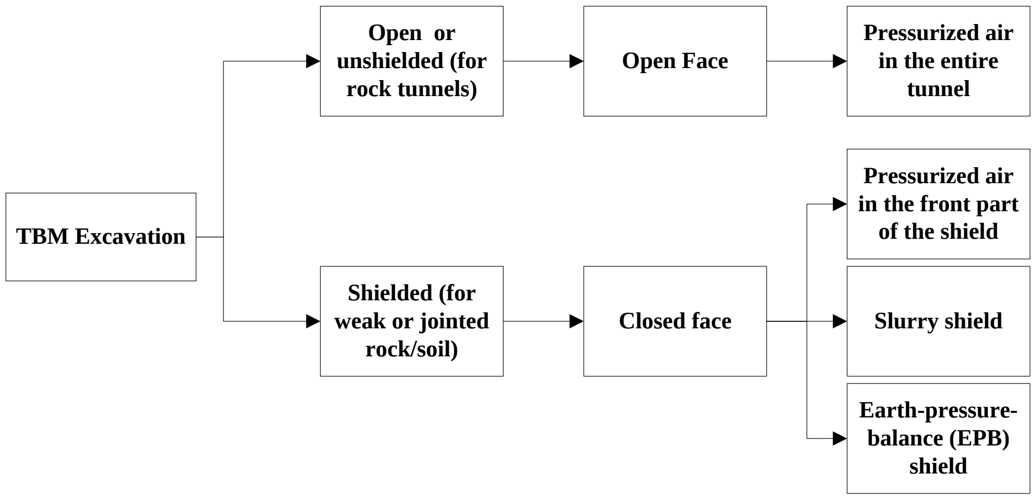


Figure 2-4 TBM Excavation Method Classification

For tunneling under the water bodies, two methods are available. The first method considers a backfilling ground between the tunnel and water mass and then, the tunnel is driven under the water body using borers. In the second method, prefabricated steel tubing or reinforced cement concrete build the tunnel by constructing a trench under the water level (Tatiya-b, 2005).

In tunneling through unstable, weak, or abrasive ground, treatment methods are applied to ensure stability during excavation. These methods are usually required in weathered ground/rocks, soft ground conditions, and in grounds with excessive joints or inflow of water. In these conditions, major ground treatment methods are reinforcement (with the aid of bolts, anchors, and surface coaters or prefabricated concrete blocks) and actions that alleviate the presence of water in the tunneling site. The methods for reducing the water impact on tunnels include lowering the water table, or alternatively, using pressurized air to hold the water back. Grouting and freezing, similar to ground treatment for shaft sinking, are common methods in the presence of excessive amounts of ground water (Tatiya-b, 2005).

In a tunneling project, the lining process of the main tunnel itself exceeds more than 80% of the tunnel construction costs (Kolymbas, 2005). The lining for the tunnel, similar to the shaft lining, includes temporary and permanent supports.

The temporary support aims at providing a short-term safe working environment, whereas the permanent lining has a long performance time through the lifespan of the tunnel. There is no need for temporary linings while tunneling in rock and competent ground. In this case, shotcrete can be used as a permanent support for the operation period. Secondary support is applied as a finishing surface that does not bear any load, but it gives certain desired shape to the permanent lining. Secondary lining can also act as water proofing, sealing, or a fire resistant coating for the permanent support. Table 2-4 shows different methods of tunnel lining based on Tatiya-b (2005) classification.

Table 2-4 Tunnel Lining Variations

Tunnel Support Types	Comments
Natural (self support)	In competent rock
Rock reinforcement using rock bolts, rock dowels, and rock anchors	Majorly acts as temporarily support during tunneling operations
Segmental supports in shape of cast iron, steel, or reinforced concrete tubings	Segmental tubing lining is rarely used in tunnels whereas it has a vast application in shaft lining.
Steel sets or rolled steel joist (RSJ) supports	In cases, where a fractured rock mass is faced in excavation and rock bolts are not sufficient, this support is used as temporary lining and usually followed by permanent supports
Concrete supports monolithic (cast in place) or prefabricated segments or blocks	Monolithic concrete support is suitable where strata movement is negligible and tunneling includes handling excessive amount of underground water
Shotcrete	Majorly used as temporary support before installing permanent support. It also prevents slabbing of the tunneling surfaces right after excavation
Wooden support	In weak and soft ground, timber for-poling is used as a mandatory and temporarily support

2.4.3 Tail Tunnel and Undercut

After reaching to the tunnel level through shaft sinking and installing the pump and required sump at the bottom of the shaft, preparations are necessary to commence the tunneling process. These preparations include the initial setup and arranging for sufficient space in order to install tunneling equipment and handling materials. The initial setup organizes the tunneling equipment and facilities for dirt removal (i.e., TBM, conveyer belts, trains, tracks) (Zhang et al., 2010). The requirements for providing enough space are commonly established by the tail tunnel and under cut at the bottom of the shaft and the beginning of the tunnel alignment.

A tail tunnel provides suitable space for handling material and equipment. It also provides enough room to avoid interruption in the sequential tunneling process. The undercut is constructed at the beginning of the tunnel alignment to further help for TBM and other equipment assembly. The common method for excavation and lining of these elements are hand excavation and rib & lagging (Al-Bataineh, 2008). Other than excavation and support of major components in a tunneling project, supplemental activities in underground constructions are site and portal preparation, surveying, ventilation, drainage, water control, hazard prevention, and finally controlling environmental effects (US Army, 1997).

2.5 Tunneling projects - Associated Risks, Problems, and Solutions

Tunnel projects are associated with a higher amount of risk during their design, construction, and exploitation process compared to other civil engineering projects (Thomas and Banyai, 2007). These risks originate from unpredictable conditions in the geology of the tunnel, weather conditions, third party impacts, contamination, procurement methods, and the project's unique specifications such as location, orientation, and purpose.

An unexplored environment, as one of the key factors, generates various uncertainties that need to be controlled and mitigated in tunneling projects (Wood, 2000). There are multiple sources of risk for tunnels that depend upon the environments where they are located. The tunnels in urban areas suffer from their unknown interaction with surrounding structures during the construction and operation process (Thomas and Banyai, 2007). Moreover, tunneling in congested cities requires dealing with complicated constraints and probable hazards such as pollution and decreased serviceability during the construction period (Roisin, 1992). In the tunnel projects located in areas with low accessibility, reliable knowledge on the properties of project site is not easy to achieve. Further investigations, based on ground models and evaluation tools, are necessary during the planning phase. These evaluations are continually refined and updated during the construction phase, in which more information is revealed as the tunnel excavation progresses (Solak, 2009). Therefore, the criticality of tunnel projects and associated risks have resulted in a high demand for the development of enhanced risk management (Thomas and Banyai, 2007) and good project management practices (Roisin, 1992). Roisin (1992) mentioned that the principals of good management practices are identical for underground projects and typical engineering projects. However, tunneling management requires the consideration of a wide variety of integrated constraints to satisfy the requirements of all the participating factors.

Different remedies have been proposed to respond to the risk factors in underground projects. For instance, Thomas and Banyai (2007) recommended a hierarchal approach to confront risk factors. This hierarchal approach includes initially, trying to remove the risk factor and in the next step, using mitigation methods to decrease the consequences of the risk factor. Probable protection against risk factors would be the final remedy.

However, despite of extensive precautions and mitigation strategies to reduce risks, a set of frequent problems is common practice in a significant number of tunneling projects. Disputes between project parties, major cost/time overruns (Abramson, 1998), and serviceability problems (Thewes et al., 2007) frequently happen in tunneling projects.

The major causes of disputes result from the misunderstandings and misrepresentations during the planning/design or construction phase of the project. However, tracing the causes with the goal of eliminating the problem or avoiding a future occurrence is not viable, since the project phases are discontinuous and are managed by different parties, systems, or attitudes. Therefore, finding the root of the problem requires a significant amount of time and energy (Abramson, 1998).

Wood (2000) identified that the dissociated nature between management and the engineering sections involved in delivering a tunnel project is a major rationale for these downfalls. Moreover, the conventional method of sharing and transferring information between different sectors results in missing information and the accumulation of substantial errors.

Abramson (1998) described the probable problems and their consequences during the design and construction phases as a result of aforementioned dissociated nature. Table 2-5 shows the potential pitfalls that are exclusively relevant to information exchange, based on Abramson (1998).

Table 2-5 Potential Problems during a Typical Tunneling Project

PROBLEMS IN A TUNNELING PROJECT
Design phase through construction process
Insufficient or incorrect interpretation of geotechnical data
Insufficient disclosure of geotechnical data to the contractor
Poor integration of geotechnical data into design
Insufficient data given in plans
Insufficient data given in specifications
Poor coordination of plans and specifications
Inadequate or duplicate dimensioning on plans
Poor coordination with adjacent contracts
Poor control of owner and third party expectations
Construction phase
Inaccurate interpretation of design intentions in construction process
Inadequate monitoring of work progress
Poor concurrence of designer and owner
Excessive amount of Change Orders (OC)
Excessive amount of Request For Information (RFI)

On the other hand, underground infrastructures including tunneling projects are highly sensitive to service availability problems. These problems stem from inaccuracy during the design period, unsuccessful design implementation during construction, and improper maintenance plans. To ensure that a tunnel project is implemented successfully, a robust management system is needed to both attain and transfer data throughout the project lifecycle. An accurate facility management system management system that is supported by “preventive and proactive” methods is capable of increasing the lifespan of the project and reducing maintenance costs. Aside from operational solutions for design specifications, proactive methods such as applying data collection strategies to gather information -reusable for future projects- and developing a central database were recommended. Thus, all of the tunneling information can be transferred throughout the project lifecycle, from the planning and construction phases of the project to the operation phase. This integrated system creates an optimized facility management plan (Thewes et al., 2007).

A combination of factors should be satisfied in order to accomplish a successful tunnel design. The scope of the project needs to be clarified and agreed upon amongst all participants. The performance criteria require constant adjustments as the construction work proceeds. The collaboration of a unified design team results in a higher level of understanding and clarification among project participants. Moreover, early identification of potential risks enhances the quality of the future decision making process (Wood, 2000). In this context, proper flow of information between the different parties and throughout the project lifecycle is essential to maintain the integrity of the design specifications and facilitate the risk management process of the tunnel project.

2.6 An Overview of Previous Solutions for Managing Information and Processes in Tunneling Projects

Underground and tunneling construction management relies on multiple factors, constraints, and variables. New demands, modern techniques, and extra complexity in tunneling projects also contribute to the challenges in the management process. Improvement in the management process requires replacing traditional techniques with modern management processes in design, construction, and procurement (Reilly, 2000). Meanwhile, the new techniques in managing the tunneling projects, call for dealing with the overwhelming amount of information that needs to be analyzed and interpreted during a project lifespan.

2.6.1 Information Systems

A strong medium to deal with the abundance of information is information systems. Information systems provide unbounded structured frameworks to capture, store, and recall knowledge. Case-Base Reasoning (CBR), data warehousing techniques, anthology for construction cost estimation, and integration of Computer Aided Design (CAD) and Geographic Information System (GIS) data are examples of such efforts in developing structured information in construction projects to enhance the decision making process (Lee et al., 2009).

The body of research, which is specifically focused on information management of tunneling projects, is not substantial. In fact, the majority of the studies focused on the management of a fragment of information. This fragment was obtained from isolated investigations and further employed to promote a particular aspect of the tunneling process. The resulting structured information is organized and defined in a particular format, practical for the special sub-processes. Although, each isolated system specifically enhances the knowledge and understanding in a particular area and helps to improve the decision making process, the valuable inputs and results of the system is not applicable to other design and planning sub-processes. On the contrary, the studies that focused on a comprehensive information management for the entire tunnel project data during its lifecycle, is scarce.

A lot of effort was put into setting up databases on ground information, which resulted from geological studies, for the purpose of employing them in the design and planning processes. Identifying the accurate state of soil layers and ground conditions is a vital process during any underground construction project. Interactions between soil and underground structure impose a high level of uncertainty in the planning and management process. Maurenbrecher and Herbschleb (1994) examined the valuable application of INGEOBASE geotechnical database, initially set up for a 4 square kilometer area of the west central district of Amsterdam, in a subway tunnel planning and design. The cone and borehole penetration data derived from INGEOBASE database were expected to produce subsurface maps that would be valuable for the planning and design of the tunnel project. The most valuable outcome of the research was the emphasis on the beneficial contribution of computerized information management systems for tunneling projects. Such information systems were proposed to go beyond the geotechnical data and cover other aspects, such as underground utilities and land use, for potential applications in anticipating hazards and developing tunnel design.

2.6.2 Decision Aid Systems

Anthologies, called Decision Aid for Tunneling (DAT), developed by Einstein et al. (1999), is capable of incorporating tunnel standard information and thus considering associated uncertainties in the management process. These computer-based tools employ the geology of the tunnel along with simulation to produce distributions for cost, time, and resource allocation. Also, the effect of applying different methods such as diverse drilling patterns or lining methods can be analyzed and assessed prior to the actual construction process. Hence, Applying

DAT in the decision-making process helps to consider the associated risks more effectively. Although DAT anthology as a group of versatile tools enhances the management of the whole process, the final products are in a form of simulated results that are required to be incorporated in the design specifications and construction process. In other words, the results of DAT is an exclusive recommendation for further decisions in the tunneling process and in fact, the interference of an expert is needed to employ these outcomes in the actual modeling of the tunnel. Thus, physical re-entering and manipulation of simulation results are essential to use the results in scheduling, cost estimating, and designing applications. Moreover, a new version of DAT, capable of updating the information, was proposed in Has and Einstein (2002). The updating approach allows enhancement of the initial information that entered prior to the construction phase. Therefore, the new information from the already performed job can be used not only in fixing the previous assumption, but also in improving the predictions for the future segments. Nevertheless, the aforementioned problem, which involves the participation of a third party individual or application to interpret the data, remains intact. Therefore, an extra effort is required for analyzing and applying the resulting information that was offered in the form of a cost-time scatter gram.

Carnevale et al (2000) developed GeoScan-32™ for the acquisition and management of a large quantity of tunnel information. GeoScan-32™ is a proprietary integrated image and data management system designed by Hager GeoScience, Inc. This integrated tool facilitates effective collection and management of geological data generated in the Metro West water supply tunnel constructed by the Massachusetts Water Resource Authority. The system is capable of storing and retrieving the mapping data for future projects. In addition, data querying is available to evaluate the results. Even though the generated results by the GeoScan-32 system are in the form of reports, integrated map/data format, data tables, and graphical representations of structural data for the design team, they need to be interpreted and translated further in the design process. Thus, the integrating process is manual and automation is not possible.

An expert system was developed by Yu and Chern (2007) to provide a multi expertise decision making tool for drill and blast tunnel construction in Taiwan. This expert system is capable of supplying a rational estimation of tunnel deformation and construction procedure based on the selected support system by using an artificial neural network approach. The system comprises of a data bank, tool bank, and a decision making auxiliary system. The tool bank includes various subsystems to carry out data collection, construction simulation, safety evaluation, deformation prediction, etc. Each subsystem processes, evaluates, and analyzes the required data collected in the data bank and produces the associated result. Therefore, the results of the expert system are in form of isolated or unstructured data that need further manipulation to apply to the design process. For instance, the prediction of a suggested support system is provided in form of a table containing the support type and its associated advance rate, rock bolt length, shotcrete thickness, and steel rib size. Although these parameters help to discover the best feasible support system for the drill and blast process, they are single results with no connection to other parts of the system, such as simulation model. They require to be re-generated in other design subsystems for further analysis and finally complete the design process.

2.6.3 Operation Simulation

Operation simulation also vastly contributes to an enhanced project management process in underground projects and helps to control the uncertainties through the handling of knowledge and information. Operation simulation is an effective solution to assist construction managers with planning large scale and complex projects. Construction simulation emerged in 1970s to help construction managers with enhanced project plans, optimized resource allocation, and easier conflict detection that aimed at reducing the cost and duration of construction projects.

Discrete-event simulation is the most common procedure in managing construction projects (AbouRizk, 2010 & Lu et al., 2007). Simulation tools assist in experimenting with different scenarios, thus eliminating factors of uncertainty. During the preconstruction phase, different alternatives are proposed and discussed to produce the final product or to advance the project's improvement. Multiple factors are considered to evaluate the alternatives and assess the possible outcomes, such as evaluated risk, cost, schedule, and production. Simulation operation tools assist in evaluating each alternative by creating an imitated computerized model, which is an abstract representation of the project (Al-Bataineh, 2008).

According to AbouRizk (2010), the development of simulation theory in academia was implemented through three main stages. The emergence of the first stage goes back to the late 1970s by introducing CYCLONE developed by (Halpin, 1977). The capability to model cyclic operation coupled with special simplicity is considered as its major advantages over Critical Path Method (CPM). However, it is not suitable in allocating a complex chain of resources. Several enhancements have been implemented to eliminate this limitation and develop improved versions of CYCLONE. The second stage in developing simulation tools evolved with the assistance of revolution in programming tools and introducing the object-oriented programming concept. Thus, a new generation of simulation tools such as CIPROS (University of Michigan), MODSIM (Pennsylvania State University), STROBOSCOPE (Purdue University), and Simphony (University of Alberta) has been introduced. This new collection of simulation languages has highly contributed to the overall advancement of the modeling process that was empowered by integrating programming capacity and "*user written code*" capability. Consequently, this resulted in visible advantages over the first stage products such as CYCLONE and its improved versions.

However, constructing a simulation model using one of the available tools requires a significant amount of time. Its complexities necessitate employing a professional modeler to achieve the final reliable model (Shi & AbouRizk, 1997). Each simulation tool possesses a number of different elements that are complex and time-consuming to employ because it creates a complicated networks of elements. Also, sufficient programming capabilities along with satisfactory skill and experience level to precisely validate the model and its final results are among the necessary requirements of the simulation modeler. Interpreting the statistical results is complicated and implementing a spatial analysis in the absence of any visualization aspect in simulation tools is not possible (Ting, 2008). The statistical form of results in simulation systems and the lack of a visualized outcome have dragged the industry's attention to a more tangible form of reviewing what-if scenarios and alternative analysis. The conventional method of simulation outputs, which generates solid statistical results, has made it difficult for the AEC industry to take advantage of the simulation capabilities (Zhang et al., 2010). It stems from the fact that construction parties are usually seeking to find visualized and easy-to-interpret results, which simplify the decision making process and help to engage almost all of the factors in the final decision. For instance, three-dimensional (3D) visualization has been proved to significantly enhance the representation of simulation results and therefore attracts more desire to be applied in the planning process in actual real-life projects (Kamat and Martinez, 2001).

The burden to re-enter the data in case of a change or update is another factor for limited use of simulation (Zhang et al., 2010). Moreover, the current statistical results in the form of tables or graphs require a trained professional to evaluate the outcome and present it as an apprehensible report usable for general constructability reviews and meetings. Thus, the use of the simulation tools by all the inexpert sectors of the industry is limited and this in turn reduces its popularity. In spite of implementing advanced research studies in academia on simulation operation, the construction industry does not recognize it extensively as an applicable and effective method to support the management and decision making processes (AbouRizk, 2010). Even though simulation operation has been investigated and analyzed in construction research groups for more than three decades, and its merits are undeniably proved, the construction industry is hesitant to apply it extensively in real projects (Hajjar & AbouRizk, 2002). These shortcomings have led to the emergence of the third stage simulation applications (AbouRizk, 2010).

Further improvements forming the third stage in simulation technology are employed through integrating systems where the combination of a popular commercial application and a simulation tool utilized to handle the management process in a project. The integration of 3D CAD models and a simulation system is an excellent example of the third stage (AbouRizk, 2010). Development of special purpose simulation tools and integrated systems has encouraged the industrial section to utilize simulation operation in the management process of construction projects. Numerous examples of successful cooperation between the construction industry and the simulation lab at University of Alberta illustrate the assured potentials of operation simulation as a robust tool to improve and handle the management and planning process in construction projects (AbouRizk, 2010). In this regard, a construction synthetic environment (COSYE) was developed based on High Level Architecture (HLA) standard and distributed simulation technology (AbouRizk and Hague, 2009). HLA is a standard for complex models developed by the United States Department of Defense (DoD) and is capable of integrating different simulation models (federates) in a unified virtual environment (federation). Its run-time interface (RTI) utilizes the data flow between federates and supports communication among components of the federation environment (Zhang et al., 2010 and Al-Bataineh, 2008).

Ruwanpura et al. (2004) developed an analytical approach coupled with a simulation environment to identify accurate soil levels and anticipate their behavior before actual tunnel construction commences. Although determining actual soil layers in the pre-construction process via drilling boreholes in the field have become the common practice, assumptions should be taken to picture the soil profiles in distances between the boreholes. Using the proposed system, the assumptions were replaced by accurate results from the simulation environment. However, the system required a huge amount of data -related to the field test samplers- to be fed into the simulation environment. The data entry may include errors and redundant information that mislead the ultimate estimates and increased the uncertainties in the decision making process. Therefore, larger margins would be considered to compensate for risks during excavation and tunneling construction. The greater risk margins can increase the probability of unnecessary costs and result in lost efficiency. Moreover, six simulation tools for managing underground infrastructure projects were introduced by Ruwanpura and Ariaratnam (2007). Special purpose simulation (SPS) (Hajjar and AbouRizk, 2000) and rule-based simulation (Ruwanpura and AbouRizk, 2001) concepts were used to develop simulation environment specifically for underground projects.

Although, integrated simulation tools have significantly proved their strength in simulating construction processes, seamless interoperability and information exchange is still not achievable between simulation environment and other applications. In an HLA-based distributed simulation environment, the federation object model (FOM) provides interoperability among federates and prescribes the data that needs to be shared within the simulation model. It facilitates communication between federates and includes all the object classes and data types embedded in each federate represented in a tree-shape hierarchy (Zhang et al., 2010). This capability assists to develop specific simulation components that mimic the real processes in a specific area (e.g., weather condition and equipment breakdown) and allows developers to focus on each process individually which can result in a standardization of simulation environment for a specific process and utilizes reusability of the simulation components for future projects (AbouRizk, 2010). All the aforementioned procedures need to be applied in a structured simulation framework based on HLA standards. Thus, despite of the significant contributions of such a simulation environment, seamless interoperability is still not accessible merely by incorporating different models. Because of the variety of the participants and software applications used to design and analyze each process, not all the information packages and data models are compliant with HLA standard or any other simulation based specifications. Any process modeled in any other software application needs to interface with RTI to be considered as a HLA-compliant federate that matches with other parts of the simulation model (AbouRizk, 2010). Extensive programming and coding are required to achieve a compliant model. Moreover, it is not feasible to develop a compliant model for each specific process and participants are probably not willing to change their previous platforms and procedures and adopt new standards and applications in their processes. Therefore, extensive sharing and exchanging of information between other applications and the simulation environment is not feasible. Consequently, part of the limitations described in the second stages of the simulation development in academia (AbouRizk, 2010) still persists in simulation applications and reduces the industry's appetite for adopting such a practice in real projects.

Li and Zhu (2009) defined a framework that focuses on geometrical modeling, operation sequencing, and dynamic updating of ground excavations for the visualization and dynamic simulation of underground projects. A great amount of effort was devoted to enhance the efficiency of the visualized model. In this regard, techniques such as layering the visualized objects, Level of Detailing (LOD), querying special information from the model, and thematic viewing were employed. Although the final model exclusively addressed the visualization issues of the model and improved the participant's knowledge on the project characterizations, it lacked any remedy for information management during the tunnel project life cycle.

Zhang et al. (2010) improved the modeling process in tunnel construction simulation by employing 3D CAD modeling and visualization techniques. The proposed model was created to integrate the 3D model data and tunnel simulation. A tunnel information model consisting of tunnel attributes and geological data was proposed. The 3D visualization model projects the results of the HLA-based tunnel simulation environment. The integration process is proved to simplify the application of simulation tools and promotes simulation use in the construction industry. However, the information model used in the federated simulation architecture is based on a conceptual product model designed for this project as the exchange format. Therefore, the integration process based on this proprietary data structure may not be efficient for other projects in which the participating disciplines perform based on a dissimilar data structure. Moreover, the system requires extensive preliminary coding and collaboration between different segments of the project process to fully adapt to the integrated system.

Li et al (2012) developed a web-based monitoring tunnel management system, which integrates the geological information and construction parameters to provide a robust platform for data analysis. The system acquires the monitoring data automatically. The collected information is visualized through two-dimensional (2D) and 3D views. Thus, the system provides a comprehensive management tool to acquire and handle a range of information that can be shared among project parties. Although the system integrates the monitoring information, it lacks the capability to exchange the information with design applications and incorporate the results of the design process in the system. In other words, the design or management tools need to read the data through a third application or professional trainer, in order to employ the stored data. Therefore, the web-based system solely acts as a central database for the tunnel information and is not capable of exchanging the information with other design applications, or contributing actively to the design process.

In general, the process of reviewing all of the previous solutions reveals a range of shortcomings, which prevents successful management of information in underground projects. These problems, identified in the previously developed systems as mentioned, are summarized below:

- Generated results are not compatible with other applications. Therefore, they cannot be shared or reused.
- Results are required to be re-entered in other design applications manually.
- Generally, the primary information (inputs of the system) is enormous and entering data is a tedious and time-consuming job.
- The data structure of the system is specific and therefore different from other systems that result in a lack of universal data structure as well as, confusion for the participating parties. Besides, any further amendment or update needs to follow the original information structure definitions in the system.
- In some cases, the system and its targeted sub-processes are not capable of interacting effectively as a result of lack of interoperability. Even in case of providing sufficient tools for exchanges between internal sub-processes, there might be other streams or disciplines that are not fully covered. Moreover, the interoperability in the system is commonly provided by a proprietary tool that needs special requirements and specifications to be responsive for varied applications and disciplines in the project. Any other application anticipated to be integrated into the original system, needs to install the proprietary medium designed to connect different parts of the system together. As mentioned before, AEC industry sectors are hesitant to apply changes to their routine and are more likely to use their internal application/platform/format. Therefore, there is no standardized data exchange method between different components of the system.

- The majority of the systems are unable to project changes and updates during the project lifecycle, which makes them incapable of adopting further analysis of the changed results.

In the following sections, the recommended remedies to avoid the aforementioned problems in general construction projects are reviewed to find a final solution applicable to tunneling projects.

2.7 Integrated Project Systems and Collaborative Construction Management

Construction management tools are individually successful in coping with a convoluted network of construction tasks and complex architectural aspects mixed with an overburdened amount of data. However, the incompatibility of standalone applications used by project participants along with inefficient information flow between project participants causes cost/time overruns, since the efficient exchange of information requires extra efforts. Lack of integration and collaboration between the project's down streams necessitates the duplication of information to implement the isolated project processes.

The modern construction industry requires a collaborative teamwork process to operate in a multi-stakeholder global environment. The key factor for successful performance in the competitive market is through partnering and collaboration among the working society which consists of owners, architects, designers, contractors and construction/facility managers (Xue et al., 2012). Cheng et al., (2001) identified the fundamental functions of the partnering systems in both real and virtual environments as receiving, storing, retrieving, and coding. An IT collaborative working environment promotes information sharing and compensates for the data gaps among distributed project participants. According to Xue et al. (2012), the use of IT solutions to provide collaborative work has significantly promoted the integration of fragmented segments of the construction management process.

Tunneling projects are associated with high uncertainties and accumulated risks (Ruwanpura and Ariaratnam, 2007). Participation of so many individuals and disciplines along the project life cycle, despite strict administration, resulted in applying fragmented elements during the design and construction of tunnel projects. Thus, tunneling projects have suffered from lack of adequate integration and high volume of construction information. The fragmented nature of tunneling projects, similar to other construction projects, is caused by the information gaps between project phases. Halfawy and Froese (2005) affirmed that the information gaps, coupled with financial constraints and market competition, have contributed to the vast demand for integrated project processes and integrated software systems. They claimed that adopting an integrated approach in project delivery systems and software applications would significantly decrease the planning and construction cycle time and improve the overall lifecycle efficiency of the project.

The efforts to find coherent IT solutions for the AEC industry has been a major goal in several research studies since the 1980's. IT-supported collaborative work played a prominent role in design, construction management, and integrated inter-organizational management information systems. The collaborative integrated inter-organizational management information systems (IIMIS) facilitate the management of the project information during the project lifecycle. Data transfer among project parties is the most important enabler in IIMIS systems. Therefore, the consistency of the data format and data structure plays a prominent role in performing successful data transfers between project segments (Xue et al., 2012). In this regard, seeking to find standard data structures have been the topic of many research studies in the last two decades.

To better understand the functionality and infrastructure of integrated project systems and apply the integration concept to tunneling projects, it is essential to recognize the most important trends in this regard;

- Four-dimensional (4D)/five-dimensional (5D)/n-D Construction Management
- BIM modeling
- Construction Virtual Prototyping (CVP)
- Standard Data Models (i.e., IFC, CIMSteel Integration Standards (CIS/2))

2.7.1 4D/5D and n-D Construction Management

Traditionally, 2D paper-based drawings were the common method to illustrate the intensions of the designer. Currently, the 2D model uses graphical elements such as lines, curves, and extra annotations to graphically represent project components. This 2D model lacks semantics to precisely document the intentions of the designer. The concept of layering in CAD products is adopted to give mutual meaning to the group of elements in one layer and eventually made it easier to understand the notion behind the simple drawings. The emergence of 3D modeling assists in the improvement of the visualization of the drawing components. It offers to picture a realistic outlook of the actual world (Howell and Batcheler, 2005).

Moreover, implementing a 3D modeling process improves efficiency in comparison to the conventional 2D drawings. Even adopting the principles of 3D modeling in the design process, with least possible interoperability (physical exchange of 3D model between architectures, prefabricators, and contractors) boosts productivity significantly from 20.3% to 47.4% (Sacks et al., 2005). The demand for integrating design and construction information in the AEC industry has been a motivation for the incorporation of the management tools with 3D CAD models and the production of multi-dimensional project models (Zhang et al., 2010). Various integrated systems have been developed in the previous studies that emphasized the practical integration of the 3D model with other management tools, such as scheduling and cost estimation. Time related data as the 4^{th} dimension and cost related data as the 5^{th} dimension are added to the 3D model project's data. The results of such incorporation produce 4D and 5D project models.

An n-dimensional (n-D) model represents an extended information model that integrates all the knowledge and information during project lifecycle (Aouad et al., 2008). Incorporating multiple design specifications in a data model allows different views of the information to be included in the data model concurrently. These dimensions assist in the effortless automation and interpretation of changes, updates, and amendments in any part of the information system.

Popov et al. (2010) developed a 5D virtual building design and construction. The 5D virtual model enables analysis of alternative solutions for project implementation. The proposed model consists of a core 3D graphical BIM model containing quantitative and qualitative information of the object models. The 5D model, which is incorporated with an evaluation system, provides the feasible economic criteria of the project design. Moreover, the virtual implementation of the projects helps to prevent accidents by virtually locating the project components (i.e., cranes, equipment).

Meadati (2007) has linked the Microsoft Project application with the as-built 3D model to generate an as-built 4D model for depicting the actual daily progress of the project. The partial improvement of visualization is the key advantage in the proposed model. Generally, during the construction progress, there are times in which only a percentage of the whole building element is completely finished. Typically, the elements in the 4D model can exclusively show the final completed shape of that element. However, this real-time 4D representation of the actual progress helps to visually represent real improvements in each element.

Several construction planning methodologies have been developed by integrating 4D CAD and operations simulations that aim to contribute to the what-if scenario in the decision making process (Lue et al. 2007). A management system called four-dimensional graphics for construction planning and resource utilization 2005 (4D-GCPSU 2005) was proposed by Zhang et al. (2006). The intention of this application is to provide large-scale construction projects with a robust management system capable of handling complicated architectural and structural designs. This system stores project information in a central database and includes a 3D model integrated with schedule, site layout, and resources. It is also capable of solving the time conflicts while considering the resource and site layout limitations. The system provides visual schedule planning, which is especially beneficial for non-professional project participants and clients who want to track a project's progress.

Therefore, the n-D model can be defined as an extension of a BIM model with unlimited incorporated dimensions that helps to improve the level of accuracy and consistency of information in the data model (Aouad, et al., 2008). Reviewing some of the developed n-D models in literature (Lu et al. (2009), Tanyer and Aouad (2005), Lu et al. (2007), Huang et al. (2007)) reveals the potential and effectiveness of integrated management systems and illustrates the crucial role of the adequate level of integration despite of their shortcomings described by Ting (2008).

2.7.2 BIM and CVP

The concept of BIM was first introduced in the mid-1970s by Eastman (1975), when the construction industry recognized the urgent need for an innovative information model, which enables the participating parties to incorporate diverse data and create a central model to control the rapidly changing nature of the construction process. Although the embedded idea (utilizing product models) was implemented much earlier in the manufacturing industry, the first attempts to create building product models happened in 1980s (Holt, 2009).

The development of object-oriented product models was the focus of many studies during the 1980s. This trend created new approaches in the computer modeling and drafting industries (Ito et al., 1989). The integration of the object oriented concept with CAD technology evolved as the Object-Oriented CAD systems (OOCAD). The OOCAD not only enhances the visual aspects of the model, but also contributes to the semantics of the model by incorporating the information and relationship in and between different components of the model. Moreover, adding parametric capability by embedding rules and variable dimensions in the object-oriented system extends the embedded intelligence. It allows for a further complex geometric and functional relationship between the model components. In an object-oriented system, even abstract meanings such as void, space, or room in a building project become suggestive of a real element that otherwise, cannot be represented with 2D or 3D models. Therefore, the industry came to thoroughly understand the importance of capturing the proposed richness and intelligence offered by the object-oriented modeling concept during the modeling process (Howell and Batcheler, 2005). The BIM modeling concept is the latest interpretation of object-oriented notion in the building area of the AEC industry. The Ideal BIM model aims at combining the semantics from geometric and non-geometric components of the building elements and this creates a “virtual model in a single project database” (Howell and Batcheler, 2005).

BIM is a comprehensive representation of geometry, spatial relationship, and functional characteristics of a building project model. It describes the whole project lifecycle and facilitates the concurrent contributions of all project disciplines to the project model. The BIM model helps to maintain the consistency and accuracy of the information throughout the project lifecycle (Eastman et al., 2008). As the project progresses over time, the inclusion of more information in the model makes it complete and comprehensive and provides a comprehensive IT abstraction of the real project (Graphisoft, 2003). BIM, as a Virtual Construction (VC) tool, is an emerging process in the AEC industry. Its focus is to assist with generating, storing, managing, exchanging, and sharing information effectively (Vanlande et al., 2008). BIM is an integrated method of managing unbounded construction data during the building lifecycle (Lee et al. 2006)**.** 3D modeling representation, as the main feature of BIM, integrates with data management capabilities and enables users to reach the building data and domain knowledge (Vanlande et al., 2008).

The appearance of the first potential BIM models goes back to the late 1980s and early 1990s, although positive feedback started to emerge only a few years ago (Linderoth, 2010). However, the AEC industry is still struggling to overcome the limitations of BIM, that have sprung from different shortcomings in the technical tools (Holt, 2009 & Vanlande et al., 2008) and the comprehension of the organizational requirements of performing BIM (Linderoth, 2010).

2.7.3 IFC

In general, infrastructure projects consist of heterogeneous data sources and applications performed by the interdependent network of professionals (Halfawy, 2010). The huge amount of information in construction projects necessitates employing IT applications. Although, computerized IT applications ascertain successful management of information in a specialized process, multiple applications and teams are required to organize and analyze the dissociated processes during project lifecycle (Froese, 2003). Likewise, there is no single computer application to carry out all the tasks associated with tunneling projects. The design and construction of a tunnel project depends on a series of collaborative team activities. Each activity and specific professional team is supported by its own computer application. Therefore, similar to other infrastructure projects, adopting integrated approaches proves to decrease management gaps and unexpected conflicts between project parties.

According to Halfawy and Froese (2005), integrated project systems should support the management of project information, integration of project processes, and the implementation of project workflows. Based on Halfawy (2010), successful implementation of integrated project systems is enabled by establishing interoperability among disparate data and software applications across different departments. Eastman et al. (2008) defined interoperability as a catalyst for a collaborative work environment that plays a prominent role to establish data exchanges between applications, eliminates the need to replicate data input, and facilitates workflow and automation among contributing project segments.

Data exchange and seamless interoperability is not possible with traditional ad-hoc methods (i.e., paper-based drawings and documents). The conventional methods are usually associated with a great amount of "*non-value adding activities*" and the risk of information error and loss. A standard information structure assists to achieve the interoperability between project participants. A dominant standard structure requires a neutral file format in order to exchange information and address the interoperability issue effectively in the AEC/FM industry (Froese, 2003 and Eastman et al., 2008). According to Gallaher (2004), lack of interoperability among project sectors and incompatibility of software tools results in approximately a 4.25% loss for the US capital facility industry. Eastman et al. (2008) identified four distinct methods for exchanging data that facilitate interoperability between two applications, presented in Table 2-6.

Table 2-6 Common Exchange Methods between two Applications based on Eastman et al. (2008)

Data Exchange Format	Description	Examples
Direct proprietary link between two applications	*A runtime or binary interface which makes portions of the model accessible for creation, export, modifications, and deletion.*	Archicad's GDL, Bentley's MDL, Revit's SDK
Proprietary File	*A human readable text format primarily dealing with geometry and interfacing with corresponding applications*	DXF (Data eXchange Format) by Autodesk, SAT by Spatial Technology
Public Product Model	*An open standard product model which in addition to geometry carries object, material properties, and relations between objects*	IFC (Industry Foundation Classes) by IAI, CIS/2 for steel
XML-based	*XML is eXtensible Markup Language, and extension to HTML. The XML structure called schema which is suitable in exchanging small amounts of business data between two applications.*	AecXML, bcXML

Until the mid- 1980s, various file formats used to exchange design and construction information in all engineering domains (i.e., DXF, IGES). Application providers prefer direct linking to avoid market demands from reaching their competitors. Direct linking employs the Application's API such as SDK in Revit or GDL in ArchiCAD to make data streaming possible between two applications. On the other hand, proprietary exchange formats are special files in a human readable text format created for an application. This file functions as an interface to represent the data model in its corresponding application. Thus, it represents a specific functionality of the data model. Finally, the most desirable form of exchange is via the use of public formats.

Therefore, the International Standard Organization (ISO) initiated a TC184 committee to develop STEP (Standard for the Exchange of Product Model Data). Table 2-7 shows the most common data modeling standards for infrastructure asset management based on Halfawy et al. (2006).

Table 2-7 Data Modeling Standards for municipal infrastructure systems based on Halfawy et al. (2006)

	Standard Name	Details	Implementations
Spatial Data Modeling Standards	**Open GIS Consortium standards (OGC)**	✓Involves defining standard software interfaces rather than using standard data model ✓ Includes two main sets: abstract and implementation specifications	GML: a set of XML-based schemas and a generic framework for defining domain-specific application schemas
Spatial Data Modeling Standards	**ISO/TC 211 Geographic information/Geomatics standards**	✓The ISO Technical Committee (TC) 211 includes representatives from 33 countries, 17 observing countries, and many external observers ✓Define spatial data models and processes for managing, acquiring, processing, exchanging analyzing, and presenting spatial data	ISO 19107 (spatial schema) ISO 19115 (metadata) ISO 19111 (spatial referencing by coordinates) ISO 19112 (spatial referencing by geographic identifiers) ISO 19136 (GML standard developed jointly by OGC and ISO/TC 211)
Data Modeling Standards	**Federal Geographic Data Committee data standards (FGDC)**	✓Data content standards ✓Spatial Data Transfer Standards (STDS)	Cadastral content standard (FGDC-STD-003) Utilities content standard (FGDC-STD-010) The base specifications (STDS parts 1-3) The profile specifications (STDS parts 4-7)
Data Modeling Standards	**Spatial Data Standards for Facilities, Infrastructure, and Environment (SDSFIE) or NCITS 353**	✓ Many FGDC data content model standards were harmonized with them. However, SDSFIE do not define a neutral data formats for	ESRI's ArcGIS® Intergraph's GeoMedia® Autodesk's AutoCAD Map® Bentley's Geographics®
Data Modeling Standards	**Environmental Systems Research Institute data models (ESRI)**	✓application-specific data models in 24 domains	Water utilities data model
Data Modeling Standards	**LandXML**	✓Primarily defines land and road classes based on XML data models	LandXML
Data Modeling Standards	**Municipal Infrastructure Data Standards (MIDS)**	✓Developed for owners to support efficient collection and management of lifecycle data	A number of road, water distribution networks, wastewater, and storm collection standard data models
Data Modeling Standards	**Pipeline Open Data Standard (PODS) and ISO 15926-2**	✓Originally developed in Oil and gas industry	---
Data Modeling Standards	**Industry Foundation Classes Standard (IFC)**	✓covers non-linear assets such as facilities. It is recognized as the most mature effort to standardize facility design and construction data.	ISO/PAS 16739

The participation of AEC organizations in the TC184 meetings resulted in STEP AP development projects based on ISO-STEP technology such as IFC, CIS/2, AP225, and AP241. However, only IFC and CIS/2 (for steel) are recognized as international public standards today. IFC has become a de-facto in AEC industry to exchange information between participated applications and platforms. These formats provide explicit data models, which carry geometry, attributes and properties of objects as well as the embedded relationship between objects (Eastman et al., 2008). Table 2-8 presents a collection of common exchange formats in AEC industry based on Eastman et al. (2008).

Table 2-8 Common Exchange Formats in AEC Industry from Eastman et al. (2008)

Formats	Application/Properties	Examples
Image (raster)	Data loss as a result of compactness or number of color per pixel	JPG, GIF, TIF, BMP, PIC, PNG, RAW, TGA,RLE
2D Vector	Vary in term of compactness, line thickness, pattern control, etc.	DXF, DWG, AI, CGM, EMF, IGS, WMF, DGN
3D Surface and Shape	Vary in terms of type of surface and edges	3DS, WRL, STL, IGS, SAT, DXF, DWG, OBJ, DGN, PDF(3D), XGL, DWF, U3D, IPT, PTS
3D Object Exchange	Public product models carry geometry, object properties, and relations between objects	STP,EXP,CIS/2
Game	Vary according to type of surface	RWQ, X, GOF, FACT
GIS	Geographical information system formats	SHP, SHX, DBF, DEM, NED
XML	Developed for exchange of building data and vary based on exchanged information and supported workflows.	AecXLM, Obix, AEX, bcXML, AGCxml

IFC is developed by the IAI as a standard data structure for exchanging data sets between different AEC applications. EXPRESS-G is the visual representation of the EXPRESS, which is an information model specification language included in STEP. EXPRESS-G is frequently used to show the hierarchal distribution of main classes and sub-classes in the IFC schema (Arnold and Podehl, 1999). The IFC2x2 version that immerged in 2003 included the capability for exchanging 2D CAD data along with annotations and styles such as text, hatching, etc. from the ISO 10303 and intends to be a more completed version of the IFC standard (Kim and Seo, 2008). IFC2x Edition3, which was mainly a quality improvement of

IFC2x2, was released in 2006. The current version, which was published in 2007, is IFC2x Edition3 Technical Corrigendum1. This version along with IFC2x3 is the most recommended release for implementation (BuildingSMART, 2011)

2.8 Current State of Employing Integrated Information Models and Virtual Construction in Tunneling Projects

Despite successful studies in implementing integration in underground projects, the industry is hesitant to apply such practices to real projects. According to Yabuki (2010), the full application of integrated project systems and virtual construction is limited in infrastructure projects. There is a significant lag to employ efficient product models in civil engineering infrastructures, compared to building construction projects. In the Asian Construction Information Technology meeting held in August 2009, the barriers facing the adoption of new integrated technologies were identified. Based on Yabuki (2010), the major hindering factors are as follows:

- Compared to privately-owned structures, civil infrastructures usually have public ownership with less sensitivity to cost efficiency and business competition. Therefore, the motivation to take the risk of applying new procedures is relatively less than other segments of the AEC industry.
- The uniqueness of each infrastructure project leaves minimum opportunity for recycling the developed project system and its application in future projects.
- Most infrastructure projects are constructed based on Design-Bid-Build (DBB) delivery method that limits the interoperability between project participants. Inadequate collaboration of the construction team during the design process limits the integration degree between project processes.

- The large magnitude of the infrastructure projects, which commonly takes longer than other projects, requires the application of various coordinating and controlling system to track down the state of the project during its lifecycle. CAD tools are not fully equipped to carry out the complex procedures.
- In civil infrastructures, the process of creating 3D project model is complex and requires a lot of effort. Besides, the lack of special 3D modeling software in the infrastructure domain is a contributing factor.
- The low rate of benefit/cost ratio for adopting the new technology in small infrastructure projects is considered to be an additional discouragement.

Froese (2003) identified the lack of the IFC data model to support infrastructure projects as the most important barrier to the adoption of integrated systems in such projects. Lack of an official standardized product model for infrastructure projects, along with the domination of element-based approach in IFC original classes, have worsened the scenario.

In recent years, a number of studies have focused on developing standard product models for potential domains of infrastructure projects. An IFC-based product model, called YLPC-BRIDGE was developed by Yabuki and Shitani (2003) for a pre-stressed concrete bridge, as an extension of the IFC data model. Further, few multi-agent systems were developed to support the design process in the CAD system. The collection of the multi-agents, pre-stressed concrete product model, and a steel girder-bridge product model (developed further in the process) were merged to build the J-IFC-Bridge. Concurrently, an IFC-based product model was developed by the IAI French speaking chapter. Finally, the combination of the Japanese and French bridge product models called the IFC-Bridge was proposed with the support of IAI (Yabuki and Li, 2006). Ji et al. (2011) proposed an object-oriented data model to capture the parametric design of bridge geometry to improve the IFC-Bridge data model. The proposed model focuses on parametric relationships and constraints rather than the mere definition of the bridge components and their hierarchical relationships that were previously defined in the original IFC-Bridge. In addition, a tunnel product model is under development in Japan and some of the problems have been identified and discussed (Yabuki, 2008).

In road-based construction works, such as tunneling, a linear-based scheme is needed to mimic the real project configuration. Moreover, extending the scope of the IFCs to the infrastructure domain requires the adoption of the data model structure to include GIS-based systems, which are extensively employed for locating construction processes and components (Froese, 2003). Integration of spatial data models with GIS functionality that consist of geometric and positional attributes, can improve the municipal asset management systems (Halfawy et al., 2006).

3D modeling techniques and visualization tools proved to solve the challenges in different phases of an underground construction project (Li and Zhu, 2009). In addition, the concept of applying a central database in tunnel constructions to keep track of all the information during project lifecycle can be implemented using a standard data model. Such a unified model is capable of storing and retrieving the information. Using this database, the facility manager can access all of the information relating to the previous activities such as modifications and change orders. Deulofeu et al. (2007) developed a shared database capable of saving and analyzing the data before and during construction to enhance the data management of tunnel projects. However, the developed data structure was a proprietary product model defined for a specific project.

A 3D information modeling of tunnel structures based on a standard object-oriented data model establishes a framework to manage the information and processes in complex tunneling projects. This ultimately eliminates the data and domain fragmentation during project lifecycle. Lee et al. (2009) developed a 3D-based information model tool for road structures. Although the information model includes road, bridge, and tunnel structures as components of a road network, it lacks the presentation of the details for a tunnel system and assumes that the whole structure is a whole block. Therefore, the information system includes only a general representation of the tunnel component and falls short in covering the properties associated with various segments of the tunnel structure.

2.9 Conclusion

The complexity and magnitude of the current construction industry necessitates the employment of IT applications to improve the efficiency and enhance the accuracy of the decisions made before and during the construction process. In this regard, recent improvements in project delivery methods and software applications are potential forces that could eliminate the hindrances for management relating to the implementation of complex construction projects. However, the involvement of several tools and individuals throughout the process has worsened the scenario and resulted in information loss and inefficiency. Therefore, a collaborative project environment is the key to achieve seamless interoperability in AEC industry.

Tunnel construction projects, as one of the major civil infrastructures, are a potential target for adopting collaborative project solutions. The fundamental enabler for successful collaboration is a generic product model. This model will facilitate the management process and benefit from the advantages of an integrated information system. In the case of tunneling projects, integrated project systems can improve the collaboration among the project processes. An integrated solution requires a unified approach for communicating the project information. Therefore, developing a standard product model that covers all the tunnel components, their hierarchical relationships, geometry constraints, and important controlling processes will solve the fragmentation and lack of interoperability between the software applications and project disciplines. Moreover, parametric modeling capability promises the applicability of the developed elements for future projects. The resulting benefits of employing an efficient integrated project system will reduce the risk of the initial high investment and encourage the universal application of the integrated tunneling system. Moreover, it holds the promise to be a foundation for establishing a specialized modeling application for tunnelling projects.

Chapter 3: Tunnel Information Modeling (TIM) - Research Methodology and Objectives

3.1 Introduction

This chapter introduces the TIM concept and its methodology as a data model for tunneling projects that intends to promote the collaboration and integration during project lifecycle. At the beginning, the principals of a TIM system as a multi-dimensional modeling project are demonstrated. The TIM system includes the knowledge and historical data of project geometric and non-geometric components and is capable of sharing this data among multiple domains. The intentions of this research are then clarified and the methodology schema that explains how to create TIM on a conceptual tunnel project is presented. The methodology plan illustrates the proposed framework and the consecutive steps used to build the TIM model components. Finally, the anticipated benefits and objectives of an ideal TIM system are addressed.

3.2 Tunnel Information Modeling

This research discusses the development of underground information models and in particular, the tunnel information model. AbouRizk and Mather (2000) and Xu et al. (2003) are among the researchers who initiated the development of integrated 3D models to enhance the management and decision making process, specifically in underground projects. Their studies employed 3D CAD models and simulation techniques to form an integrated project system for analyzing earthmoving projects. The outcomes of these works resulted in the first introduction of the TIM concept by Zhang et al. (2010) as part of the ongoing research in University of Alberta construction management program to develop a distributed simulation environment for tunneling projects. The proposed system incorporated 3D modeling and process simulation to achieve a higher level of semantics in visualizing the actual processes in the project environment. The project visualization assists in the decision making process and helps to identify probable deficiencies during distinct tunneling processes.

Although the TIM system proposed in this research is similar to the one introduced by Zhang et al. (2010), it concentrates on enriching a comprehensive framework for 3D and eventually n-D modeling process, as well as encapsulating the project data in an integrated data model during the management and design processes of tunnel projects. The scope of this study is to identify key resources and background processes to develop an integrated system and express its vital requirements to reach ultimate target efficiency in the tunnel projects. The previous studies revealed the effectiveness of information management (Froese, 2010) and the IT supported collaborative environment (Xue et al., 2012) in construction project management. Therefore, such an outcome is also anticipated for the TIM project system.

Moreover, the TIM concept in this research refers to the interpretations of an integrated information modeling system rather than emphasizing the nature and sequence of the actual processes during the tunneling lifecycle, which is the scope of the operation simulation techniques. Therefore, it is accurate to say that the proposed TIM system aims at developing an integrated information framework for tunneling projects that is capable of sharing project information with other applications and individuals participating in generating the final product. However, studying the tunneling processes is vital to the identification of the different aspects of a tunnel project such as construction elements, materials, equipment, actors, etc. These parts are the essential components needed to design the TIM data model and to promote the different dimensions of the project system.

The framework proposed for TIM system is an abstraction of the BIM concept previously developed and widely used in the building domain. It intends to produce a multi-dimensional model of any tunneling project that initially starts with producing a 3D object model that acts as a data repository to store design and construction process information. The 3D model not only represents the geometric elements of the tunnel and its components, but also embraces all non-geometric data such as attributes, methods, and relationships. Therefore, it represents a computerized generalization of the tunneling process. The 3D model can be combined with scheduling, cost estimation, simulation, clash detection, etc. to analyze and maintain information in a multi-dimensional model. This integrated model consequently builds a simulated environment, which is the reference and backbone of decision making process. Hence, the management policies for the entire project life span, from its preliminary conceptual drafts to the very detailed specifications of the facility maintenance, can be generated based on the integrated TIM model.

By using the TIM system in a project, participants can contribute dynamically to a unique project model. The TIM model acts as a central database that includes all the information related to different phases of the project in different domains. The central database in a tunneling project assists in maintaining the integrity, validity, and accuracy of the project model and provides different parties with reliable and consistent information during the project's lifecycle. As a result, in an ideal integrated TIM environment, the model is updated dynamically and thus, modifications and changes are immediately reflected in the database. As real-time changes allow conflicts to be revealed in the early stages of the project, early detection authorizes effective revisions and eliminates the root causes of disputes before the actual construction process commences. Figure 3-1 shows the TIM model as a central database and all the corresponding project sectors accessing the data.

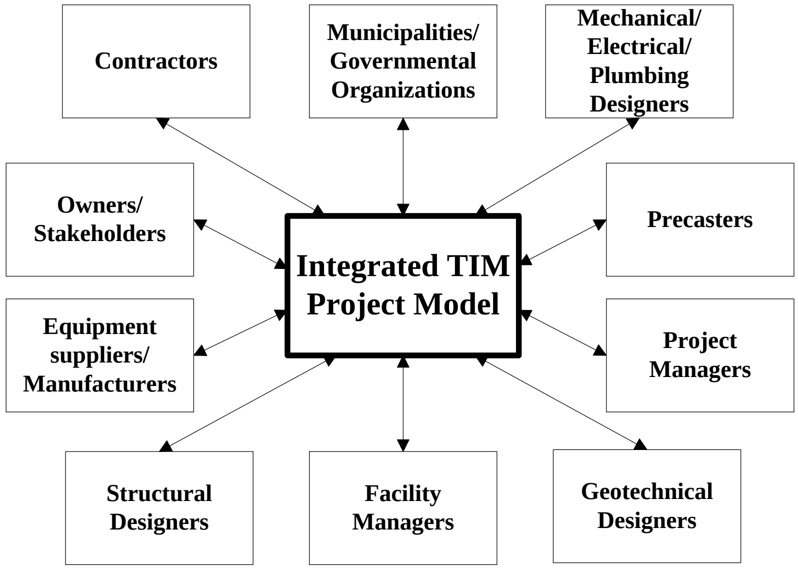


Figure 3-1 The TIM Integrated Central Database

The core part of an integrated TIM system is an intelligent 3D model that contains the smart objects of the tunnel model. A smart object consists of the multi-disciplinary aspects of the project's components and is not limited to physical, geometrical, and visual characteristics that can be found in a 3D CAD model. It includes different varieties of information that shape the actual capabilities and desired performance of project elements, such as methods, processes, tasks, quantities, etc. (usually referred to as non-geometric parameters) along with geometric parameters. According to Halfawy and Froese (2005), a 3D smart object has the capability to embrace the behavioral aspects, design constraints, and facility management parameters of the projects data. Moreover, an integrated model requires a benchmark data structure that standardizes the common data definitions. Therefore, the standard data model facilitates interoperability throughout the project life cycle. Based on Fu et al. (2006), IFC classes are the de-facto medium for providing interoperability between different parties and applications in a building construction project.

This research shows that different applications and participants contribute to the TIM model. Therefore, a standard data model is required to supply the seamless interoperability among participants and applications. Since the current IFC classes only cover the entities and types specific for building type projects (Zhang et al., 2010), an amendment is required to extend the semantics of the original IFC data model by adding tunnel-specific classes to the original IFC classes, previously developed by BuildingSMART (2011). Utilizing such tunnel-specific IFC classes, the information embedded in the 3D model can be transferred and applied to other software applications used by multiple project participants. Thus, additional dimensions such as scheduling, cost estimation, clash detection, 3D strata, simulation, machinery, and material management systems can be added to the project integration system database to form a universal multi-dimensional and monolithic model for the whole project. Eventually, the TIM central project system would provide integration through different phases and multiple participants in order to facilitate information management in a tunnel project.

As discussed previously in section 1.3, a major part of the methodology focuses on a step-by step procedure to extend IFC classes for tunnel projects. The framework proposed in this study merely provides the project management processes with seamless interoperability. The scope of the proposed TIM framework addresses the specific requirements and purposes to fulfill the basic management processes, such as scheduling and cost estimation. Nevertheless, a comprehensive TIM project system also requires incorporating information from other processes in tunneling works that are not covered in this study to produce TIM-IFC classes, such as design process and quality management

3.3 Proposed Methodology- Developing the TIM Model

To introduce the TIM project system two phases are performed. These phases build the main framework for creating a TIM project system for a typical tunneling project. The two phases are:

- Phase-A: Developing a framework to build the TIM system and create an integrated project system for tunnel projects.
- Phase-B: Designing a framework for creating TIM-IFC classes via extending IFC 2x Edition 3 classes.

Developing the TIM data model based on the original IFC classes is beneficial in many ways. It reduces the time and effort required for developing the TIM data model, since a great number of classes, which already exist in the original IFC classes and used for building structures, are applicable in tunnel project model. Moreover, by referencing part of the model, there is a significant reduction of the size of the extension. In addition, the current IFC data model is widely accepted and developed to be the medium for interoperability among multiple applications and organizational boundaries.

The core parts representing a TIM system are the object-oriented intelligent 3D model and the tunnel specific IFC classes (TIM-IFC classes). The 3D model is the basis for commencing the TIM development. The first step for developing the 3D TIM project system is to identify the tunneling processes, required elements, and methods of construction. Acquiring this information helps to determine the components of the 3D model and understand the relationships between the numerous parts of a tunnel project. This information has been comprehensively investigated in Chapter 2 from versatile resources.

The typical abstraction of a tunnel project includes its major parts such as the main tunnel, working/exit shaft, undercut, and tail tunnel (AbouRizk, 2010). To create the 3D model of the project, this study focuses on building the main parts of the tunnel. However, for a more realistic and precise representation of an actual project, generating the facilities, equipment, and barriers are required. The 3D presentation of the tunnel is simplified and limited to the main components of the tunnel structure to achieve a general solution for tunneling projects. This generalized attitude, which helps to overcome the limitations and obstacles, results from the lack of a popular and specialized object-oriented modeling tool for underground structures. Therefore, the two main components of the tunnel system (main tunnel and shaft) are modeled.

The main intention of a TIM information model is to use the capacity of the IT technology to build sustainable models. Such models can be moderately modified to adjust to the specific requirements of a particular project without an obligation to create the whole model from scratch. Therefore, to create the 3D model, a methodology should be taken to give generality to the model, so that it can be used in different projects with varied specifications. A parametric solution assists to build a 3D tunnel model that is able to be modified easily. In a parametric 3D model, it is feasible to change dimensions and other properties during the project lifecycle or when applying them to future projects. Moreover, additional information such as project data, construction codes, or the results from constructability reviews can be added to the tunnel objects. Hence, the 3D object components are not merely geometric/visual representations of the real project. The 3D objects are smart object-models intended to include a vast variety of non-geometric information.

Different applications known as BIM tools are available in the market to develop the 3D object-based intelligent models, particularly for the building projects. These BIM tools are able to produce 3D models and enter supplementary information known as intelligence to the model components. BIM tools are capable of producing different views of a single drawing and propagating the changes to different views by simply applying them in one view.

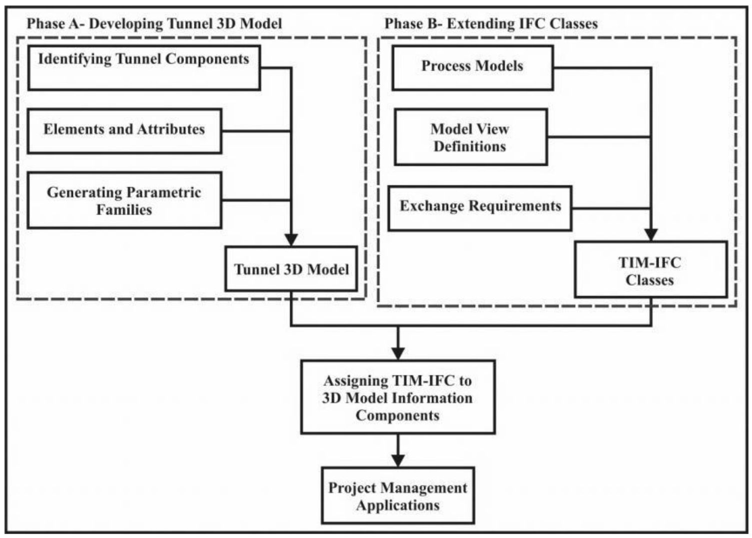
ArchiCAD ® by Graphisoft™, *Revit Architecture*® by Autodesk™, and *MicroStation* by Bentley Systems™ are the most conventional BIM tools available in the market which have heavily promoted the BIM application in the building sector of the AEC industry (Holt, 2009). These leading CAD vendors have not offered any specific solution for underground structures such as tunnels or sewage systems. Since there is no other specific application to produce 3D intelligent objects for underground projects, a BIM tool is used to generate the 3D model of the tunnel project.

In this research, because of the relative robustness of the BIM platform and its popularity in construction firms to develop intelligent 3D models, which is extensively discussed by Holt (2009), the Autodesk Revit® Architecture 2013 has been employed to produce the tunnel 3D model. In the Revit environment, parametric families are incorporated to develop the 3D components of the tunnel in order to maintain the universality of the 3D model. Therefore, the user will be able to modify the geometric and non-geometric parameters based on the specific requirements and constraints of a particular tunnel project.

In Phase B of implementing the TIM concept, the TIM-IFC data model is developed and the step-by-step framework to create a standard tunnel product model is described. The framework aims at extending additional classes to the original IFC data model. It acts as a neutral and universal data format for tunneling projects. The resulting product model provides a unique skeleton to establish the interoperability between different applications that are participating in the project. The existing IFC data model, version IFC 2x Edition3, developed by BuildingSMART™ is a neutral data format to exchange building specific information. However, it is a proprietary medium for building structures and does not include classes that define entities and types for tunnel or other infrastructure projects. In other words, the specific elements and properties in other civil engineering projects have not been incorporated in the development of the IFC data model. TIM classes or TIM-IFC in this study refers to a data model that is based on the original IFC classes. However, a collection of tunnel-specific classes have been added to the existing IFC classes to define and specify basic requirements of the tunnel components. Different steps are required to be fulfilled in order to define tunnel-specific classes. In this regard, a conceptual product model representing different components of a tunnel project has been developed.

The conceptual product model along with the process models, exchange requirements, and model view definitions are the basic supplies that are employed to develop the TIM classes. In Chapter 4 the framework to extend the IFC classes for tunneling project management are widely described. Figure 3-2 shows a general overview of the major components of the TIM development plan and the sequential procedure to achieve a TIM project system.

Figure 3-2 The stages of the TIM system development



3.4 The TIM System Architecture

An ideal TIM project system consists of three major tiers. These tiers are as follows:

- Central n-D Data Model
- Knowledge Management Layer
- Interoperability Layer

3.4.1 The Central Data Model

The first tier is the TIM central data model. The central data model is an intelligent 3D object-oriented tunnel model. The 3D data model represents the shape, geometry, and coordination of the tunnel elements. Moreover, it includes other non-geometric information, known as meta data (e.g., material, quality, and cost) in the form of attributes and properties associated with the geometric representation of the tunnel components. The information resources which contribute to the central data model can be originated from different backgrounds such as tunnel project specifications, preliminary studies, project documents, constructability reviews, municipal and safety regulations, environmental regulations, etc.

3.4.2 The Knowledge Management Layer

The second tier is the knowledge management layer. It consists of tools to store, modify, and record the history of the transactions and modifications. In this layer, the TIM database stores the information in a central archive holding all the project data. The data management tools assist in performing multiple tasks such as editing, copying, deleting, categorizing, and querying the stored data. Moreover, it is capable of creating different versions of the data to keep track of any modification and data access. For instance, it keeps records of all the transactions in the following scenario; consider a directory of the TIM database that stores the material inventory information for a sample tunnel project. When a project manager accesses this directory, the detailed information regarding the entered data and modifications is recorded and kept. Also, the executed modifications are registered by referring to the individual who made the modifications for future reference. As a result, project information is achieved and maintained in the TIM database to ensure accessibility in all phases of the project construction and even after completion (Operation and maintenance phase).

3.4.3 The Interoperability Layer

The interoperability layer defines a unique data structure to describe semantics in the tunneling project. This layer contains TIM-IFC classes, as an extension to the original IFC classes, which facilitate the information flow between the TIM 3D model and other management applications that contribute to the project. The TIM-IFC model allows the tunnel information to be operated and viewed in any specific domain used by different participants. Figure 3-3 shows the general architecture of the TIM project system and the different layers within it.

3.5 TIM System Process

A TIM integrated model starts with defining a set of 3D objects in an object-oriented software application. The tunnel 3D objects present a conceptual model of tunnel components that can be further used to populate with the other design and management information. The interoperability layer, which is facilitated by TIM-IFC classes, assists in exchanging data with a wide range of application tools.

Furthermore, the dynamic contribution of the project disciplines assists in enriching the project model as the project processes are improving. As a result, an integrated project model would evolve that contains all the project information throughout project phases. This integrated project model acts as a project repository and maintains all the information in a single model. The probable conflicts between models that are propagated by different function-specific application tools will be revealed directly after the synchronization of the central project data model. A typical scenario for an IFC based TIM project model is as follows:

- A 3D conceptual model representing different physical components of the tunnel project is created. These physical components are the main tunnel, working shaft, exit shaft, undercut, tail tunnel, etc. Then, based on the conceptual model, a preliminary architectural design is developed which contains more detailed information such as accurate dimensions, materials, etc. In the next step, for creating the ultimate 3D model, a collection of non-geometric information would be assigned to the model in order to add intelligence to the model components.

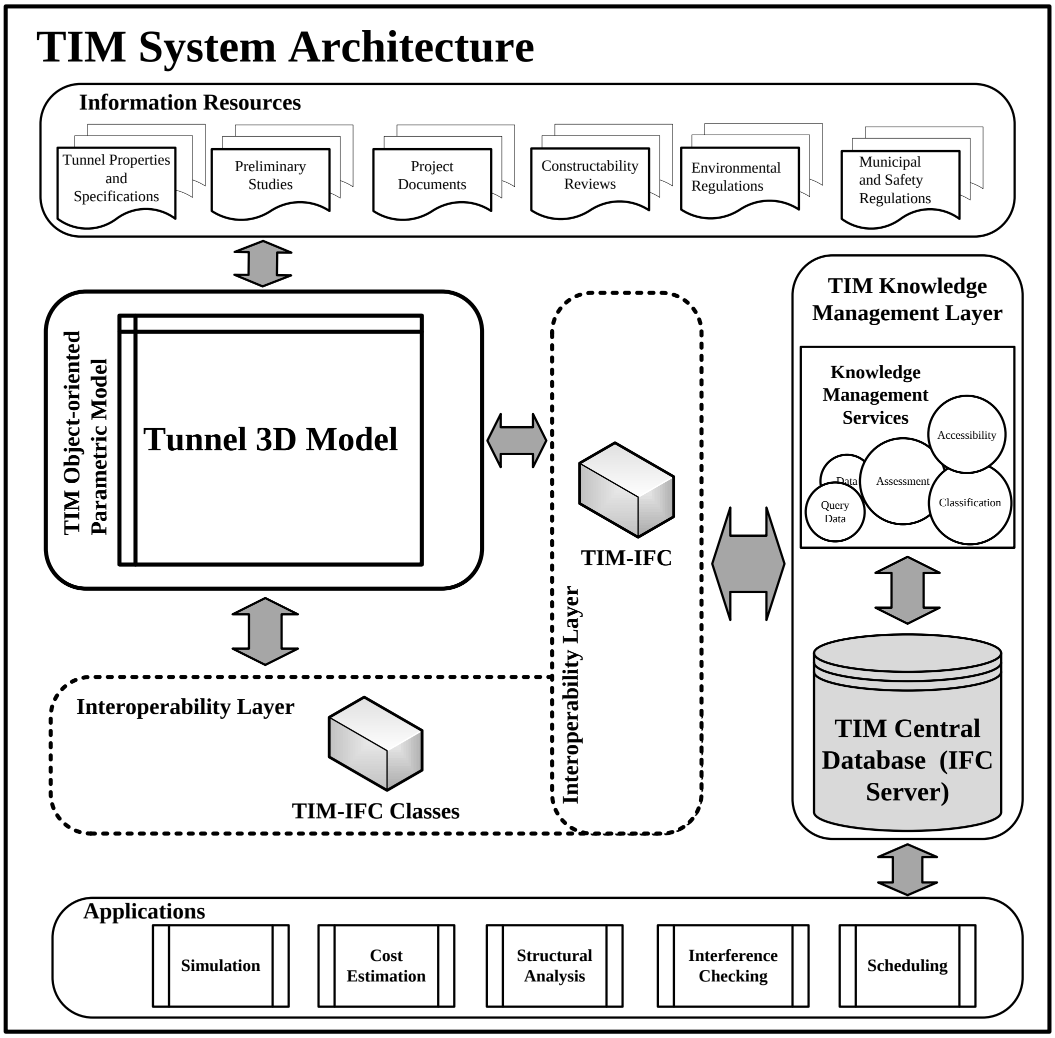


Figure 3-3 The architecture of the TIM system

- Incorporating a set of TIM-IFC classes, which represents different tunnel entities and types, exact data packages from the tunnel project model are mapped to the TIM-IFC classes. Therefore, all the project data would be defined as the instances of the TIM-IFC classes. Different information in the TIM central data model is structurally based on the TIM-IFC standard data format framework.
- Eventually, the created TIM model can be shared and exchanged with other project participants and applications, such as cost estimation and scheduling applications, through the TIM interoperability layer. Therefore,

further analysis and assessment of the tunnel project data will be possible without confronting any information loss or error.

The final project model contains all the data that resulted from the incremental generation of information throughout the project lifecycle by different disciplines. This bulk of information creates an integrated project model that represents a comprehensive view of the whole project.

The underling processes in a TIM system is shown in Figure 3-4 using IDEF0, which is a function modeling methodology to show how a system works. In this representation the processes and components by which the TIM system performs are demonstrated for the interactions between the 3D model and the cost/scheduling model. The main processes in the TIM system are preparing the 3D model, IFC based data model for the tunneling projects, the 4D scheduling model, and finally the 5D cost estimation model. The IDEF0 presentation shows the information flow within the TIM system among these processes.

In an ideal TIM project model, the updates and changes would be reflected automatically in the project model. Moreover, notifications would be sent to the affiliated party to get the final check and approval for the recent changes or modifications. The tracking and performing of such changes would be possible via the unique identifiers defined for the TIM-IFC objects. These identifiers ensure that the accurate modification is assigned to the right portion of data in the central project model repository.

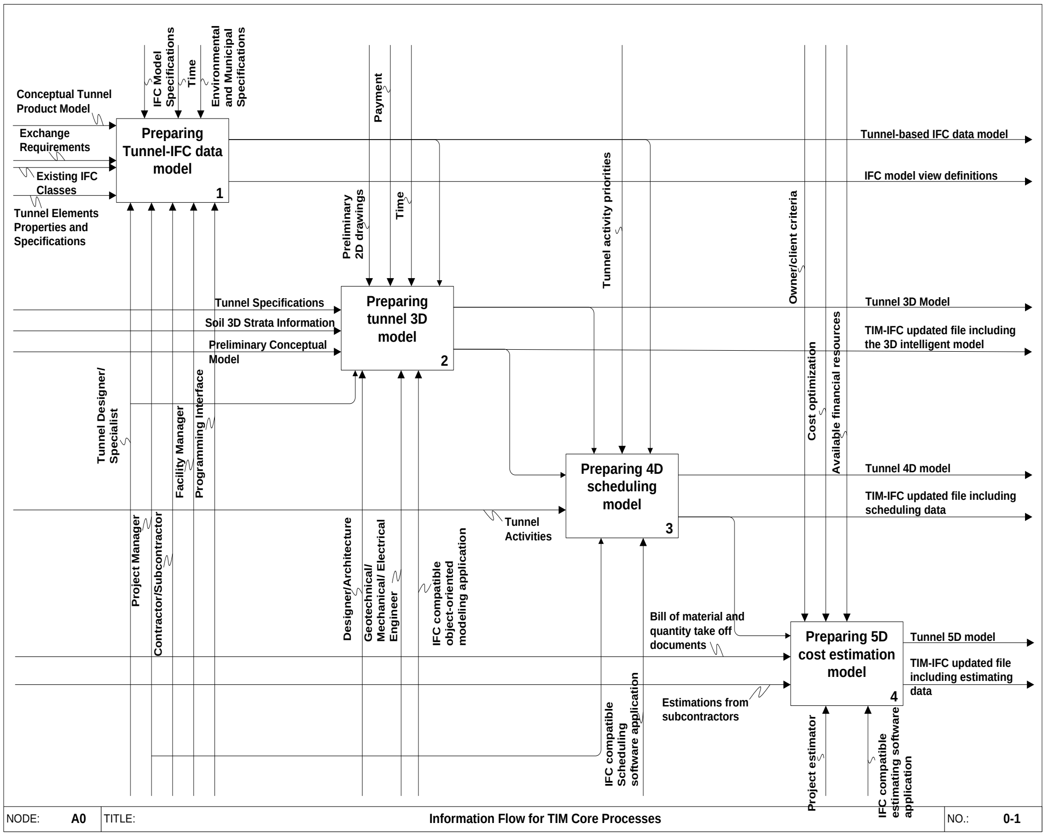


Figure 3-4 IDEF0 Diagram showing TIM Information Flow

3.6 Developing the TIM 3D Model

Prior to creating the 3D presentation of the tunneling objects, the main characteristics of an intelligent object-oriented parametric project model are clarified. Also, the available software applications to create tunnel objects are listed and analyzed. Finally, the tunnel 3D model will be created using an interface that provides the aforementioned properties.

3.6.1 Object-Oriented CAD Models

CAD has been the main digital drafting tool since its first commercial emergence in the late 1970s and early 1980s. It is developed from the entity-based modeling technique where the model is presented with graphical entities such as lines and arcs (Tse et al., 2005). The development of object-oriented product models was the focus of many studies during the 1980s. This trend created new approaches in the computer modeling and drafting industries (Ito et al., 1989). The integration of object-oriented concept with Computer-Aided Design (CAD) technology evolved into Object-Oriented CAD systems (OOCAD). OOCAD not only enhances the visual aspects of the model, but also contributes to the semantics of the model by incorporating the information from and relationship between different components of the model (Howell and Batcheler, 2005). The Building Information Modeling (BIM) concept is the latest interpretation of the object-oriented notion in the building area of the AEC industry.

An object-oriented model consists of objects instead of graphical entities. Hence, the minimum visualization unit in an object-oriented model is an object representing the real world being drafted. For instance, in a building model, these objects are composed of multiple lines and therefore possess a generalized description such as a wall, column, or beam. According to Tse et al. (2005), object-based modeling allows for the encapsulation of rich semantic meaning, which is not adopted in the entity-based modeling trend. Although layering and using line types, colors, and blocks provides a foundation for an enriched entity-based model, it is associated with long and tedious drafting hours because it takes an extraordinary amount of work to unify and standardize the process.

In this study, the TIM data model is based on an object-oriented modeling process to gain the rich semantics offered by this trend in a reasonable amount of drafting time. Moreover, the encapsulated information is intended to be applied in other parts of the management process and the procurement of the tunnel project. Figure 3-5 shows the fundamental difference between entity-based and object-based modeling trends.

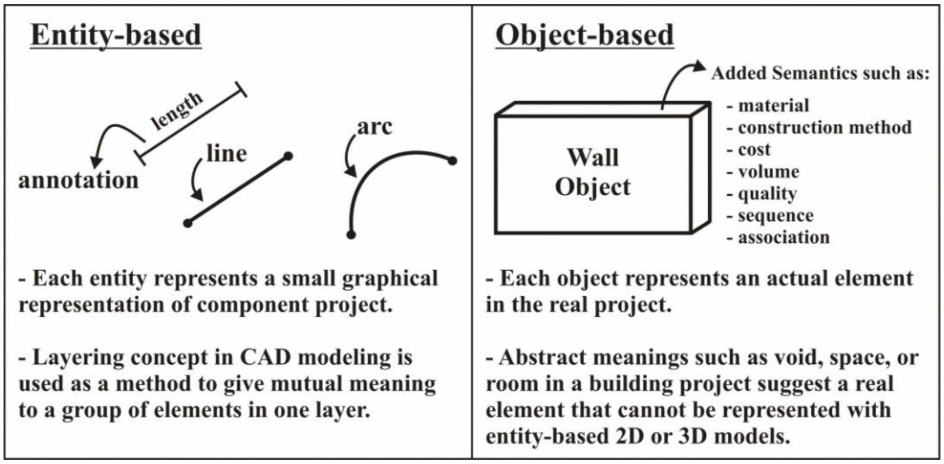


Figure 3-5 Entity-based modeling vs. object-based modeling techniques

3.6.2 Smart Objects and Parametric Modeling Concept

Smart objects refer to the object-based modeling components composed of an extended amount of non-geographic and visualized information. The non-geographic data (meta data) adds the extra dimensions to the project model. The parametric modeling phenomenon refers to the parametric definition of the objects in order to preserve the sustainability and ease of modifications both in future projects and in different stages of the same project. In a parametric model, parameters are used to define dimensions, model features, material density, and formulas to describe the relativity and association in one object or among multiple objects.

3.6.3 BIM-Based Object-Oriented Application Tools

Currently, there is no universal or industry-wide accepted object-oriented and integrated modeling application (similar to BIM in the building domain) that is specifically designed for tunneling projects. Therefore, to be able to benefit from the object-oriented and interoperability advantages offered by BIM applications, the available BIM applications in the market are evaluated based on the targeted specifications for a tunneling project. Finally the most favorable software, which provides sufficient features for tunneling requirements, is selected. Appendix-A presents a list of well marketed BIM applications that are currently available. The successful employment of any tool depends on the specific requirements of the organization and the project, so none of the listed platforms would be ideal for a project. Appendix-B presents all the applications compatible with the IFC data modeling standard (BuildingSMART, 2011). The BIM application that is finally selected needs to be an IFC-compatible platform in order to provide the interoperability requirements for phase-B of the TIM methodology.

According to Holt (2009), Autodesk™ Revit Architecture®, Graphisoft™ ArchiCAD®, and Bentley™ MicroStation® are the most common applications used in US engineering firms. The evaluation in this study has been narrowed down to these three options. Table 3-1 presents a comparison between Revit Architecture®, ArchiCAD®, and MicroStation® as the main modeling platforms for developing the TIM 3D model and evaluates their most beneficial aspects for modeling tunneling construction projects. The evaluation shows that any of the tools is robust enough to use as the TIM modeling platform. However, since the Revit Autodesk offers an easier process to create parametric components, known as families, and therefore results in more sustainable models, it is the most favorable tool to use in the development of the 3D TIM model.

Moreover, Holt (2009) also studied these applications and identified Revit Architecture® as the most popular BIM application in US engineering firms. Consequently, Revit Architecture® by Autodesk™ is used in this study to generate the tunnel 3D model components. It is necessary to mention that based on the unique characteristics of the project and the involvement of professional teams, the two other applications can also be used to model the 3D components and their embedded intelligence.

3.6.4 Revit® Software

There are three versions of Revit® software available for the building design discipline. The Revit® Architecture is solely designed to cover the architectural aspects of the building model. Respectively, Revit Structure® and Revit MEP® are specific to structural design and mechanical/electrical/plumping modeling of building structures. The Autodesk® Revit® as a BIM modeling application has the integrated capability of Autodesk® Revit Architecture®, Autodesk® Revit MEP®, and Autodesk® Revit Structure® software (Autodesk, 2012).

Table 3-1 Comparison between Revit, ArchiCAD, and MicroStation

	Revit	ArchiCAD	MicroStation
Developer	Autodesk	Graphisoft	Bentley
File Format	.rvt	.pln	.dgn
General Remarks	- BIM modeling specifically designed for building construction projects, and covering architectural, structural and facility design and management specifically for building construction projects.	- BIM-based information documentation and modeling for architects. It works very well with other 2D information from other applications.	- Information modeling environment explicitly for the architecture, engineering, construction, and operation of all infrastructure types.
	- Changes are propagated in different views automatically	- Provides parametric modeling with data enhanced smart objects.	- Either a software application or as a technology platform.
	- Parametric modeling allows for rule-based relationship between object models	- Includes a huge library of pre-designed and customizable objects.	- Integrates engineering geometry and data from an unmatched range of CAD software and engineering formats.
	- Mass modeling allows for an easy conceptual modeling in preliminary stages of the project lifecycle	-Specifically robust in terms of bi-lateral and easily generated scheduling data.	- A technology platform for discipline-specific applications from Bentley and other software vendors. Bentley Architecture, Bentley Structural (RAM), Bentley Building Electrical Systems, Bentley Building Mechanical Systems, and Bentley Piping.
	- Loadable families can be used to create custom-based objects for specific projects and be stored to use in future projects.	- User-friendly interface, easy to learn and explore, even for big projects with multiple stakeholders dealing with the ArchiCAD model.	- Offers robust subsystems for consistent integration of geometry and data. Provides real-time design data and dynamically leverage the changes in the model.
	- Easy to use, but relatively difficult to work with specially when the project size grows and more people share the project data on the network.	-Interactive two way communication between the model and the schedule.	- Provides a rigorous performance simulation and what-if-scenario analysis to explore various options and maximize design objectives.
	- Designed to facilitate structural, architectural and facility design for building projects in three separate platforms. Offers in three compatible modules: Revit Architecture, Revit MEP, and Revit Structure.	- Employs GDL information which contains all the information necessary to completely describe building elements as 2D CAD symbols, 3D models and text specifications for use in drawings, presentations and quantity calculations.	- Federation and integration of design data helps to have efficient clash detection in the modeling process between different segments of the project.
	- Offers a robust API to create customized rules and objects.	- ArchiCAD API and ODBC database connections allows for plugin programs and add-ons to perform new operations.	- Easily annotates and visualize terrain models and GIS information to meet project deliverables.

Table 3-1 Comparison between Revit, ArchiCAD, and MicroStation (Continued)

Compatibility and Interoperability	- IFC-compatible. - Revit uses its import and export tools to move from .rvt files to IFC files and vice versa. It successfully exchanges element parameters. It is possible to define the desired element categories via a map for Revit to IFC exchange. Similarly, for the import action, it is possible to define exactly which IFC classes are translated to a specific Revit element groups. Generally, Revit is significantly better in exporting from .rvt to IFC format than importing. The imported file is much useful as a linked file. The importing process enhances in case of using a template with the IFC parameters preloaded.	- IFC-compatible - Two different export functions: 1- "Save as" (file) which exports the entire ArchiCAD file to a new IFC file. 2- Merge to IFC Model/ "IFC 2x3" which only merge certain IFC elements or entire current ArchiCAD file into an existing IFC file. ArchiCAD exchanges smoothly between IFC and .pln file format. - Two options for importing data: 1- Open (file) which opens the entire model. ArchiCAD will transform all the imported elements into the corresponding ArchiCAD elements. 2- Merge ("File special") which insets the IFC file into the running ArchiCAD file.	- IFC-compatible - Since Bentley is a founding member of IAI, it is an active board member to define IFC classes and subsequently define an IFC interface for the Bentley Building applications. Bentley Architecture has the certification for IFC 2 Edition 3. Other Bentley platforms also support IFC 2x3. The Bentley IFC interface supports common property sets and similar to Revit, these property sets are controlled via an IFC-based data group schema. Also non-common properties are customizable through Bentley Architecture DataGroup schema.
Parametric Modeling	- Parametric components in Revit are called families. Revit families are highly customizable and are capable of supporting rule-based relationships and scenarios. There are three types of Revit families: System families, Loadable families, and In-place families. - Parametric modeling for new instant objects for the current project via in-place families. - Rule-based families are built components predefined in Revit. Loadable families are those than can be created and saved for use in future projects. No programming is required to build loadable and in-place Revit families. - Revit recognizes the unidentified imported objects as generic models. These generic models can be assigned as an existed Revit element group.	- ArchiCAD allows for modeling scale sensitive parametric objects, often called as "smart objects". ArchiCAD contains a rich database of pre-designed customizable objects. - ArchiCAD includes Geometric Description Language (GDL) which is used to create new components. - Creation of new and custom-made ArchiCAD smart objects requires the knowledge of programming with GDL language and as a result, is not as convenient as Revit loadable and in-place families.	- Parametric modeling in MicroStation is possible by employing a dimension-driven, feature-based modeling technology known as Parametric Cell Studio (PC Studio). The PC Studio technology generates parametric building components based on used-defined attributes. - The PC Studio is an important part of the Bentley Architecture which is installed with the program to accommodate parametric modeling. - The resulted parametric models are facilitated with associations between user-defined attributes and PC Studio components. Therefore, multiple variations and changes are possible to take place during the modeling process.

The Revit Architecture® stores files in .rvt format. It uses 3D objects of different building components (e.g., walls, roofs, floors, windows, generic systems) in the design process. It has object models for each category of the building elements known as *Revit Families.* A family represents a group of elements with a common set of properties and graphical representation. The family properties are called parameters and can take on different values. However, the set of parameters are always identical for all the instances of the same family. The variations of parameter values for a specific family group are called *family types* or simply *types*. Moreover, a family can be parametric or non-parametric based on the model requirements (Autodesk Families Guide, 2010). Generally, based on

Autodesk Families Guide (2010), there are three kinds of Revit families:

A- System families- are the components that are predefined by Revit. New types can be made by changing the parameters to create the required components from system families. Although system families are the least customizable of the three kinds, they have the most intelligent behavior in terms of recognizing the attachments, and merge with other components (e.g., placing a door in a wall type does not need a void in the wall, it automatically changes to accommodate the door and required opening).

B- Loadable families- are families that can be made from scratch and stored to be loaded in different projects. They are saved in .rfa files. Loadable families can be combined to create nested and shared families.

C- In-place families- are families created instantly for use in current projects and cannot be used in future projects.

More information regarding the Revit application, and particularly Revit families, is included in Appendix-C. Moreover, the steps to create a shaft family are described in Appendix-C.

3.7 TIM Model - Objectives and Contributions

Although the true business value of any information system depends mainly on its application area, and thus difficult to actually verify or express in absolute terms (Aouad et al., 2008), its benefits can be anticipated based on similar data models or previously examined tools. Likewise, the expected contributions of a TIM data model are predicted based on the proved advantages of other successful integrated data models.

The anticipated objectives of a TIM model are categorized into two groups. The first type is the immediate objectives of a TIM project data model, which are those that are easily observable during the project control and management. The second type is the long-term objectives, which would evolve in the later stages of the project. The long-term values are required to be studied and analyzed based on project performance and productivity after the project completion. Some of these long-term advantages are enhanced productivity and efficiency, a smaller number of Request For Information (RFI) and Change Orders (CO), and subsequently less rework. However, some of the main immediate objectives are summarized as follows:

- *Data Accessibility and Integrity:* TIM's central integrated project system would enable users to access the project information concurrently, and hence the changes and modifications would be propagated and managed easily without damaging information consistency and accuracy. A TIM project system keeps track of these changes throughout the project lifespan and documents the access properties (e.g., date, time, user, etc.). Therefore, this information would be useful to understand the performed procedures and it effortlessly assists to disclose the root causes of disputes in a very reasonable amount of time.
- *Enhanced Data Exchanges:* The full implementation of the TIM project system would support different types of data exchanges. Exchanging files, accessing a central data repository, connecting applications to transfer data and online web access are different forms of data exchange. Moreover, employing the TIM-IFC data model, which defines tunnel semantics in the IFC data modeling, promotes TIM data exchanges. It helps to eliminate data loss and information re-entry, which were inevitable in the traditional forms of data exchange.
- *Parametric Design:* The parametric nature of the TIM 3D modeling approach helps to produce design variations as well as use models from previous projects. The parametric design in a TIM project system refers to the definition of interdependencies between different parameters and geometrical constraints. By implementing the parametric object-oriented models, model generation would be less tedious and time consuming,

compared to the process of creating the model from scratch for any new tunnel project.

- *Enhanced Flow of Information between project phases*: TIM facilitates the flow of information between different phases of the project and hence intends to remove the burden of unknown factors and parameters in the previous stages of the project. For instance, in the transition from construction phase to the operation phase, documenting the project facilities' periodical surveillance, primary condition, and previous malfunctions or incidents would help to outline a rigorous maintenance plan. Moreover, keeping track of pitfalls during the operation phase can assist to improve the decisions for future projects that deal with a similar facility or operation plan.
- *Better Plan for O&M Phase of the Tunnel Project:* The TIM system also enhances the operation and maintenance (O&M) phase. Since the O&M team can easily access the TIM integrated data base, they can develop effective plans to preserve optimum maintenance performance.
- *Less Data Re-entry:* By using TIM as a central holistic database of project information, there is no need for re-entering and reconstructing the same piece of information that has already been used or created in other disciplines for the same project. The information that has been added by the first application is readable by the second application, because of the standard data model format. Therefore, error prone data entries and human intervention is reduced. Project parties can easily reach the TIM database to access the latest version of the project model in their specific application tool interface without missing any part of the information.

3.8 Chapter Summary and Conclusion

In this chapter, the scope of the research is clarified. The background and principals of the TIM project system for tunneling projects are explained. Furthermore, the requirements for developing the system and its main components are discussed. The implementation of a TIM system requires accomplishing two distinct phases; phase-A, 3D data modeling and phase-B, TIM-IFC classes. IFC is a neutral data model, which is widely accepted to exchange building-specific information. However, it does not cover tunnel-specific elements. TIM-IFC classes are defined as an extension to the original IFC 2x Edition 3 to enable the interoperability in the TIM project system. Finally, the architecture and process of a TIM project system are demonstrated, and the advantages and objectives through implementing the TIM concept are anticipated.

Chapter 4: Implementing TIM Project Model and TIM-IFC Standard Data Model Framework

4.1 Introduction

An information model for tunneling projects depicts the data structure and information flow among project segments. In the previous chapters the general methodology and background for designing the TIM framework were discussed. This chapter is devoted to the implementation of the described framework and its requirements. First, a brief introduction describes the TIM architecture that was comprehensively discussed in Chapter three. Then, the principles of developing a 3D project model (Phase-A) for a typical tunnel project is described and the associated limitations and shortcomings are discussed. Later on, the framework for designing a standard data model for tunnel projects (Phase-B) is defined. In each stage of development, multiple steps complete the requirements for a section of the tunnel information model. These steps have been implemented by employing a section of a railway tunnel project.

4.2 TIM Project Model System

The TIM project system is an integrated project model that facilitates efficient cooperation between management processes. It consists of three major tiers: a multi-dimensional object-oriented project model, knowledge management services, and an interoperability layer. Figure 4-1 shows the architecture of the TIM project system.

4.3 Phase A- 3D Modeling of Tunnel Objects

The goal of the intended 3D model is to be a general representation of tunnel elements, components, and final products. The tunnel 3D model is an object-oriented and parametric design that is populated with extra information (non-geometric data) known as meta data.

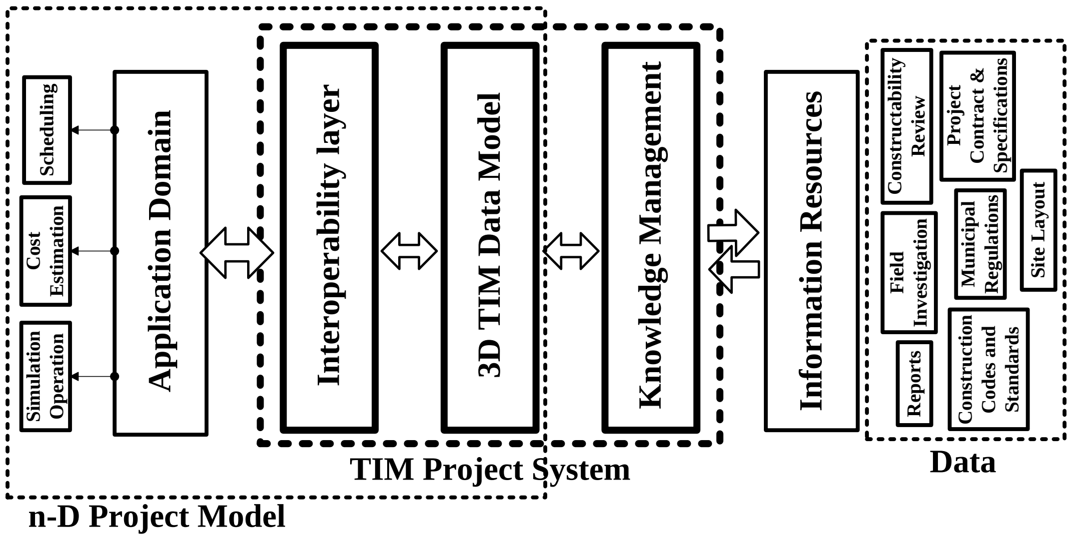


Figure 4-1 TIM system architecture

The meta data includes any non-visualized information such as material, time, cost, association, quantity, quality, and resources. The tunnel 3D model is created using Autodesk Revit Architecture 2013 that provides the aforementioned properties to add geometric and non-geometric information to the tunnel 3D model.

Obviously, since Revit® only offers predefined families specifically defined for building structures, the tunnel components need to be created as loadable families and customized as necessary to accommodate the 3D modeling requirements of a TIM project model. Therefore, separate families have to be generated for each tunnel component. Next, these components can be loaded to a project environment and then attached to create the final model. The details and methods of creating loadable families for the main tunnel and tunnel shaft are described in Appendix-C.

The tunnel Revit families are customizable based on the specific properties of a unique project. Some of the most common variations for each element can be created (e.g., rectangular shaft and circular shaft). Moreover, general properties can be defined for each family and the most common values can be assumed as default or based on a particular equation.

Apparently, these components are not applicable for any random tunnel project. The arrangement and properties of a sewage tunnel may significantly differ from a road tunnel. In this study, the focus is towards a general representation and implementation of the described project system. For a particular type of tunnel project, the first obvious difference, from the already created objects, would be the section shape of the main tunnel, which is unique for any tunnel project based on the underground type and target performance (Figure 4-2).

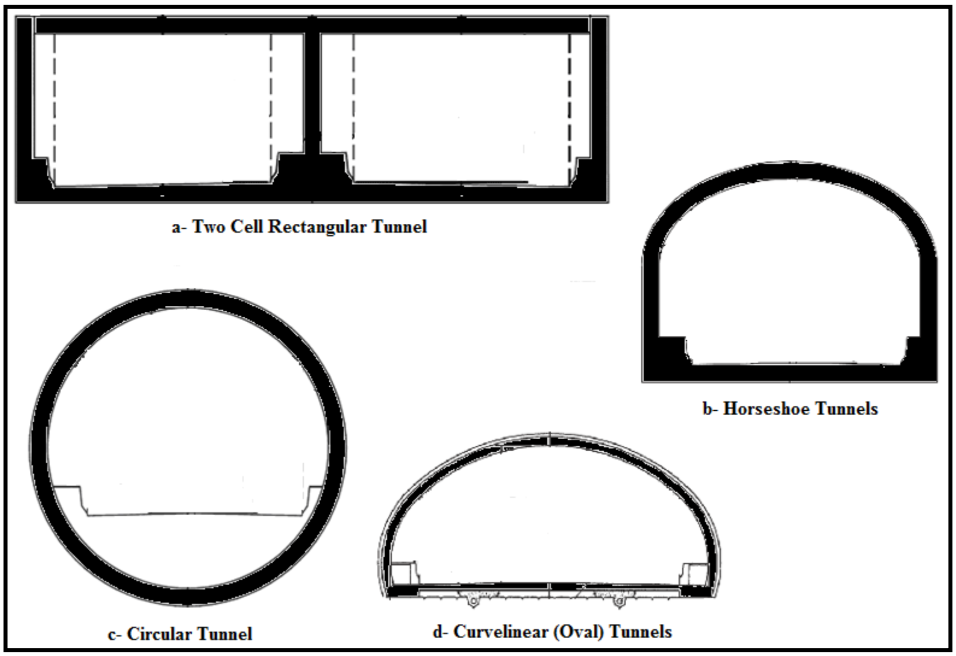


Figure 4-2 Different tunnel profiles (a-d) based on FHWA (2005)

Moreover, based on the project requirements, new parameters may be required for a tunnel component that can be defined as needed. Also, the default values/equations can be edited for that specific project. As mentioned before, the 3D modeling part of the TIM project system consists of both the geometric and non-geometric (meta data) presentation of the tunnel components. The tunnel-specific loaded families include both presentations, since they preserve the 3D logistic and the embedded properties for each component. These properties can range from dimension specifications to measured data.

As described comprehensively in Chapter 2 and Chapter 3, in an integrated project system, the goal is to facilitate the cooperation among project participants. Each participant needs a specific part of the information to exchange and operate its share of the project tasks (e.g., design, plan, estimate, supervise, regulate, maintain). It is essential to include all the information required for exchanging and sharing among project participants in this 3D central data model. Providing a central project model for storing and sharing project data is not solely sufficient to improve collaboration in a construction project. Interoperability plays a prominent role to provide a responsive project environment that easily propagates the project participants' objectives and accommodates the dynamic changes that any project may confront. In the next section, the common tool for creating an interoperable project environment, its requirements, and implementation process for a TIM project system are presented.

4.4 Phase B- IFC-based Data Model for Tunneling Projects

In this section, the proposed framework to extend the IFC classes and create tunnel-specific classes is described.

4.4.1 TIM- IFC Development Phases

The tunnel construction process involves technical and often complex work packages that require handling a great amount of information through multiple project phases. A high number of classes, entities, and properties are required to cover all the tunneling data. The sequential methodology to develop the TIM-IFC data model is based on the methodologies provided in Hietanen (2006) and the national BIM standards (NBIMS) coordinated by the Facilities Information Council (FIC) of the National Institute of Building Sciences (NIBS) (Figure 4-3).

NBIMS is a framework to define the configuration and arrangement of information exchanges. This standard intends to determine the required information to be exchanged in any stage of the building project lifecycle. It defines the exact attributes and properties to be exchanged in any transaction

(Sacks et al., 2010). Sacks et al. (2010) described the consecutive phases of developing a STEP based BIM standard procedure in the construction domain. It begins with defining a process map, called an Application Activity Model (AAM), which is a basis for generating an application Requirement Model (ARM). ARM focuses on identifying the exchange requirements and is a data model for products representing specifications of data objects, their entities, and attributes along with the relationship between data objects. The ARM needs to be refined based on Integrated Resources (IR). The IR expresses specific requirements and entry values for different applications. The resulted integrated data model is an Application Integrated Model (AIM). The IFC also represents an AIM model written in EXPRESS language.

Deployment of a successful IFC solution to overcome the interoperability problems requires implementing specific procedures in order to maintain the validity to apply for real construction projects.

The following steps in Figure 4-4 outline the process of creating an IFC-based model to support interoperability among applications in the AEC industry. This pyramid shape hierarchy demonstrates the dependency of each upper level to its lower level rather than the sequential procedure of the steps (Hietanen, 2006). The notes in the rectangles partly describe the specific procedure to extend the existing IFC classes and develop the TIM-IFC classes for tunnel projects.

The method to develop the TIM-IFC classes as an extension of the original IFC classes is composed of two major parts, shown in Table 4-1. The first part is generating a conceptual product model consisting of all geometric and non-geometric components of the tunnel and its environment. The second part focuses on deploying the IFC-based structure for elements and data in a tunneling construction project. It is necessary to compare the conceptual model with the original IFC classes to eliminate any similar categories and add new categories to the existing IFC structure.

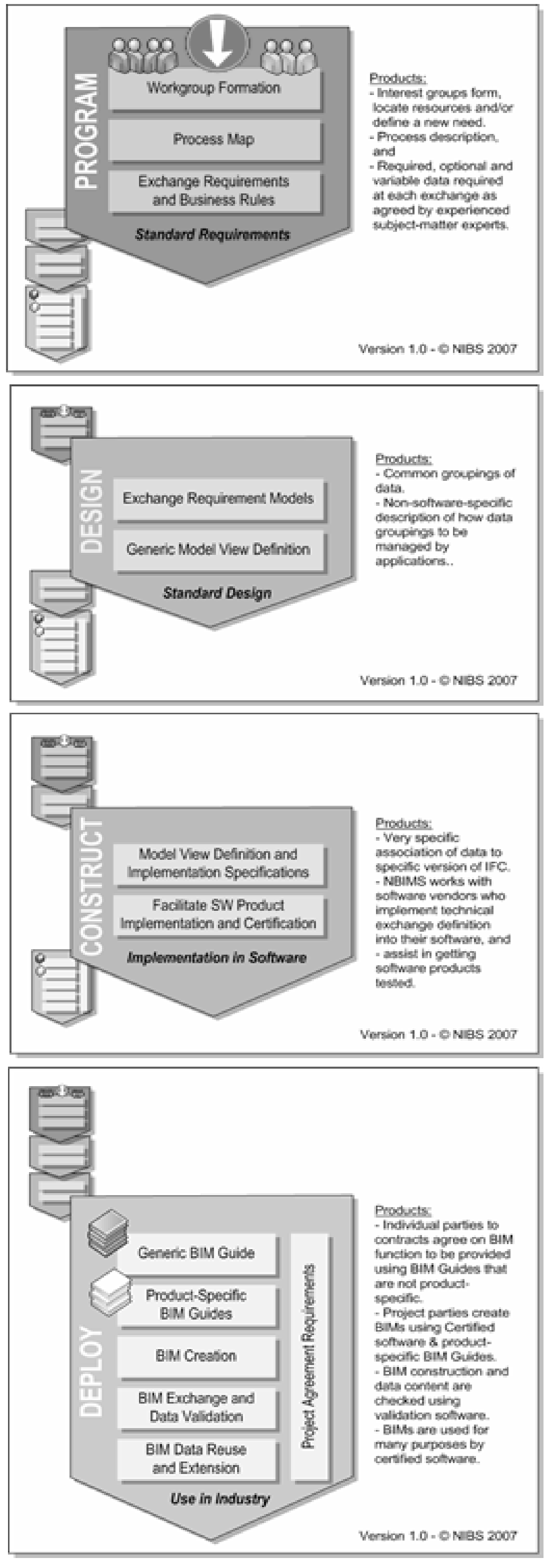


Figure 4-3 NBIMS development and use process (from NIBS, 2007)

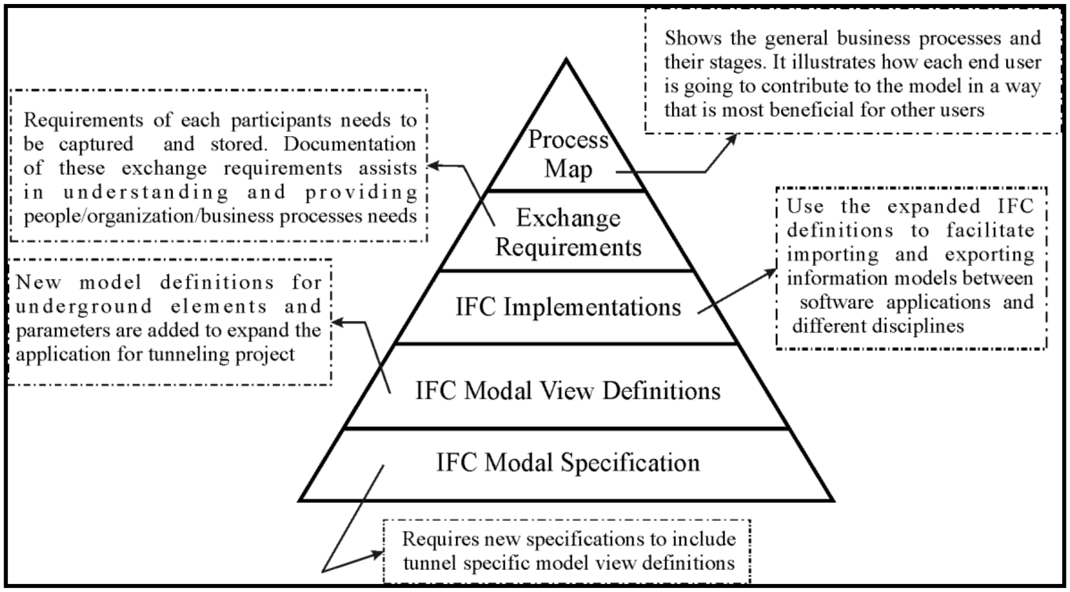


Figure 4-4 The process of creating IFC-based model (Hietanen, 2006)

Table 4-1 General methodology for designing the IFC-based tunnel information model

Design of Tunnel Information Model		
Sequential Methodology		
i	**Develop the Tunnel Product Model**	Physical and Spatial Elements
		Processes
		Resources
		Knowledge
		Measured Data
ii	**Deploy IFC-based Solution for Tunnel Projects**	Create the end user Process Map (PM)
		Identify and document the Exchange Requirements (ER)
		Create the Model View Definitions (MVD)
		Demonstrate the IFC Model Schema and documentation
		Implement the developed IFC model

4.4.2 Tunnel Product Model

In order to reach a valid conceptual product model, it is necessary to identify physical/spatial tunnel elements, underlying processes, required resources, tunnel information, specifications, and finally, the information required for and resulting from executing these processes. The required information objects that build the tunnel product model can be identified by organizing and documenting ongoing processes, required resources, participating actors, and the embedded relationships among them. This information is gathered based on a comprehensive investigation in previous studies and the field documents of the tunnel projects in Chapter 2.

The scope of developing the TIM classes in this study is to capture the main entities and properties of the tunnel structure to provide a foundation for full development in the future. Therefore, only the major tunnel components are incorporated to generate the new classes. The minimal approach in this preliminary general framework prevents redundant or excessive classes, and consequently, larger models that are significantly hard to handle and implement.

Lee et al. (2006) identified the information objects by utilizing ISO 12006-2 standard, which is a framework for classification of information about construction works. This standard helps to determine the required classes for organization of information objects and the relationship between these classes. Yabuki (2008) considered a simplified approach through defining the classes by answering "What and where", "when and how", "Who", and "why". These questions, known as 5W1H, help to identify the products, processes, organizations, measured data, and knowledge, respectively. Zhang et al. (2010) described the tunneling process and construction resources in shield tunneling projects for urban areas and developed a conceptual project model based on the gathered information from previous field documents. In this study, a combination of all mentioned strategies has been employed to determine the information objects for tunneling construction projects. Table 4-2 shows a preliminary classification of common tunnel components by investigating previous studies on tunnel construction and field documents of tunnel projects.

In order to understand the relationship between different components of a tunneling project, Figure 4-5 shows a hierarchal diagram of the main spatial components and their major required knowledge for managing the tunneling process. The geometric components are those represented in the tunnel 3D model and they are considered to be parameterized and generalized (via Revit loaded families) in order to be restored and used in future projects.

Table 4-2 Common Components of Tunnel Projects

Common Components of Tunnel Projects				
Physical and Spatial Elements	**Processes**	**Resources**	**Knowledge**	**Measured Data**
Shaft	Tunnel Excavation	Labor	Material Type	Cost Data
Shaft Section	Tunnel Lining	Equipment	Site Layout	Scheduling Data
Tail Tunnel	Shaft Excavation	Material	Contract Documents	
Tunnel	Shaft Lining		Construction Method	
Undercut	Geographic Survey		Equipment Specification	
Borehole	Pre-design Studies		Site Topography	
Ground and Underground Barriers	Ground Stabilization		Plans and Drawings	
Primary Liner	TBM Installation			
Secondary Liner	TMB Removal			
Soil Layer in Borehole	Temporary Structure Removal			
Temporary Structures				

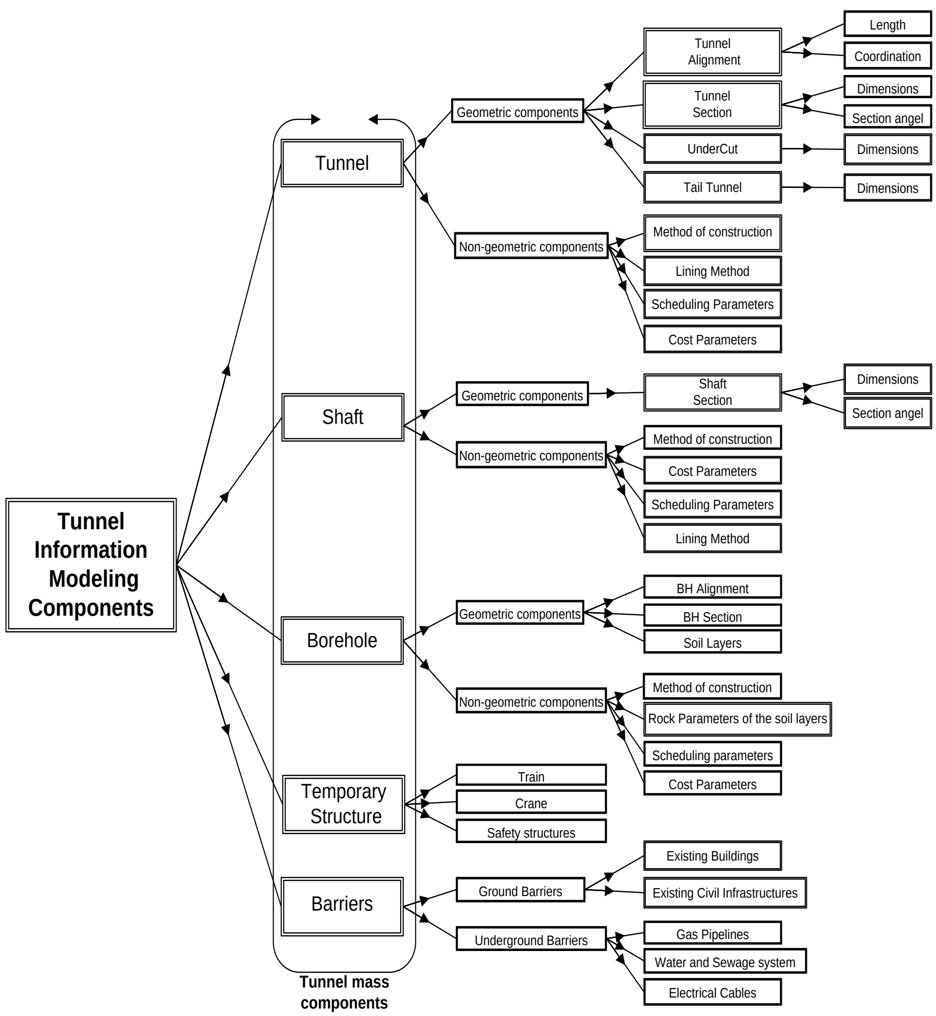


Figure 4-5 Main Spatial Components and their Common Properties

Non-geometric components are conceptual knowledge embedded in the model that either demonstrate the geometric attributes of the model or display the nature of the process, participating organization, methods of construction, etc.

Although, it is not a comprehensive inclusion of all the elements or relationships, it helps to realize the main physical and spatial components. Physical components refer to the actual mass elements of the tunneling process or the corresponding procedure or material such as primary lining, secondary lining, and backfilling material, while spatial components represent the general zones or group of products that form the final tunnel project such as tunnel and shaft. By employing the components in Table 4-2 and Figure 4-5, a conceptual tunnel product model has been developed in Figure 4-6.

The next step for developing an IFC-based tunnel information model is to evaluate and compare the existing IFC classes with the product model to remove any similar classes or to add new classes to better describe the tunneling process. The goal here is to extend the existing classes in IFC2x Edition 3 Technical Corrigendum 1, in an approach that best suits the business processes in tunneling projects.

4.4.3 TIM-IFC Development based on the Tunnel Conceptual Product Model

In order to extend the original IFC classes, it is necessary to accomplish two steps. The first one is to investigate the IFC classes, the existing relationships, and scenarios. The early investigation would help to avoid adding any redundant classes that already exist. More importantly, it would assist to identify the classes that are required to be created specifically for the use of the TIM-IFC data model. Therefore, in the next two sections, the original IFC classes are studied and the classes that are required for creating TIM-IFC classes are identified. The second step is performing the IFC development process in Table 4-1.

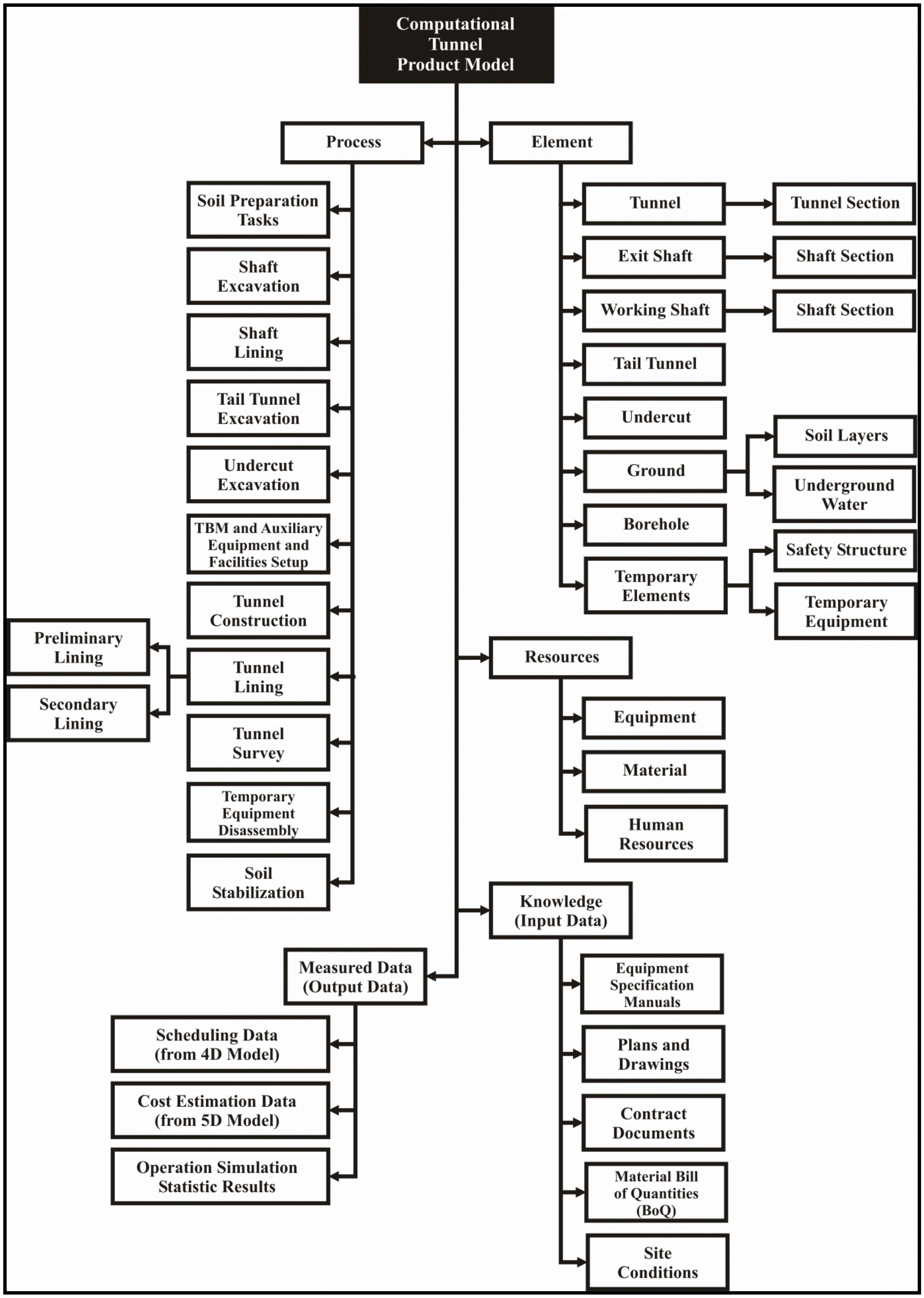


Figure 4-6 Conceptual Tunnel Product Model

4.4.3.1 IFC Architecture and Extension Potential

The architecture of the IFC data model consists of four conceptual layers: core layer (Kernel), domain/application layer, interoperability layer, and resource layer (Figure 4-7). The IFC kernel provides independent information objects that support sustainability of the model and assist in adding new entities to the IFC structure (Lee et al., 2009).

Each layer contains a set of schemas, which represent the detailed information on a particular subject such as geometry, material, process, cost, etc. IfcRoot is the supertype for all of the element classes, except the resource layer classes. The properties of the IfcRoot class are object identity, local naming and ownership information, which are propagated to all the subtypes through inheritance rule. The ladder principle, which is the idea of referencing the classes in the same or lower layers, is a principal aspect of the IFC architecture. In addition to the ladder principle and inheritance capacity of IFC classes, the object-oriented concept and classification rules are necessary to consider when defining the new extended classes (Weise et al., 2000). The IFC standard offers a generalized definition for project information, and therefore, specific use case scenarios can be defined to include a particular project workflow (Eastman et al., 2008). A use case specifies the information exchanges between two actors for a particular workflow. EXPRESS-G is the visual representation of the EXPRESS language and is frequently used to show the hierarchal distribution of the main classes and sub-classes in the IFC schema (Arnold and Podehl, 1999).

In this study, the IFC2x Edition 3 Technical Corrigendum 1 is used as the basis for defining the new TIM-classes. The TIM-IFC definition promotes a solution with multiple objectives. The first one is to offer a general description of tunnel architecture and its associated information that is useful for the implementation of the TIM 3D data model. A 3D tunnel depiction includes both a physical representation of the working shaft (e.g., displacement, geometry, and shape) and its associated properties (e.g., material, sinking method, and lining method). Such a general description provides the project participants with a unique representation of the tunnel project and eventually prevents different portrayals of the actual project boundaries.

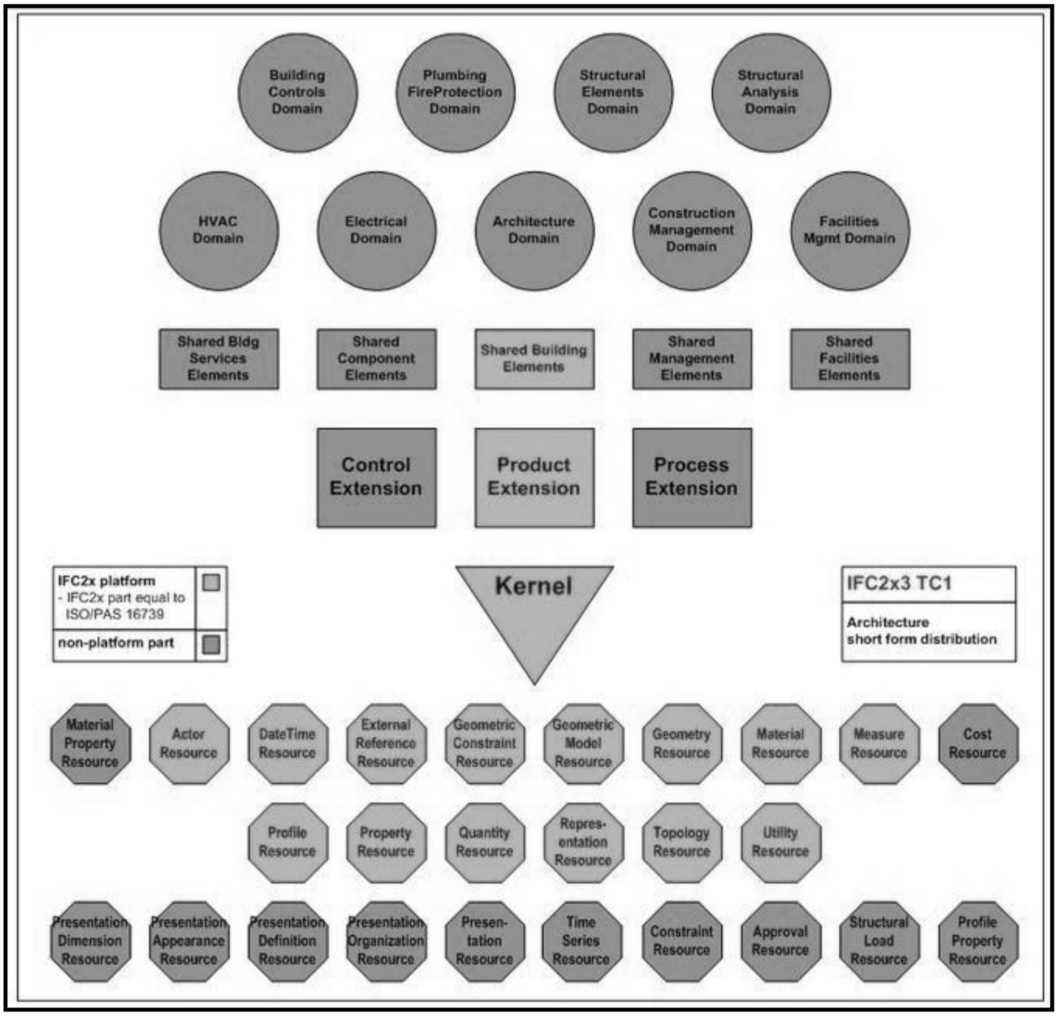


Figure 4-7 IFC Architecture Diagram (From BuildingSMART, 2011)

The second objective is to provide a unique format for exchanging the information among project teams. For instance, in an interoperable tunnel project model, the cost information does not need to be re-entered into the estimating application because it is possible to reach that information directly by importing the required cost information already generated in the 3D TIM model.

4.4.3.2 Original IFC Classes- IFC2x Edition3 Technical Corrigendum1

The IFC classes are classified into four major categories (BuildingSMART, 2011):

1- Defined Types: These are the data types that are defined to be valid in the IFC data model. They describe the type for measures, weights, numbers, quantities, etc. The defined types are characterized by a data type (e.g., real, integer, string, count number, font style) and an arbitrary rule-based specification.

Example-1: IfcHourInDay:

```
EXPRESS Specification
TYPE IfcHourInDay       = INTEGER
      WHERE
            WR1         : { 0 <= SELF < 24}
END_TYPE;
```

Formal Proposition

WR1 : The value of the integer shall be between 0 and 23.

Example-2: IfcIdentifier

```
EXPRESS Specification
TYPE IfcIdentifier      = STRING
END_TYPE;
```

2- Enumerations: basically defines different types for an entity in the IFC data model. The enumerations describe the different kinds that exist in the real project for a specific entity.

Example-1: IfcBeamTypeEnum: This enumeration defines the different types of linear elements that an IfcBeamType entity can fulfill.

Beam: A standard beam usually used horizontally.
Joist: A beam used to support a floor or ceiling.
Lintel: A beam or horizontal piece of material over an opening (e.g., door, window)
T-Beam: A T-Shape beam that forms part of a slab construction
Userdefined: User-defined linear beam element.
NotDefined: Undefined linear beam element.

EXPRESS Specification

```
TYPE IfcObjectTypeEnum   =  ENUMERATION OF
                            (BEAM,
                            JOIST,
                            LINTEL,
                            T-BEAM,
                            USERDEFINED,
                            NOTDEFINED);
END_TYPE;
```

Example-2: IfcObjectTypeEnum: This enumeration identifies the corresponding object category (subtypes of IfcObject) for an object.

EXPRESS Specification

```
Type IfcObjectTypeEnum   =  ENUMERATION OF
                            (PRODUCT,
                            PROCESS,
                            CONTROL,
                            RESOURCE,
                            ACTOR,
                            GROUP,
                            PROJECT,
                            NOTDEFINED);
END_TYPE;
```

3- Select Types: allows the user to reference the selected types and define which entity/entities are associated with another entity.

Example-1: IfcActorSelect: This select type allows a person or organization to be referenced.

EXPRESS Specification

```
TYPE IfcActorSelect          =  SELECT
                                (IfcOrganization,
                                IfcPerson,
                                IfcPersonAndOrganization);
END_TYPE;
```

Example-2: IfcDocumentSelect: enables the user to reference a document from a self-contained data source within IFC data model or an external resource.

IfcDocumentInformation (for metadata of an external document)
IfcDocumentReference (for reference to the location of a document)

EXPRESS Specification

```
TYPE IfcDocumentSelect    =  SELECT
                             (IfcDocumentReference,
                             IfcDocumentInformation)
END_TYPE;
```

4- Entities: Defines all the semantics, elements, and objects present in a project. For each entity, there's a property set definition by a specified entity (IfcPropertySet) and an attachment device (IfcRelDefinesByProperties) for each object entities. The collection of these properties for each object entity is named as: “Pset_.....Common”.

Example: IfcActor: defines all the human factors during project lifecycle and maintains the human/organization definitions of the IFC data model.

IfcActor	
Defined by	=> IfcPropertySet
Attached by	=> IfcRelDefinesByProperties
Accessible by	=> IsDefinedBy
Specific Property Set Definition	=> Pset_ActorCommon

EXPRESS Specification

```
ENTITY IfcActor;
        SUBTYPE OF (IfcObject);
                    TheActor     : IfcActorSelect
        INVERSE
                    IsActingUp  : Set OF IfcRelAssignsToActor For RelatingActor
End_Entity;
```

Attribute definitions

TheActor: Information about the actor.

IsActingUpon: Reference to the relationship that associates the actor to an object.

Inheritance Diagram

```
ENTITY IfcActor;
    ENTITY IfcRoot;
            GlobalId           : IfcGloballyUniqueId;
            OwnerHistory       : IfcOwnerHistory;
            Name               : OPTIONAL IfcLabel;
            Description        : OPTIONAL IfcText;
    ENTITY IfcObjectDefinition;
    INVERSE
            HasAssignments     : SET OF IfcRelAssigns FOR RelatedObjects;
            IsDecomposedBy     : SET OF IfcRelDecomposes FOR RelatingObject;
            Decomposes         : SET [0:1] OF IfcRelDecomposes FOR RelatedObjects;
            HasAssociations    : SET OF IfcRelAssociates FOR RelatedObjects;
    ENTITY IfcObject;
            ObjectType         : OPTIONAL IfcLabel;
    INVERSE
            IsDefinedBy        : SET OF IfcRelDefines FOR RelatedObjects;
    ENTITY IfcActor;
            TheActor           : IfcActorSelect;
    INVERSE
            IsActingUpon       : SET OF IfcRelAssignsToActor FOR RelatingActor;
END_ENTITY;
```

IFC architecture is comprised of hundreds of entities that are organized based on the inheritance rule in a hierarchical order. At the abstract level, the entities are divided into rooted and non-rooted entities. The rooted entities are subtypes of the IfcRoot and have a globally unique identifier (GUID) and assigned properties. The IfcRoot entity has three abstract concepts; IfcObjectDefinition, IfcPropertyDefinition, and IfcRelationship. The non-rooted entities have no GUID and instances only exist if referred by a rooted entity. Therefore, the IFC extension usually occurs in the rooted elements (Figure 4-8).

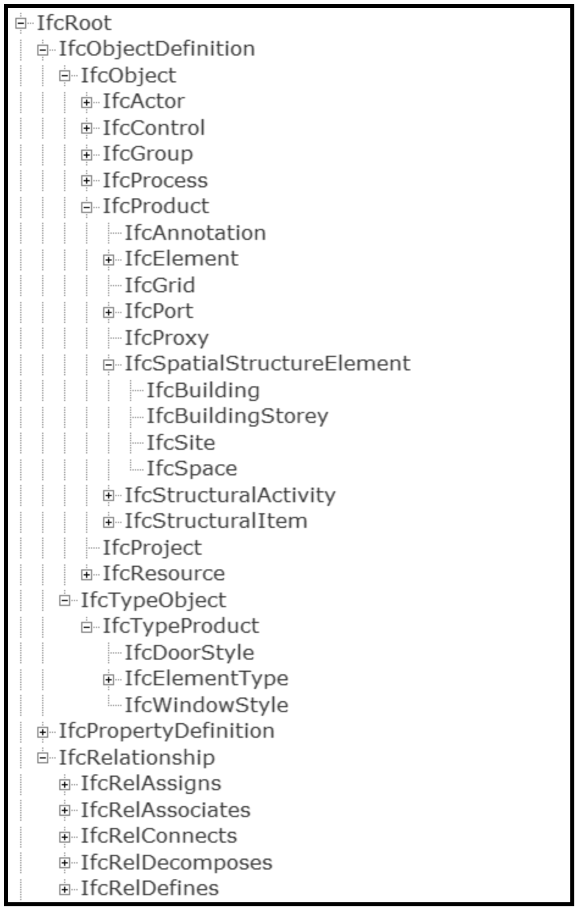


Figure 4-8 The hierarchical architecture of the IfcRoot

The IfcObjectDefinition as one of the subtypes of the IfcRoot has two branches. The IfcObject captures object occurrences, and the IfcTypeObject captures the object types or templates. The six fundamental concepts of Who (IfcActor), Why (IfcControl), What (IfcGroup), Where (IfcProduct), When (IfcProcess), How (IfcResource), known as the 5W1H, are described in the subtypes of the IfcObject. These are the main classes to define all the objects in the tunneling domain. The IfcProduct specifically defines the occurrences of spaces and elements (Spatial and Physical elements) in the TIM-IFC data model.

The IfcRelationship captures the relationship among objects defined under the IfcObject. The five fundamental relationships are IfcRelDecomposes, IfcRelAssigns, IfcRelConnects, IfcRelAssociates, and IfcRelDefines. These entities are critical to define the relationship between the TIM-IFC entities.

The IfcPropertyDefinition describes the generalization of all the characteristics. It has a subtype of IfcPropertySetDefintion and defines the information that is shared among multiple instances of objects. The connection between these properties and the corresponding objects are handled by IfcRelDefines relationship. The subtypes of the IfcRelationship provides enough flexibility to define any relation type between independent information objects in the TIM-IFC development and the required tunnel objects can be easily added into the conceptually same entity groups that existed in the original IFC data model.

4.4.4 TIM-IFC Development

As mentioned in section 4.4.1, the deployment of the IFC-based solution for tunneling projects needs to accomplish certain requirements. These requirements are creating the tunnel project process map, identifying exchange requirements, creating model view definitions, demonstrating the IFC model schema, and finally implementing the developed TIM-IFC data model. It is necessary to mention that since the concept of the extended classes is unique to the tunneling projects and entirely independent from the building domain of the existing IFC classes, such an extension does not have an effect on the already defined classes. Perhaps, by using the TIM-IFC extended classes, it is possible to integrate different parts of a large project in a single data model. For example, in a rail transit subway tunnel, the information associated with the service buildings and surrounding structures can be described by building domain classes. Concurrently, TIM-IFC classes can represent the data regarding the tunnel part of the project. Therefore, by employing a single data model, the project management process benefits from an integrated project model that contains every aspect of the actual project.

4.4.4.1 Tunneling Process Map (PM)

A Process Map (PM) is a model describing the stages in a project and the sequence of end user processes that take place in each stage (Hietanen, 2006). In the TIM-IFC development, creating the tunnel PM assists in identifying the processes, responsible parties, and information flow through different stages of the tunnel phases. It also represents the general work flow in a typical tunneling project by utilizing the TIM concept.

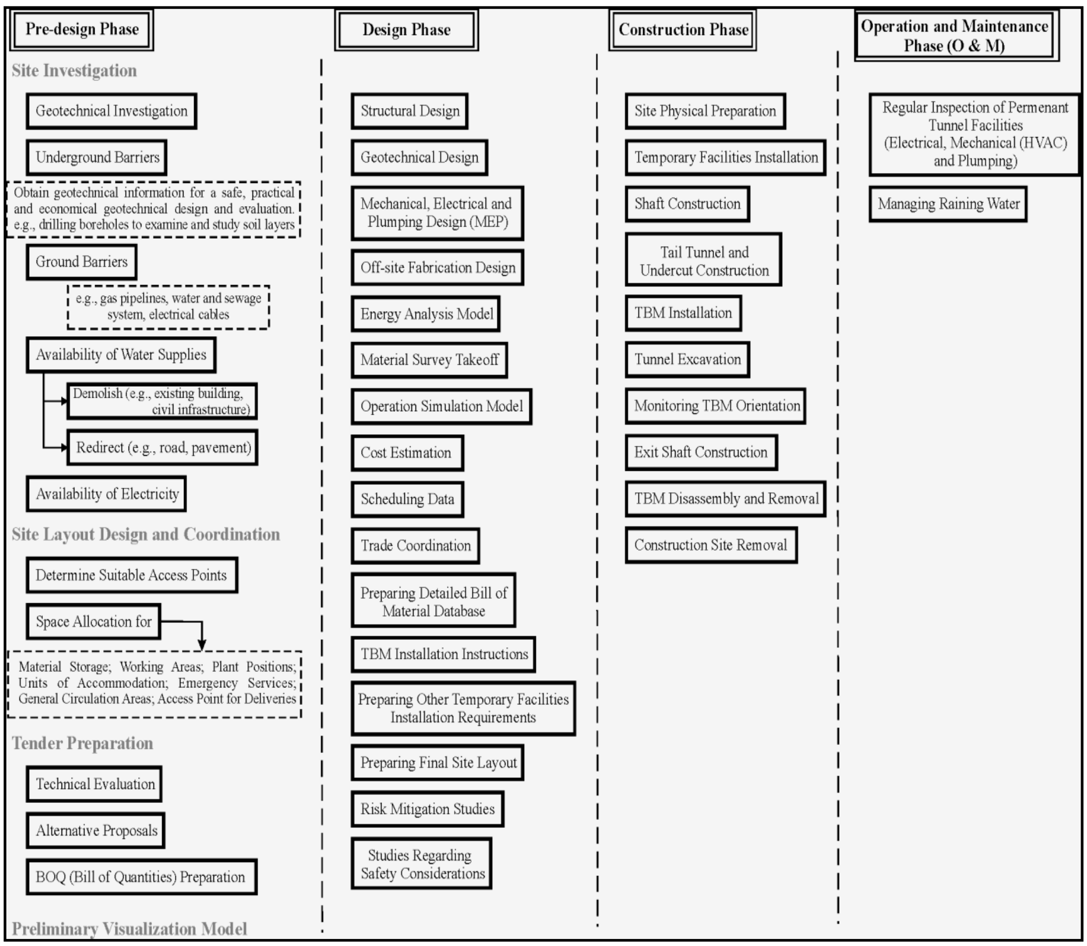


Figure 4-9 Major activities in Tunnel Construction Projects

Developing a process map for a conceptual tunnel project involves first; identifying the business processes in the project and second; investigating the interactions and business flow between different sectors of the business processes. In order to precisely determine elements of the process model, the major processes in each stage have been determined based on the comprehensive literature review in Chapter 2. As a result, the major activities in tunneling projects are those presented in Figure 4-9. These activities are categorized based on their implementation phases.

By identifying the business processes in tunneling projects, development of a process map would be possible. A business process is a combination of multiple tasks and procedures that results in producing a final product. In Figure 4-10, the result of some of the main business processes in tunnel projects are presented.

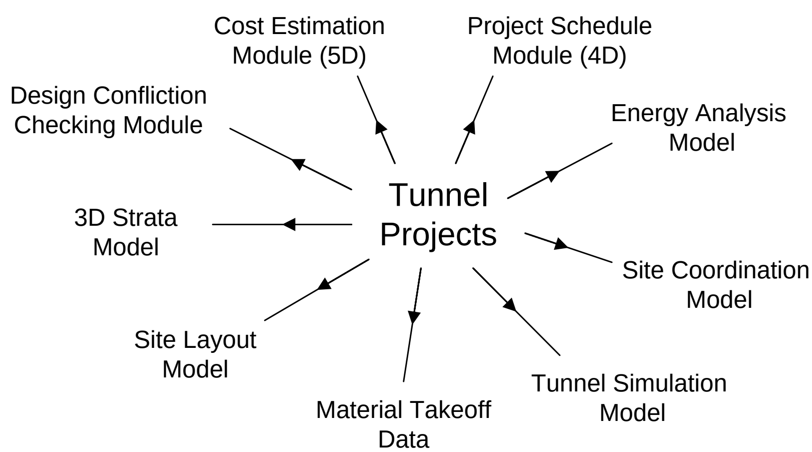


Figure 4-10 Business Processes in Tunneling Projects

A comprehensive PM is shown in Figure 4-12 for a conceptual tunnel project, which illustrates all the undergoing processes and actors from the pre-design phase through the construction phase. The processes and phases can be altered to provide a project's specific needs and are not necessarily as described in Figure 4-11.

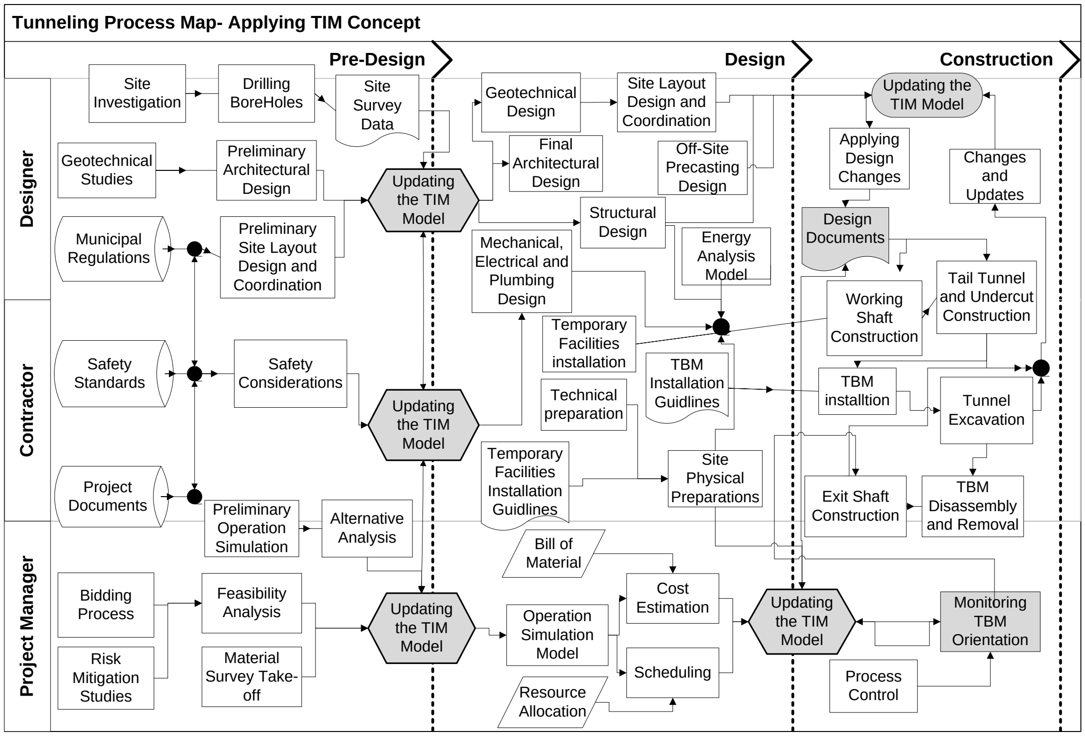


Figure 4-11 A tunnel Process Map from preliminary design to construction completion

4.4.4.2 Exchange Requirements (ER) and Model View Definitions (MVD)

To develop an IFC solution for tunneling projects, it is not merely sufficient to determine the business processes. Still, a detailed framework is required to designate precisely what information is required to be exchanged between the applications or users. The exchange requirements describe the scope of the data exchange in business processes (Hietanen, 2006). Therefore, it reveals the exact objects and attributes to be included in each exchange scenario.

In the building domain, the IFC data structure provides the interoperability tool for exchanging building data. However, IFC implementations require detailed specifications to perform the data transfers. These specifications are described through the exchange requirement (ER) analysis and MVD diagrams using the NBIMS model view approach (Venugopal et al., 2012). Venugopal et al. (2012) identified two sets of semantics as the required specifications of any model exchange. The first one is the semantics in each application interface, and the second is the semantics available in the IFC data structure that defines the exchanged information.

Documentation of exchange requirements assists in understanding and providing user/ /application needs. Informal requirements are collected by the model developer based on the common terms of the domain experts. Identification of these requirements assists in achieving a final tunnel requirement model. This requirement model exhibits the main information packages and their embedded relationships for the target processes. Such exchanges are efficient and to the point (Lee et al., 2009). Exchange requirements present a selection of the information entities from an exchange schema (i.e., IFC, TIM-IFC) and their attributes for a particular use-case scenario (Venugopal et al., 2012).

A tunnel product model contains a variety of information describing different parts and aspects of the tunnel. A single piece of the project model may be interpreted and analyzed from different perspectives by project participants. Consider the rib and lagging support system for one segment of the main tunnel. A detailed design of the steel ribs is used by the engineering team for structural design review, by the contractor for sequencing, coordination, and installation, by the prefabrication team for plant production, and finally by the management team for resource allocation, cost estimation, scheduling, and clash detection purposes. In order to perform each work flow, a different piece of information is required depending on the level of details and the context of the operation. There are a number of feasible ways to present the steel ribs data using the tunnel product model. However, not all the data is necessary for each professional team to complete the design work; for instance:

- The cost estimation process requires the general volume of the work, meaning that by integrating external dimensions and volume of the piece, it is possible to estimate the cost for the material. Hence, the installation details are redundant in this case.

- The clash detection process is possible by using the general representation of the steel rib as a whole block. There is no need for the material information.
- In the coordination process, the geometry information and detailed dimensions are useless. However, the project schedule plays the prominent role in achieving the most efficient sequencing option.

To identify the exchange requirements for business processes in a tunneling project, it is necessary to study the properties and common attributes of tunnel elements and then, recognize which properties are vital enough to be considered as part of the information package for each specific exchange scenario. To determine the required properties to prescribe exchange requirements, these steps (Figure 4-12) are essential to follow:

- Specify the business processes in a typical tunneling project.
- Identify the parties/users participating in different business processes.
- Identify the specific applications that each party uses to perform its associated tasks throughout project lifespan.
- Identify the user or application semantics that describe the data that need to be exchanged.
- Identify the IFC semantics that signifies the user's intentions and successfully describes the exchanged information in the IFC neutral format.
- Finally, gathering information based on the known semantics in the user/application domains and IFC data structure. The medium for representing the required information is provided by model views.

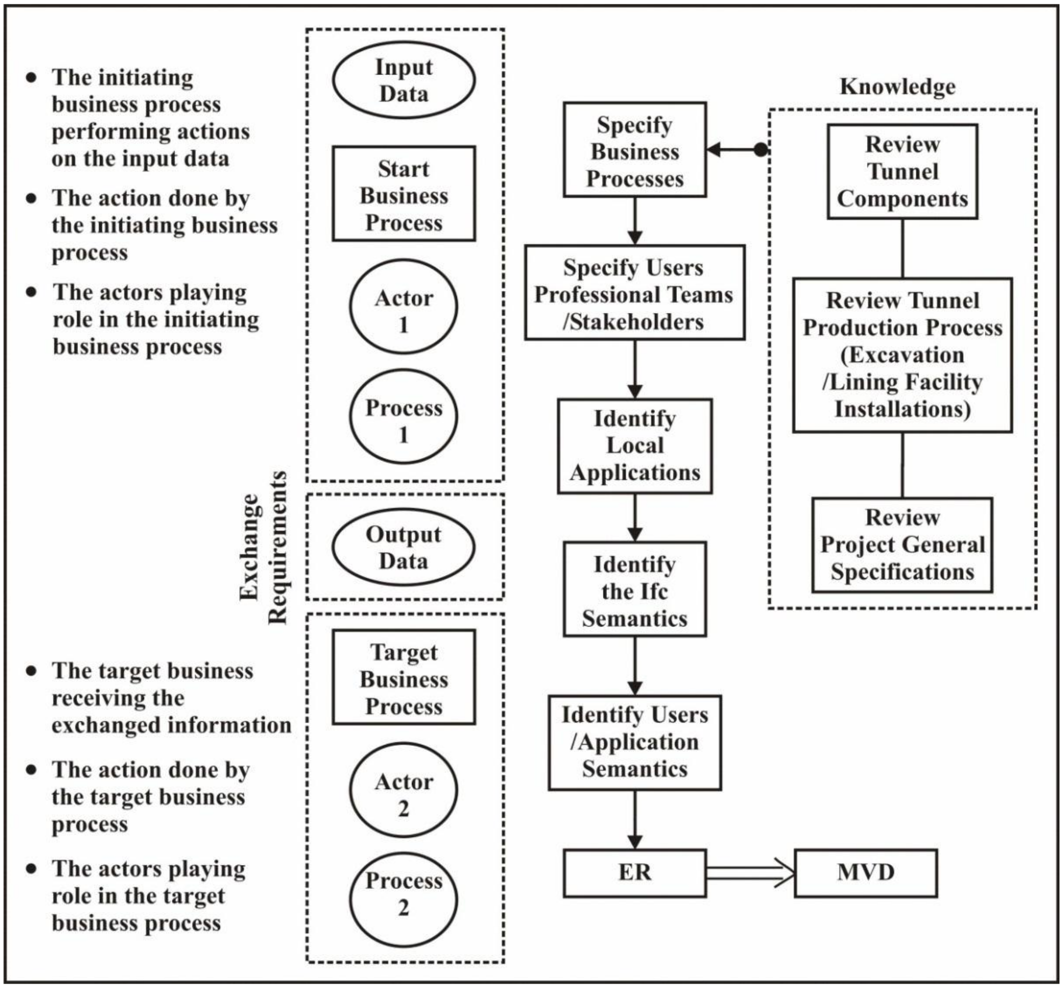


Figure 4-12 The procedural steps to deliver ER and MVD

A typical scenario of the above steps for identifying the exchange requirements and forming the model views is described for the preliminary studies/planning phase of a typical tunneling project (Table 4-3). The results of this figure is prescribing the exchange requirements for a prefabricated concrete segment for the shaft lining process based on the interrelations between designer, contractor, prefabricator, and project manager.

Table 4-3 Typical scenario to explore exchange requirements among applications/participants

	Preliminary Studies (Planning phase)				
	Business Processes	Users	Applications	User/Application Semantics	Ifc Semantics
Prefabricated Shaft Concrete Segment	Cost Estimation	Project Manager- Contractor- Client	Financial Analyzer- Spread Sheet	Cost per Unit- Quantity Take Off- Bill of Material	IfcTask- IfcCostItem- IfcCostSchedule- IfcCostValue- IfcAppliedValue- IfcAppliedValueRelationship
	Design	Engineering Team- Architectural Team	3D CAD Modeling Interface- 3D Strata Modeling Tool	Design Specifications- Detailed Dimensions- Soil types and Specifications-	IfcProduct- IfcElement- IfcSpatialStructure- IfcElementType- IfcAnnotation
	Production	Prefabrication Team	3D Manufacturing Design	Detailed Geometry- 2D/3D Layout- Fabrication Sequence	IfcProduct- IfcProductDefinitionShape- IfcElementComponent- IfcAnnotation
	Installation	Contractor- Designer	3D CAD Modeling Interface- 3D Strata Modeling Tool	Connection Details- Installation Specifications- Safety Limits- Work Schedule	IfcConnectionGeometry- IfcElement- IfcAnnotation- IfcLocalPlacement

There are multiple representations to show and classify the same piece of information in different applications. As a result, several arrangements of information are possible. Therefore, the translators, which assist in mapping the data, would follow dissimilar ways to depict the information. Such deviation results in unreliable exchange outcomes and threatens precise information mapping between multiple applications. MVD supports different exchange scenarios and modeling guidelines. Such a uniform data structure, which acts as a universal standard, prevents further confusion and errors in the exchanging data models (Sacks et al., 2010).

The IFC model views, as a subset of the IFC model specification, facilitate the IFC implementation process. Creating MVD is the mechanism in which a standardized schema for representing data models is comprehended to unify the data structure in all the applications used within a specific domain of the industry. The IFC MVD describes definitions and configurations. They assist in prescribing the possibilities of a concept and then determine how to arrange and use the meanings while following a structured framework in a specific case. The major role of the IFC MVD is to satisfy the requirements of the end users in the IFC implementations and as a result, it has connections to the larger concept of Information Delivery Manuals (IDM) (Hietanen, 2006). The IDM includes but is not limited to the Reference Processes, Process Map, Business Rules, Verification Test, Exchange Requirements, Functional Parts, and Concepts (Kang and Lee, 2009). The IDM unifies the user requirements with software solutions (Wix et al., 2006). The model views in the original IFC help to identify the data structure required for any working exchange between the subdomains of building construction. They describe the particular information required for the exchange process and specify the form and structure of the IFC entities in such exchanges (Venugopal et al., 2012).

Generally, there are two formats for IFC model view definitions; IFC release independent and IFC release specific. The IFC release independent format is understandable for all industry professionals without any previous experience in IFC coding or implementing software applications. It describes the concepts that are generally used in data exchange. The IFC release specific format is more detailed and defines how the data is going to be exchanged through the employment of the IFC model specification. Therefore, the later format assists programmers to enhance or develop corresponding software applications (Hietanen, 2006).

In this study, the major step in creating the IFC model view definition is to identify the information that needs to be exchanged or transferred. Based on this information, determining the relationship and classification of different classes in the hierarchy of the model view definition is feasible. It is necessary to include definition segments in the MVD to cover all data packages such as the information presented in Table 4-4 for the main tunnel and shaft components of a typical tunnel project. Moreover, it helps to add new classes in future by specifying the required criteria to be included in each object of the data model. The model views for tunneling projects define the information that needs to be exchanged and the entities that need to be involved in the TIM-IFC data structure.

Table 4-4 Shaft and tunnel components properties and attributes

	Tunnel Components	
	Shaft	**Tunnel**
Properties	Name	Name
	GUID	GUID
	Description	Description
	Owner/History	Owner/History
	Dimensions	Excavation Method
	Material	Initial lining type
	Material cost per meter	Secondary lining type
	Excavation start time	Number of sections
	Excavation finish time	Excavation start time
	Lining method	Excavation finish time
	Excavation Method	Additional lining type
	Existence of a safety wall	Mucking rate
	One pile driving time	Dewatering rate
	Pile quantity	Excavation dirt volume
	pile width	Material
	Piling start time	Material cost per meter
	Piling finish time	Longitudinal sections' length
	Pattern of drilling	Diameter
	Number of required holes for drilling	Connections to other components
	Drilling holes diameter	Shape representation
	Drilling holes length	Total length
	Mucking rate	Soil type
	Dewatering rate	Soil swell factor
	Soil type	Tunnel position
	Soil swell factor	Tunnel orientation
	Excavation dirt volume	Tunnel survey

MVD are comparable only if they follow a particular pattern that also makes the future developments feasible for new elements or modifications. The particular pattern defines a basic structure for the view definitions to have a comparable data set. The pattern of MVD for tunnel elements is composed of different classes in order to include attributes, material, covering, geometry, and connection to other tunnel elements. Figure 4-13 shows the general pattern of the common MVD for tunnel components.

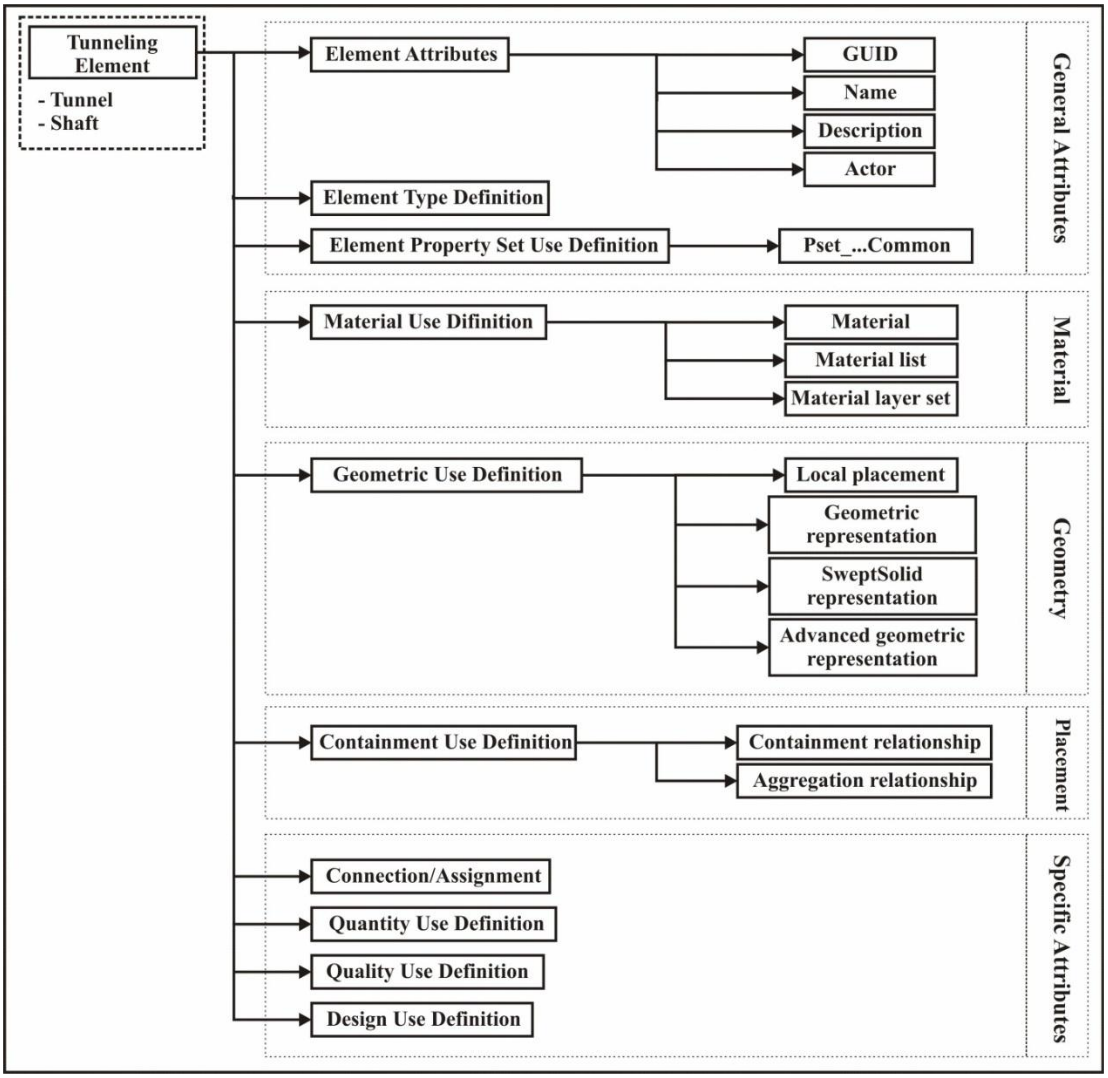


Figure 4-13 Common MVD pattern for tunnel elements

Figure 4-14 (a-d) and Figure 4-15 (a-d) shows the view definitions for shaft and tunnel components based on the general pattern.

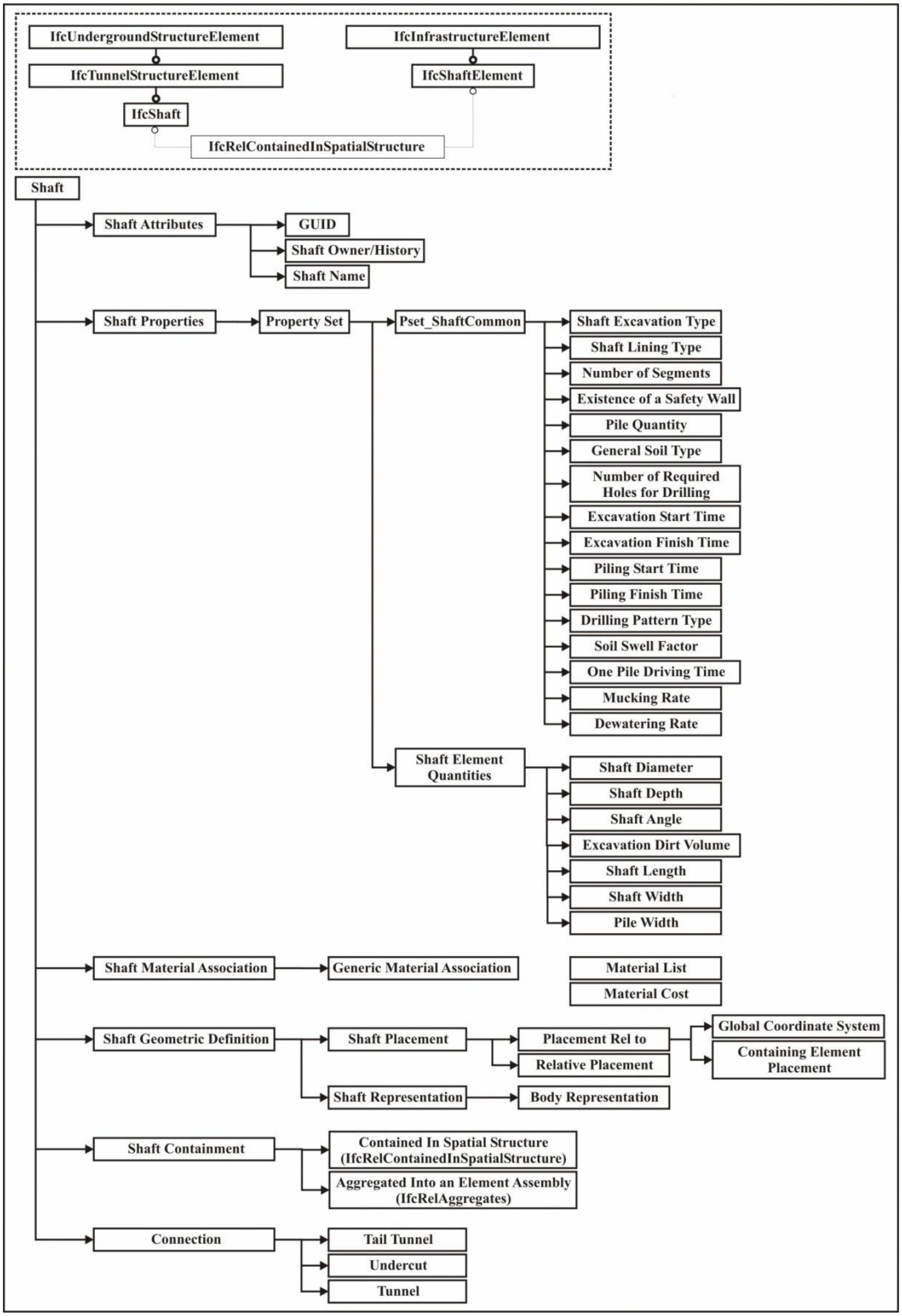


Figure 4-14 (a) MVD for shaft component and its subclasses

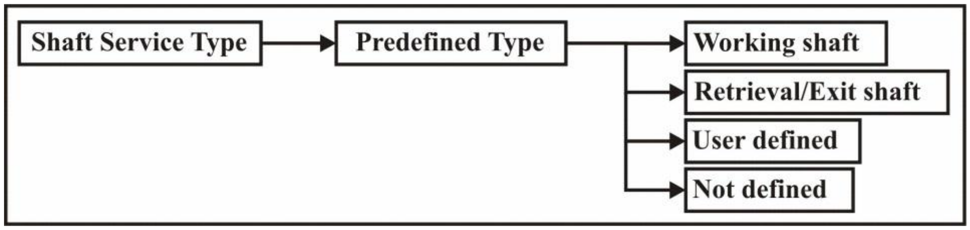


Figure 4-14 (b) MVD for shaft component and its subclasses

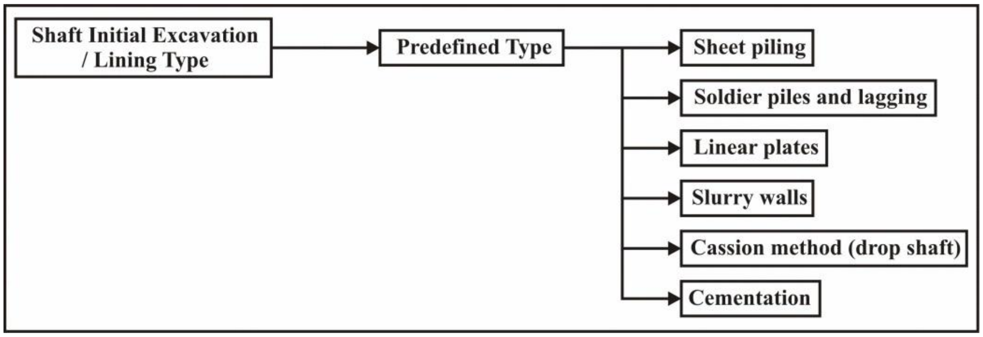


Figure 4-14 (c) MVD for shaft component and its subclasses

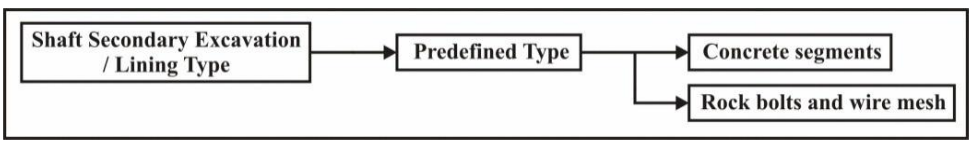


Figure 4-14 (d) MVD for shaft component and its subclasses

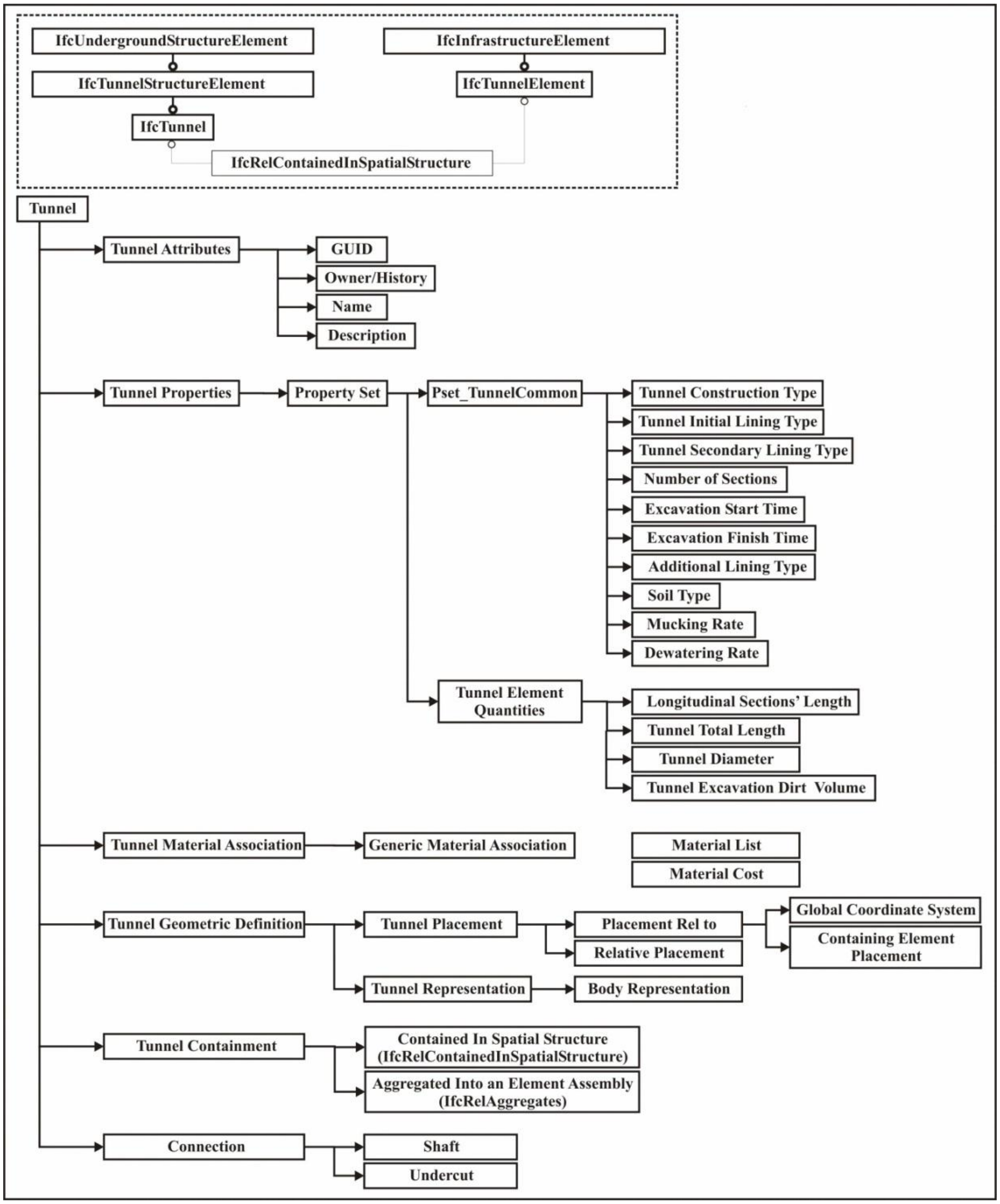


Figure 4-15 (a) MVD for tunnel components and its subclasses

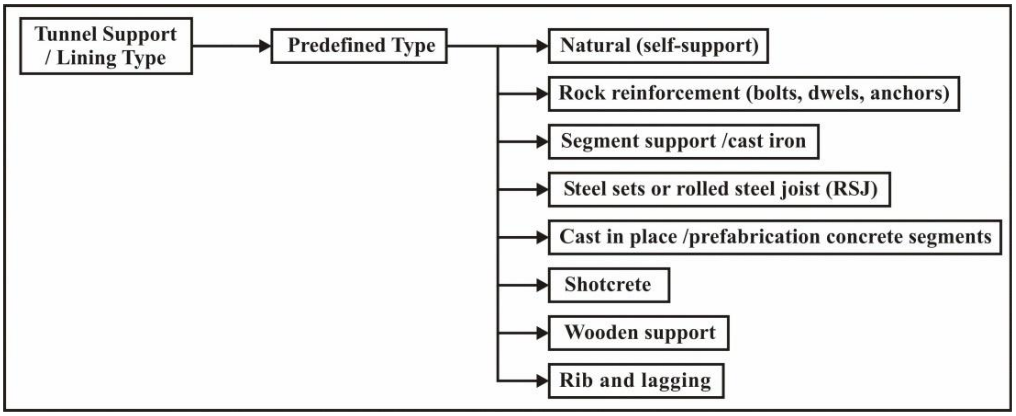


Figure 4-15 (b) MVD for tunnel components and its subclasses

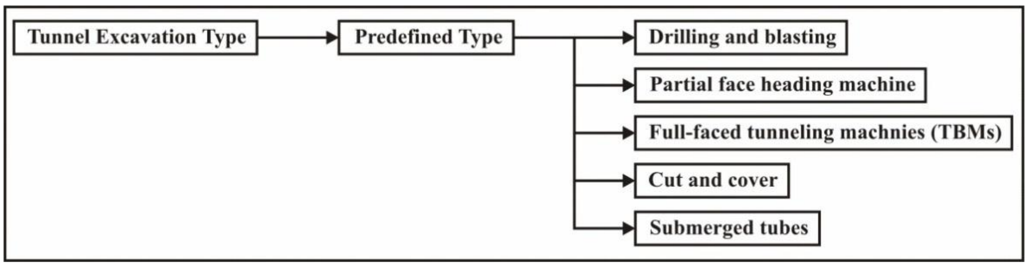


Figure 4-15 (c) MVD for tunnel components and its subclasses

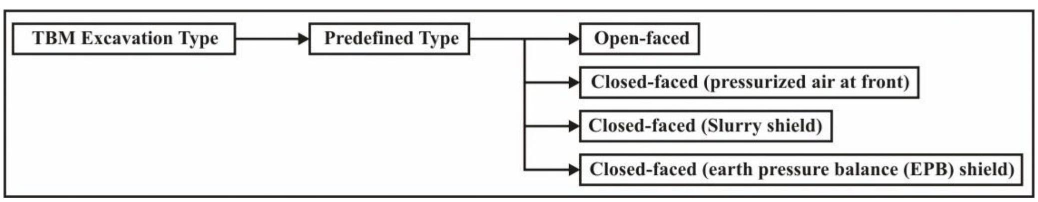


Figure 4-15 (d) MVD for tunnel components and its subclasses

It is necessary to mention that based on the NBIMS standard process to develop model views, the MVD for a specific *use case exchange* needs to be validated by comparing it with the IDM. The IDM is the result of the first step of the NBIMS procedural steps to form the model views. The IDM is determined in a workgroup of professionals for a “*use case exchange* scenario”.

4.4.4.3 TIM-IFC Model Schema and Documentation

Documenting the resulting TIM-IFC model schema helps to define the hierarchical sequence of the IFC entities and clarify the associated relationships.

All the added classes are briefly demonstrated in Table 4-5. The tunnel components are divided into subparts and smaller units for a better breakdown of the multiple related data. For instance, the mass of the general tunnel may divide into shorter segments in length (Figure 4-16). Furthermore, such divisions into smaller parts help to imitate the actual exploitation of the tunnel boring and lining processes, which additionally contribute to a better handling of information for the intended segments.

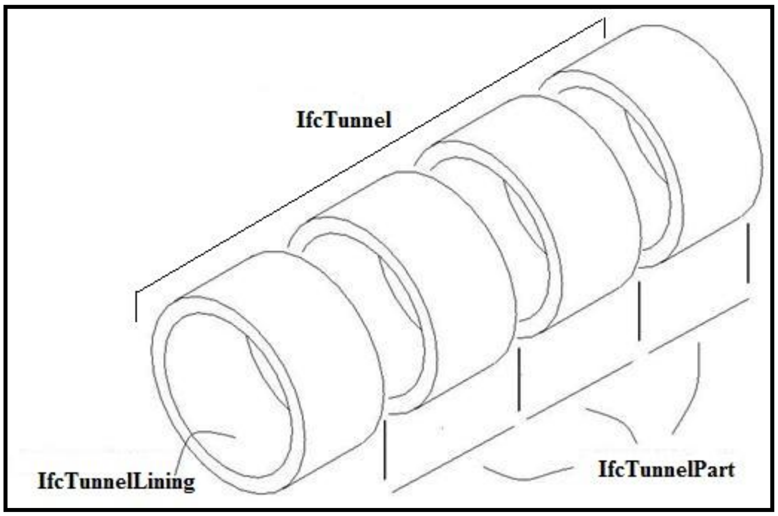


Figure 4- 16 Division of the main tunnel and related IFC classes

Original IFC entities are divided into rooted and non-rooted entities. The rooted entities are all subtypes of IfcRoot and have been assigned to a globally unique identifier (GUID); whereas the non-rooted entities are not identified by GUID and their instances only exist in the case of a referral from a rooted entity. Therefore, any extension most probably occurs under the IfcRoot entity. Each rooted entity has an identifier GUID and properties (Figure 4-17).

The TIM-IFC entities are divided into two groups; spatial entities and physical entities. The spatial entities (the subtypes of IfcSpatialStructureElement) are referred to as the abstract spaces of the tunnel project, whereas the physical entities (the subtypes of IfcElement) represent the physical elements existing in the spatial spaces. The relation between spatial entities and physical entities is facilitated by IfcRelContainedInSpatialStructure entity.

The IfcTunnelStructureElement represents the line-oriented feature of the tunnel structure. Moreover, this line-oriented representation needs to be considered for developing the geometric definition of the tunnel data model, which is not discussed in this work. The IfcTunnelStructureElement, as the subtype of the IfcSpatialStructureElement, has six subtypes: IfcTunnel, IfcTunnelPart, IfcShaft, IfcShaftPart, IfcTailTunnel, IfcUndercut (Figure 4-18). These entities are representing the spatial elements of the tunnel structure. The Containment attribute of the tunnel spatial elements provides the composition type for each spatial component. This is defined by the Composition Type attribute of the supertype IfcSpatialStructureElement.

The IfcSpatialStructureElement provides a Composition Type to all of its subtypes through the inheritance rule of the IFC data structure. The tunnel element can be decomposed in a longitudinal direction into smaller units, forming the “Partial Type”. Moreover, an Aggregation Type contains a group of tunnel elements forming the whole tunneling project or “Complex Type”. Finally, the tunnel element can be a sole element itself without any aggregation or decomposition, forming the “Element Type”. Using the same methodology, the IfcProject can represent an aggregation of IfcSite and another IfcSite, itself, can be decomposed into IfcTunnel, IfcShaft and etc. Figure 4-19 illustrates the composition type for the IfcTunnelStructureElement entity and its subtypes.

In all the TIM-IFC schema diagrams, the non-colored classes are part of the official IFC 2x Edition3 Corrigendum 1 and the grey- colored classes are those added to include tunnel elements and specifications. Appendix-D presents all the TIM-IFC classes along with their descriptions and EXPRESS specifications.

Table 4-5 extended classes defined for TIM-IFC model schema

TIM-IFC Entities	First stage supertyeps	Second stage supertypes	Third stage supertypes	Instances
Tunnel Spatial Elements	IfcGround	IfcGroundCave	IfcGroundCollar	ground collar, ground roks, ground rocks' surfaces
			IfcGorundLithology	
			IfcGroundGeology	
	IfcOnGroundStructureElement	IfcBridgeStructureElement		bridge spatial elements (based on the IFC-Bridge), station, pavement
		IfcStation		
		IfcPavement		
	IfcUnderGroundStructureElement	IfcTunnelStructureElement	IfcTunnel	tunnel, working shaft, exit shaft, tail tunnel, undercut, boreholes, manholes
			IfcTunnelPart	
			IfcShaft	
			IfcShaftPart	
			IfcTailTunnel	
			IfcUndercut	
Tunnel Physical Elements	IfcGroundReinforcingElement			tunnel, initial lining, secondary lining, shotcrete, concrete shaft collar, base slab, rock bolts, wet/dry cassion, wire mesh, slurry walls, prefabricated lined shaft, precast/insitu concrete segments, piles (timber, steel, concrete), horizontal rib and vertical lagging, excavation/hoisting/ ventilation/lighting/centering /dewatering/accessing/ safety tools
	IfcGroundElement	IfcGroundWater		
		IfcGroundLayer		
	IfcInfrastructureElement	IfcTunnelElement	IfcTunnelSegmentRing	
			IfcTunnelInitialLining	
			IfcTunnelSecondaryLining	
			IfcTunnelBackfillingMaterial	
			IfcTunnelExploitationUtilities	
			IfcTunnelSealingMaterial	
		IfcTunnelElementPart		
		IfcShaftElement	IfcShaftPile	
			IfcShaftHPile	
			IfcShaftConcreteSegment	
			IfcShaftBolt	
			IfcShaftBaseSlab	
			IfcConcreteShaftCollar	
			IfcShaftHorizVerRibLag	
			IfcWireMesh	
		IfcShaftElementPart		
		IfcTunnelConstAuxilaryElement	IfcTunnelVentilationElement	
			IfcTunnelSafetyElement	
			IfcTunnelExcavationElement	
			IfcTunnelLightingElement	
			IfcTunnelSurveyElement	
		IfcShaftConstAuxilaryElement	IfcShaftAccessToolElement	
			IfcShaftCenteringElement	
			IfcShaftDewateringElement	
			IfcShaftExcavationElement	
			IfcShaftHoistingElement	
			IfcShaftLighitngElement	
			IfcShaftVentilationElement	
			IfcShaftSafetyElement	
		IfcTunnelServiceElement	IfcRail	
			IfcTrafficSign	
Group Elements	IfcTunnelGroupSystem	IfcTunnelSystem	IfcTunnelLiningSystem	group of shaft/tunnel lining and excavation components (auxilary or permanent), group of tunnel/shaft service elements
			IfcTunnelServiceSystem	
			IfcTunnelExcavatingSystem	
		IfcShaftSystem	IfcShaftLiningSystem	
			IfcShaftlExcavatingSystem	

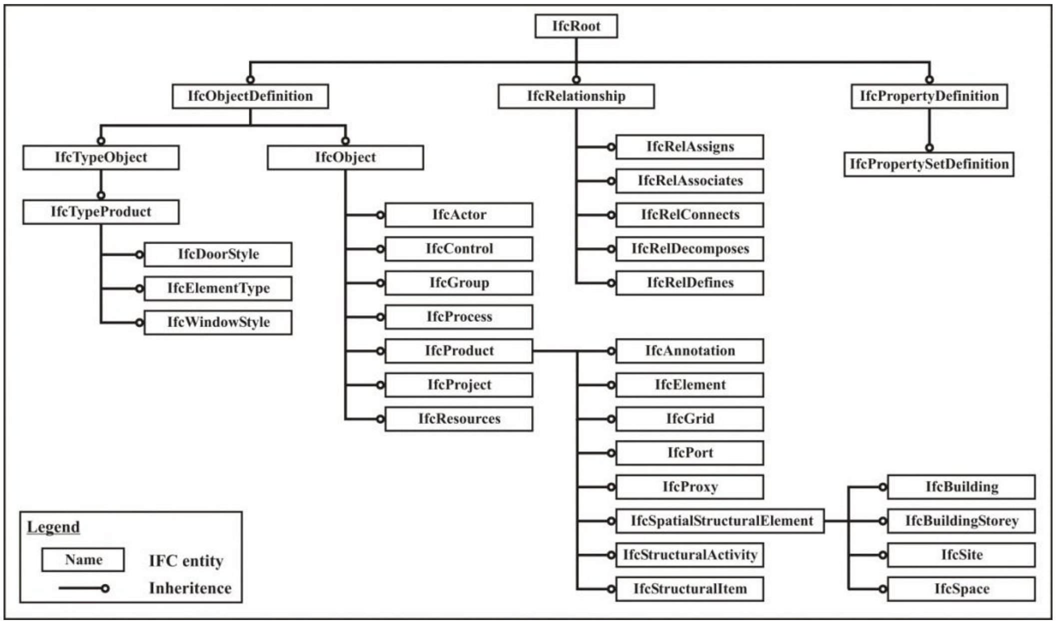


Figure 4-17 The IfcRoot entity and its sub classes in the original IFC 2x3 data model

The tunnel physical elements are presented in Figure 4-20. The tunnel physical elements are gathered in the IfcInfrastructureElement, which is a subtype of the IfcElement in the original IFC data structure. The IfcGroundElement and IfcGroundReinforcingElement represent the entities describing the ground structure such as the underground water, ground layers, and the material/devices used to fortify the soil structure through construction process. The property set objects in the IFC structure provide the container for storing the meta information associated with Spatial and physical entities of the TIM-IFC model. Moreover, the IFC Property set objects assist in defining a functional relationship between different tunnel boring and lining systems applicable in different site conditions.

The IfcRelNest and IfcRelGroup, that are used to show the hierarchical breakdown of the lining and boring systems, assist in defining subsystems with a more specialized function. For instance, the non-explosive boring system may require a divided pattern of the main tunnel into smaller parts in order to apply specialized tools in different geotechnical conditions.

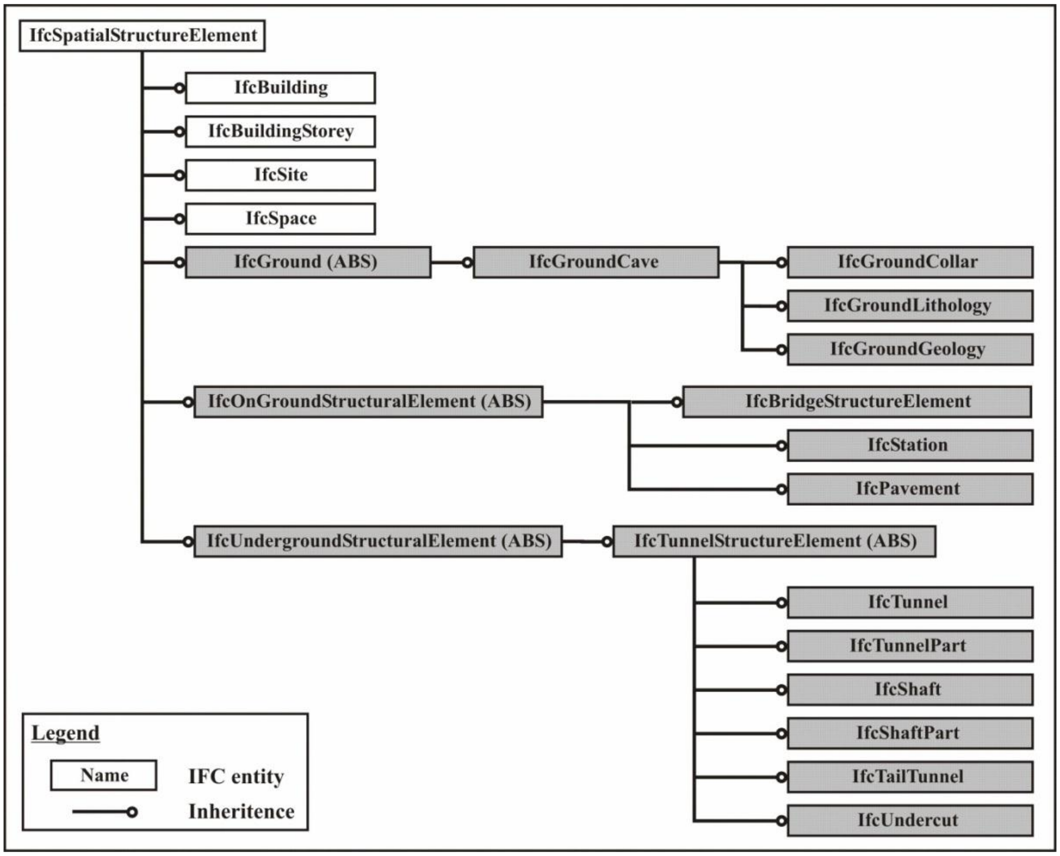


Figure 4-18 The TIM-IFC spatial elements

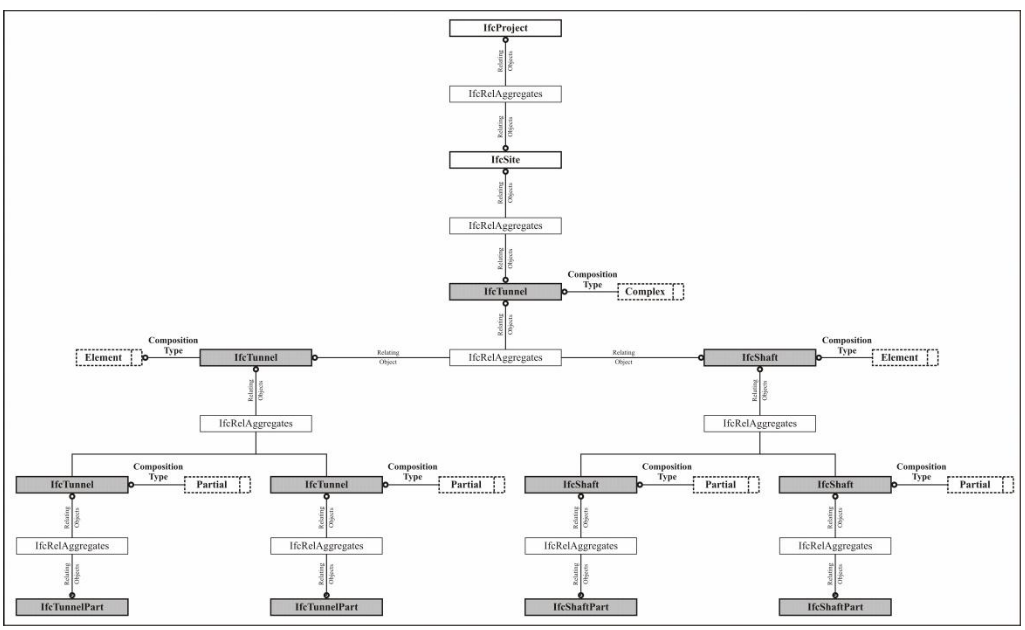


Figure 4-19 The composition type via IfcRelAggregates Relationship

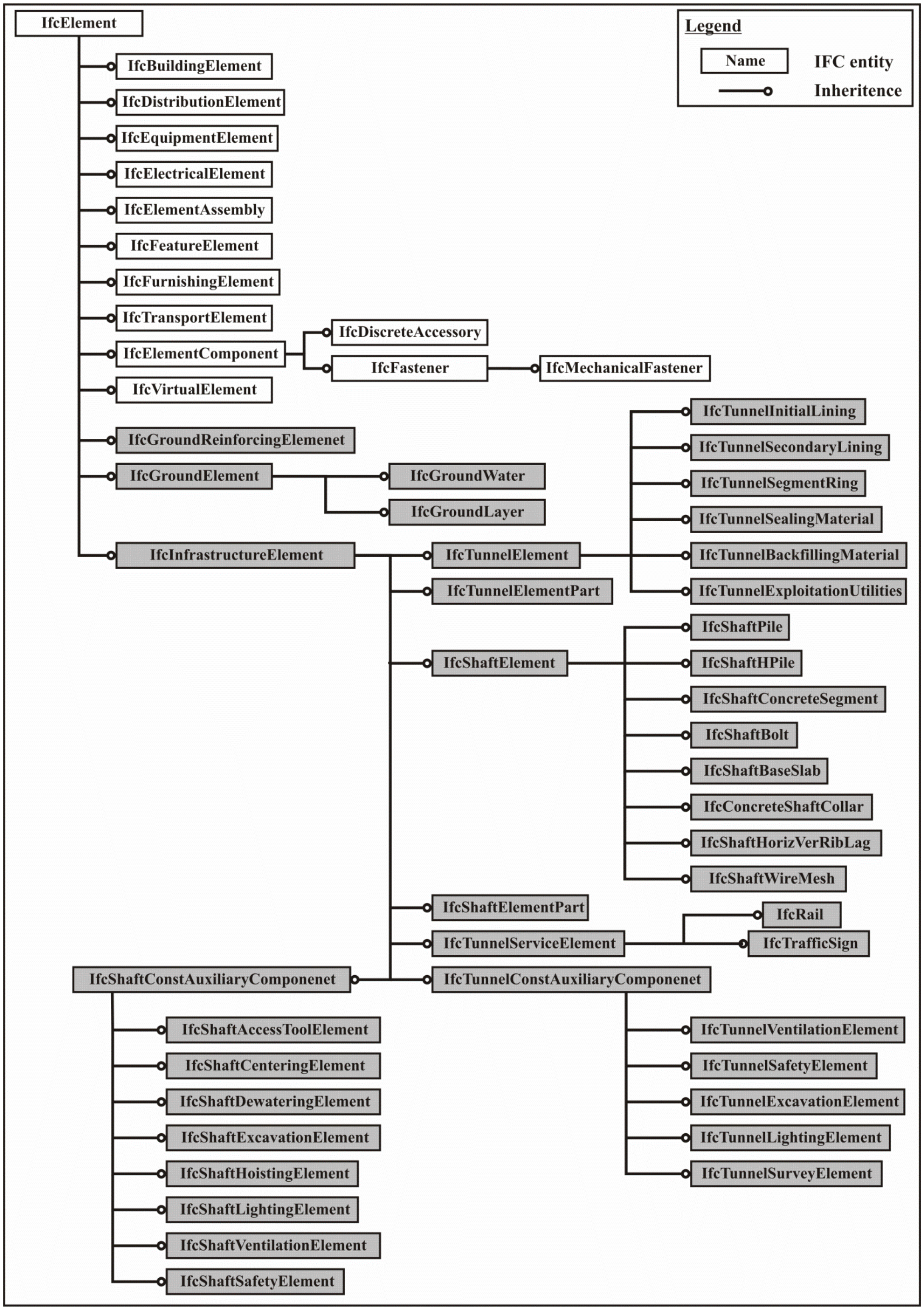


Figure 4-20 The TIM-IFC physical elements as the extended classes for the original IFC entities

The subtypes of the IfcRepresentation entity can be used as the medium for defining the geometric and topological representation of the tunnel components (Figure 4-21). The geometric representation is beyond the scope of this study. Figure 4-22 shows the TIM-IFC system group elements.

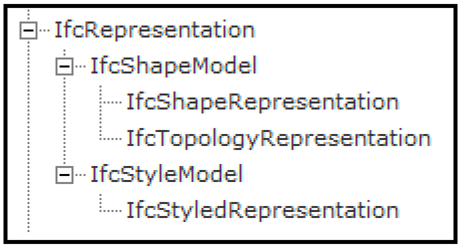


Figure 4-21 IfcRepresentation in the Original IFC 2x3 Data model

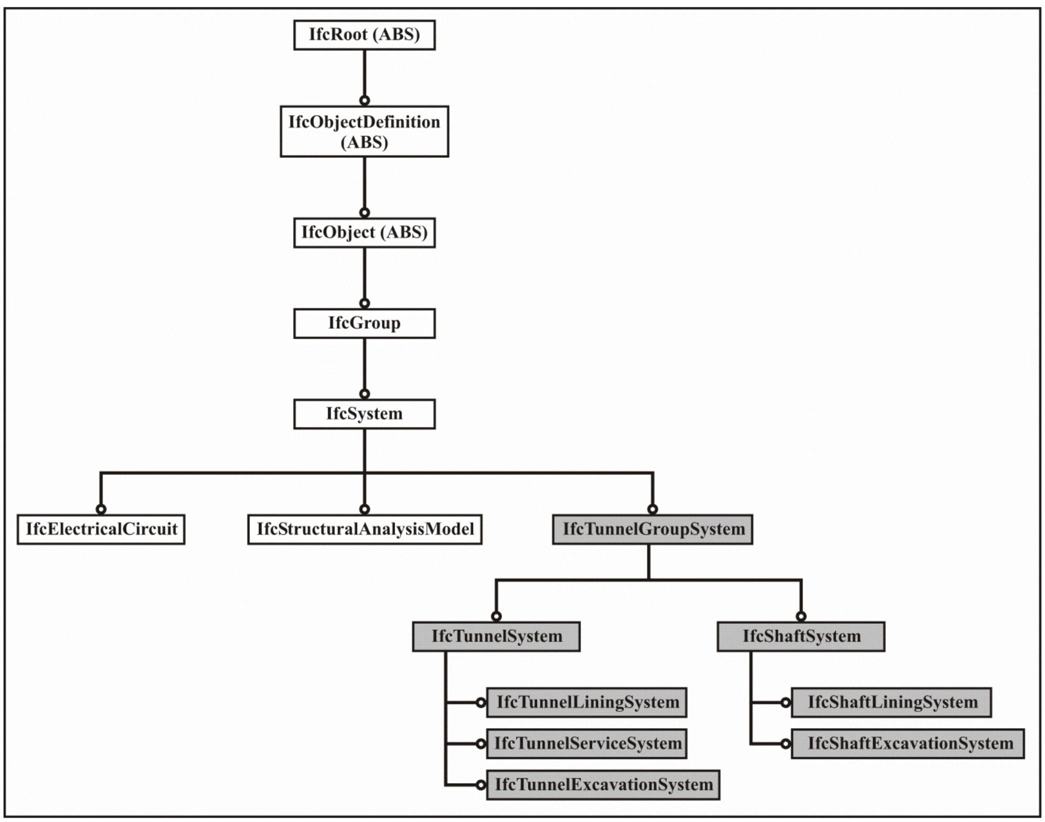


Figure 4-22 TIM-IFC system group elements

4.4.4.4 Implementing the TIM-IFC Data Model

Previous studies, which developed new classes to extend the original IFC data model, were used and intended to be a verified sources of validated classes. These new classes, as an amendment to the original IFC data model, make it possible to cover more specific data entities that particularly describe a group of civil infrastructure projects in detail. The IFC-Bridge version 2 model released in 2007 is one of the major resources used to develop the entities and classes for the TIM-IFC data model in this study. The previous section (i.e., 4.4.4.3) and Appendix-D presented a list of new entities and associated types to represent the tunnel components in the IFC data model. In this context, the new entities along with the original IFC entities and types are called the TIM-IFC.

In order to implement the tunnel specific classes, a STEP-based platform is needed to define the TIM-IFC classes. There are a plenty of STEP-based toolkits to read and write EXPRESS-based object-oriented data models. In this study, the JSDAI™ for Eclipse platform is used to generate the tunnel specific entities and attributes (Figure 4-23 (a) and (b)). JSDAI™ is an open source API for reading, writing, and run-time manipulation of object-oriented EXPRESS-based data models. EXPRESS-based data models are widely used in STEP (ISO 10303) models. Table 4-6 provides JSDAI's properties based on JSDAI (2013). This platform provides an environment to define the TIM-IFC classes. These classes are then presented by the EXPRESS-G diagram in the JSDAI™ EXG layout. Appendix-E presents the procedural steps to develop Express schema and EXPRESS-G diagrams for TIM-IFC classes by using JSDAI™ plugins for Eclipse IDE.

Figure 4-23 (a) JSDAI™ and Eclipse trademarks

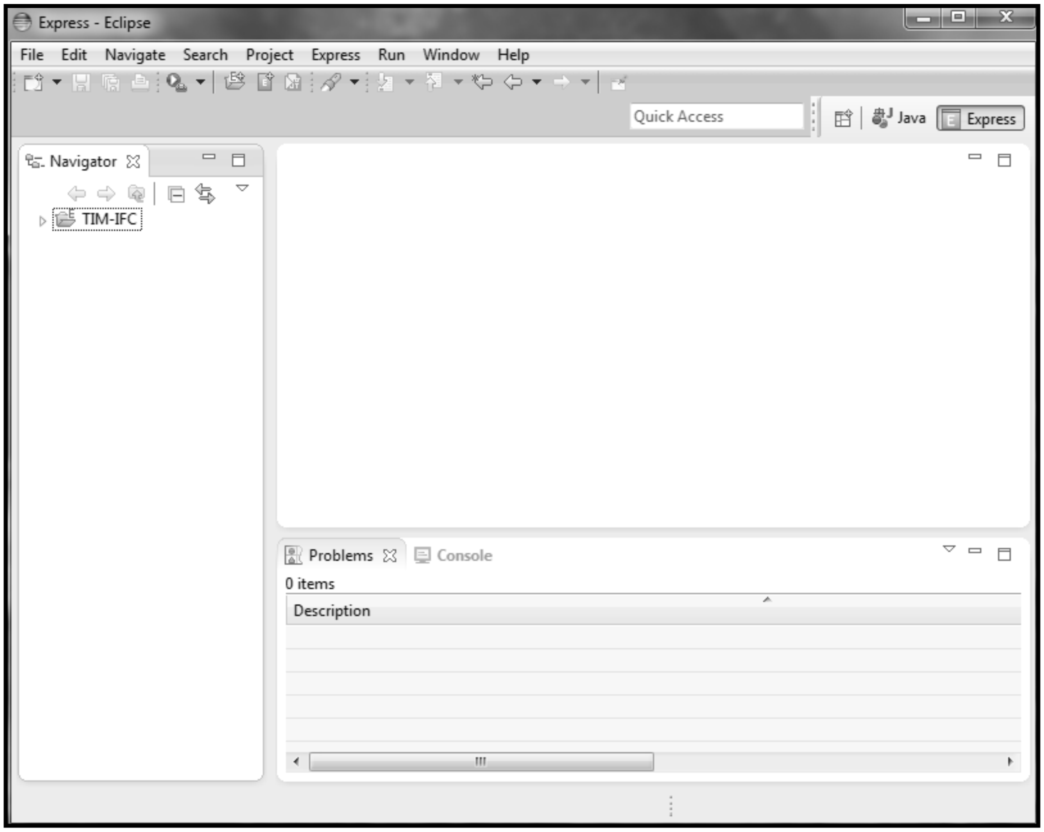


Figure 4-23 (b) JSDAI™ for Eclipse platform

Table 4-6 JSDAI™ properties from JSDAI (2013)

JSDAI™ for Eclipse Platform	Full conformance to the STEP standard (ISO 10303-11, 21, 22, 27, 28, 35)
	Supports four different API levels to optionally support different kinds of implementations
	Compiling of EXPRESS schemas
	Includes a library of practically all EXPRESS schemas from STEP and PLIB standards
	3D viewing module for displaying graphical end-user applications
	Fully Java™ based and as a result platform independent
	Import and export of persistent data using STEP-File or STEP-XML
	Validates data according to the rules defined in an EXPRESS schema
	Produces prototypes for object-oriented data models to validate concepts (e.g. quality of data model).

Figures 4-24 to 4-29 show the snapshots of the JSDAI™ for the Eclipse platform and the implementation of the TIM-IFC classes in the form of EXPRESS-G diagrams.

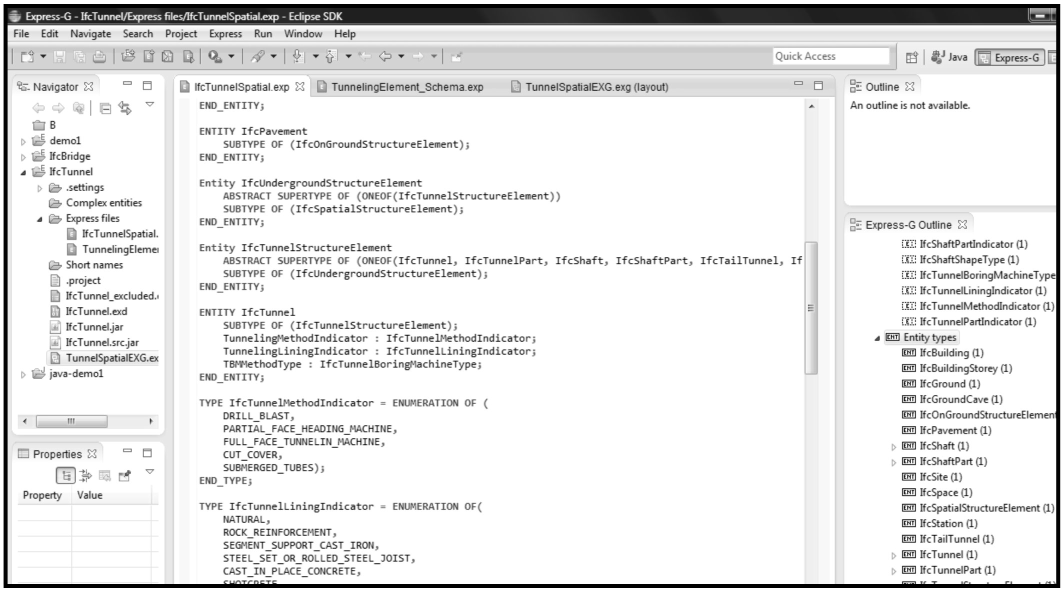


Figure 4-24 Implementing in JSDAI for Eclipse platform-IfcTunnelStructureElement

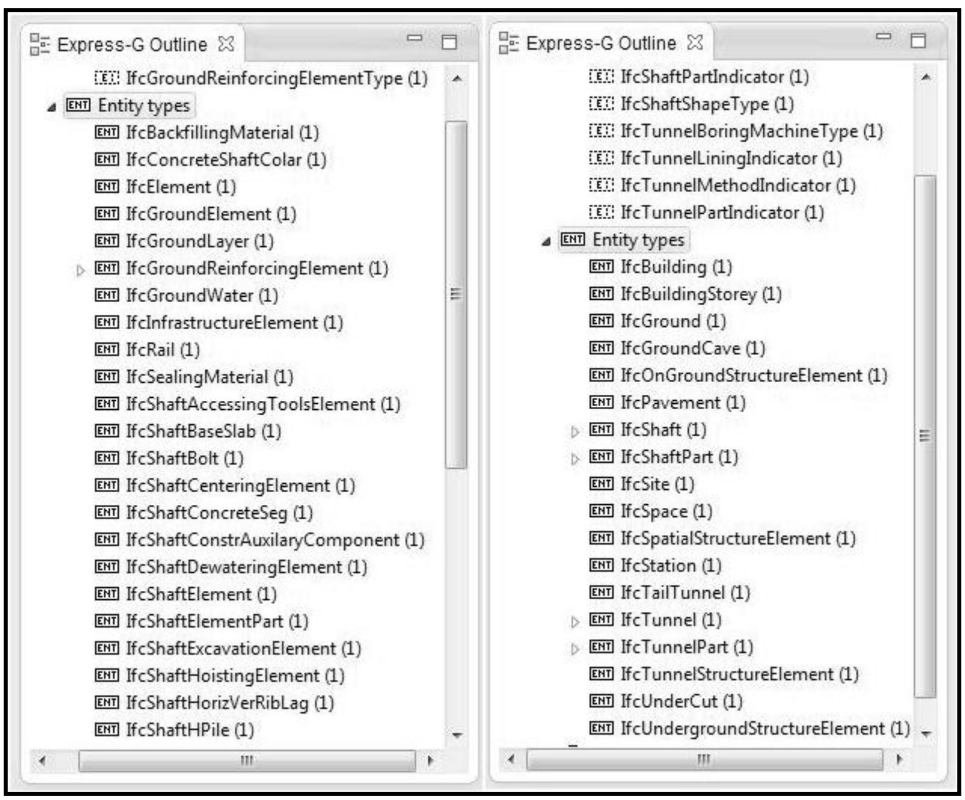


Figure 4-25 JSDAI entities for IfcInfrastructureElement (Left) and IfcTunnelStructureElement (right)

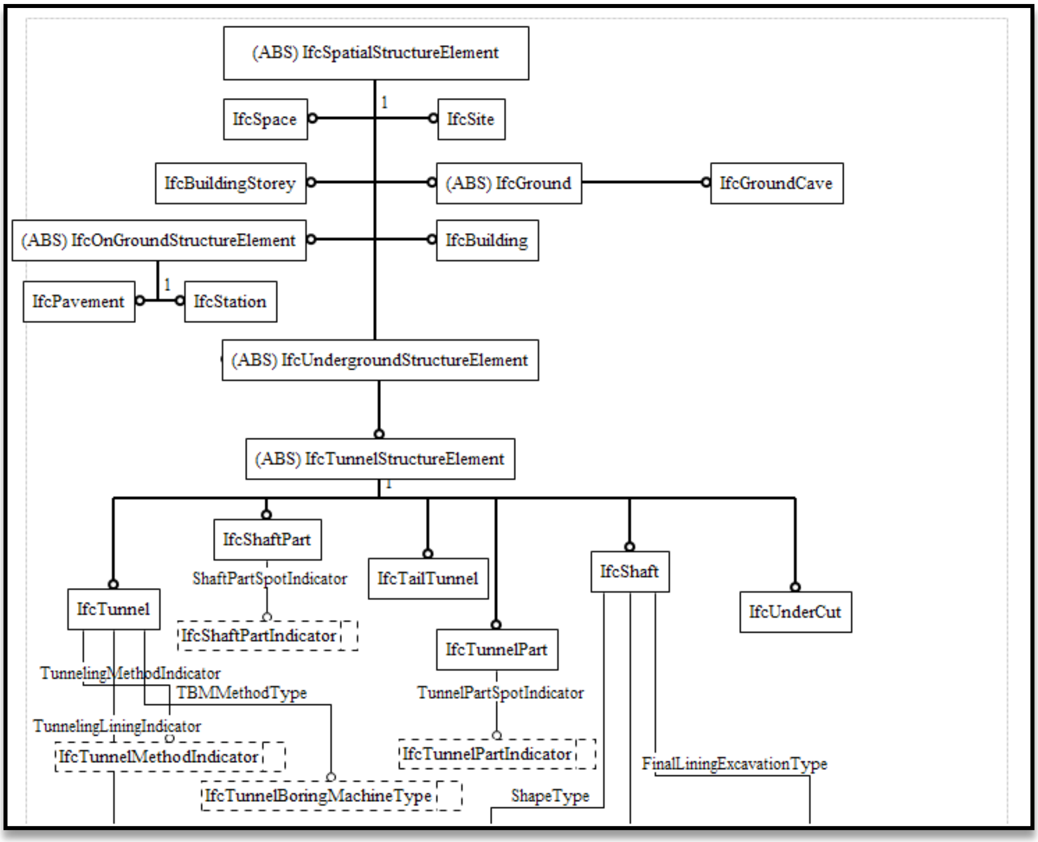


Figure 4-26 Part of the JSDAI EXPRESS-G diagram for IfcSpatialStructure entity

IfcTunnelSpatial.exp ⊠ TunnelingElement_Schema.exp

```
Entity IfcUndergroundStructureElement
    ABSTRACT SUPERTYPE OF (ONEOF(IfcTunnelStructureElement))
    SUBTYPE OF (IfcSpatialStructureElement);
END_ENTITY;

Entity IfcTunnelStructureElement
    ABSTRACT SUPERTYPE OF (ONEOF(IfcTunnel, IfcTunnelPart, IfcShaft, IfcShaftPart, IfcTailTunnel, IfcUnderCut))
    SUBTYPE OF (IfcUndergroundStructureElement);
END_ENTITY;

ENTITY IfcTunnel
    SUBTYPE OF (IfcTunnelStructureElement);
    TunnelingMethodIndicator : IfcTunnelMethodIndicator;
    TunnelingLiningIndicator : IfcTunnelLiningIndicator;
    TBMMethodType : IfcTunnelBoringMachineType;
END_ENTITY;

TYPE IfcTunnelMethodIndicator = ENUMERATION OF (
    DRILL_BLAST,
    PARTIAL_FACE_HEADING_MACHINE,
    FULL_FACE_TUNNELIN_MACHINE,
    CUT_COVER,
    SUBMERGED_TUBES);
END_TYPE;

TYPE IfcTunnelLiningIndicator = ENUMERATION OF(
    NATURAL,
    ROCK_REINFORCEMENT,
    SEGMENT_SUPPORT_CAST_IRON,
    STEEL_SET_OR_ROLLED_STEEL_JOIST,
    CAST_IN_PLACE_CONCRETE,
```

Figure 4-27 Part of IfcTunnel EXPRESS file in JSDAI for Eclipse platform

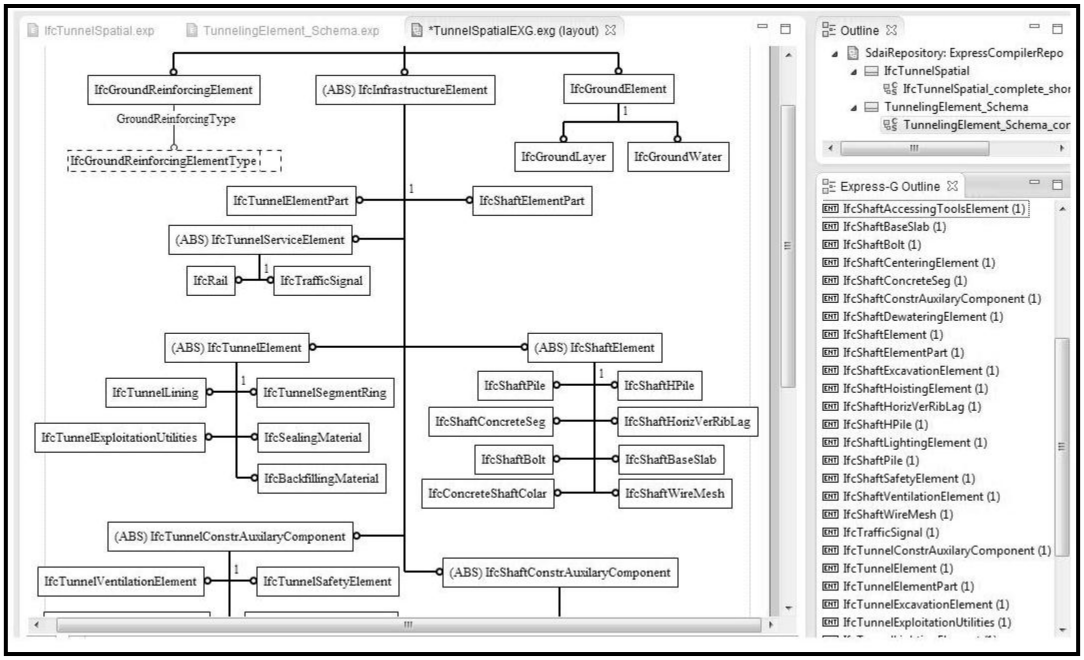


Figure 4-28 TIM-IFC implementation in JSDAI- Extended entitis for IfcElement class

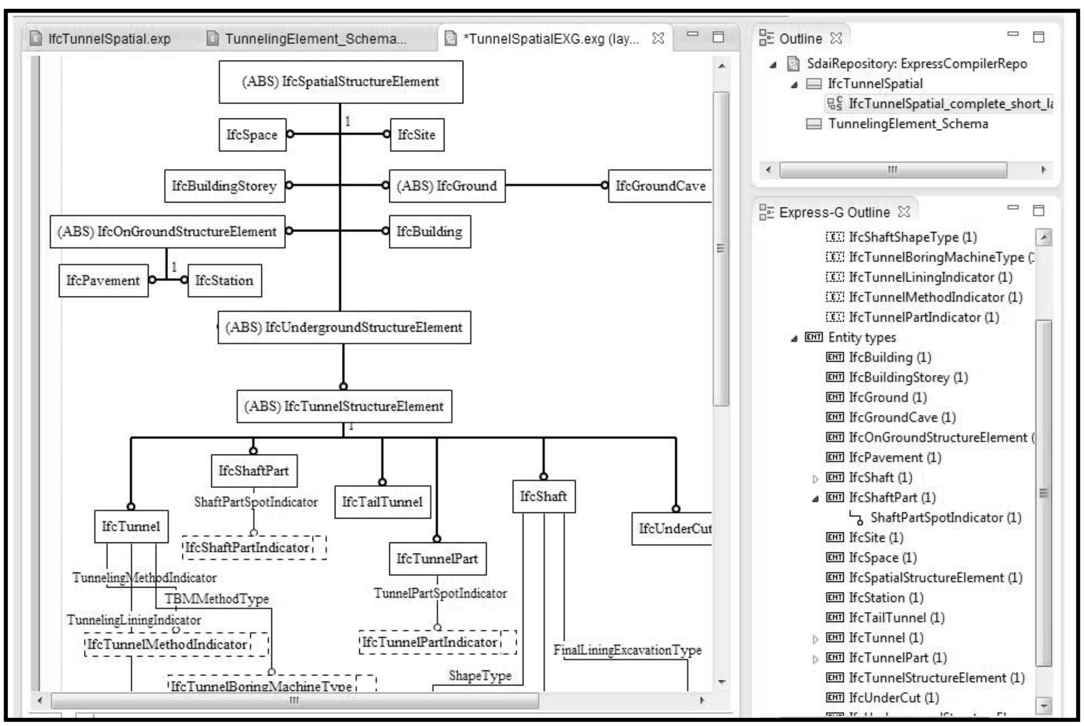


Figure 4-29 Part of IfcTunnel EXPRESS file in JSDAI for Eclipse platform- IfcSpatialStructureElement

It is possible to modify the EXPRESS file for each part of the IfcTunnel model with a Java program and add/delete entities or modify the types created in the previous step. The implementation of the resulting TIM-IFC data model includes employing the extended IFC definitions to facilitate the importing and exporting of information models between software applications among diverse disciplines. Since there is no formalized extension for tunneling projects in the official IFC data structure, none of the common application tools, which support IFC data format, would recognize the defined TIM-IFC framework. Therefore, it is necessary to develop a tunnel-specific intermediate converter that is capable of recognizing the tunnel components. To take advantage of the integrated and interoperable environment of the TIM project system, the tunnel 3D model is created in IFC-compatible modeling software that is capable of exporting and importing IFC data models. The tunnel model is exported as an IFC file to be used in other application interfaces. However, the exported IFC STEP file would be based on the used version of the official IFC data model and does not include the extended TIM-IFC entities. IfcProxy classes in the original IFC data model are the mechanisms anticipated to capture the information that is not part of the defined semantics within the IFC structure. Therefore, the tunnel information is exported as IfcProxy classes. The intermediate converter extracts the tunnel information from the exported file and creates a new STEP file based on the developed TIM-IFC data structure. This new STEP file is ready to be used as a tunnel information inventory by product server systems that are compatible with the TIM-IFC definitions. A tunnel product server is a central inventory for the TIM project system and is capable of exchanging information with other application tools via TIM-IFC data structure (Figure 4-30).

In order to verify the perfection of the TIM-IFC classes developed for TIM framework, it is necessary to practically validate the model. This can be performed through the development of a bi-directional converter between two tunneling software, such as a CAD modeling software and a cost estimation software. This is one of the potential areas for future developments based on the TIM procedural steps discussed in this study.

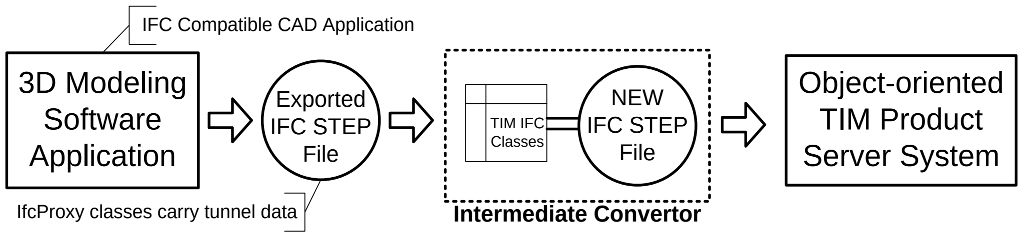


Figure 4-30 Information exchange using the TIM-IFC data model

4.5 TIM Project Model for North LRT Tunnel Project

In this section, the implementation of the TIM concept is presented for an actual tunnel project. This implementation includes steps to collect the requirements of a successful exchange scenario for the 3D-Cost use case (data exchange between the cost estimation and 3D conceptual design) of the North LRT tunnel project system.

4.5.1 Project Overview

The North LRT is a $755 million project funded by the Province of Alberta and the Government of Canada. It is a 3.3 km extension rail road designed to complete a planned LRT expansion to the Edmonton city limits near St. Albert. The project will provide easy access for 13200 weekly riders to MacEwan University, the Royal Alexander Hospital, Nait, and Kingsway Mall. The tunnel part of the project starts from Edmonton’s LRT station at Churchill station and ends at the 105 Avenue/103 Street (Figure 4-31). The tunnel eventually connects the Churchill Station and McEwan station. The detailed design of the project was completed in January 2011. The management of the project was awarded to Link Partnership in March 2011 and the construction work started in May 2011. By October 2011, the entire site preparation, road/utility relocations were completed. The entire project is expected to open for public service in the spring of 2014.

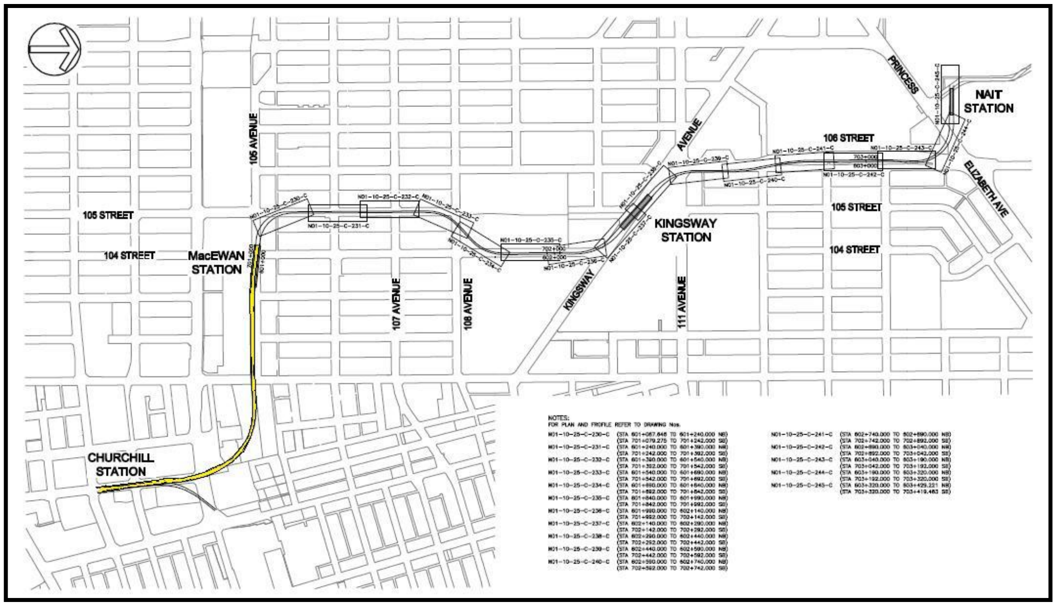


Figure 4-31 North LRT project location- from Churchill station to 105 Ave/103 St (AECOM Consultants, Inc. 2010)

4.5.2 Developing the TIM solution for the North LRT Project

The North LRT (NLRT) tunnel project is composed of two parallel tunnels with a total length of 764 m. The tunnel is constructed between an existing underground station (Churchill Station) and a street level station (MacEwan station) that constructed as part of NLRT project.

In order to implement the TIM methodology for the NLRT project, the tunnel part of the NLRT project is selected. The selected part is used to illustrate the TIM strategy in two phases; Phase-A, developing the tunnel 3D model, and Phase-B, presenting the TIM-IFC development process. The selected part of the tunnel and its cross sections are shown in Figure 4-32(a-b). The interoperability scenario is described for the exchange between the cost estimation segment and the 3D modeling segment of the NLRT tunnel project.

4.5.3 NLRT 3D Representation Model

The 3D model is based on the section NB-W11 in Figure 4-32 (a). The 3D model is developed in Revit® Architecture 2013. The tunnel section is created as a face component and then the tunnel mass is developed using the extrusion tool in Revit. Based on the section specifications of the NLRT project, the created segment can be edited to reflect the exact properties of the particular tunnel segment.

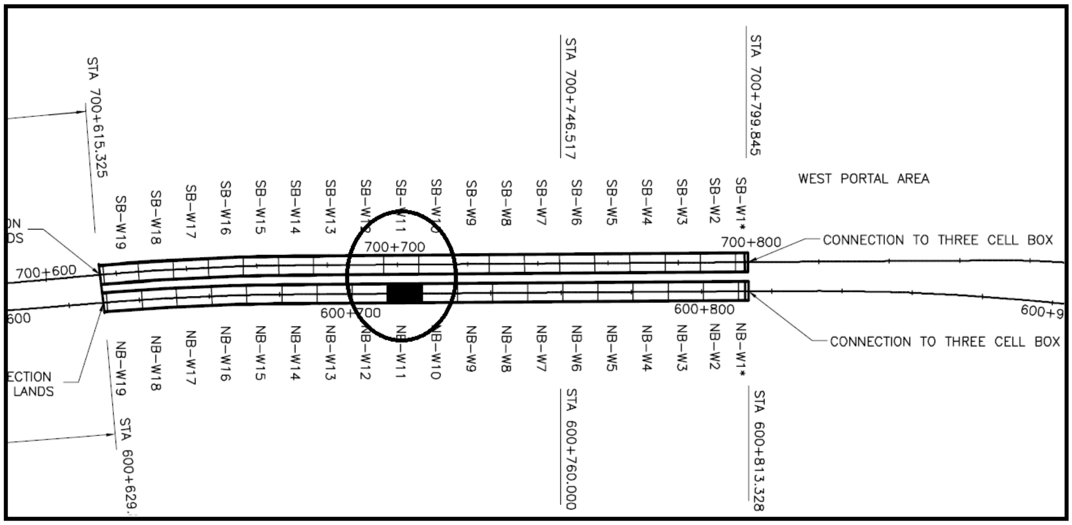


Figure 4-32 (a) Selected part of the NLRT tunnel (AECOM Consultants, Inc. 2010)

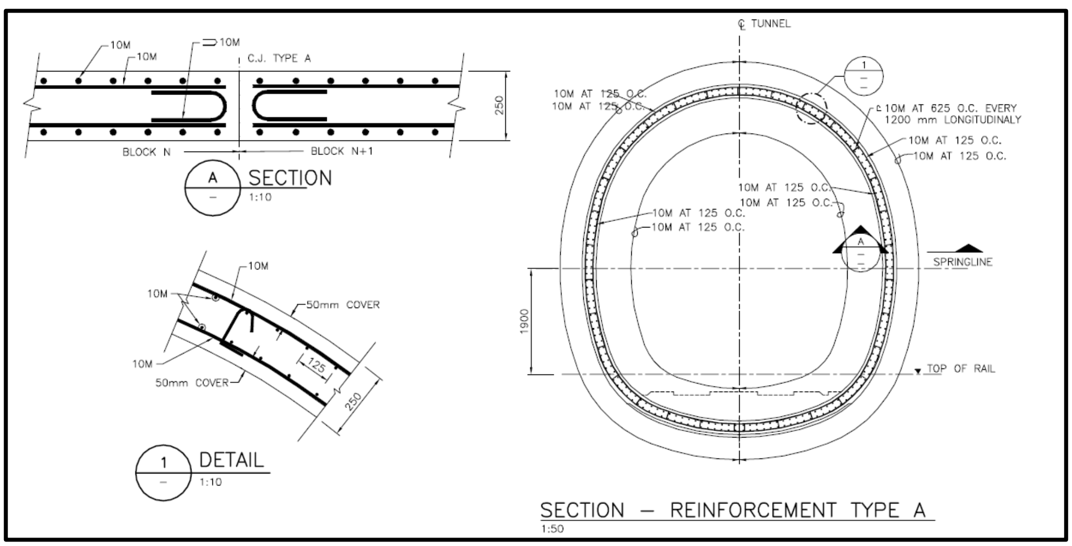


Figure 4-32 (b) Section plan and reinforcement type (AECOM Consultants, Inc. 2010)

For instance, the soil type and the corresponding support type may differ for any two parts of the tunnel. The tunnel family is specifically useful in such cases. The developed tunnel family segment can be created based on the common characteristics of the tunnel component, and the aforementioned diversities may be added afterwards. Figure 4-33 shows the tunnel family component for the NLRT project.

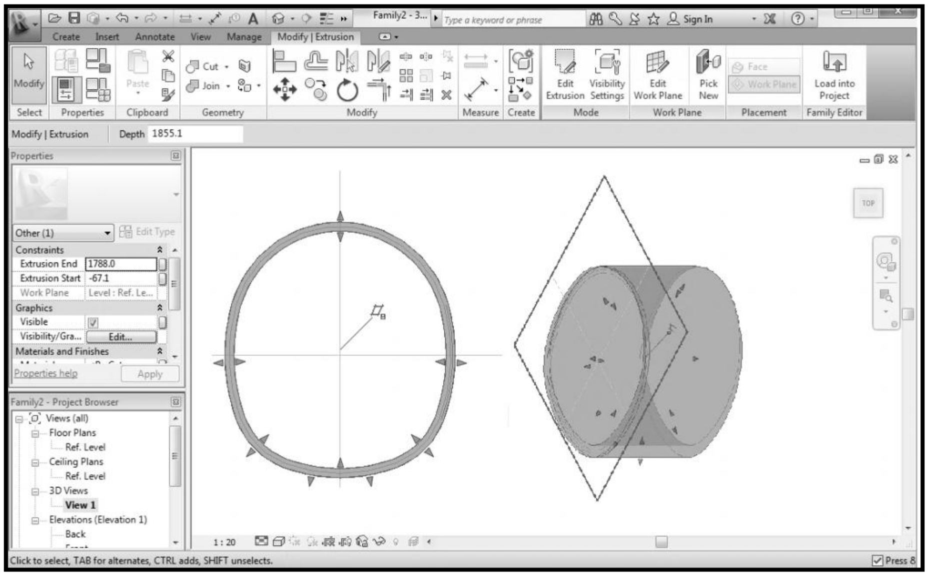


Figure 4-33 the tunnel family representing one section of the NLRT tunnel

4.5.4 Cost Estimation for Tunnel Projects

The tunnel cost can be determined by identifying the cost incurred items from the work breakdown structure (WBS) and coupling with the bill of material list and the unit per item cost found from the local standards/specifications. However, there are multiple sources of risks associated with tunnel projects. Numerous variables affect the tunnel cost during project life cycle. Since a huge amount of unknown factors are present in the preliminary evaluation studies, the reliable information is scarce and therefore, any initial estimation provides a rough number as the forecasted total project cost. The high risk associated with the unknown factors is the cause for the use of 30-35% contingency factor on top of the estimated cost in the preliminary studies and planning stage.

Commonly, the estimation process involves a comparative study to evaluate different construction scenarios to find the most efficient solution. Such evaluation is often done by developing various probabilistic models and simulation-based approaches to come up with the best alternative. For instance, Rostami et al. (2013) proposed a cost model to estimate the tunnel construction cost at the initial stages of the project; Moghani et al. (2011) proposed a simulation-based approach to find the best alternative for the construction strategy in a real project based on the available cost/ resource/performance information; Kim et al. (2010) designed a cost estimate system (LRT-LCC) for light rail transit infrastructures.

Nevertheless, independent from the methodology to estimate the tunnel cost, the TIM implementation solely focuses on the exchange of the cost data based on the TIM framework, disregarding the various factors that influence the project cost. Therefore, in reality the principals and standards for analyzing the cost data may differ from case to case, but the methodology to identify the exchange requirements and cost-related data between the two project segments are the same for different types of tunnel projects with varied service purposes, construction techniques, and national/local standards. This is also compliant with the initial perception of the TIM framework, which states the universality of the approach.

4.5.5 The IFC Process Model and Entity Components for Cost Estimation

The original IFC data model not only includes the physical representation for building components, it also contains entities and defined types to prescribe non-physical (meta information) such as cost, schedule, and resource information. The method for capturing the tunnel product information (major physical and spatial tunnel components) was discussed in the previous sections. Now, the cost-related entities in the IFC data model are reviewed to determine if they are sufficient for tunneling projects as well.

There are multiple entities responsible for handling the cost information that can be used to define the cost related information for tunneling construction projects. Basically, IfcSharedMgmtElements is a management schema in the original IFC data model that is responsible for defining the basic concepts for the management processes during project life cycle. The entities are all subtypes of the IfcControl. The main cost-related entities are IfcCostItem, IfcCostSchedule, IfcCostValue, and IfcAppliedValue. Moreover, the IfcControl includes entities that describe the scheduling information. The scheduling information can be related to the cost information using the IfcRelationship entities. The IfcRelAssignsToControl and IfcRelAssignsToProcess establish the relationship between the physical elements and the cost/schedule information. These entities are presented in the Figure 4-34.

The IfcCostItem presents a cost value along with descriptive information. The cost value can be used in a cost/schedule model and be associated with the cost of goods, services, and work execution during a process, or life cycle cost (LCC). It usually has a name and description that it inherits from its supertype (IfcRoot). The IfcRelNests entity is a self-contained relationship in which it gathers the distinct instances by using the name attribute of the IfcCostItem. The IfcCostSchedule entity brings together the IfcCostItem entities using a one-to-many relationship between the schedule and the cost items. The IfcAppliedValue is a supertype entity that specifies the common attributes for cost values. It has two subtypes; IfcCostValue and IfcEnvironmentalImpactValue. The IfcCostValue represents an amount of money and value. Each cost value may be assigned with a CostType. The relation between the IfcCostItem with the entities from schedule, product, and resource segments of the IFC data model is facilitated by the elements of the IfcRelationship class.

The previous statement also applies to the self-containing relationships in the cost segment using the IfcRelNest relation. For example, the IfcRelAssignsToControl assigns the IfcResource instances with IfcCostItem instances. The entities, which are responsible for cost estimation data and the relationship between cost, schedule, resource, and product segments based on the original IFC 2x Edition 3, are presented in Figure 4-35.

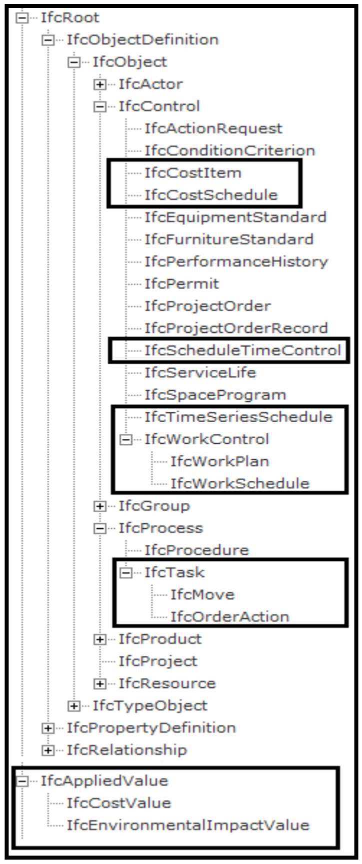


Figure 4-34 IFC entities participating in the cost/schedule estimation process

4.5.6 3D Conceptual Design to Cost Estimation Scenario for NLRT Tunnel

The NLRT tunnel conceptual design is based on the 95% design plans. The aim of this section is to demonstrate the TIM project system for NLRT tunnel through defining the requirements for information exchange between cost estimation and 3D conceptual design.

The information system for the NLRT tunnel consists of different data packages that stem from different sources (Technical reports, market reports, project contract, etc.). In order to implement the TIM procedural steps, it is required to implement TIM two main phases; 3D modeling phase and exchange phase.

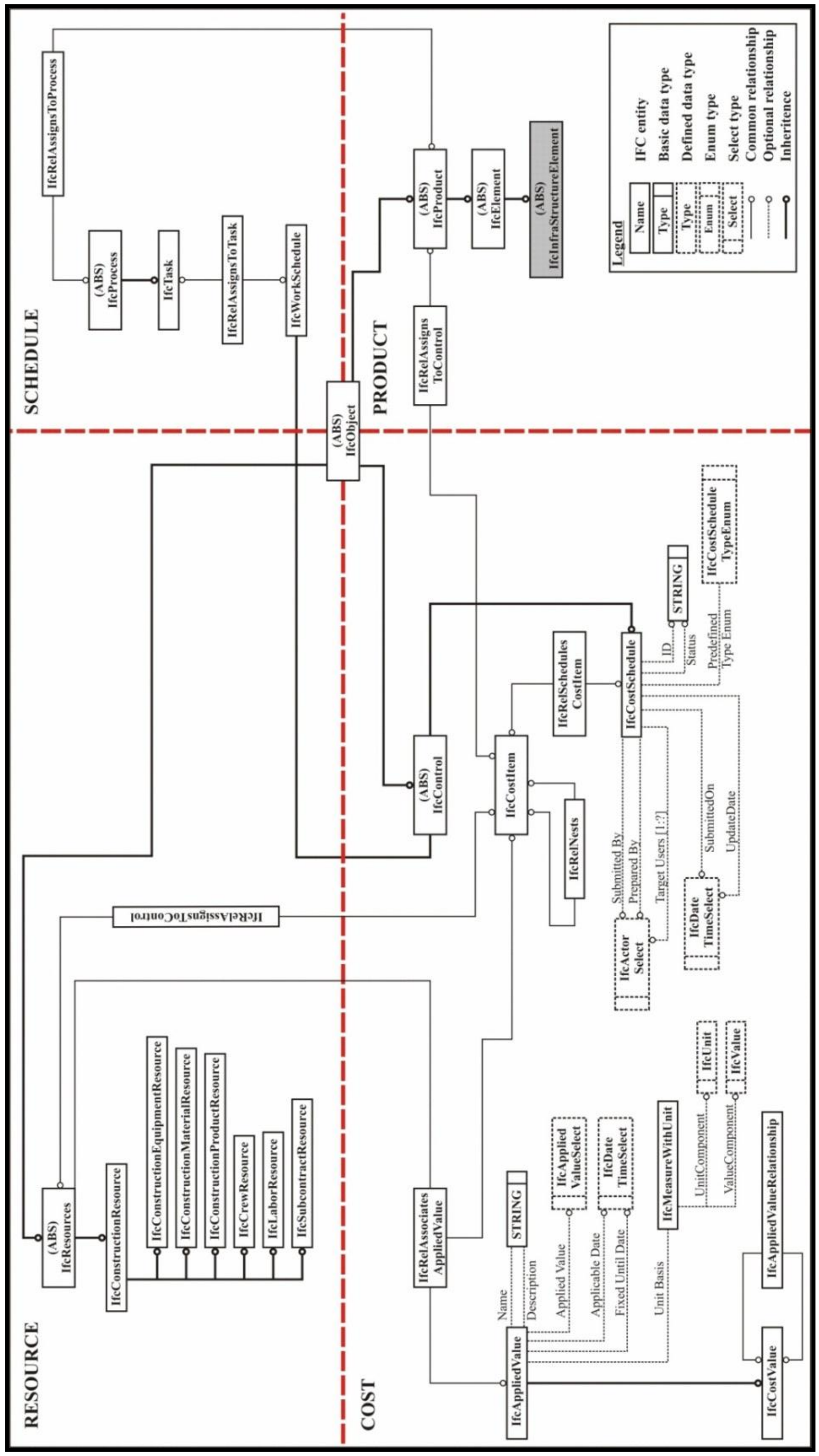


Figure 4-35 The information model for cost estimation process based on IFC 2X3

4.5.6.1 NLRT TIM Requirement Analysis

It is necessary to implement the TIM step-by step framework and perform the process modeling and requirement analysis for the intended use-case scenario. The 3D-Cost use case defines the information exchanges between the 3D conceptual model and the cost estimation module in the NLRT tunnel project, within preliminary design phase of the tunnel construction life cycle. The process map and the information flow between various project segments, in order to exchange data between tunnel product and tunnel cost, is illustrated in Figure 4-36.

This process model demonstrates the action during the preliminary project description. During the construction and exploitation phases of the project, integration of the new revealed information also plays a prominent role in overcoming the drawbacks of limited information in initial project stages as well as enhancing the risk analysis by exposing more information from the ongoing tunneling process.

The target information here is the cost incurred from the construction process, which can be categorized as the labor, material, or equipment cost. Obviously, this tunnel cost information does not account for the costs incurred from design, supervision, initial investment, and maintenance. The ER model in Table 4-7 represents the exchange requirements between 3D conceptual design and cost estimation.

In a TIM-based tunneling project, the Information Delivery Manual (IDM) is prepared for any and each required use-case scenario. An IDM describes the reference processes, process maps, business rules, verification tests, exchange requirements, business concept, and specific definitions for the participating actors in the use-case scenario. The IDM documents are prepared commonly in the process of transition to TIM for an ongoing tunnel project, or during the preliminary studies before commencing the design/planning phase.

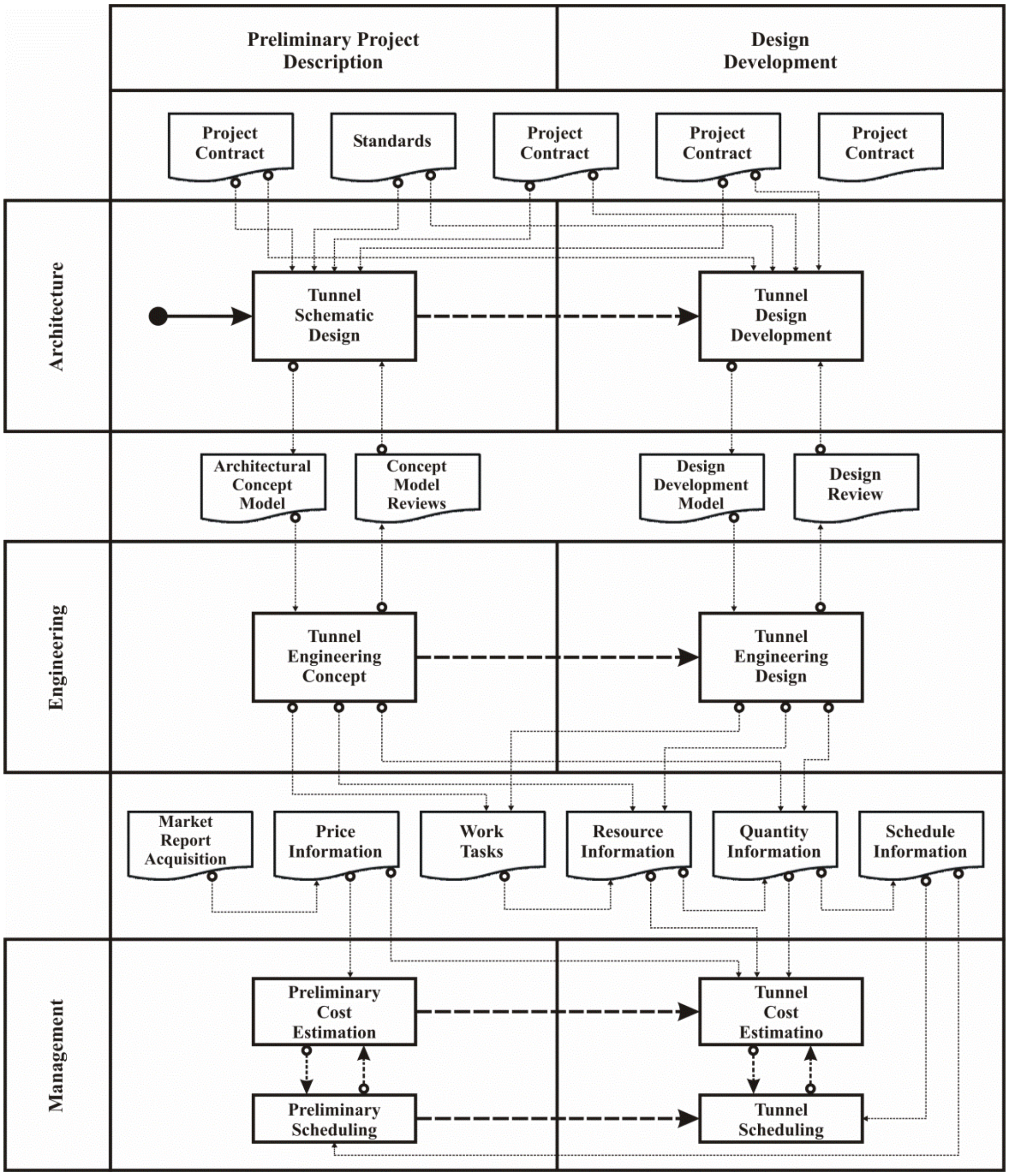


Figure 4-36 Tunnel process model showing the model requirement and information flow between design and management

For the NLRT tunnel project and the 3D-Cost use case scenario, the process map and requirement model is a valid conclusive document, while it is not complete. Other information may be added to improve the exchange process.

Table 4-7 Exchange requirements for the 3D-Cost use-case scenario

Exchange Requirements for 3D Design to Cost estimation for the Main Tunnel (NLRT Tunnel Project)						
Type of Information	**Required Properties and Attributes**	**Details**	**Required**	**Optional**	**Data Type**	**Unit**
Project	Identification		×		STRING	n/a
	Owner/Client information (name, address, phone)			×	STRING	n/a
	Author (name, address, phone)			×	STRING	n/a
Site	Address			×	STRING	n/a
	Global coordinates		×		TRIPLES	deg/min/sec
	Site elevation		×		REAL	m
Tunnel (contains various elements; tunnel, tail tunnel, undercut, excavation phase service utilities (muck carts, conveyor belts, survey tools, alignment tools, temporary track rail), lining/support, lining/excavation equipment, exploitation phase tools and installation, Plinth pads, waterproofing, filling and backfilling)	Identification		×		STRING	n/a
	Classification			×	STRING	n/a
	Global coordinates		×		TRIPLES	deg/min/sec
	Orientation			×	REAL	Angular Degree
	Service type			×	STRING	n/a
	Construction type (excavation type)		×		STRING	n/a
	Excavation dirt volume		×			
	Tunnel initial lining type		×		STRING	n/a
	Tunnel secondary/final lining type		×		STRING	n/a
	Excavation equipment type		×		STRING	n/a
	Plinth path dimensions					
		Gross area	×		REAL	mm2
		Net area	×		REAL	mm2
		Thickness	×		REAL	mm2
	Mucking rate		×			m3/h-bucket/h
	Dewatering rate		×		REAL	m3/h
	Filling material type		×		STRING	n/a
	Backfilling material type		×		STRING	n/a
	Soil type			×	STRING	n/a
	Soil swell factor			×	REAL	n/a
	Lining reinforcement type		×		STRING	n/a
	Electrical/mechanical equipment location			×	TRIPLES	deg/min/sec
	Waterproofing and contact grouting	Dimensions	×			mm
		Volume	×			mm3
		Orientation		×	REAL	Angular Degree
Tunnel Part	Identification		×		STRING	n/a
	Classification			×	STRING	n/a
	Excavation type		×		STRING	n/a
	Initial lining type		×		STRING	n/a
	Secondary lining type		×		STRING	n/a
	Excavation dirt volume		×		REAL	mm3
	Cross section general dimensions					
		Shape		×	STRING	n/a
		Length	×		REAL	mm
		Diameter	×		REAL	mm
		Interior face area	×		REAL	mm2
	Lining reinforcement type		×		STRING	n/a
	Ground reinforcing type		×		STRING	n/a

4.5.6.2 NLRT Information Exchange for the 3D-Cost Scenario

Figure 4-38 presents the information exchange between the TIM 3D model and cost estimation tool. This is to some extent different from the exchange scenario for an ideal TIM project system. This alteration stems from a number of shortcomings in the current available tools.

The Revit application used for creating the 3D model is perfectly specialized for the building structures. There is no tunnel-specific drafting application, which is also compliant with IFC data model, obviously any IFC-based tunnel data model. Therefore, the tunnel components are modeled as generic components. These components are categorized as IfcProxy classes in the exported file. The role of the intermediate convertor is to identify the tunnel-specific classes in the exported file and to assign TIM-IFC classes to the tunnel components. The resulting TIM-IFC STEP file is ready to serve in a TIM-IFC server. The TIM-IFC server is an object-oriented TIM product server system. This server is capable of presenting different segments of the tunnel product model and exchanging the tunnel information based on the TIM-IFC data structure. The TIM product server can be developed in future to be employed as a tunnel central repository. The TIM server development process requires an extensive amount of coding and programing to organize an efficient application interface. Such development process is beyond the scope of this study.

Therefore, in order to present the TIM-IFC exchange framework, the following scenario can be performed based on Figure 4-37. The IFC STEP file, which was exported from the Revit application, is checked in order to find the cost-related parameters/attributes. These attributes are assigned to the right TIM-IFC class and imported to the cost estimation spreadsheet.

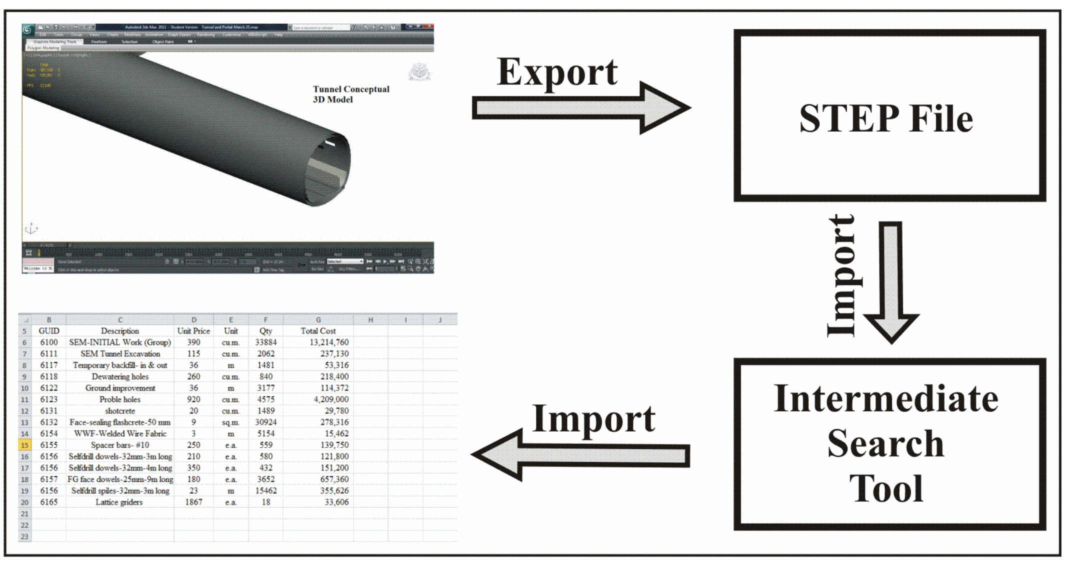


Figure 4-37 Information exchange between the TIM 3D model and cost estimation tool

4.6 Chapter Summary

In this chapter, the procedural steps to develop the TIM project system were described based on the conceptual product model for a typical tunnel project, and via implementing a cost estimation use-case scenario for an actual LRT subway tunnel in Edmonton, Alberta, Canada.

The TIM project system is implemented in two phases; Phase-A, the 3D modeling module and Phase-B, the interoperability module using the IFC data model. The procedural steps for both phases are described in detail. The 3D tunnel model is developed by Revit™ Architecture 2013. The TIM interoperability enabler is developed through the use of the extension capacity of the IFC original classes. The added classes are called TIM-IFC. These classes are presented in JSDAI™ for Eclipse platform.

The outcome of the TIM framework can be a foundation for future tunnel application developments in order to apply integrated solutions for tunneling projects. The procedural steps for developing the TIM-IFC classes and obtaining TIM requirements can be used as a preliminary design approach for a tunnel application interface. A requirement analysis and process model is required to specify the necessary information packages in any exchange scenario between various sections of the integrated project system.

Chapter 5: Summary, Conclusion, and Future Developments

5.1 Introduction

This chapter concludes the study by summarizing the work done to develop an information modeling framework for tunneling projects. It describes the contributions and the corresponding challenges. Finally, some recommendations are proposed for future developments and improving the outcomes of the TIM model.

5.2 Research Summary and Scope

As one of the major civil infrastructures, tunnel construction projects are a potential target for adopting collaborative project solutions. Project management teams encounter a growing number of participating disciplines and professional teams involved on the work site. Moreover, new technologies and innovative materials are available during the design and construction phases of the projects. Thus, choosing the best alternative requires integrated applications to examine and control every stage of the construction product development process. Integrated information systems are the current solution for adopting a collaborative environment to improve the productivity in construction projects.

This thesis presented a framework to develop an information modeling system for tunneling projects, called TIM. The aim was to initially provide a framework to create a multi-dimensional project information system for tunneling projects and to further, extend and apply the IFC standard data model to tunneling construction projects.

The standard data model has the incentive of obtaining a unique standard structure to describe information packages in tunnel projects. An information model for tunnel structures based on a standard object-oriented data model establishes a framework to manage the information and processes in the complex tunneling environment. The integrated project system ultimately eliminates the data and domain fragmentation during the project lifecycle. An integrated solution requires a unified approach for communicating the project information. Some extensions were defined to add particular domains to the IFC original classes and improve its widespread applications in other AEC domains rather than merely building structures. However, tunneling specific classes were not included in the original IFC data model structure.

In this thesis, multiple stages were performed to develop the TIM project system:

- The current problems in successful executions of tunneling projects were studied.
- The tunnel construction methods, components, and processes were reviewed.
- The solutions for handling the overwhelming amount of information and participating actors were discussed.
- The benefits of integrated project systems were clarified.
- The general concept of the TIM modeling system as an integrated model and its embedded architecture was described. The architecture consisted of three main tiers. The 3D modeling tier and the interoperability tier were further explained throughout the thesis.
- The tunnel 3D model was developed. Prior to the 3D development, the current tools and their benefits and barriers were discussed and finally, Autodesk Revit Architecture was employed as the modeling application.
- The key component of integrated project systems, which is the interoperability factor, was realized.
- The current solutions for maintaining efficient interoperability among project sectors were examined. As a result, standard data models were recognized as the most practical medium to provide integrity for handling the data between different applications and diverse professional teams.
- The potentials of the original IFC data model and its extension potentials, as the mainstream data model of BIM concept, were reviewed.

- The required steps to extend the original IFC classes and generate tunnel-specific classes were described.
- The proposed framework to develop the TIM-IFC classes, as the extension of the original IFC 2x Extension 3, was presented.
- The aforementioned steps were implemented to present the requirements for satisfying the cost estimation process in a tunneling process.

The scope of this study was to identify a solution for handling the vast amount of information and the diverse professional teams in a unified project system. The main focus was to satisfy the major project management processes.

5.3 Research Contributions

TIM project system is an integrated project model designed specifically for tunneling construction projects. The integrated project systems provide a number of benefits to AEC industry projects. In case of full implementation, the TIM system will provide robust results in terms of data integrity and the reliability of information flows between project phases and among project stakeholders. The TIM project system contributes specifically to the data exchanges between diverse project segments;

- TIM provides a unified model that contains all the tunneling data. The 3D model acts as the data repository. Therefore, the information is presented in a single model. The user is no longer required to comprehend the different data sets from different information sources or visualize the integrated results.
- The TIM-IFC data structure, as a standard tunneling data model, facilitates secure data exchanges among diverse applications and project teams. There is no need for proprietary translator tools or a professional individual to interpret the data generated by other project segments during project life cycle.

- The project participants are no longer compelled to re-enter the data in their local model to discover the probable interferences or to continue the modeling process. The exchanged information is automatically added to each local model. This eliminates the effort involved to re-enter data, which is time-consuming and prone to error.
- The TIM data model facilitates a quick access to the tunneling information without a need for specific application software. Since the TIM-IFC data model is a neutral data format, all the professional teams can reach to the information in their own local format and application.

5.4 Research Limitations

There are some problems regarding the modeling process in the first phase of the TIM project system development. Since the modeling process was implemented in Revit Architecture 2013, the problems of modeling in this platform are specifically described as follows:

- The templates and families provided in Revit are limited to the specific use of building projects. Revit "System Families" include common building categories such as walls, columns, and beams, but they lack the definitions for civil infrastructures. Thus, the solution that followed in this study was to employ a generic model template and "Loadable Families" capabilities in order to model the tunnel components. The designing of the tunnel families and parameters is a time-consuming and error-prone task due to the absence of tunnel-specific definitions. For instance, there is no presentation for tunnel cavities in Revit. Modeling the tunnel component as an empty cylindrical shape was helpful to the extent of the requirements for this thesis, which was focused solely on the major tunnel components and corresponding project management information. However, it will be problematic in case of modeling the soil layers and the on-ground project environment in future developments and research.

- “Loadable Families” in Revit are strong enough to define new parametric families based on the current project needs. However, opposed to “System Families”, there are some glitches in the process of creating “Loadable Families”. The set of properties and the graphical representation of “System Families” are pre-defined by Revit. Therefore, there are minimum errors while dealing with relationships and connections between two elements. For instance, the connection between a window element and a wall element is defined rigorously. The void required for placing the window in the wall element is automatically provided and the user does not need to create it. However, such definitions are not completely defined for the tunnel families created using the family templates. The user needs to define established and accurate connections between the tunnel components.
- It is required to use Revit API to be able to define new plug-ins that sets the tunnel parameters and relationships between tunnel family components. Working with Revit API requires extensive programming knowledge and adequate familiarity with the API definitions and format.

Similar challenges are probable in the case of using other BIM applications in the market, considering the fact that Revit was evaluated (section3.6.3) as the most practical tool for the TIM modeling framework based on its robustness in parametric modeling, market acceptability, and total cost.

Therefore, using a tunnel specific modeling environment that initiates the TIM modeling process by BIM-based 2D and 3D modeling capabilities will improve the development of a TIM project system. Furthermore, the aforementioned tunnel modeling application can adopt the TIM-IFC data structure. This can significantly reduce the efforts for developing intermediate converters and the TIM-IFC server to facilitate interoperability among diverse applications

5.5 Future Developments

During the development and implementation process of TIM project system, some recommendations were noted for further developments and future research. They were mostly stimulated through either the downfalls of the current TIM framework, or the ideas from previous studies to enhance the IFC data modeling for building construction projects.

5.5.1 Tunnel Modeling Applications based on TIM-IFC

There are a significant number of IFC-compatible applications for building construction projects that facilitate the architectural, engineering, and management roles of the project life cycle. However, there is currently no tunnel design application based on a universal data model in the market. Although modeling in IFC-compatible BIM applications was examined in this research and proved to be a possible solution, multiple challenges were encountered for partial implementation and as a result, there is a need for a tunnel-specific modeling interface based on TIM-IFC data model.

5.5.2 Extend the TIM Framework Approach

The TIM framework is based on a minimal approach in order to keep the model as simple as possible. Such an approach avoids dealing with a big model, which is relatively difficult to handle and implement. As a result, for future developments, it is necessary to include all the tunnel components and information in the TIM project system. This study only focused on a small portion of tunnel information and specific tunnel processes (i.e., construction management). In order to have a comprehensive data model, it is ideal to have all the tunneling information used and exchanged among participants during project life cycle. This information includes the detailed data about the tunnel structural design, topographic specifications of the project site, geology of the soil layers, quality, cost, risk analysis, scheduling, equipment, labor, safety, simulation, stakeholders, contractors, and subcontractors. Moreover, after the actual construction process ends, the information associated with the facility management and maintenance needs to be tracked and transferred to the facility management team.

5.5.3 TIM-IFC Server

The development of TIM-IFC Model Server for "TIM Knowledge Management" layer is essential to facilitate interoperability among the project's diverse participators.

The IFC sever has the responsibility of keeping track of exchanges, modifications, accesses, and deletions through the information exchanges between different applications. Kang and Lee (2009) developed an IFC server based on the IDM in model exchanges. The proposed server maps the IFC model to an object-relational database. A similar IFC server development is necessary for the TIM project system to manage the transactions and avoid information losses during data exchanges (Figure 5-1).

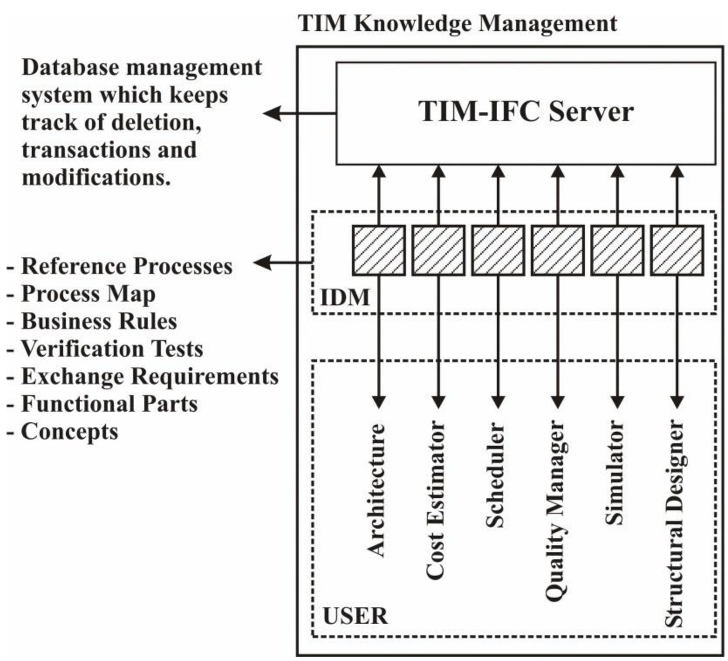


Figure 5-1 TIM-IFC Server Architecture

5.5.4 Developing tools for extracting valid subsets from the TIM-IFC EXPRESS Schema

Even after developing applications that are compatible with TIM-IFC data model, few of them would be capable of exchanging data based on the TIM standard data format. The process would still be prone to error and is subject to the translators that were developed by application developers. The reason for this problem stems from the fact that not every single piece of information is exchanged between all application platforms. Each application only needs a subset of the whole tunneling data that is structured based on the TIM-IFC data model. Several studies are devoted to defining subsets of a standard data model (e.g., Lee et al. (2009)).The standardized subset helps to define the specifications of an exchange scenario.

5.5.5 Radio Frequency Technology (RFID) and TIM project model

Radio Frequency Identification (RFID) technology is widely used to monitor construction equipment, material, people, and capital assets. One area of future development for the TIM project system can be the inclusion of the RFID tags in the project model. The RFID tags can be used to trace the construction components and assets by recording their location, frequency of use, and associated properties. Such inclusion can significantly contribute to an efficient maintenance management and quality control in tunnel construction projects. A similar effort to interrelate BIM data and RFID data is discussed by Motamedi et al. (2013).

5.6 Conclusion

Integrated project management systems can improve the efficiency of construction projects. The interoperability factor is the enabler for any collaborative environment. The IFC data model provides a powerful medium for exchanging data between applications in an integrated project system. IFC is extensively used in European countries and has even made its way to the governmental regulations and specifications in Europe (e.g., the Dutch

Governmental Building Agency has mandated the use of IFC as a deliverable for major BIM-based design and build contracts (AUGI (2013)); Whereas IFC is not widely used yet in North America. Moreover, although major BIM players such as Revit are compatible with IFC data model, there are some deficiencies and shortcomings in the exchange process. Not all the construction projects are covered in the IFC data structure, and even in the case of building projects, the data exchanges suffer from missing components in the export process as well as mistranslations in the import process. With all that being said, there is no question that the merits of a universal data model for modeling construction projects are very valuable. In this regard, tunneling projects can also benefit from an interoperable and integrated project system such as IFC. The characteristics of civil infrastructure projects (i.e., huge amounts of data, multiple stakeholders, various standalone applications and different local formats) are compromised because of the current deficiencies of the IFC.

This study reviewed the current state of project management solutions for tunneling projects and recognized interoperable integrated project models as a potential solution for enhancing efficiency. Hence, a tunnel information model, called TIM, was demonstrated and the procedural steps to satisfy the requirements of such a system were extensively discussed. Finally, an example of a real project was used to present the developmental steps of TIM.

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Appendix-A List of available BIM applications

Here is a list of most customary and well marketed BIM applications.

Platform	Version	Features	Included Software	Developed by	Current Release	Price
Autodesk® Revit® Architecture	–	Architectural design	–	Autodesk	2013	US$5,775
Autodesk® Revit® Structure	–	Structural design	–	Autodesk	2013	US$5,775
Autodesk® Revit® MEP	–	Mechanical, electrical, and plumbing engineering	–	Autodesk	2013	US$5,775
Autodesk® REVIT®	Premium/ Ultimate	Specifically built for BIM- facilitates Architectural design, Structural engineering, MEP engineering, Construction	–	Autodesk	2014	Premium- US$6,825 SRP† Ultimate- US$12,075 SRP†
Autodesk® Building Design Suite	Standard/ Premium/ Ultimate	3D building design software portfolio- Building design and documentation- Building project collaboration- Building simulation- Building visualization	AutoCAD® AutoCAD® Architecture AutoCAD® MEP AutoCAD® Structural Detailing Showcase® SketchBook® Designer AutoCAD® Raster Design Autodesk® ReCap™ 3ds Max® Design Navisworks® Simulate Navisworks® Manage Revit® Inventor® Robot™ Structural Analysis Professional Autodesk® InfraWorks	Autodesk	2014 Edition	Standard- US$5,775 SRP† Premium- US$6,825 SRP† Ultimate- US$12,075 SRP†

Appendix-A List of available BIM applications (continues)

Autodesk® Infrastructure Design Suite	Standard/ Premium/ Ultimate	A BIM for Infrastructure design solution- plan, design, build, and document for transportation, land, utility, and water projects	AutoCAD® AutoCAD® Map 3D AutoCAD® Raster Design Autodesk® ReCap™ Navisworks® Simulate Revit® Structure AutoCAD® Utility Design AutoCAD® Civil 3D® Autodesk® InfraWorks 3ds Max® Design Navisworks® Manage Robot™ Structural Analysis Professional Revit®	Autodesk	2014 Edition	Standard- US$5,775 SRP† Premium- US$7,345 SRP† Ultimate- US$12,075 SRP†
ArchiCAD	–	Provides BIM-based documentation and integrated workflow for architectural design	–	Graphisoft	17	Full Licence- $4,995
Microstation	–	Information modeling environment explicitly for the architecture, engineering, construction, and operation of all infrastructure types	–	Bentley	V8i	Full Licence- $5,050
Digital Project (DP)	–	3D BIM application developed using Dassault Systèmes (DS)' CATIA V5 as a core modeling engine- It features design, engineering, and project management in a comprehensive 3D environment specifically tailored for the Architecture, Engineering and Construction industry	–	Gehry Technologies	V1R5	~ $21,000
DProfiler	–	A macro BIM for cost estimating, sequencing, Site analysis, energy simulation	–	Beck Technologies	2013 1.0	N/A
Tekla Structures	–	An integrated solution for structural analysis and design	–	Tekla Corporation	19	Full Licence- $37,000
Vectorworks Architect	–	Architectural BIM tool	–	Nemetschek North America	2013	$2,395.00

Appendix-B IFC-Compatible Applications

The following list contains all the available application tools compatible with the standard IFC data model. The reference for the list of the applications is the BuildingSMART official website. However, some modifications have been made to the information provided so far by BuildingSMART (2011). A short description is provided for each application to clarify its major target in the AEC industry. Also, the exact URL and the final version are provided. Therefore, the recent changes and updates are considered by referring to applications' URLs.

Name	Developer	Description	Final Release	Application URL
3D PDF Convertor (for Adob Acrobot Reader)	Tetra 4D	A Modelviewer Converting 3D models into PDF files which are universally recongnized by most of the companies.	V3.5	http://www.tetra4d.com/products
IDEA Architectural	4M Software Company	BIM Software for 3D Buidling Architectural Design in DWG	V11/2012	http://www.bim-architecture.com/bim/
STRAD	4M Software Company	Structural Analysis and Design of 3D Concrete Frames	V10/2012	http://www.4msa.com/stradENG.html
FineSANI	4M Software Company	Drawing and Computation Tool for Plumbing and Sanitary Design	V10/2012	http://www.4msa.com/FineSaniENG.html
FineHVAC	4M Software Company	Drawing and Computation Tool for HVAC Design	V10/2012	http://www.4msa.com/FineHvacENG.html
FineELEC	4M Software Company	Drawings and Computation Tool for Electrical Design	V10/2012	http://www.4msa.com/FineElecENG.html
ACTIVe3D Build Server	GROUPE ARCHIMEN	Web-based Data Server for Civil Engineering Projects	_	http://www.researchgate.net/publication/3338649_The_Active3D-Build_a_Web-based_civil_engineering_platform
ACTIVe3D Facility Server	GROUPE ARCHIMEN	Facility Management Data Server	_	http://www.buildingsmart-tech.org/implementation/implementations/plomino_documents/a67ce4f6faed87b6eb1a99fd4eb05324
AEC3 BimServices	AEC 3 UK Ltd	Process and Information Integration Tasks in Construction and Facility Management Projects	_	http://www.aec3.com/en/3/3_02.htm
ActiveFacility	ActiveFacility	A Dataserver for Managing Building Data	_	http://www.activefacility.com/
Advance Concrete	GRAITEC SA	Fully Integrated with AutoCAD and Offers Automatic Creation of Formwork Plans, Reinforcement Drawings, and Bill of Material.	V2011/R10/2010	http://www.graitec.com/en/ac.asp
Advance Design	GRAITEC SA	structural analysis and design of Reinforced Concrete and Steel structures	V2011/R8/2010	http://www.graitec.com/en/ad_main.asp
Advance Steel	GRAITEC SA	structural	V2012/R9/2012	http://www.graitec.com/en/as.asp
Allplan Architecture	Nemetschek Deutschland GmbH	CAD Software Program with Allplan – the BIM platform	2013	http://www.nemetschek-allplan.eu/software/architecture/allplan-architecture.html
Allplan Engineering	Nemetschek Deutschland GmbH	CAD and structural analysis - in keeping with the BIM working method	2013	http://www.nemetschek-allplan.eu/software/engineering/allplan-engineering.html

IFC-Compatible Applications (Continues)

ArcGIS Desktop	Esri	geographic information system	10.1	http://www.esri.com/software/arcgis/arcgis-for-desktop
ArchiCAD	GRAPHISOFT	Architectural BIM Platform	16	http://www.graphisoft.com/products/archicad/
ArtrA Field BIM & Life Cycle Management	ARTRA BIMProducts Ltd	An enterprise solution for asset and plant lifecycle management and facility management	_	http://artra.co.uk/field_bim_1.htm
AutoBid SheetMetal	QuickPen	Construction Management-Graphical takeoff for HVAC and sheetmetal estimation	_	http://www.quickpen.com/index.php/Products/AutoBid-SheetMetal-Product-Overview.html
AutoCAD Architecture	Autodesk, Inc.	AutoCAD based tool specially designed for architectural work	2013 SP 1	http://usa.autodesk.com/autocad-architecture/
AutoCAD MEP	Autodesk, Inc.	AutoCAD based tool specially designed for buildingservices	2013	http://usa.autodesk.com/autocad-mep/
AutoVue 3D Professional Advanced	Oracle	Modelviewer used for document viewing, digital markup, and real-time collaboration	_	http://www.oracle.com/us/products/applications/autoVue/autovue-3d-professional-advanced/index.html
AxisVM	InterCAD Kft.	Intuitive and graphical structural analysis	11/R4	http://axisvm.eu/eu/index.php#/-SOFTWARE/
BIM Collaboration Hub	Eurostep Group AS	A dataserver and collaboration software allowing for sharing of product data between a few or many business partners	_	http://www.eurostep.com/products/product-support-collaboration-hub.aspx
BIMProject evolution	AceCad Software Ltd.	construction lifecycle management software, for procurement and construction teams	_	http://www.acecadsoftware.com/en/bim_project_management_software
BIMReview evolution	AceCad Software Ltd.	A model viewer managing supply content from design to the construction site	_	http://www.acecadsoftware.com/en/free_bim_software
BIMserver	BIMserver.org	Dataserver	_	http://bimserver.org/
BIMsurfer WebGL viewer	BIMsurfer.org	Open source WebGL viewer for IFC models	_	http://bimsurfer.org/
BSPro	Granlund	A development tool for transfering BIM models in the IFC format between different programs	_	http://www.granlund.fi/en/software/bspro/
Benchmark	ITI International Training Institute	Building services	_	https://www.sheetmetal-iti.org/store/results.asp?cat=27
Bentley Architecture V8i	Bentley Systems, Inc.	BIM Application for architectural design and documentation	V8i	http://www.bentley.com/en-US/Products/Bentley+Architecture/
Bentley Building Electrical Systems V8i	Bentley Systems, Inc.	BIM for design and documentation of building electrical systems	V8i	http://www.bentley.com/en-US/Products/Bentley+Building+Electrical+Systems/
Bentley Building Mechanical Systems V8i	Bentley Systems, Inc.	BIM for design and documentation of air-handling and plumbing systems	V8i	http://www.bentley.com/en-US/Products/Bentley+Building+Mechanical+Systems/
Bentley Structural Modeler v8i	Bentley Systems, Inc.	BIM for design and documentation of structural systems	V8i	http://www.bentley.com/en-US/Products/Bentley+Structural/
Bentley speedikon V8i (SELECTseries4)	Bentley Systems, Inc.	An architectural 2D/3D BIM application for MicroStation, PowerDraft, and AutoCAD	V8i	http://www.bentley.com/en-US/Products/Bentley+speedikon+Architectural/
Bimshare	Gehry Technologies	Model viewer	_	http://www.mybimshare.com/
CAD/QST	TQS Informática Ltda.	Structural analysis	V17/2013	http://www.tqs.com.br/
CADS Planner Electric	Kymdata Oy	Designing and documenting for electrical installation, industrial electricity and automation, layout design, and distribution networks	16	http://www.cadsplanner.com/en/products/

IFC-Compatible Applications (Continues)

CADduct	MAP Software	Estimation software for mechanical, electrical and plumbing projects	–	http://www.map-software.pl/oferta/cad/cad-duct
CADiE Sähäkkä	Cad-Quality Oy	buildingservices	2011	http://www.cadie.fi/CADiE/Index.Html
CADmep+	MAP Software	Design, detail, and fabricates building systems in a familiar AutoCAD® software	2013	http://usa.autodesk.com/adsk/servlet/pc/item?siteID=123112&id=18995661
CSiBridge	Computers and Structures, Inc. (CSi)	Structural and seismic analysis, design, and rating of simple and complex bridges	V15.2.0	http://www.csiberkeley.com/csibridge/overview
CYPECAD	CYPE Ingenieros, S.A.	Analysis and design of reinforced concrete and steel structures	2013	http://cypecad.en.cype.com/
Constructivity Model Editor	Constructivity.com, LLC	Information model- provides access to building components, product geometry, analysis models, automation systems, cost estimates, construction schedules, contracts, and much more	–	http://www.constructivity.com/cmeditor.htm
Constructivity Model Server	Constructivity.com, LLC	Coordinate changes throughout construction projects and organizations, maintain project history, and keep project documents in sync.	–	http://www.constructivity.com/cmserver.htm
Constructivity Model Viewer	Constructivity.com, LLC	Access building information models in all levels of detail. Supports IFC2x3/IFC4 files and downloading from Constructivity Model Server	–	http://www.constructivity.com/cmviewer.htm
CostOS BIM Estimating	Nomitech	Provides quantity take off and bill of quantities directly on the 3D model and finally provides cost estimation	–	http://www.nomitech.eu/cms/c/bimestimating.html
CostX	Exactal Technologies Pty Ltd	3D/BIM and 2D estimating solution	3.51	http://www.exactal.com/products/costX
DDS-CAD Architect	Data Design System	not designed to be general architecture system like Revit. Specifically useful for timber residential building.	–	http://www.dds-cad.net/63x2x0.xhtml
DDS-CAD Construction	Data Design System	It generates all relevant production drawings in 2D and 3D, including cutting bills and complete bill of quantities	–	http://www.dds-cad.net/134x2x0.xhtml
DDS-CAD MEP	Data Design System	BIM tool for the design and documentation of electrical, mechanical and plumbing systems for buildings	–	http://www.dds-cad.net/130x2x0.xhtml
DDS-CAD Viewer	Data Design System	IFC models from different disciplines (i.e. Architecture, Mechanical, Electrical, Piping etc.) can be opened in the same window. The viewer contains a light version of the DDS-CAD clash detection engine.	–	http://www.dds-cad.net/132x2x0.xhtml
DProfiler	The Beck Technology	Cost estimating, sequencing, Site analysis, energy simulation,	–	http://www.beck-technology.com/dprofiler.html
Dalux BIM Checker	Dalux	a tool for Quality Assurance and Quality Check for BIM and IFC.	–	http://www.dalux.dk/flx/en/products/dalux_bim_checker_qa_of_bim_and_ifc/

IFC-Compatible Applications (Continues)

DaluxUI - User Involvement	Dalux	Publishes BIM models to the web	–	http://www.dalux.dk/flx/en/products/daluxui_user_involvement/
DaluxQA - Punch Lists	Dalux	Fast access to BIM and punch lists in the field- Supports large BIM projects- Register tasks in the BIM model	–	http://www.dalux.dk/flx/en/products/daluxqa_punch_lists_for_ipad_or_android/
Design Master Electrical	Design Master Software, Inc.	complete electrical drafting and calculation software program that works directly inside AutoCAD	–	http://www.designmaster.biz/products/electrical/index.html
Design Master HVAC	Design Master Software, Inc.	complete ductwork drafting and calculation software program that works directly inside AutoCAD	–	http://www.designmaster.biz/products/hvac/index.html
Design Master Plumbing	Design Master Software, Inc.	a complete plumbing and piping drafting and calculation software program that works directly inside AutoCAD	–	http://www.designmaster.biz/plumbing/index.html
Digital Project	Gehry Technologies	A high-performance 3D modeling tool for architectural design, engineering, and construction	–	http://www.gehrytechnologies.com/digital-project
DuctDesigner 3D	Trimble QuickPen	a field productivity workhorse that empowers electrical, mechanical, HVAC and plumbing contractors with the ability to increase field productivity	–	http://mep.trimble.com/products/design-detailing/duct-designer-3d
ECCO Toolkit	PDTec AG	product data software for developing data exchange solutions and converters between data models and representation formats (XML, STEP Parts 21, 25 and 28).	3.1.5	http://www.pdtec.de/products/ecco_toolkit.aspx
EDMserver	Jotne EPM Technology AS	A Product Model Server capable of storing all your data for complex systems, including native support for any standard data model, like IFC, STEP, PLM/PLCS or Reference Data Libraries	–	http://www.epmtech.jotne.com/index.php?id=562520
ETABS	Computers and Structures, Inc. (CSi)	Integrated software package for the structural analysis and design of buildings	2013	http://www.csiberkeley.com/etabs2013
EcoDomus FM	EcoDomus	Provides for real-time integration of BIM with Building Automation Systems and facility management.	–	http://www.ecodomus.com/index.php/ecodomus-fm/
EcoDomus PM	EcoDomus	Enables the usage of Building Information Models (BIM) and Lean processes for managing facility data during new construction for BIM handover, renovation of existing buildings, or just collecting data to create accurate as-builts.	–	http://www.ecodomus.com/index.php/ecodomus-pm/
EliteCAD AR	Roland Messerli AG Informatik	an architectural model-orientated 3D-Software for the planning of building construction	–	http://www.elitecad.co.uk/products/eliteCAD-AR/
FEM-Design	StruSoft- Structural Design Software in Europe AB / StruSoft	modelling software for finite element analysis and design of load-bearing concrete, steel and timber structures according to Eurocode	12	http://www.strusoft.com/products/fem-design
FME	Safe Software Inc.	Provide Unparalleled Access to Data (specifically spatial data).	–	http://www.safe.com/fme/fme-technology/fme-server/overview/
FZK Viewer	Karlsruhe Institute of Technology	Modelviewer application	–	http://www.iai.fzk.de/www-extern/

IFC-Compatible Applications (Continues)

Fame	FAME Asset Management Solutions	Web-based capital asset management solution designed for infrastructure managers	_	http://www.fameassets.com/products.php
GALA Construction Software	GALA Construction software	Calculation, planning, expenditure control, accounting of derivative works.	_	http://gala-construction-software.com/en/gala-construction-estimating-software/gala2010-basic-information
HOOPS Exchange	Tech Soft 3D	Imports complete 3D CAD data, including PMI, tessellations and B-Rep from 21 file formats, faster than any other solution on the market.	_	http://www.techsoft3d.com/our-products/hoops-exchange
Horizontal Glue	Horizontal Systems, Inc.	a data server application currently owned by Autodesk and vastly contributed to the Autodesk 360 for BIM.	_	http://usa.autodesk.com/adsk/servlet/pc/index?id=19729180&siteID=123112
IDA ICE	Equa Simulation AB	A simulation tool to evaluate the building performance.	_	http://www.equa-solutions.co.uk/en/software/idaice
IFC BIM Validation Service	Digital Alchemy	IFC BIM Validation Service	_	http://www.digitalalchemypro.com/html/services/IfcBimValidationService.html
IFC Engine DLL	TNO	a STEP Toolbox with ability to generate 3D geometry for popular versions of the IFC schema	_	http://rdf.bg/ifcenginedll/product_ifcdll.html
IFC File Analyzer	National Institute of Standards and Technology (NIST)	Generates a spreadsheet from an IFC file and provides model viewer services.	_	http://www.nist.gov/el/msid/infotest/ifc-file-analyzer.cfm
IFC Model Exchange for Microsoft Visio	Digital Alchemy	A vertical market extension to Microsoft® Visio®. The IFC Model Exchange module is able to correctly interpret the objects and relationships in the drawing to create IFC BIM models	_	http://www.digitalalchemypro.com/html/products/DAProducts_IfcModelExchange.html
IFC Quick Browser	GEM Team Solutions GbR	IFC Model Viewer	1.1.	http://g-e-m-team-solutions-ifc-quick-browser.software.informer.com/
IFC SDK	Centre Scientifique et Technique du Batiment (CSTB)	Development tool	_	http://www.cstb.fr/actualites/webzine/editions/octobre-2008/les-rendez-vous-de-la-maquette-numerique.html
IFC Takeoff for Microsoft Excell	Digital Alchemy	An extension to Microsoft® Excel®. It enables users to quickly and accurately perform quantity takeoffs from IFC BIM models	_	http://www.digitalalchemypro.com/html/products/DAProducts_IfcTakeoff.html
IFC Toolbox	Eurostep Group AS	The IFC Classic Toolbox is the original C++ class library toolbox. It provides pure object oriented programming methodology to access IFC data.	_	http://www.uni-koblenz-landau.de/koblenz/fb4/institute/uebergreifend/er/stormodelling/tools/eurostepifc
IFC-to-RDF Web Service	UGent SMARTLAB	Generates IFC/RDF instances based on IFC instances obtained from existing BIM applications	_	https://github.com/mmlab/IFC-to-RDF-converter/wiki/IFC-to-RDF
IFC2SKP plugin	SECOM CO., LTD. / Secom IS Lab	A modelviewer a plug-in for Google SketchUp 8 only. It has the ability to load IFC data from popular BIM (CAD) applications and display the BIM data of each imported objects.	0.86 Beta	http://www.ohyeahcad.com/ifc2skp/index.php

IFC-Compatible Applications (Continues)

IFCsvr ActiveX Component	SECOM CO., LTD. / Secom IS Lab	an ActiveX component for handling IFC(Industry Foundation Classes) data model.	_	http://cic.vtt.fi/projects/ifcsvr/ifcsvrr200/default.html
ISY Calcus	Norconsult Informasjonssystemer AS	construction management tool	_	http://nois.no/?aid=9088857
IfcGears	Bauhaus Universität Weimar	Open source implementation of the open product model standard IFC.	_	http://code.google.com/p/ifcgears/
IfcOpenShell	Krijnen, Thomas	An open source (LGPL) software library that helps to work with the IFC file format.	0.3.0	http://ifcopenshell.org/
IfcWebServer	Ismail, Ali	A free to use IFC data model server and online viewer written in Ruby.	_	http://code.google.com/p/ifcwebserver/
InfoCAD	InfoGraph GmbH	IFC-based Structural tool	10.4.	http://infograph-gmbh-kackertstrasse-10-52072-a.software.informer.com/
MORADA	SMB AG	IFC-based Facility management tool	_	http://www.smbag.de/
MagiCAD	Progman Oy	Provides building services design on AutoCAD and Revit.	_	http://www.magicad.com/en
NTItools Arkitekt (Revit plug-ins)	NTI Nestor AS	IFC-based architectural tool	_	http://www.nti.dk/cad-byggeri/produkter/ntitools.aspx
NTItools Konstruksjon (Revit plug-ins)	NTI Nestor AS	IFC-based Structural tool	_	http://www.nti.dk/cad-byggeri/produkter/ntitools.aspx
Navisworks	Autodesk, Inc.	A project review software helps to review integrated models and data with stakeholders to gain better control over project outcomes.	2014	http://www.autodesk.com/products/autodesk-navisworks-family/overview
Nemetschek IFC Viewer	Nemetschek Deutschland GmbH	The IFC Viewer makes it possible to check an IFC file without an installed CAD program.	_	http://www.nemetschek.com/en/home/the_company/strategy_philosophy/innovation.html
Onuma System	Onuma, Inc.	Web Based BIM Planning, Programming and Project System	_	http://onuma.com/products/OnumaPlanningSystem.php
PipeDesigner 3D	QuickPen	It interoperable BIM Solutions through 3D modeling software for the piping and plumbing contractor.	_	http://www.quickpen.com/index.php/Products/PipeDesigner-3D-Overview.html
RFEM	Ing.-Software Dlubal GmbH	Structural analysis and design software.	_	http://www.dlubal.com/rfem-5xx.aspx
RIUSKA	Granlund	A 3D modeling tool to compare a variety of design alternatives for clients and architects	_	http://no.dds-cad.com/files/no.dds-cad.com/downloads/PDF-Datein/RIUSKA_english.pdf
RSTAB	Ing.-Software Dlubal GmbH	IFC-based structural analysis tool	8.xx	http://www.dlubal.com/rstab-8xx.aspx
Raumtool 3D	SOLAR-COMPUTER GmbH	3D building services	_	http://www.solar-computer.de/index.php?seite=produkte&sub=CAD&software=Raumtool%203D%20Geb%E4udedatenerfassung
Revit Architecture	Autodesk, Inc.	Architectural	2013	http://www.autodesk.com/products/autodesk-revit-family/overview
Revit MEP	Autodesk, Inc.	building services	2013	http://www.autodesk.com/industry/architecture-engineering-construction/mep-engineering
Revit Structure	Autodesk, Inc.	An object-oriented structural modeling tool	2013	http://www.autodesk.com/industry/architecture-engineering-construction/structural-engineering

IFC-Compatible Applications (Continues)

SAP2000	Computers and Structures, Inc. (CSi)	Integrated solution for structural analysis and design	V14	http://www.csiberkeley.com/sap2000
SDS/2	Design Data	3D steel detailing tool	V7.3	http://www.sds2.com/
SOFiSTiK Structural Desktop (SSD)	SOFiSTiK AG	A finite element software for structural design and integration	2012	http://www.sofistik.com/no_cache/en/solutions/structural-fea/structural-desktop/
SPACE GASS	SPACE GASS	A 3D analysis and design program for structural engineers	11.04	http://www.spacegass.com/
SPIRIT	STI / SOFTTECH	Architectural tool which includes intelligent building and parametric ZAC components	2012	http://www.softtech.com/index.php?id=15
ST-Developer	STEP Tools, Inc.	broadly supported SDK for STEP Application Protocols, STEP-NC, Industry Foundation Classes, or CIMsteel CIS/2!	V16 Beta	http://www.steptools.com/products/stdev/
SUperPlan	Deliver Simulation Ltd	A construction management tool specially developed for scheduling	1.4	http://deliverysimulation.com/superplan-scheduling-direction-explained/
ScaleCAD	Jidea Ltd.	Structural	_	http://scalecad.jidea.fi/index.html
Scia Engineer	Nemetschek Scia	An integrated, multi-material platform for structural analysis and design of all kinds of projects	_	http://nemetschek-scia.com/en/software/product-selection/scia-engineer
SmartKalk	Holte Byggsafe AS	construction management tool	V2.1	http://www.holte.no/smartkalk.aspx
Solibri Model Checker	Solibri, Inc.	Analyzes Building Information Models for integrity, quality and physical safety	V8.1	http://www.solibri.com/solibri-model-checker.html
Solibri Model Optimizer	Solibri, Inc.	A free tool built for optimizing Open Standard IFC files. all redundancy is removed from the file by updating the references.	_	http://www.solibri.com/solibri-ifc-optimizer.html
Solibri Model Viewer	Solibri, Inc.	A free software built for viewing Open Standard IFC files and Solibri Model Checker files.It brings BIM files from all IFC compatible software products in a single environment.	_	http://www.solibri.com/solibri-model-viewer.html
SolidWorks Premium	Dassault Systèmes SolidWorks Corp	A comprehensive 3D design solution that adds to the capabilities of SolidWorks Professional with powerful simulation, motion, and design validation tools, etc.	2013	http://www.solidworks.com/sw/products/3d-cad/solidworks-premium.htm
Space Layout Editor for Microsoft Visio	Digital Alchemy	An extension to Microsoft Visio which provides an easy-to-use user interface for the early stage creation and manipulation of space objects, based on the building owner/client requirements captured in Microsoft Excel.	_	http://www.digitalalchemypro.com/Joomla/index.php?option=com_content&task=view&id=22&Itemid=34
SteelVis	National Institute of Standards and Technology (NIST)	A viewer for CIS/2 files and a translator from CIS/2 to IFC files	_	http://www.nist.gov/el/msid/infotest/steelvis.cfm
StruCad	Previously owned by AceCad Software Ltd. And currently by Tekla	A 3D structural steel detailing and information management system, with rapid automatic fabrication shop drawing and CNC production delivery	_	http://www.acecadsoftware.com/en/steel_fabrication_management_software
StruWalker	AceCad Software Ltd.	an advanced collaborative tool for 3D Structural model review. It combines the power of 3D BIM modeling visualization with intuitive review and mark-up tools	_	http://struwalker-launcher.software.informer.com/

IFC-Compatible Applications (Continues)

Structural Modeler	Bentley Systems, Inc.	A BIM application createS structural systems for buildings and industrial plants in steel, concrete, and timber with unlimited freedom.	V8i	http://www.bentley.com/en-US/Products/Bentley+Structural/
Synchro Professional	Synchro Ltd.	A BIM integrated facilitymanagement tools which provides 4D project planning, scheduling and management.	4.7.2	http://synchroltd.com/synchro-professional-4-7/synchro-professional-4-6/
TRIRIGA Facilities	TRIRIGA Inc.	Delivers facility management software to increase facilities utilization and improve the effectiveness of a distributed workforce.	_	http://www-03.ibm.com/software/products/us/en/ibmtrirfacimana/
Tekla BIMsight	Tekla Corporation	A professional tool for construction project collaboration	_	http://www.teklabimsight.com/getStarted.jsp
Tekla Structures	Tekla Corporation	An integrated solution for structural analysis and design	19	http://www.tekla.com/international/solutions/building-construction/Documents/tekla-structures-19/index.html
Tilt-Werks	Tilt-Up Design Systems, LLC	Integrates structural engineering design with the generation of drawings, BIM data, material quantities and cost estimates in one package	_	http://www.tilt-werks.com/
Tricalcar	Arktec, S.A.	Structural analysis and design	7.5	http://www.arktec.com/ES/Productos/Tricalc/Caracteristicas/Caracteristicas.aspx
Trimble Design Link for MEP	QuickPen	A building services tool providing task-based workflows, customizable views and a new user-interface designed to optimize the information presented.	V2.0.0	http://www.quickpen.com/index.php/Products/Trimble-Field-Link-MEP-Overview.html
Vectorworks Architect	Nemetschek Vectorworks, Inc.	Architectural BIM tool	2013	http://www.vectorworks.net/architect/
Vico Office Suite	Vico Software, Inc.	A BIM-neutral platform by which multiple types of BIM models can be published, synthesized, and augmented with cost and schedule information.	R4	http://www.vicosoftware.com/products/Vico-Office/tabid/85286/Default.aspx
VisualARQ	Asuni CAD, S.A.	Architectural tool suitable for 3D modeling and 2D doucmentation	R1.7.2	http://www.visualarq.com/
Ziggurat	Ziggurat Systems Ltd.	General BIM modeling tool	_	http://www.zigguratsystems.com/overview/the-ziggurat-advantage.html
bocad-3D	bocad Software GmbH	Structural design and analysis	_	http://www.bocad.com/en/products/bocad-3d.html
cBIM Manager	Asite Solutions Ltd.	A dataserver that brings integrity to the shared BIM information throughout the project life cycle.	_	http://www.asite.com/adoddle/corporate-collaboration/collaborative-bim
cadwork wood	cadwork	architectural CAD/CAM system for solid wood builders	V18	http://www.cadwork.com/indexL1.jsp?neid=10217
dRofus	Nosyko AS	An integrated program management tool that provides excellent process support from early phase programming to completion.	_	http://www.drofus.no/en/index.html
ifc-dotnet	Sproat, Ian	A library which provides .Net classes and serializers/deserializers for working with Industry Foundation Classes.	Alpha (testing)	http://code.google.com/p/ifc-dotnet/

IFC-Compatible Applications (Continues)

nova	Plancal GmbH	Offers integrated CAD/BIM and engineering calculations in one unified system	–	http://www.plancal.com/product.html
simplebim	Datacubist Oy	A BIM model viewer for data exchange	–	http://www.datacubist.com/
simplebim.Developer	Datacubist Oy	A development tool	–	http://www.datacubist.com/Support/sdd.Root&structure=sdd.Root
ssiIFC - Rhino 3D Smart Structural Interpreter	GeometryGym	Base Plug-in containg tools and routines to use in Rhino and Grasshopper to model structure, relax meshes and perform tasks like Curve Network Cell Generation.	–	http://ssi.wikidot.com/summary

Appendix-C An overview for Revit Architecture 2013

C-1 Introduction

Autodesk Revit Architecture is the BIM application in the Autodesk's building design portfolio that contributes to the architectural design of building projects. Revit Architecture along with Revit structure and Revit MEP are the three integrated platforms provided for building design. The results of these platforms are successfully compatible and collectable in one unique model which facilitate the clash detection and change management during a building process. Currently, Autodesk has introduced its "Building Design Suite" which offers a 3D building design portfolio. Also, the latest update for Revit application is an integrated form of all the three separate platforms (Revit Architecture, Revit Structure, and Revit MEP), known as Autodesk® Revit®. According to Autodesk (2013), the Autodesk Revit 2014 is a tool for architectural design, structural engineering, MEP design, and construction which offers a medium for transition to BIM workflows. In this study, Revit Architecture 2013 has been used to create the TIM 3D model.

The objective here is to present the initial step of the TIM framework and implement the modeling process in BIM-based application software. Therefore, any BIM-based platform could have been used to present the feasibility and merits of implementing TIM. A comparison between the major BIM applications has been provided in Table 4-1. Moreover, Revit Architecture was the best option among the three platforms of Revit (Revit Architecture, Revit MEP, and Revit Structure) to work on tunneling projects, since the modeling process was focused on the geometric and meta data for tunneling components and the main focus was to facilitate the construction management processes via the TIM model. Therefore, Revit Architecture was used to model the tunnel components.

C-2 Revit Architecture Overview

Revit Architecture provides a BIM platform for designing, documenting, and scheduling required for building projects. Revit is an integrated 2D and 3D modeling that can present different views of the project from a unique data model. The modifications to each of these views are automatically propagated to the other views and therefore, the 2D model, 3D model, the quantities, drawing sheets, schedules, and sections are perfectly synchronized. The change management process is facilitated by parametric modeling to define relationships and connections among Revit elements. A set of rules describe the associativity of different elements. These rules are either pre-defined by Revit (e.g., in system families), or by the user. The numbers and characteristics describing the parametric rules are "parameters". Any change to these parameters in any section of the Revit model is recognized by Revit and the consistency of the model is maintained by coordinating the changes to the entire project.

Revit is an object-oriented application. The objects in Revit are called "elements". Revit classifies the elements in three groups; categories, families, and types. A group of building elements forms a Revit category such as wall, column, and beam. Objects such as tags, and text notes are included in the annotation category.

Classes of elements in a category create a Revit family. The elements in a same family share identical parameters (properties) and graphical presentation. Elements of a family may have different values for similar parameters. There are three kind of families; system families, loadable families, and in-place families. System families are pre-defined by Revit and generally include elements that are commonly used in building projects (e.g., external walls, interior walls). Loadable families can be made from scratch for specific use of a project and can be saved for use in future projects. In-place families are specific for the current project and cannot be saved.

C.3 Revit Loadable Families (Standard Component Families)

The loadable families in Revit are initially used in Revit for creating building components and corresponding annotation elements. They are generally custom-made or not commonly used as often as those components provided in Revit system families. These components are unique for the use of a specific project (e.g., custom-made windows, doors, fixtures, or furniture) and can be stored and loaded in future projects. Loadable families are highly customizable and are considerably more flexible than system families in terms of modifications to present a distinctive component. Loadable families are created as external .rfa files and loaded to the target project. The graphical presentation and set of parameters can be defined for loadable families, but the common problem is that the methods for controlling the relation between different instances of loadable families in the project interface are limited. In case of a complex new family, Revit falls short in recognizing the connections and reflecting that in information exchanges with other project segments.

Moreover, there are no similar system families in Revit that can be used to present the underground components of the tunneling projects, and therefore, the loadable families were the only method to create unique families that present the tunneling components. The procedure to create loadable families for the major components of the tunneling project (tunnel and shaft) is described in the following section.

C.4 Creating a Shaft Family

Basically the following steps demonstrate how to create any loadable family in Revit.

1- Planning a loadable family

Identify the basic requirements such as sizes, displays, detail levels, probable host, and origin point. Defining present sizes to in order to generate most common elements adds convenience to the modeling process. It is necessary to identify if the component needs a specific view (plan, elevation, or section). Identifying the origin of the family helps to realize the insertion point when the component is loaded into the project view. For instance, for a shaft collar, the insertion point can be defined as the center of the shaft element and a minimum distance from the ground level.

2- Choosing a family template

Create a new family file with a suitable family template. Each template contains the major information required to start the family creation. Revit has various templates, which covers the minimum requirements of specific components with a default insertion point. It is necessary to mention the host-based families (wall-based, ceiling-based, floor-based, and roof-based) require the presence of the host type element in order to load the created family into the project view.

3- Creating family sub-categories

Creating the sub-categories for a family component helps to control its visibility and geometry. This is especially useful for defining kinds of material, color, line-weight to a group of elements in a family component.

4- Defining the family origin

Define the insertion point for the family. This point is where the family is going to be loaded into the project view. The intersection of two reference planes can be a insertion point. Sometimes it is possible to apply construction codes with the family origin. For instance, it is possible to define a certain distance for a reinforcing bar to comply with the minimum concrete cover in a tunnel lining segment.

5- Laying out and dimensioning the reference planes

The reference planes help in sketching the family geometry. The reference planes are usually created aligned with the main lines of the family component. Placing dimensions between the reference planes/lines facilitates the foundation for defining the parametric relationships between different dimensions in the family. The reference plane dimension helps to define the parameters and then assigning component dimension to these parameters to create ruled relationship between dimensions.

6- Labeling dimensions to create parameters

It is recommended to label the dimensions. Therefore, it will be possible to modify the family parameters later during the modeling process.

7- Flexing the family framework

Flexing in Revit, means testing the created parameters to make sure that they are correctly assigned to the right reference planes and they change accordingly in case of any modification.

8- Creating the family types

Family types refer to the different sizes for a family component, which can create various customizations for the family's parameters.

9- Creating the family geometry

Create the shape geometry of the family. The shape geometry represents the element's best conceptual shape in the actual project. It is possible to specify the element's visibility and material. The visibility of a family defines which parts of the family shape will be visible in different views.

10- Testing the family

Repeat step 7 in order to test the created parameters, visibility, geometry, and reference planes after defining the family's actual shape and representation.

11- Creating a type catalogue

In order to create a type catalogue, a test file (TXT) is needed that contains the parameters and parameter values, which have been used to create different types in a specific Revit family.

Revit offers a variety of family templates to begin designing a loadable family which help to use a common representation and save time instead of starting from scratch. The most suitable template for the tunnel components is the "Metric Generic Model.rft". It is a general description which allows modeling a generic model without any default reference lines or family origin. It is not possible to change the category or the template that the family originally was assigned with.

Moreover, It is not possible to copy and paste model geometry from one family to another.

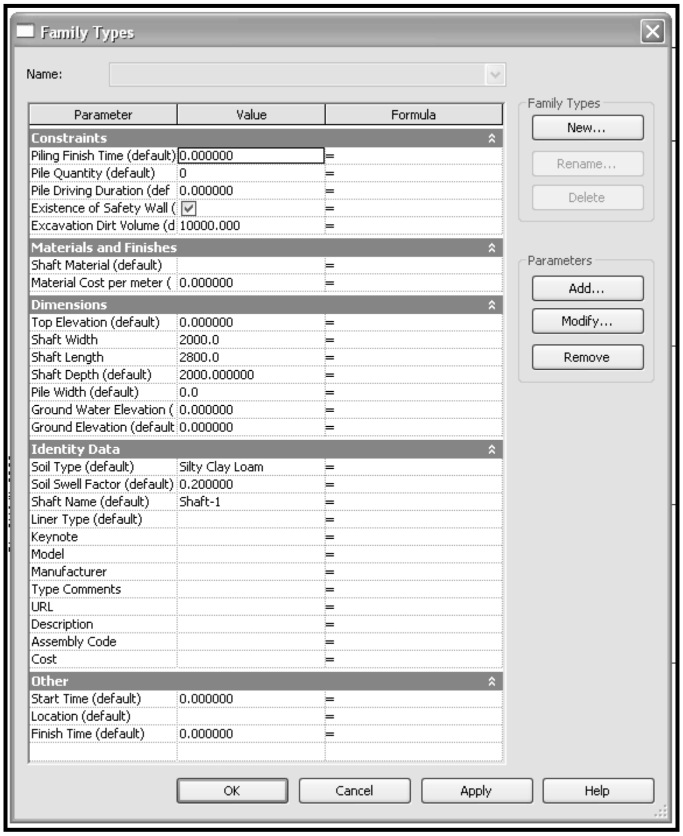

Figure C-1 Defining family or shared parameters for a rectangular shaft family

- Define all Reference planes needed to define the geometry in three dimensions. Provide names for any that may need to be used as work planes in future.
- Constrain the reference planes with dimensions and parameters.
- Create the shaft shape (rectangular shaft) and assign the dimensions to the parameters.

The shaft family needs to be loaded based on its central axis in the project environment, which is probably the shaft central axis.

In general, all shaft specifications such as name and location are categorized under Identity Data. It is possible to change the type of parameter (Family or

Shared) in future to meet particular requirements of exported data or other parallel applications.

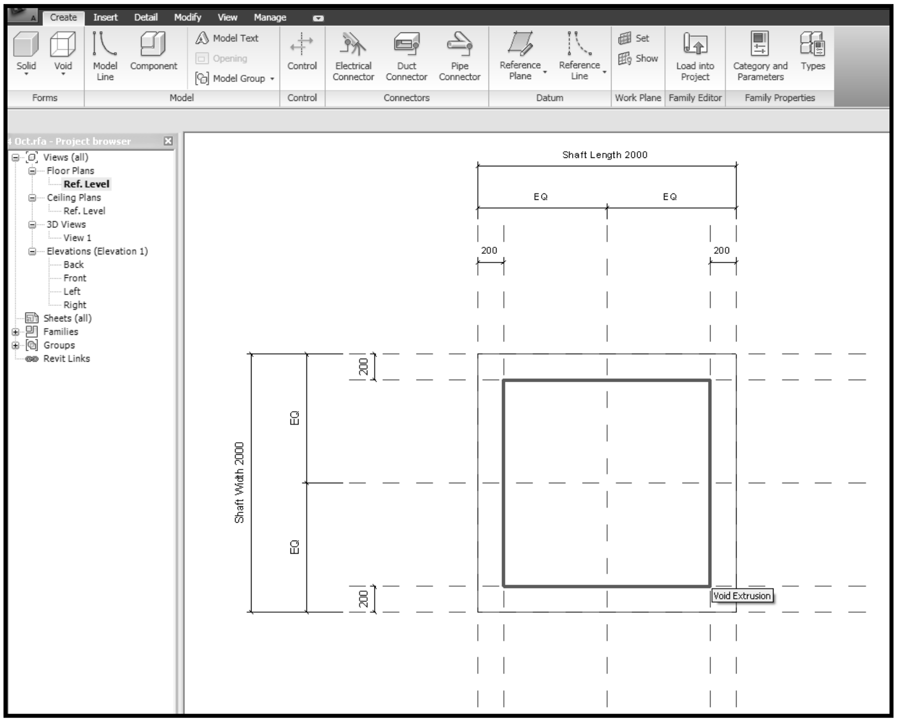

Figure C-2 using Void-Extrusion tool to build the model

The rest of the model is expanded by using the Solid-Extrusion and Void-Extrusion tools.

Figure-3 shows an initial 3D view of a shaft family. The family allows the user to change the depth of the shaft as an instance parameter. However, the length and width of the shaft is considered as type parameters to be able to have different type of rectangular shafts in the shaft Type Catalogue.

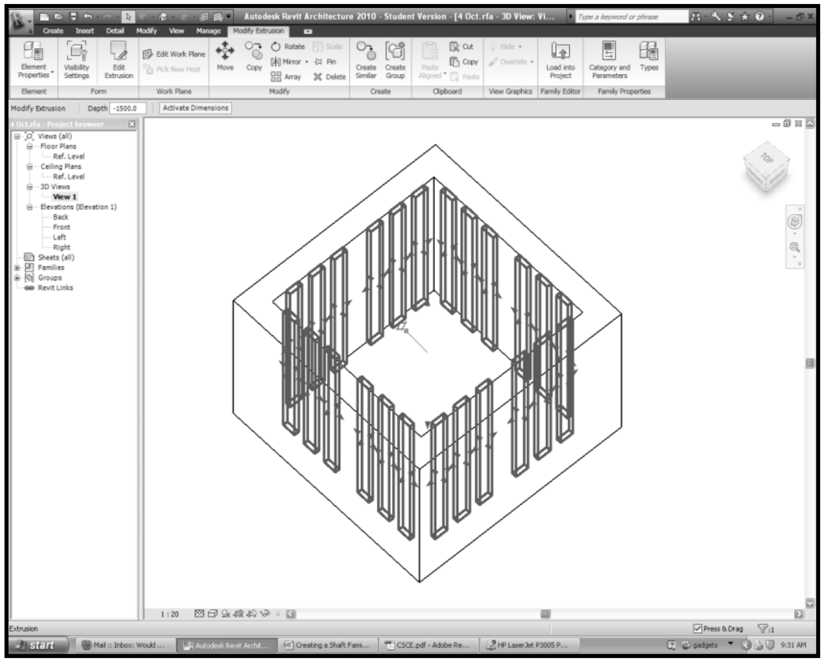

Figure C-3 3D view of the shaft family

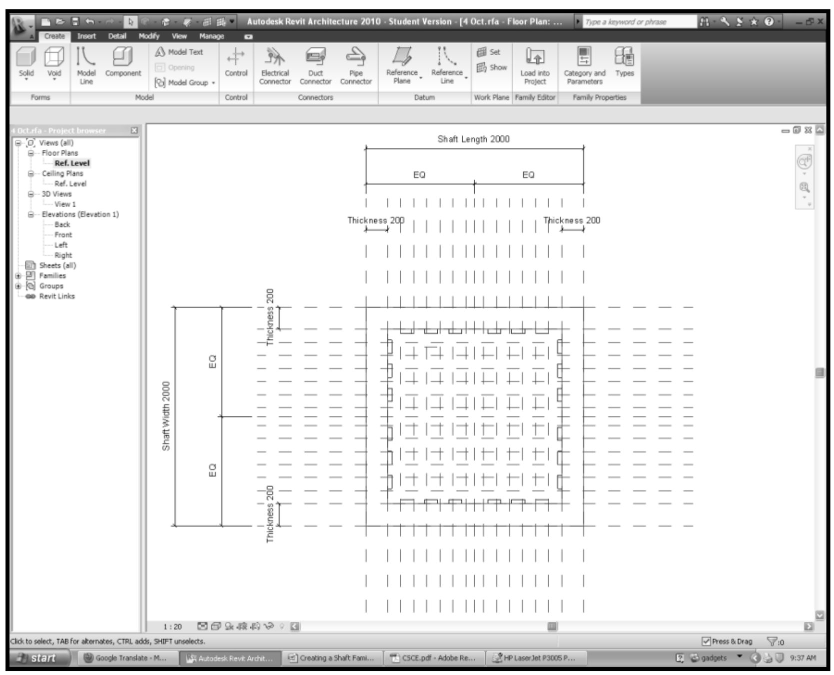

Figure C-4 Reference level of the rectangular shaft family

Figure C-4 shows a general reference level for a rectangular shaft family which is flexible to have specific details and model dimensions based on the type of tunnel project that user needs.

Appendix-D TIM-IFC Schema, classes, and EXPRESS specification

Original IFC entities are divided into rooted and non-rooted entities. The rooted entities are all subtypes of IfcRoot and has been assigned to a globally unique identifier (GUID); whereas the non-rooted entities are not identified by GUID and their instances are only exist in case of a referral from a rooted entity. Therefore, any extension most probably occurs under the IfcRoot entity. Each rooted entity has an identifier GUID and properties.

In this document, the entities added to the original IFC2x Edition 3 Corriegendum1 and specifically defined for tunneling projects are described and their EXPRESS specifications are presented. The TIM-IFC physical entities are classified into two groups; spatial structure elements and physical Elements. Spatial elements are those used to describe a spatial structure or zone, such as tunnel and shaft. On the other hand, physical elements refer to physically existent objects, such as tunnel lining, sealing, or back filling material.

D-1 TIM-IFC Spatial Structure Elements:

IfcSpatialStructureElement

The IfcSpatialStructureElement in the original IFC data model is the supertype of IfcBuilding, IfcBuildingStorey, IfcSite, and IfcSpace. Three new classes are added to the Spatial Element class to be able to define the tunnel entities (for on and under the ground) and also the ground entities. These classes inherit from their supertype and are further ramified to include the spatial elements of tunnel projects. Therefore, the extended entities are IfcUndergroundStructureElement, IfcOnGroundStructureElement, and IfcGround.

EXPRESS Specification:

ENTITY IfcSpatialStructureElement

ABSTRACT SUPERTYPE OF (ONE OF (IfcUndergroundStructureElement, IfcSpace, IfcBuildingStorey, IfcBuilding, IfcSite, IfcGround, IfcOnGroundStructureElement));
END_ENTITY;

IfcOnGroundStructureElement

The IfcOnGroundStructureElement is an abstract entity that represents the civil elements on the tunnel project site which are not directly part of the tunnel structure, but are necessary to accompany a typical tunnel project. Examples of these components are the station and pavement components in rail tunnel projects. In this study, we focused on the components which are part of the rail tunnel projects. In general tunneling projects, such as sewage, service, or utility tunnels, multiple spatial elements may be defined using this class (for instance, the space on the ground which provides access or service to the main underground project). IfcOnGroundStructureElement can also support other civil infrastructures commonly built on the ground or not necessarily under the ground level. It serves the same functionality as the IfcCivilStructureElement in the IFC-Bridge. Moreover, the instances of this class are not necessarily above the ground level, but they are not also part of the tunnel structure or lining. The IfcOnGroundStructureElement has two subtypes: IfcStation and IfcPavement.

<u>EXPRESS Specification:</u>

ENTITY IfcOnGroundStructureElement
ABSTRACT SUPERTYPE OF (ONEOF (IfcStation, IfcPavement))
SUBTYPE OF (IfcSpatialStructureElement);
END_ENTITY;

IfcStation

In road tunnels, IfcStation represents the tunnel elements in the station area of the tunnel route. These elements are either the ones that connect the tunnel to the ground level, or the elements that build the station cavity. For instance, for a metropolitan subway system, the station components are access stairs to the ground, station walls, or service elements.

EXPRESS Specification:

ENTITY IfcStation

SUBTYPE OF (IfcOnGroundStructureElement);

END_ENTITY;

IfcPavement

EXPRESS Specification:

ENTITY IfcPavement

SUBTYPE OF (IfcOnGroundStructureElement);

END_ENTITY;

IfcGround

The IfcGround entity defines all the spatial entities resulting from earth work activities. It has one subtype which is IfcGroundCave. The IfcGroundCave covers the information in three categories which are presented by three subtype entities; IfcGroundCollar, IfcGroundLithology, and IfcGroundGeology. The IfcGroundCollar contains the information about the ground collar, such as collar ID, collar position, depth, and azimuth (angular measurement in a spherical coordinate system). The IfcGroundLithology includes the properties of the rocks found in the earth work and consist of physical characteristic of the outcrop (the visible exposure of the rock), such as pattern, size, density, and thickness. The IfcGroundGeology covers the general specifications of the geology studies, such as ID and elevation.

EXPRESS Specification:

ENTITY IfcGround

ABSTRACT SUPERTYPE OF (ONEOF (IfcGroundCave))

SUBTYPE OF (IfcSpatialStructureElement);

```
END_ENTITY;
```

IfcGroundCave

EXPRESS Specification:

```
ENTITY IfcGroundCave
    SUBTYPE OF (IfcGround);
END_ENTITY;
```

IfcGroundCollar

EXPRESS Specification:

```
ENTITY IfcGroundCollar
    SUBTYPE OF (IfcGroundCave);
END_ENTITY;
```

IfcGroundLithology

EXPRESS Specification:

```
ENTITY IfcGroundLithology
    SUBTYPE OF (IfcGroundCave);
END_ENTITY;
```

IfcGroundGeology

EXPRESS Specification:

```
ENTITY IfcGroundGeology
    SUBTYPE OF (IfcGroundCave);
END_ENTITY;
```

IfcUndergroundStructureElement

The IfcUndergroundStructureElement is an abstract entity which describes all the spatial elements for any underground civil structure. In this work, the only subtype defined for this entity is IfcTunnelStructureElement. In the future works, it can represent any type of civil structure or facility that is constructed under the ground level (i.e., pipes, wires, sewers, conduits, ducts).

EXPRESS Specification:

```
Entity IfcUndergroundStructureElement
    ABSTRACT SUPERTYPE OF (ONEOF (IfcTunnelStructureElement))
    SUBTYPE OF (IfcSpatialStructureElement);
END_ENTITY;
```

IfcTunnelStructureElement

The IfcTunnelStructureElement is a subtype of the IfcUndergroundStructureElement. It is an abstract description for all the spatial components of the tunnel project. Each type of tunnel spatial component is associated with its matching name in the spatial structure elements group. This entity has six subtypes; IfcTunnel, IfcTunnelPart, IfcShaft, IfcShaftPart, IfcTailTunnel, IfcUndercut; The composition type of the IfcSpatialStructureElement is inherited by all the subtypes and declare the aggregation or decomposition of the entities. Therefore, each subtypes of the IfcTunnelStructureElement can be either an element itself, an aggregation (complex), or a decomposition (partial) type.

EXPRESS Specification:

```
ENTITY IfcTunnelStructureElement
    ABSTRACT SUPERTYPE OF (ONEOF (IfcTunnel, IfcTunnelPart, IfcShaft,
    IfcShaftPart, IfcTailTunnel, IfcUndercut))
    SUBTYPE OF (IfcUndergroundStructureElement);
END_ENTITY;
```

IfcTunnel

This entity represents the tunnel element of a tunneling project. It can be either a tunnel element itself, or an aggregation of more than one tunnel in a project. Also, it can be decomposed to small sections in the longitudinal direction. This is basically practical to consider different soil types and its resulting alterations in the excavation and support methods in the construction phase of the project. The tunnel body can be divided into small sections based on the equipment or material used for mucking and lining processes. Different types describe the excavation method, lining method, and TBM method for the tunnel element of the project.

<u>EXPRESS Specification:</u>

```
ENTITY IfcTunnel
    SUBTYPE OF (IfcTunnelStructureElement);
    TunnelingMethodIndicator: IfcTunnelMethodIndicator;
    TunnelingLiningIndicator: IfcTunnelLiningIndicator;
    TBMMethodType: OPTIONAL IfcTunnelBoringMachineType;
END_ENTITY;

TYPE IfcTunnelMethodIndicator = ENUMERATION OF (
    DRILL_BLAST,
    PARTIAL_FACE_HEADING_MACHINE,
    FULL_FACE_TUNNELIN_MACHINE,
    CUT_COVER,
    SUBMERGED_TUBES);
END_TYPE;

TYPE IfcTunnelLiningIndicator = ENUMERATION OF (
    NATURAL,
    ROCK_REINFORCEMENT,
    SEGMENT_SUPPORT_CAST_IRON,
    STEEL_SET_OR_ROLLED_STEEL_JOIST,
    CAST_IN_PLACE_CONCRETE,
    SHOTCRETE,
    WOODEN_SUPPORT);
```

```
END_TYPE;

TYPE IfcTunnelBoringMachineType = ENUMERATION OF (
    OPEN_FACE,
    CLOSED_FACE_PRESSURIZED_AIR_IN_FRONT,
    CLOSED_FACE_SLURRY_SHIELD,
    CLOSED_FACE_EPB_SHIELD);
END_TYPE;
```

IfcTunnelPart

This entity represents any specific part of the whole tunnel element. It is a section part of the tunnel that is supposed to have a specific application or designation.

EXPRESS Specification:

```
ENTITY IfcTunnelPart
    SUBTYPE OF (IfcTunnelStructureElement);
    TunnelPartSpotIndicator: IfcTunnelPartIndicator;
END_ENTITY;

TYPE IfcTunnelPartSpotIndicator = ENUMERATION OF (
    STARTING,
    ENDING,
    MIDDLE,
    SERVICE_EXIT,
    USER_DEFINED,
    UNDEFINED);
END_TYPE;
```

IfcShaft

This entity represents the shaft component of the tunneling project. Similar to other subtypes of the IfcTunnelStructureElement, it uses the composition types (Complex, Partial, and Element) to be aggregated or decomposed further in the tunnel model. It is associated with three different types to describe the initial lining, final lining, and geometric shape of the shaft element.

<u>EXPRESS Specification:</u>

```
ENTITY IfcShaft
    SUBTYPE OF (IfcTunnelStructureElement);
    InitialLiningExcavationType: IfcInitialShaftLiningType;
    FinalLiningExcavationType: IfcFinalShaftLiningType;
    ShapeType: IfcShaftShapeType;
END_ENTITY;

TYPE IfcInitialShaftLiningType = ENUMERATION OF (
    SHEET_PILING,
    SOLDIER_PILES_LAGGING,
    LINER_PLATES,
    RIBS_AND_LAGGING,
    SLURRY_WALLS,
    CASSION_METHOD,
    CEMENTATION,
    FREEZING,
    SHAFT_DRILLING,
    SHAFT_BORING);
END_TYPE;

TYPE IfcFinalShaftLiningType = ENUMERATION OF (
    CONCRETE_SEGMENTS,
    ROCK_BOLTS_AND_WIRE_MESH);
END_TYPE;

TYPE IfcShaftShapeType = ENUMERATION OF (
    CIRCULAR,
    RECTANGULAR,
```

```
    USER-DEFINED);
END_TYPE;
```

IfcShaftPart

This entity represents any segment of the shaft element in the tunneling structure. It is a section part of the shaft that is supposed to have a specific application or designation.

<u>EXPRESS Specification:</u>

```
ENTITY IfcShaftPart
    SUBTYPE OF (IfcTunnelStructureElement);
    ShaftPartSpotIndicator: IfcShaftPartIndicator;
END_ENTITY;

TYPE IfcShaftPartIndicator = ENUMERATION OF (
    SURFACE,
    BOTTOM,
    USER_DEFINED,
    NOT_DEFINED);
END_TYPE;
```

IfcTailTunnel

IfcTailTunnel is assigned to the tail tunnel component of the tunnel element. It provides extra space for enhanced movability and performance.

<u>EXPRESS Specification:</u>

```
ENTITY IfcTailTunnel
    SUBTYPE OF (IfcTunnelStructureElement);
END_ENTITY;
```

IfcUndercut

This entity represents undercut element which attaches the tunnel element to the shaft component of the tunnel project. It provides enough space for equipment installation and maneuver.

<u>EXPRESS Specification:</u>

```
ENTITY IfcUndercut
	SUBTYPE OF (IfcTunnelStructureElement);
END_ENTITY;
```

D-2 TIM-IFC Physical Element:

In the original IFC data model, the IfcElement entity represents the physical elements of the building projects such as IfcWall, IfcColumn, IfcBeam, IfcCurtainWall, IfcRoof, IfcSlab, etc.

The extended classes in the TIM-IFC structure to represent the tunnel physical classes includes but not limited to:

IfcGroundReinforcingElement

This entity presents the reinforcing elements used to fortify the soil structure while preforming the tunnel excavation/lining process. It has a predefined type to define the type of the reinforcing method/material (e.g., mesh, injection, grouting).

<u>EXPRESS Specification:</u>

```
ENTITY IfcGroundReinforcingElement
	SUBTYPE OF (IfcElement);
	GroundReinforcingType : IfcGroundReinforcingElementType;
END_ENTITY;

TYPE IfcGroundReinforcingElementType = ENUMERATION OF(
	MESH,
	INJECTION,
```

GROUTING,
NOT_DEFINED);
END_TYPE;

IfcGroundElement

This entity represents the soil elements such as ground water and ground layer.

<u>EXPRESS Specification:</u>

Entity IfcGroundElement
ABSTRACT SUPERTYPE OF (ONEOF (IfcGroundWater, IfcGroundLayer))
SUBTYPE OF (IfcElement);
END_ENTITY;

IfcGroundWater

<u>EXPRESS Specification:</u>

Entity IfcGroundWater
SUBTYPE OF (IfcGroundElement);
END_ENTITY;

IfcGroundLayer

<u>EXPRESS Specification:</u>

Entity IfcGroundLayer
SUBTYPE OF (IfcGroundElement);
END_ENTITY;

IfcInfrastructureElement

The IfcInfrastructureElement contains all the physical elements related to tunneling projects. It is a subtype of the IfcElement and inherits all the attributes of its supertype. The IfcInfrastructureElement includes physical elements associated with tunnel and shaft components. It includes tunnel, shaft, tunnel ring, sealing material, backfilling material, excavation/lining utilities, Service elements (e.g., rail, traffic signal), and auxiliary components required for the construction process.

It is possible to add physical elements associated with other infrastructure projects into this class, in order to have a comprehensive category of the project physical elements. For instance, the physical elements of the IFC-Bridge schema can be included in this class.

<u>EXPRESS Specification:</u>

```
Entity IfcInfrastructureElement
    ABSTRACT SUPERTYPE OF (ONEOF (IfcTunnelElement,
    IfcTunnelElementPart, IfcShaftElement, IfcShaftElemenetPart,
    IfcTunnelServiceElement, IfcTunnelAuxiliaryConstructionComponent,
    IfcShaftAuxiliaryConstructionComponent))
    SUBTYPE OF (IfcElement);
END_ENTITY;
```

IfcTunnelElement

This element contains all the information regarding the main tunnel part of the project. As mentioned before, it inherits all the attributes from the upper classes such as the Complex type, element type, and partial type (seen in the IfcTunnelPart element). The IfcTunnelElement represents all the physical details of the tunnel such as tunnel lining, sealing and backfilling material, and also the remaining utilities to perform the construction work (e.g., material, partial equipment, etc.)

<u>EXPRESS Specification:</u>

```
Entity IfcTunnelElement
    ABSTRACT SUPERTYPE OF (ONEOF (IfcTunnelSegmentRing,
    IfcTunnelInitialLining, IfcTunnelSecondaryLining,
    IfcTunnelSealingMaterial, IfcTunnelBackfillingMaterial,
    IfcTunnelExploitationUtilities))
```

SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY;

IfcTunnelElementPart

It is a segment of the tunnel supporting technological or physical specification.

EXPRESS Specification:

Entity IfcTunnelElementPart
SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY

IfcShaftElement

This entity represents any information regarding the shaft part of the tunneling project. The shaft component has different applications (service, working, exit). It includes all the information regarding any physical component participating in the excavation/lining process or contributing to these processes. The reinforcing specifications can be captured as part of the IfcReinforcingElement which is also predicted in the original IFC data model to hold the building reinforcing element specifications.

EXPRESS Specification:

ENTITY IfcShaftElement
ABSTRACT SUPERTYPE OF (ONE OF (IfcShaftPile, IfcShaftHPile, IfcShaftConcreteSegment, IfcShaftBolt, IfcShaftBaseSlab, IfcConcreteShaftCollar, IfcShaftHorizVerRibLag, IfcShaftWireMesh))
SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY;

IfcShaftElementPart

The IfcShaftElementPart is a segment of the shaft component supporting technological or physical specifications.

EXPRESS Specification:

Entity IfcShaftElementPart

    SUBTYPE OF (IfcInfrastructureElement);

END_ENTITY

IfcTunnelServiceElement

The IfcTunnelServiceElement defines the necessary components to perform the tunnel services during the exploitation phase. It also includes the plinth path specifications (e.g., dimensions) as part of the IfcRail element.

EXPRESS Specification:

```
Entity IfcTunnelServiceElement
    ABSTRACT SUPERTYPE OF (ONE OF ( IfcTrafficSign, IfcRail));
    SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY;
```

IfcRail

EXPRESS Specification:

```
ENTITY IfcRail
    SUBTYPE OF (IfcTunnelServiceElement);
END_ENTITY;
```

IfcTrafficSign

EXPRESS Specification:

```
ENTITY IfcTrafficSign
    SUBTYPE OF (IfcTunnelServiceElement);
END_ENTITY;
```

IfcTunnelConstrAuxiliaryComponent

This entity contains the information associated with elements required for different services during the tunnel construction process, such as ventilation, safety, fire protection, excavation, lining, and surveying.

<u>EXPRESS Specification:</u>

ENTITY IfcTunnelConstrAuxiliaryComponent

ABSTRACT SUPERTYPE OF (ONEOF(IfcTunnelVentilationElement, IfcTunnelSafetyElement, IfcTunnelExcavationElement, IfcTunnelLightingElement, IfcTunnelSurveyElement))

SUBTYPE OF (IfcInfrastructureElement);

END_ENTITY;

IfcShaftConstrAuxiliaryComponent

This entity contains the information associated with elements required for different services during the shaft construction process, such as accessing, centering, dewatering, excavation, hoisting, lighting, ventilation, safety, and fire protection tools.

<u>EXPRESS Specification:</u>

ENTITY IfcShaftConstrAuxiliaryComponent

ABSTRACT SUPERTYPE OF (ONE OF (IfcShaftAccessToolElement, IfcShaftCenteringElement, IfcShaftDewateringElement, IfcShaftExcavationElement, IfcShaftHoistingElement, IfcShaftLightingElement, IfcShaftVentilationElement, IfcShaftSafetyElement))

SUBTYPE OF (IfcInfrastructureElement);

END_ENTITY;

IfcTunnelSegmentRing

The IfcTunnelSegmentRing represents prefabricated or cast-in-place concrete segments. It also can be used as the representation for the segmented parts of the tunnel excavation process in the sequential excavation method. Therefore, the associated information for each segment is defined specifically for a particular section of the tunnel. This allows for defining different sets of attributes which is probable as a result of different soil type and excavation method along the length of the tunnel.

<u>EXPRESS Specification:</u>

```
Entity IfcTunnelSegmentRing
    SUBTYPE OF (IfcTunnelElement);
END_ENTITY
```

IfcTunnelInitialLining

This entity contains the data for the tunnel initial (primary lining). For instance, the compressive strength of the shotcrete for the initial lining is part of the data included in the IfcTunnelInitialLining. Moreover, the thickness of shotcrete is defined by this entity.

<u>EXPRESS Specification:</u>

```
Entity IfcTunnelInitialLining
    SUBTYPE OF (IfcTunnelElement);
END_ENTITY;
```

It is also possible to define different types for the tunnel initial lining as a Type entity for the IfcTunnelInitialLining and specify the enumeration for the predefined type.

IfcTunnelSecondaryLining

Similar to IfcTunnelInitialLining, the IfcTunnelSecondaryLining includes information regarding the final lining of the tunnel component.

EXPRESS Specification:

Entity IfcTunnelSecondaryLining

SUBTYPE OF (IfcTunnelElement);

END_ENTITY;

IfcTunnelSealingMaterial

EXPRESS Specification:

Entity IfcTunnelSealingMaterial

SUBTYPE OF (IfcTunnelElement);

END_ENTITY

IfcTunnelBackfillingMaterial

EXPRESS Specification:

Entity IfcTunnelBackfillingMaterial

SUBTYPE OF (IfcTunnelElement);

END_ENTITY

IfcTunnelExploitationUtilities

This element of the TIM model contains the information regarding the elements required in the exploitation phase of the project. It can also define the details for the temporary elements prior to the exploitation phase such as muck carts and conveyor belts that are required during the excavation process, but not a significant part of the excavation utilities.

EXPRESS Specification:

Entity IfcTunnelExploitationUtilities

SUBTYPE OF (IfcTunnelElement);

END_ENTITY;

IfcShaftPile

The IfcShaftPile represents the pile component during the piling process for shaft sinking. It is the container for information such as one pile driving time and pile width. This is also the case for the IfcShaftHPile element.

EXPRESS Specification:

```
Entity IfcShaftPile
    SUBTYPE OF (IfcShaftElement);
END_ENTITY;
```

IfcShaftHPile

EXPRESS Specification:

```
Entity IfcShaftHPile
    SUBTYPE OF (IfcShaftElement);
END_ENTITY;
```

IfcShaftConcreteSegment

The IfcShaftConcreteSegment contains the information related to the cast-in-place or prefabricated concrete segment used for shaft support during the sinking process. It can include the data on the material technical specifications, or the work duration, quality, cost, and schedule. The IfcShaftBolt is the container for the bolt or any similar details used during the shaft lining process.

EXPRESS Specification:

```
Entity IfcShaftConcreteSegment
    SUBTYPE OF (IfcShaftElement);
END_ENTITY;
```

IfcShaftBolt

EXPRESS Specification:

```
Entity IfcShaftBolt
    SUBTYPE OF (IfcShaftElement);
END_ENTITY;
```

IfcShaftBaseSlab

The IfcShaftBaseSlab contains the data related to the base slab or slump constructed at the bottom part the shaft. The information regarding the dewatering will be captured with the subtype of the IfcShaftConstrAuxiliaryComponent which is IfcShaftDewateringElement.

<u>EXPRESS Specification:</u>

```
Entity IfcShaftBaseSlab
    SUBTYPE OF (IfcShaftElement);
END_ENTITY;
```

IfcConcreteShaftCollar

This TIM element is the container for the shaft collar related data. The shaft collar is the shaft segment part at/near the ground level. It usually includes the dimension information. The information regarding the devices/tools used at the ground level for shaft sinking (temporary safety elements, access tools, centering devices) are captured by using the IfcShaftConstrAuxiliaryComponent and its subtypes.

<u>EXPRESS Specification:</u>

```
Entity IfcConcreteShaftCollar
    SUBTYPE OF (IfcShaftElement);
END_ENTITY;
```

IfcShaftHorizVerRibLag

The IfcShaftHorizVerRibLag captures any detailed information regarding the rib and lagging process that already has not been captured by IfcShaftConcreteSegment.

<u>EXPRESS Specification:</u>

Entity IfcShaftHorizVerRibLag

SUBTYPE OF (IfcShaftElement);

END_ENTITY;

IfcShaftWireMesh

This element contains the information related to the wire mesh details (specifications, dimension, quantity, construction details and quality).

<u>EXPRESS Specification:</u>

Entity IfcShaftWireMesh

SUBTYPE OF (IfcShaftElement);

END_ENTITY;

The subtypes of the IfcTunnelConstrAuxiliaryComponent contain the information related to the ventilation, plumbing, excavation, surveying, lighting, etc.

IfcTunnelVentilationElement

<u>EXPRESS Specification:</u>

Entity IfcTunnelVentilationElement

SUBTYPE OF (IfcTunnelConstrAuxiliaryComponent);

END_ENTITY;

IfcTunnelSafetyElement

<u>EXPRESS Specification:</u>

Entity IfcTunnelSafetyElement

SUBTYPE OF (IfcTunnelConstrAuxiliaryComponent);

END_ENTITY;

IfcTunnelExcavationElement

EXPRESS Specification:

Entity IfcTunnelExcavationElement

SUBTYPE OF (IfcTunnelConstrAuxiliaryComponent);

END_ENTITY;

IfcTunnelLightingElement

EXPRESS Specification:

Entity IfcTunnelLightingElement

SUBTYPE OF (IfcTunnelConstrAuxiliaryComponent);

END_ENTITY;

IfcTunnelSurveyElement

EXPRESS Specification:

Entity IfcTunnelSurveyElement

SUBTYPE OF (IfcTunnelConstrAuxiliaryComponent);

END_ENTITY;

The subtypes of the IfcShaftConstrAuxiliaryComponent contain the information regarding the construction phase of the shaft sinking and lining process, such as accessing tools, centering tools, dewatering tools, lighting, excavation, etc.

IfcShaftAccessToolElement

EXPRESS Specification:

Entity IfcShaftAccessToolElement

SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);

END_ENTITY;

IfcShaftCenteringElement

EXPRESS Specification:

Entity IfcShaftCenteringElement

SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);

END_ENTITY;

IfcShaftDewateringElement

<u>EXPRESS Specification:</u>

Entity IfcShaftDewateringElement

SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);

END_ENTITY;

IfcShaftExcavationElement

<u>EXPRESS Specification:</u>

Entity IfcShaftExcavationElement

SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);

END_ENTITY;

IfcShaftHoistingElement

<u>EXPRESS Specification:</u>

Entity IfcShaftHoistingElement

SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);

END_ENTITY;

IfcShaftLightingElement

<u>EXPRESS Specification:</u>

Entity IfcShaftLightingElement

SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);

END_ENTITY;

IfcShaftVentilationUtilities

<u>EXPRESS Specification:</u>

```
Entity IfcShaftVentilationElement
      SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);
END_ENTITY;
```

IfcShaftSafetyElement

<u>EXPRESS Specification:</u>

```
Entity IfcShaftSafetyElement
      SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);
END_ENTITY;
```

Appendix-E EXPRESS Schema Development Using JSDAI Plugins for Eclipse IDE- Implementing TIM-IFC Classes in JSDAI (based on JSDAI tutorials available at: http://www.jsdai.net/support/tutorials)

JSDAI™ is an open source API for reading, writing, and run-time manipulation of object-oriented EXPRESS-based data models. EXPRESS-based data models are widely used in STEP (ISO 10303) models. This platform provides an environment to define the TIM-IFC classes. These classes are then presented by EXPRESS-G diagram in the JSDAI™ EXG layout. Appendix-F presents the procedural steps to develop Express schema and EXPRESS-G diagrams for TIM-IFC classes by using JSDAI™ plugins for Eclipse IDE.

E-1 Download JSDAI and Install the Eclipse IDE (Figure F-1 (a-e))

The JSDAI Express compiler and Express-G Editor are designed as plugins for the Eclipse platform. The Eclipse platform is an open extensible IDE.

In the Eclipse Platform:
Help >Install New Software…
Enter the name and address of the update site → ***Next***
Select the 2 plugins (JSDAI Express Compiler and JSDAI Express-G Editor) → ***Next*** → *Accept the license agreement for the JSDAI plugins* → ***Finish*** → ***Install All***

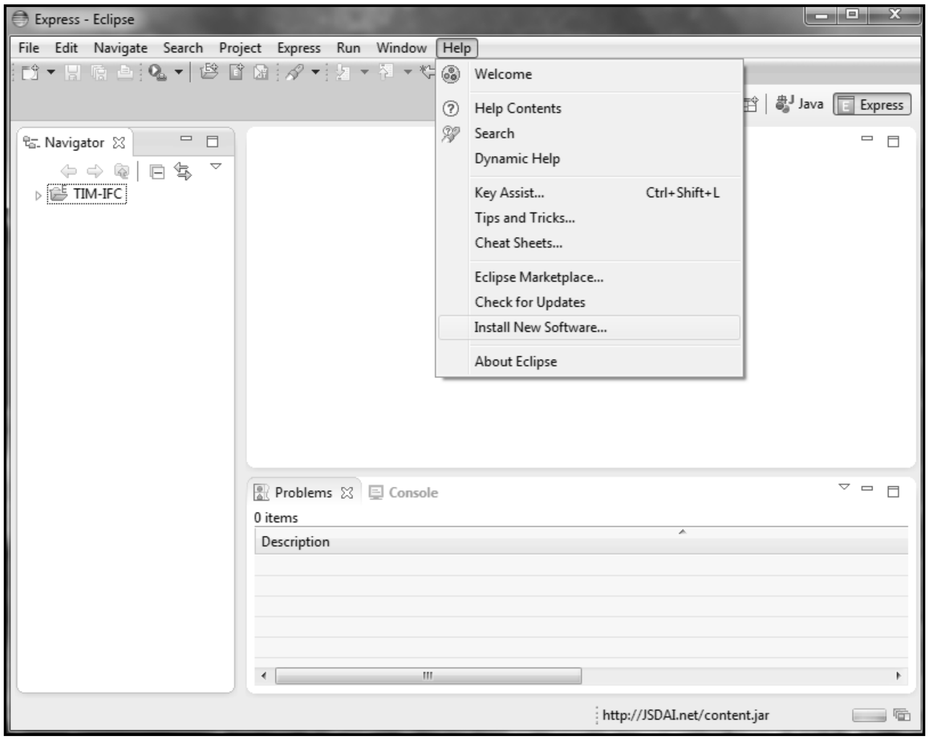

Figure E-1 (a) Install new plugins

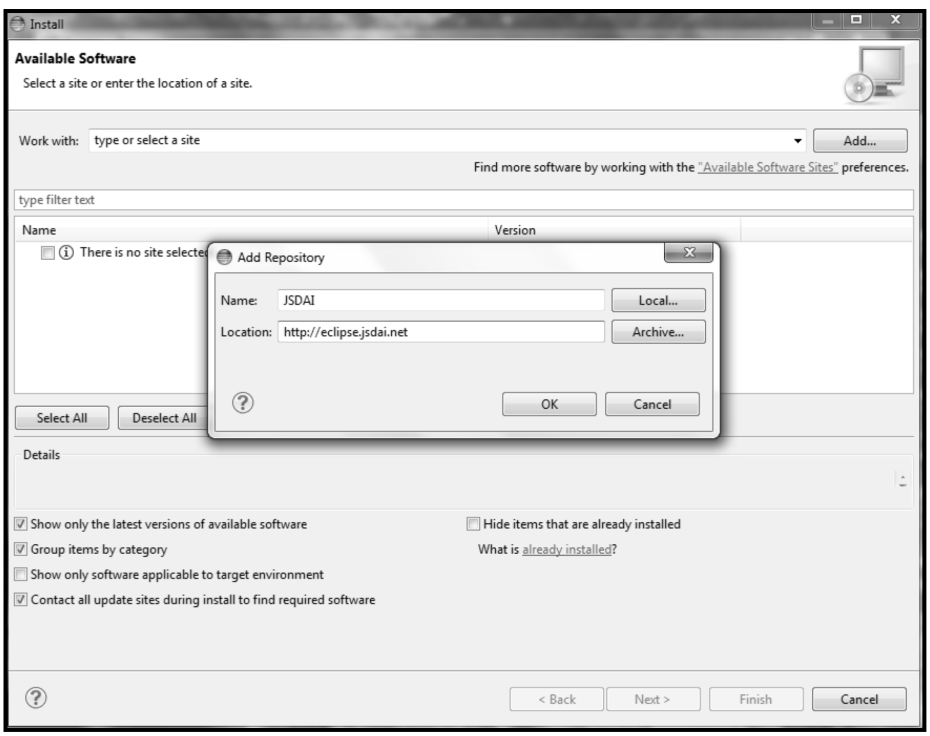

Figure E-1 (b) Enter the source of the Plugin to install

The Eclipse platform needs to be restarted after the installation. To make sure that the plugins are installed: *Help > About Eclipse SDK*

The installed plugins introduce two new perspectives for Eclipse. Perspectives are Eclipse layouts. To switch between different perspectives, select from the tab on the outline window. The Express Perspective is used for Express file editing. The Express-G Perspective is used for Express-G diagrams display and management.

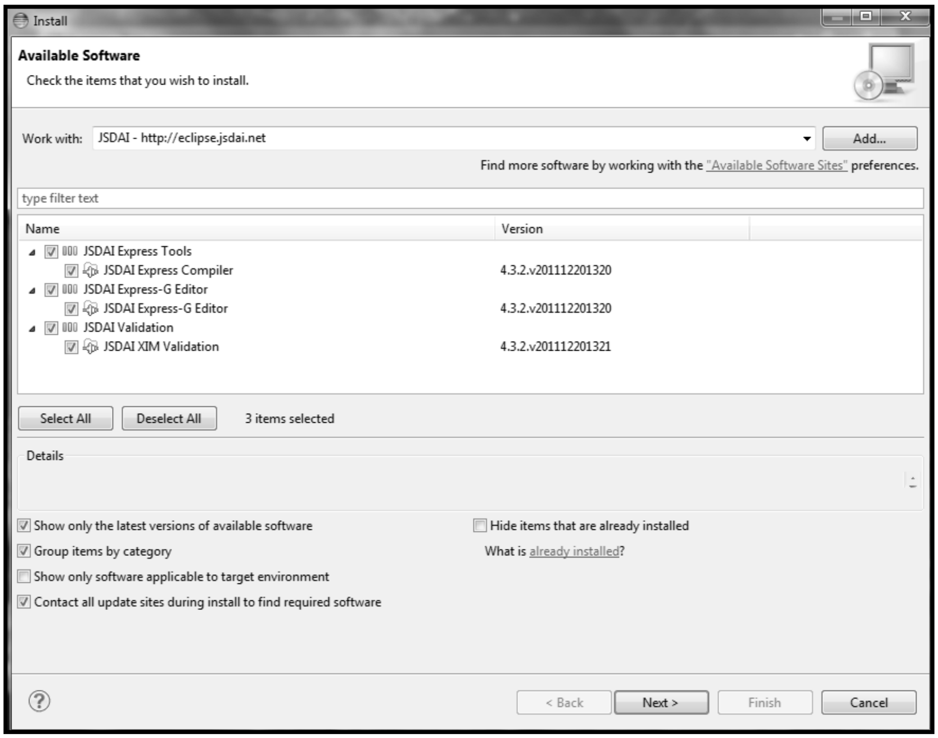

Figure E-1 (c) Choose the plugins to install

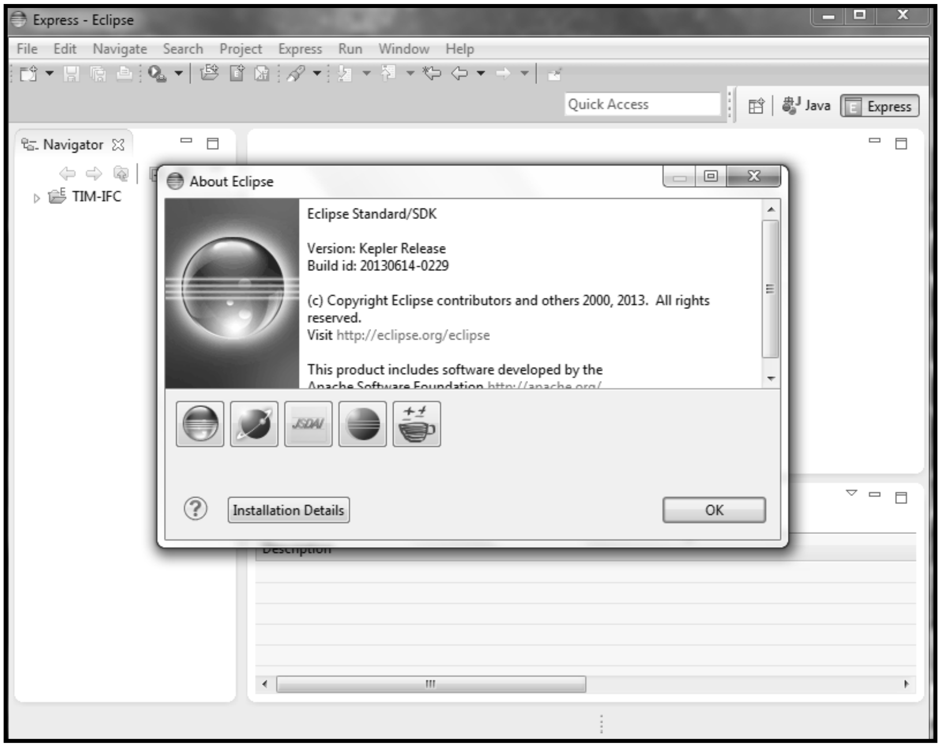

Figure E-1 (d) Checking the installed Plugins

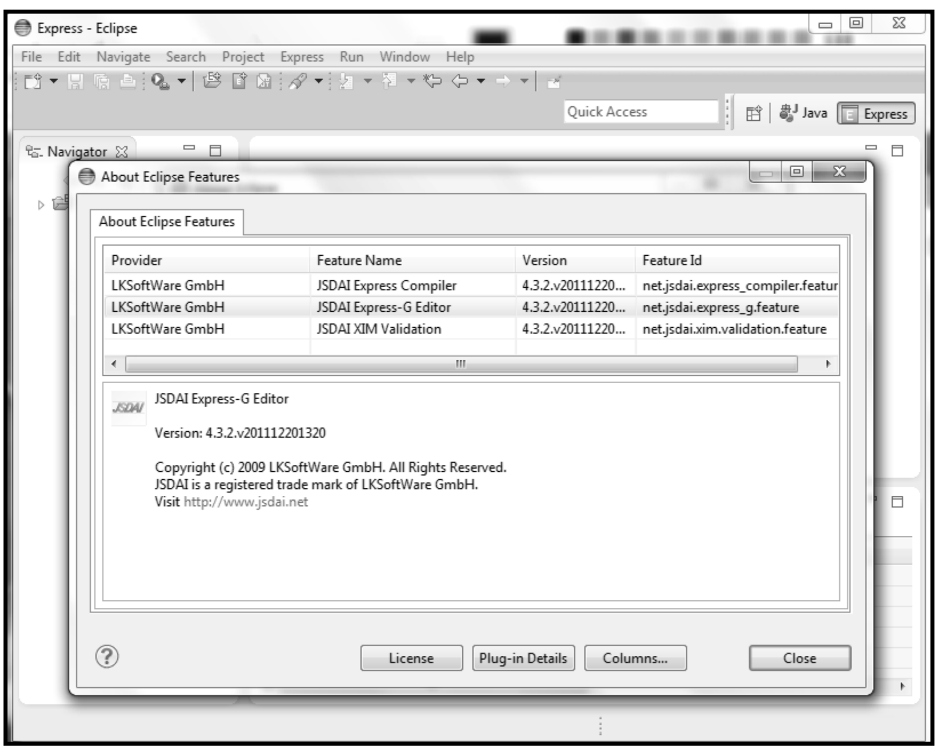

Figure E-1 (e) The installed JSDAI Express compiler and Express-G editor

E-2 Compiling the Express file (Figure F-2 (a-j))

To create a new Express project;

Right click in the Package Explorer.

New > Project… > Express Project → Enter the name of the new project

The created Express project and its classes are visible in the Navigator window. The Express data model is stored in an Express file. To create one, right click on the Express Files class of the created Express file.

Express File > New > Other… > Express File → ***Next*** *→ Enter the name for Express file →* ***Finish***

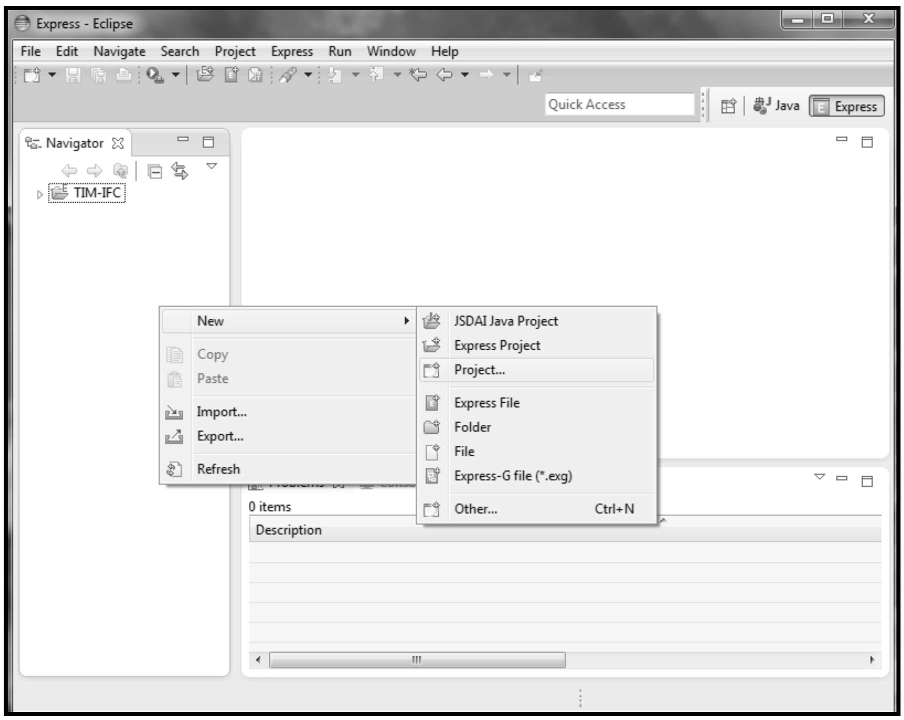

Figure E-2 (a) Add a new Express project

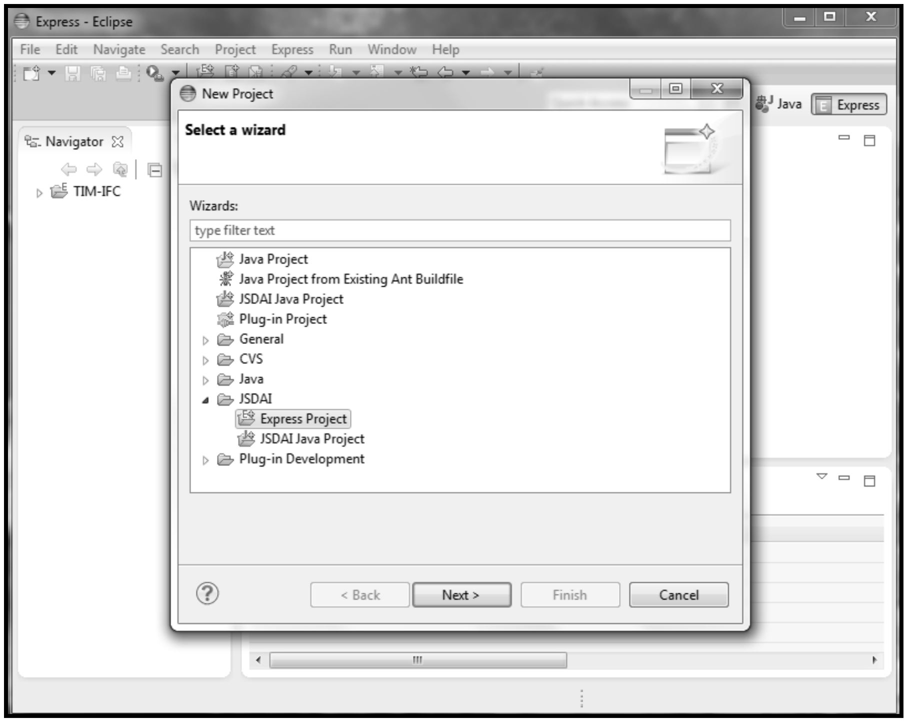

Figure E-2 (b) Specify the type of the project as a JSDAI Express project

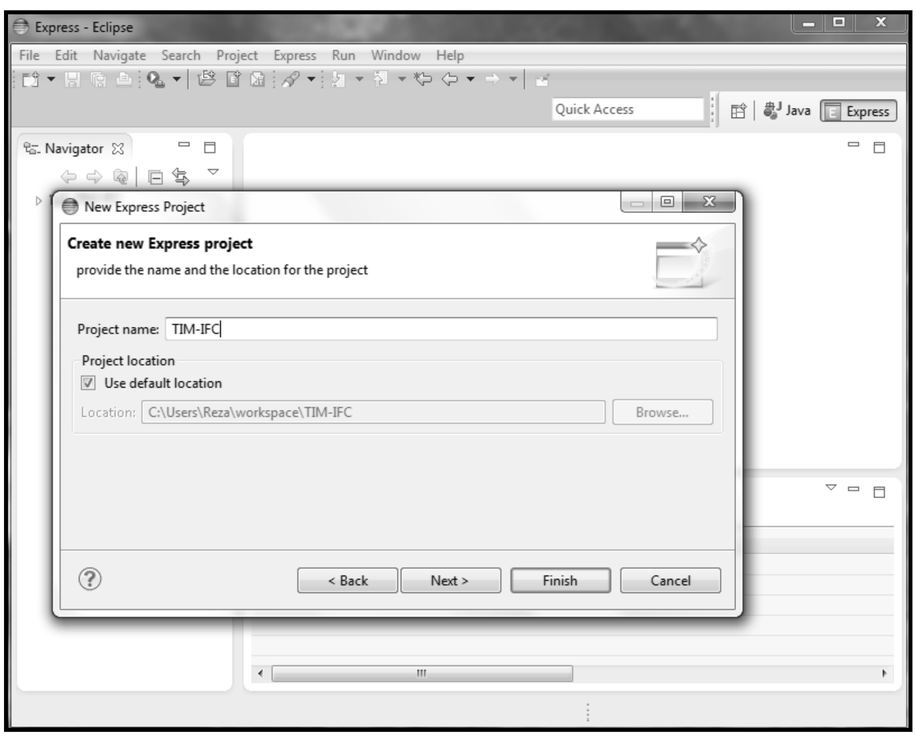

Figure E-2 (c) Enter the name for the Express project

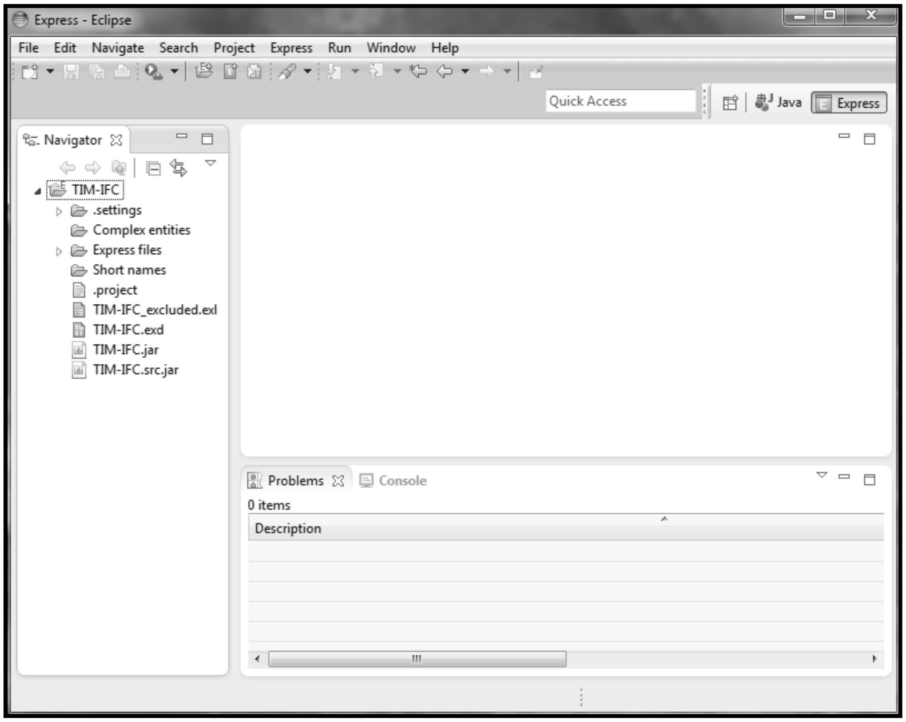

Figure E-2 (d) The tree of the new Express project

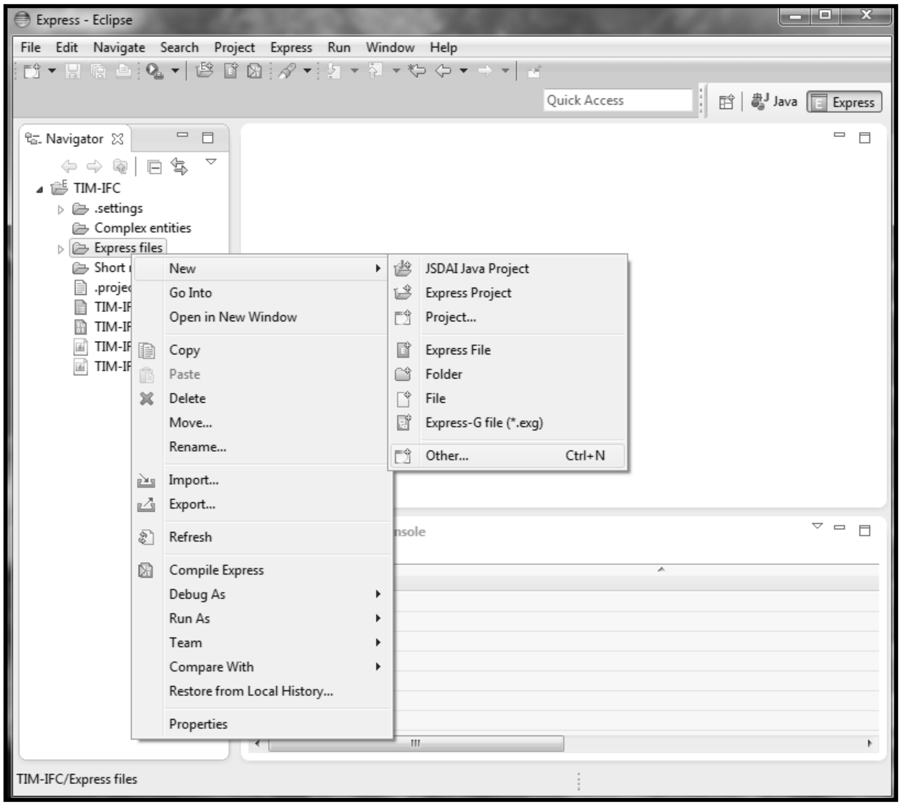

Figure E-2 (e) Create an Express file for the new Express project

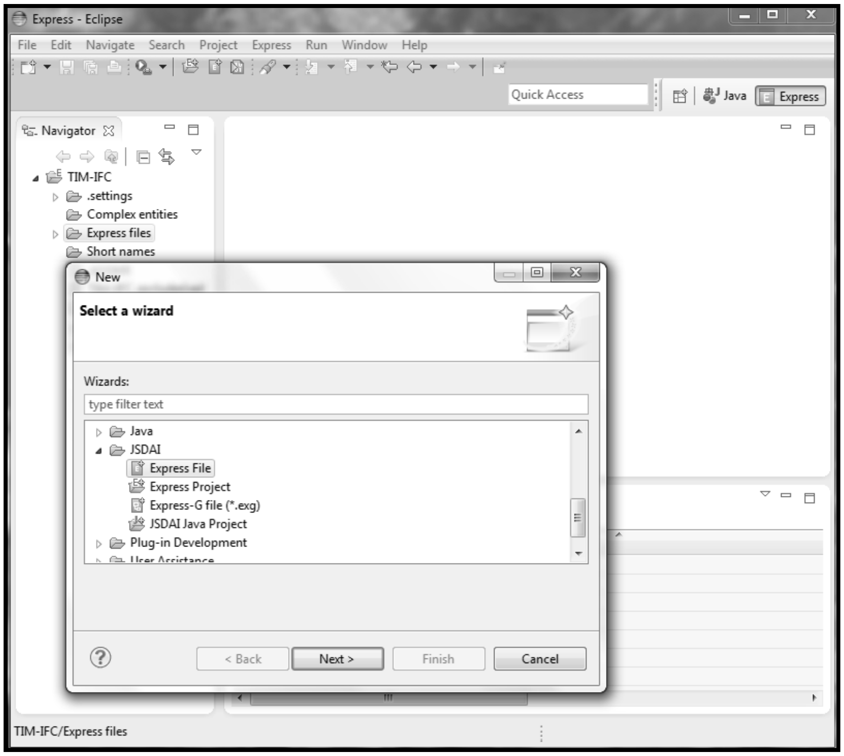

Figure E-2 (f) The Express file

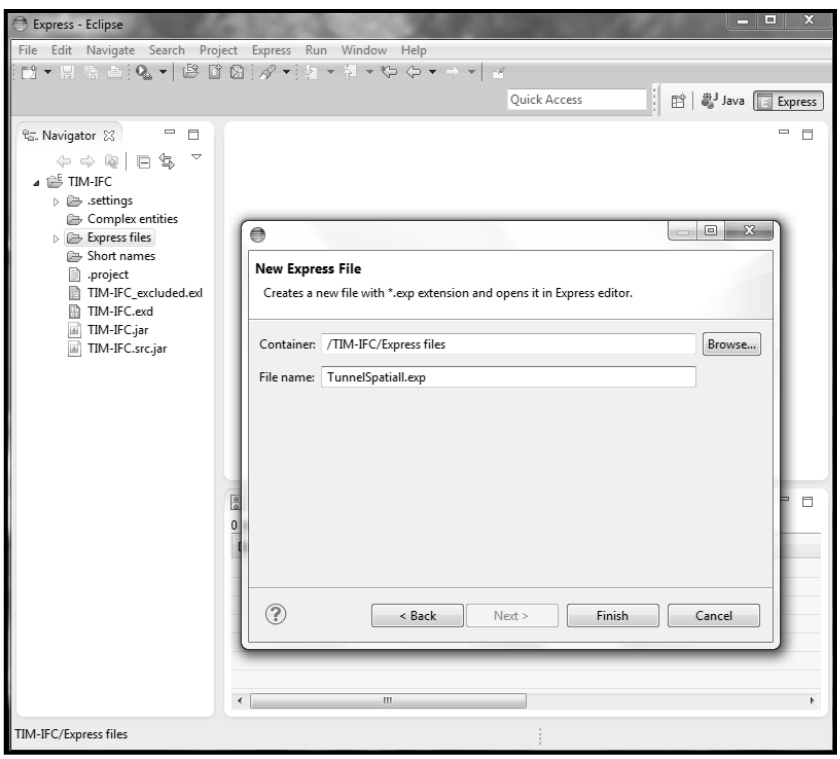

Figure E-2 (g) The new Express file in the created Express project to develop new Schema

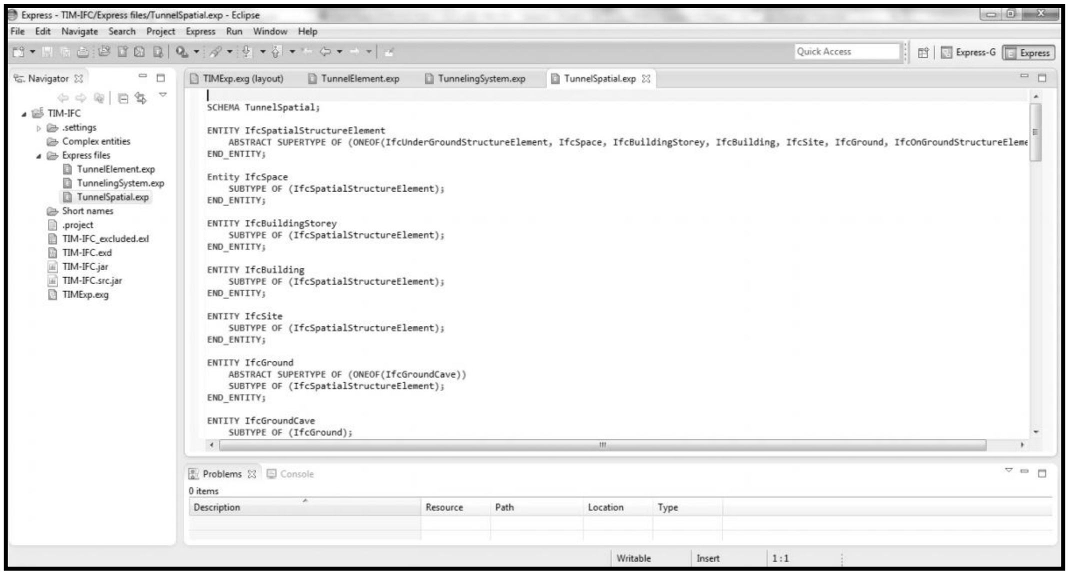

Figure E-2 (h) TunnelSpatial Schema

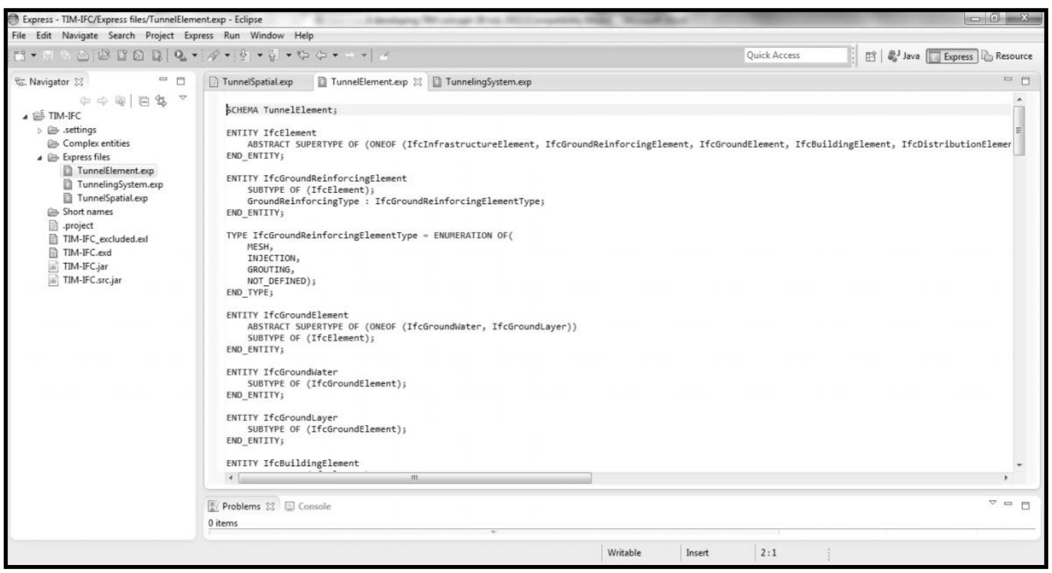

Figure E-2 (i) TunnelElement Schema

As a result, Express file contents with an empty schema are displayed. The Extension .exp represents Express file (plain text). The created schema in the main window of the Eclipse platform is ready for entering Express data model.

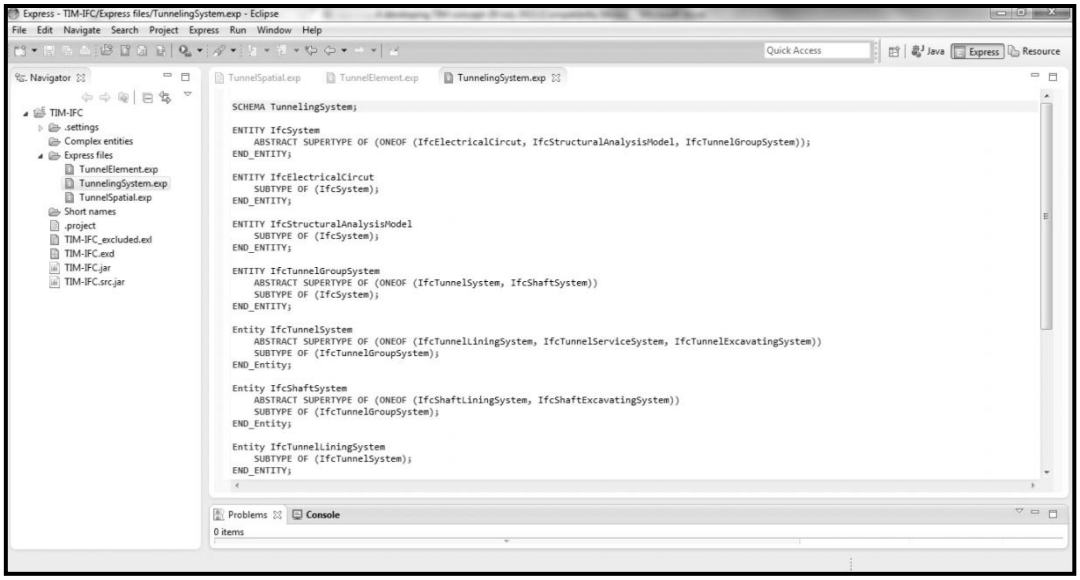

Figure E-2 (j) TunnellingSystem Schema

E-3 Creating Express-G Diagrams (Figure F-3 (a-k))

To create graphical Express data model representation- Express-G diagram, right-click on the Express dictionary (.exd) file.

New > Other… > Express-G file (.exg)*
Select the place, where the file will be stored and file name → ***Next***
Select "Import dictionary data at once" → ***Finish***

The outline section displays diagrams of schemas. To create new diagrams, right-click on the available Schema.

New Diagram > Complete Short > Enter the name for the Diagram → ***Finish***

The Express-G outline lists graphical elements. They can be put on the layout pages as needed. To create entity-level diagram, select an entity element. Drag the element on the layout page and release. Therefore, the entity with its relations is displayed graphically. Other entities can be added similarly. Schema- level diagrams can also be created similarly. Note that Schema diagrams can have multiple diagrams by using the + tab at the bottom of the Express-G layout window.

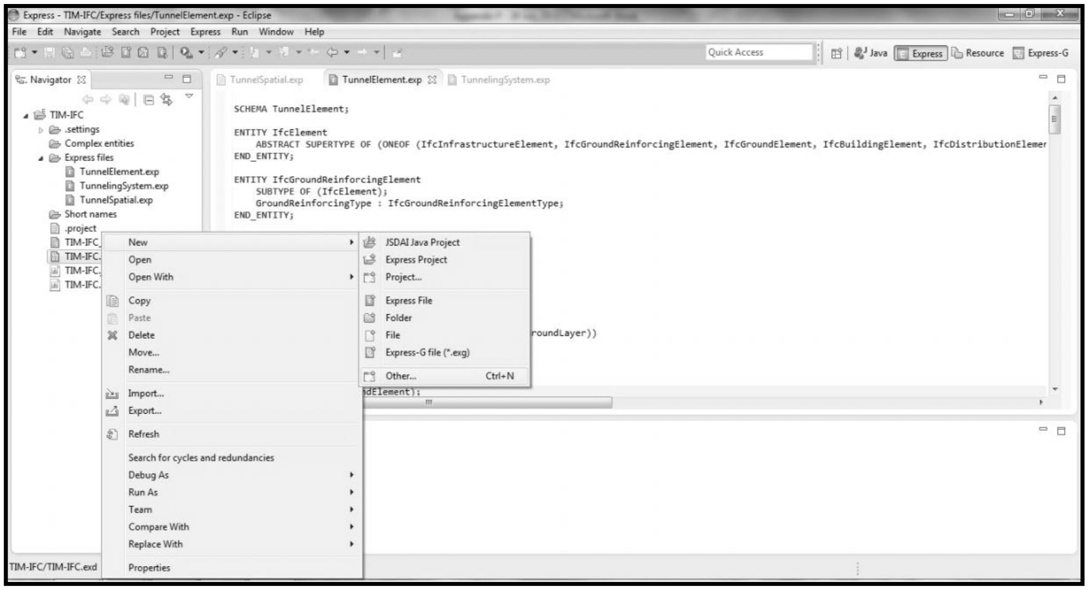

Figure E-3 (a) Creating the Express-G file

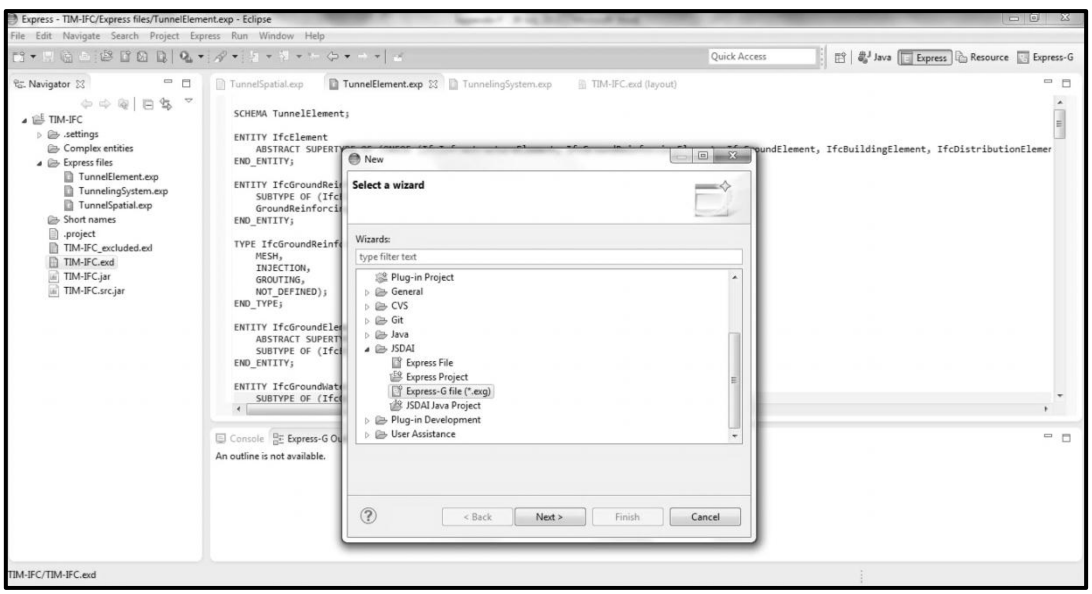

Figure E-3 (b) Selecting a new wizard (*.exg) for the Express-G file

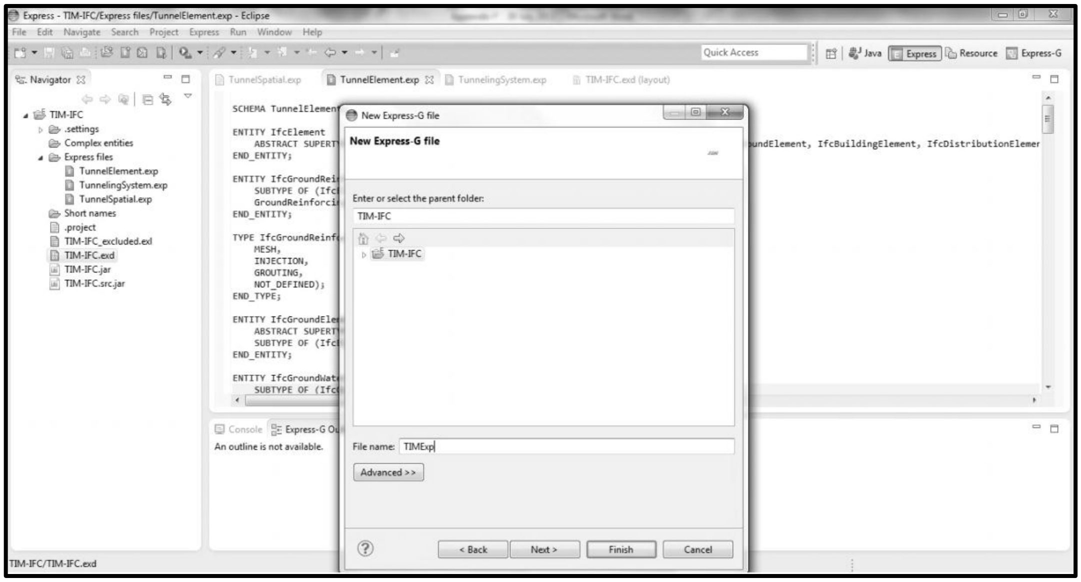

Figure E-3 (c) Select a name for the new Express-G file

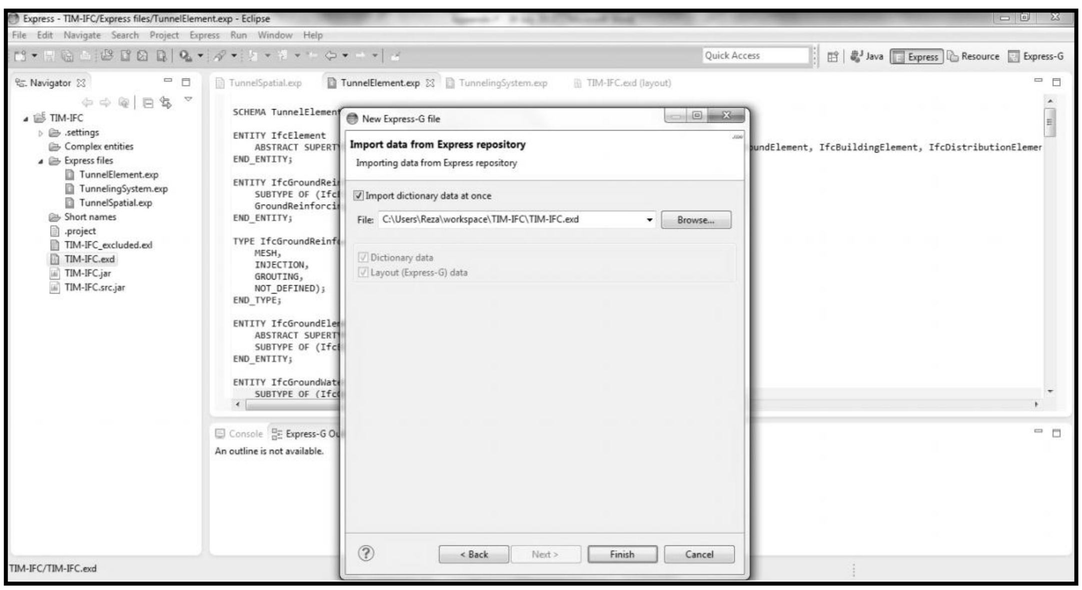

Figure E-3 (d) Enter the address to import data from Express repository

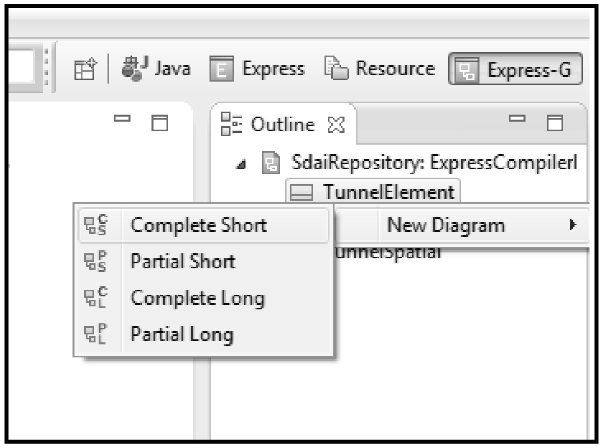

Figure E-3 (e) Right click on a schema to create a new diagram

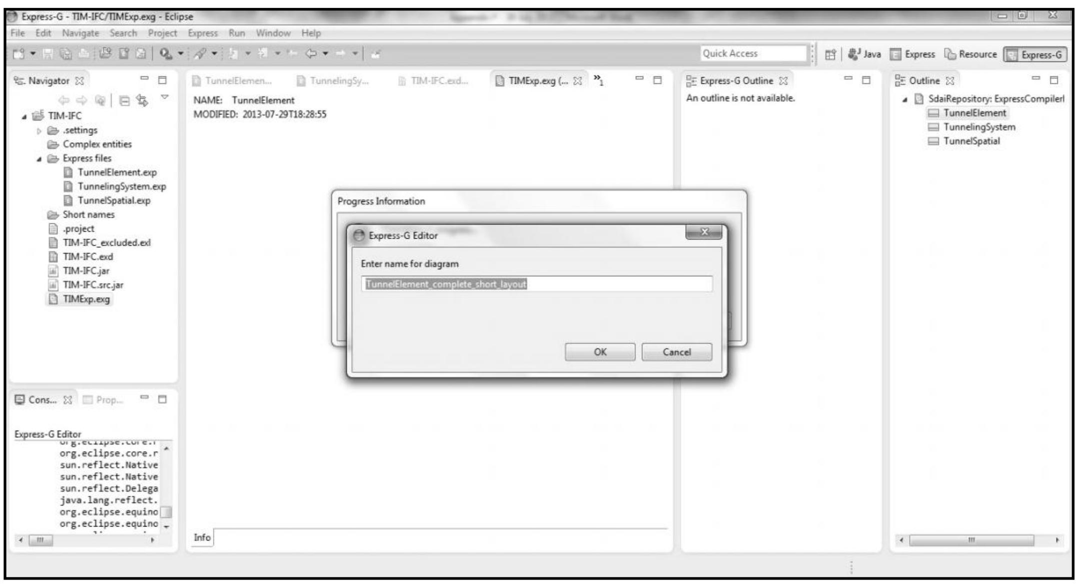

Figure E-3 (f) Enter a name for the new diagram

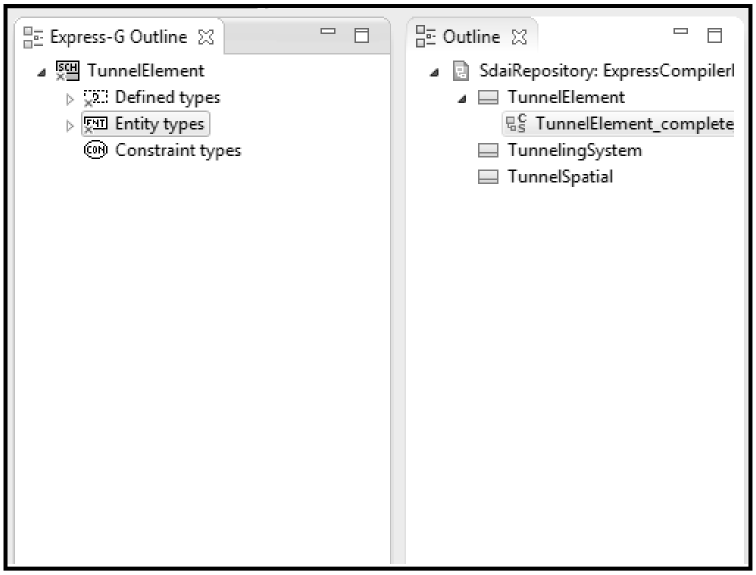

Figure E-3 (g) The resulting Schema and the Express-G outline containing the entities

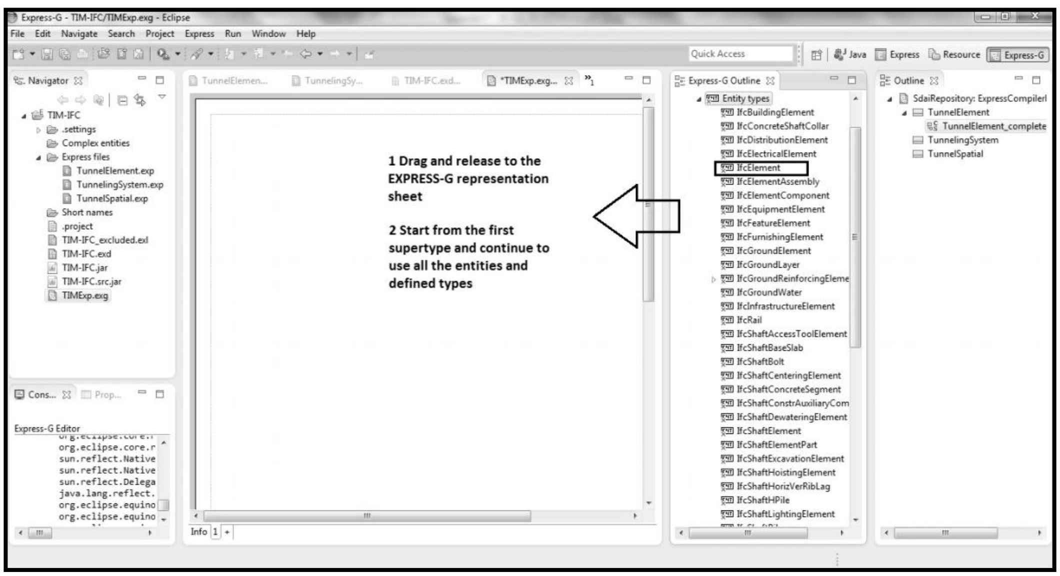

Figure E-3 (h) Creating Express diagram by dragging and releasing to the Express-G sheet

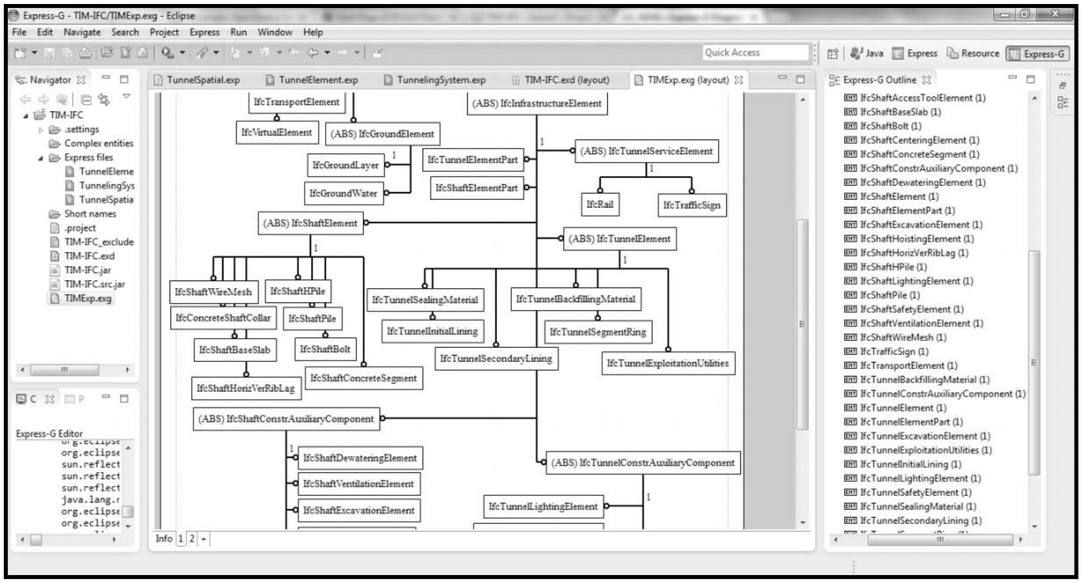

Figure E-3 (i) Express-G diagram for tunnel physical element classes

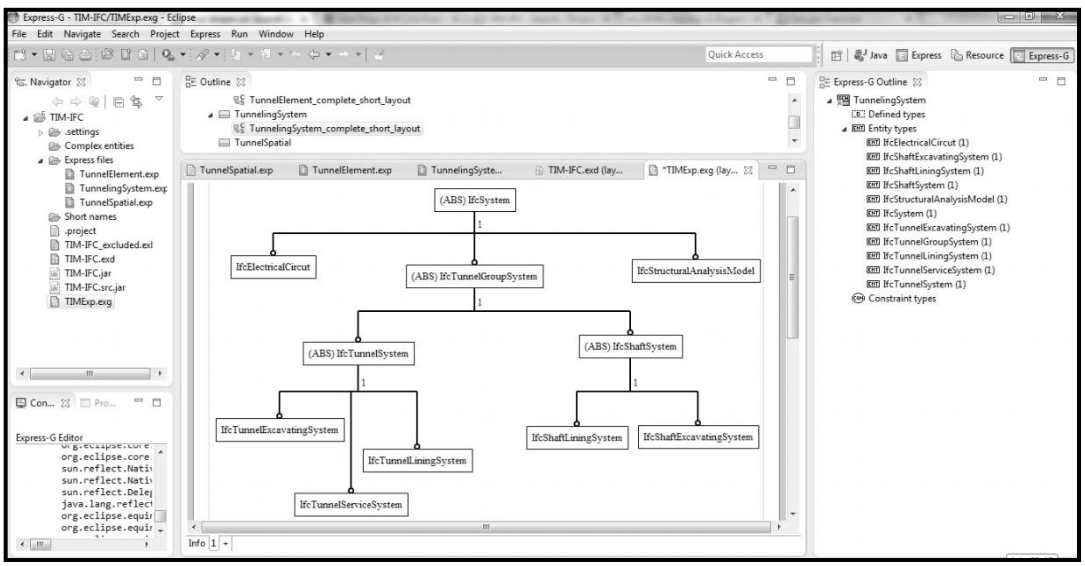

Figure E-3 (j) Express-G diagram for tunnel system group classes

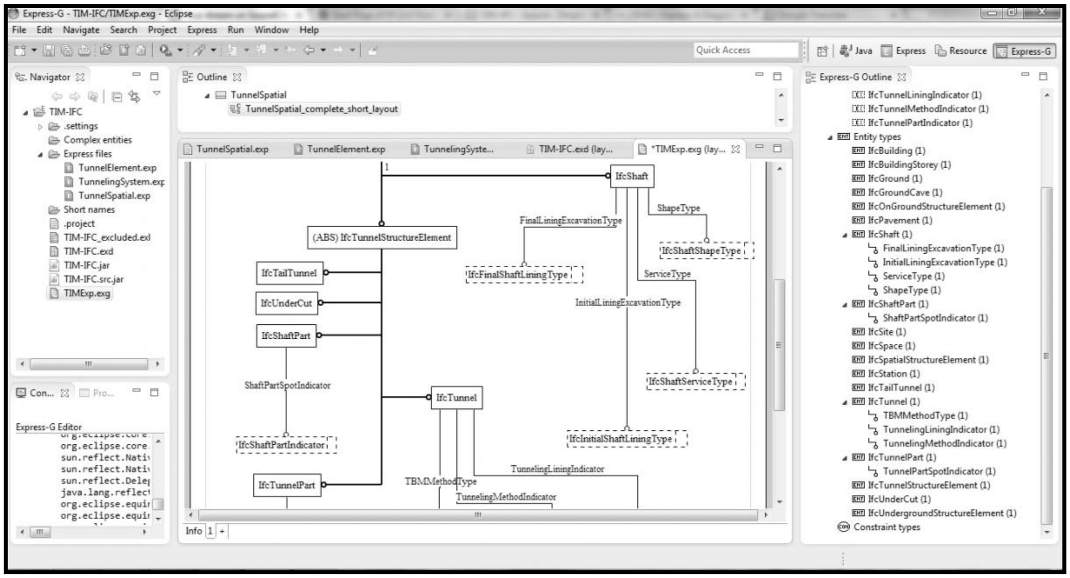

Figure E-3 (k) Express-G diagram for tunnel spatial element classes

E-4 Updating Express Schema and Express-G Diagrams

In order to update the Express schema, simply update the schema through the main window of the Eclipse platform. The changes will be effective by compiling the project with the “Compile” button. However, the Express-G diagrams are not automatically updated when the Schema is changed. To update the Express-G files, open the Express-G diagram.

Right click on the Express Dictionary (.exd) file.

Import > Data from Express Dictionary → ***Finish***

Select and open the changed schema. Note that marks in the Express-G outline near updated element indicate that diagram needs updating. Select and drag new entities to the layout page. By saving the file, the Express-G diagram is updated according to the changed schema.

E-5 Codes in JSDAI for Eclipse Platform for Representing TIM-IFC elements

TIM Physical Elements

```
SCHEMA TunnelElement;

ENTITY IfcElement
        ABSTRACT SUPERTYPE OF (ONEOF (IfcInfrastructureElement,
        IfcGroundReinforcingElement, IfcGroundElement, IfcBuildingElement,
        IfcDistributionElement, IfcEquipmentElement, IfcElectricalElement,
        IfcElementAssembly, IfcFeatureElement, IfcFurnishingElement,
        IfcTransportElement, IfcElementComponent, IfcVirtualElement));
END_ENTITY;

ENTITY IfcGroundReinforcingElement
        SUBTYPE OF (IfcElement);
        GroundReinforcingType : IfcGroundReinforcingElementType;
END_ENTITY;

TYPE IfcGroundReinforcingElementType = ENUMERATION OF(
        MESH,
        INJECTION,
        GROUTING,
        NOT_DEFINED);
END_TYPE;

ENTITY IfcGroundElement
        ABSTRACT SUPERTYPE OF (ONEOF (IfcGroundWater,
IfcGroundLayer))
        SUBTYPE OF (IfcElement);
END_ENTITY;

ENTITY IfcGroundWater
        SUBTYPE OF (IfcGroundElement);
END_ENTITY;

ENTITY IfcGroundLayer
        SUBTYPE OF (IfcGroundElement);
END_ENTITY;

ENTITY IfcBuildingElement
        SUBTYPE OF (IfcElement);
```

```
END_ENTITY;

ENTITY IfcDistributionElement
	SUBTYPE OF (IfcElement);
END_ENTITY;

ENTITY IfcEquipmentElement
	SUBTYPE OF (IfcElement);
END_ENTITY;

ENTITY IfcElectricalElement
	SUBTYPE OF (IfcElement);
END_ENTITY;

ENTITY IfcElementAssembly
	SUBTYPE OF (IfcElement);
END_ENTITY;

ENTITY IfcFeatureElement
	SUBTYPE OF (IfcElement);
END_ENTITY;

ENTITY IfcFurnishingElement
	SUBTYPE OF (IfcElement);
END_ENTITY;

ENTITY IfcTransportElement
	SUBTYPE OF (IfcElement);
END_ENTITY;

ENTITY IfcElementComponent
	SUBTYPE OF (IfcElement);
END_ENTITY;

ENTITY IfcVirtualElement
	SUBTYPE OF (IfcElement);
END_ENTITY;


ENTITY IfcInfrastructureElement
	ABSTRACT                                        SUPERTYPE
	OF(ONEOF(IfcTunnelElement,IfcTunnelElementPart,IfcShaftElement,
	IfcShaftElementPart,                   IfcTunnelServiceElement,
	IfcTunnelConstrAuxiliaryComponent,
	IfcShaftConstrAuxiliaryComponent))
```

```
    SUBTYPE OF (IfcElement);
END_ENTITY;


ENTITY IfcTunnelElement
    ABSTRACT SUPERTYPE OF(ONEOF(IfcTunnelSegmentRing,
    IfcTunnelInitialLining, IfcTunnelSecondaryLining,
    IfcTunnelSealingMaterial, IfcTunnelBackfillingMaterial,
    IfcTunnelExploitationUtilities))
    SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY;


Entity IfcTunnelServiceElement
    ABSTRACT SUPERTYPE OF (ONEOF( IfcTrafficSign, IfcRail))
    SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY;

ENTITY IfcRail
    SUBTYPE OF (IfcTunnelServiceElement);
END_ENTITY;

ENTITY IfcTrafficSign
    SUBTYPE OF (IfcTunnelServiceElement);
END_ENTITY;


ENTITY IfcShaftElement
    ABSTRACT SUPERTYPE OF (ONEOF(IfcShaftPile, IfcShaftHPile,
    IfcShaftConcreteSegment, IfcShaftBolt, IfcShaftBaseSlab,
    IfcConcreteShaftCollar, IfcShaftHorizVerRibLag, IfcShaftWireMesh))
    SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY;

ENTITY IfcTunnelElementPart
    SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY;

ENTITY IfcShaftElementPart
    SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY;

ENTITY IfcTunnelConstrAuxiliaryComponent
```

```
    ABSTRACT SUPERTYPE OF (ONEOF(IfcTunnelVentilationElement,
    IfcTunnelSafetyElement, IfcTunnelExcavationElement,
    IfcTunnelLightingElement, IfcTunnelSurveyElement))
    SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY;

ENTITY IfcShaftConstrAuxiliaryComponent
    ABSTRACT SUPERTYPE OF (ONEOF(IfcShaftAccessToolElement,
    IfcShaftCenteringElement, IfcShaftDewateringElement,
    IfcShaftExcavationElement, IfcShaftHoistingElement,
    IfcShaftLightingElement, IfcShaftVentilationElement,
    IfcShaftSafetyElement))
    SUBTYPE OF (IfcInfrastructureElement);
END_ENTITY;

Entity IfcTunnelSegmentRing
    SUBTYPE OF (IfcTunnelElement);
END_ENTITY;

Entity IfcTunnelInitialLining
    SUBTYPE OF (IfcTunnelElement);
END_ENTITY;

Entity IfcTunnelSecondaryLining
    SUBTYPE OF (IfcTunnelElement);
END_ENTITY;

Entity IfcTunnelSealingMaterial
    SUBTYPE OF (IfcTunnelElement);
END_ENTITY;

Entity IfcTunnelBackfillingMaterial
    SUBTYPE OF (IfcTunnelElement);
END_ENTITY;

Entity IfcTunnelExploitationUtilities
    SUBTYPE OF (IfcTunnelElement);
END_ENTITY;

Entity IfcShaftPile
    SUBTYPE OF (IfcShaftElement);
END_ENTITY;

Entity IfcShaftHPile
    SUBTYPE OF (IfcShaftElement);
```

```
END_ENTITY;

Entity IfcShaftConcreteSegment
	SUBTYPE OF (IfcShaftElement);
END_ENTITY;

Entity IfcShaftBolt
	SUBTYPE OF (IfcShaftElement);
END_ENTITY;

Entity IfcShaftBaseSlab
SUBTYPE OF (IfcShaftElement);
END_ENTITY;

	Entity IfcConcreteShaftCollar
SUBTYPE OF (IfcShaftElement);
END_ENTITY;

Entity IfcShaftHorizVerRibLag
	SUBTYPE OF (IfcShaftElement);
END_ENTITY;

Entity IfcShaftWireMesh
	SUBTYPE OF (IfcShaftElement);
END_ENTITY;

Entity IfcTunnelVentilationElement
	SUBTYPE OF (IfcTunnelConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcTunnelSafetyElement
	SUBTYPE OF (IfcTunnelConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcTunnelExcavationElement
	SUBTYPE OF (IfcTunnelConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcTunnelLightingElement
	SUBTYPE OF (IfcTunnelConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcTunnelSurveyElement
	SUBTYPE OF (IfcTunnelConstrAuxiliaryComponent);
END_ENTITY;
```

```
Entity IfcShaftAccessToolElement
	SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcShaftCenteringElement
	SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcShaftDewateringElement
	SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcShaftExcavationElement
	SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcShaftHoistingElement
	SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcShaftLightingElement
	SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcShaftVentilationElement
	SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);
END_ENTITY;

Entity IfcShaftSafetyElement
	SUBTYPE OF (IfcShaftConstrAuxiliaryComponent);
END_ENTITY;

END_SCHEMA;
```

TIM Spatial Elements

```
SCHEMA TunnelSpatial;

ENTITY IfcSpatialStructureElement
	ABSTRACT SUPERTYPE OF (ONEOF(IfcUnderGroundStructureElement, IfcSpace, IfcBuildingStorey, IfcBuilding, IfcSite, IfcGround, IfcOnGroundStructureElement));
END_ENTITY;
```

```
Entity IfcSpace
	SUBTYPE OF (IfcSpatialStructureElement);
END_ENTITY;

ENTITY IfcBuildingStorey
	SUBTYPE OF (IfcSpatialStructureElement);
END_ENTITY;

ENTITY IfcBuilding
	SUBTYPE OF (IfcSpatialStructureElement);
END_ENTITY;

ENTITY IfcSite
	SUBTYPE OF (IfcSpatialStructureElement);
END_ENTITY;

ENTITY IfcGround
	ABSTRACT SUPERTYPE OF (ONE OF (IfcGroundCave))
	SUBTYPE OF (IfcSpatialStructureElement);
END_ENTITY;

ENTITY IfcGroundCave
	SUBTYPE OF (IfcGround);
END_ENTITY;

ENTITY IfcOnGroundStructureElement
	ABSTRACT SUPERTYPE OF (ONE OF (IfcStation,IfcPavement))
	SUBTYPE OF (IfcSpatialStructureElement);
END_ENTITY;

ENTITY IfcStation
	SUBTYPE OF (IfcOnGroundStructureElement);
END_ENTITY;

ENTITY IfcPavement
	SUBTYPE OF (IfcOnGroundStructureElement);
END_ENTITY;

Entity IfcUndergroundStructureElement
	ABSTRACT SUPERTYPE OF (ONE OF (IfcTunnelStructureElement))
	SUBTYPE OF (IfcSpatialStructureElement);
END_ENTITY;

Entity IfcTunnelStructureElement
```

```
        ABSTRACT SUPERTYPE OF (ONE OF (IfcTunnel, IfcTunnelPart,
IfcShaft, IfcShaftPart, IfcTailTunnel, IfcUndercut))
        SUBTYPE OF (IfcUndergroundStructureElement);
END_ENTITY;

ENTITY IfcTunnel
        SUBTYPE OF (IfcTunnelStructureElement);
        TunnelingMethodIndicator: IfcTunnelMethodIndicator;
        TunnelingLiningIndicator: IfcTunnelLiningIndicator;
        TBMMethodType: IfcTunnelBoringMachineType;
END_ENTITY;

TYPE IfcTunnelMethodIndicator = ENUMERATION OF (
        DRILL_BLAST,
        PARTIAL_FACE_HEADING_MACHINE,
        FULL_FACE_TUNNELING_MACHINE,
        CUT_COVER,
        SUBMERGED_TUBES);
END_TYPE;

TYPE IfcTunnelLiningIndicator = ENUMERATION OF(
        NATURAL,
        ROCK_REINFORCEMENT,
        SEGMENT_SUPPORT_CAST_IRON,
        STEEL_SET_OR_ROLLED_STEEL_JOIST,
        CAST_IN_PLACE_CONCRETE,
        SHOTCRETE,
        WOODEN_SUPPORT,
        RIB_LAGGING);
END_TYPE;

TYPE IfcTunnelBoringMachineType = ENUMERATION OF(
        OPEN_FACE,
        CLOSED_FACE_PRESSURIZED_AIR_IN_FRONT,
        CLOSED_FACE_SLURRY_SHIELD,
        CLOSED_FACE_EPB_SHIELD);
END_TYPE;

ENTITY IfcTunnelPart
        SUBTYPE OF (IfcTunnelStructureElement);
        TunnelPartSpotIndicator: IfcTunnelPartIndicator;
END_ENTITY;

TYPE IfcTunnelPartIndicator = ENUMERATION OF (
        STARTING,
```

```
        ENDING,
        MIDDLE,
        SERVICE_EXIT,
        USER_DEFINED,
        UNDEFINED);
END_TYPE;

ENTITY IfcShaft
  SUBTYPE OF (IfcTunnelStructureElement);
        InitialLiningExcavationType: IfcInitialShaftLiningType;
        FinalLiningExcavationType: IfcFinalShaftLiningType;
        ShapeType: IfcShaftShapeType;
        ServiceType: IfcShaftServiceType;
END_ENTITY;

TYPE IfcInitialShaftLiningType = ENUMERATION OF (
        SHEET_PILING,
        SOLDIER_PILES_LAGGING,
        LINER_PLATES,
        RIBS_AND_LAGGING,
        SLURRY_WALLS,
        CASSION_METHOD,
        CEMENTATION,
        FREEZING,
        SHAFT_DRILLING,
        SHAFT_BORING);
END_TYPE;

TYPE IfcFinalShaftLiningType = ENUMERATION OF (
        CONCRETE_SEGMENTS,
        ROCK_BOLTS_AND_WIRE_MESH);
END_TYPE;

TYPE IfcShaftShapeType = ENUMERATION OF (
        CIRCULAR,
        RECTANGULAR,
        USER_DEFINED);
END_TYPE;

TYPE IfcShaftServiceType = ENUMERATION OF (
        WORKING,
        RETRIEVAL_EXIT,
        USER_DEFINED,
        NOT_DEFINED);
END_TYPE;
```

```
ENTITY IfcShaftPart
        SUBTYPE OF (IfcTunnelStructureElement);
        ShaftPartSpotIndicator: IfcShaftPartIndicator;
END_ENTITY;

TYPE IfcShaftPartIndicator = ENUMERATION OF(
        SURFACE,
        BOTTOM,
        NOT_DEFINED);
END_TYPE;

ENTITY IfcTailTunnel
        SUBTYPE OF (IfcTunnelStructureElement);
END_ENTITY;

ENTITY IfcUndercut
        SUBTYPE OF (IfcTunnelStructureElement);
END_ENTITY;

END_SCHEMA;
```

TIM System Groups

```
SCHEMA TunnellingSystem;

ENTITY IfcSystem
        ABSTRACT SUPERTYPE OF (ONEOF (IfcElectricalCircut,
IfcStructuralAnalysisModel, IfcTunnelGroupSystem));
END_ENTITY;

ENTITY IfcElectricalCircut
        SUBTYPE OF (IfcSystem);
END_ENTITY;

ENTITY IfcStructuralAnalysisModel
        SUBTYPE OF (IfcSystem);
END_ENTITY;

ENTITY IfcTunnelGroupSystem
        ABSTRACT SUPERTYPE OF (ONEOF (IfcTunnelSystem,
IfcShaftSystem))
        SUBTYPE OF (IfcSystem);
END_ENTITY;
```

```
Entity IfcTunnelSystem
	ABSTRACT SUPERTYPE OF (ONEOF (IfcTunnelLiningSystem,
IfcTunnelServiceSystem, IfcTunnelExcavatingSystem))
	SUBTYPE OF (IfcTunnelGroupSystem);
END_Entity;

Entity IfcShaftSystem
	ABSTRACT SUPERTYPE OF (ONEOF (IfcShaftLiningSystem,
IfcShaftExcavatingSystem))
	SUBTYPE OF (IfcTunnelGroupSystem);
END_Entity;

Entity IfcTunnelLiningSystem
	SUBTYPE OF (IfcTunnelSystem);
END_ENTITY;

Entity IfcTunnelServiceSystem
	SUBTYPE OF (IfcTunnelSystem);
END_ENTITY;

Entity IfcTunnelExcavatingSystem
	SUBTYPE OF (IfcTunnelSystem);
END_ENTITY;

Entity IfcShaftLiningSystem
	SUBTYPE OF (IfcShaftSystem);
END_ENTITY;

Entity IfcShaftExcavatingSystem
	SUBTYPE OF (IfcShaftSystem);
END_ENTITY;

END_SCHEMA;
```