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An Integrated Multi-Dimensional Information Model Framework for Tunneling Projects Using IFC Data Model

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Abstract: This study utilizes the extension capability of the current Industry Foundation Class (IFC) standard 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 extended classes, along with existing IFC classes, form a Tunnel Information Modeling (TIM) system, which intends to form a data model structure for tunneling construction projects. Similar to the vastly extended Building Information Modeling (BIM) phenomena in the building sector of the Architecture/Engineering/Construction (AEC) industry, the proposed TIM model offers a multi-dimensional modeling procedure to develop an integrated project system. The integrated project system provides a control medium for project managers during planning and construction processes. The resulting TIM system demonstrates a framework for generating the TIM classes and presenting their use to supply seamless interoperability among tunnel project participants and applications. This objective is fulfilled by adding new classes to the current IFC 2x3 data model, and also taking advantage of the property set objects offered in the original IFC data model, which helps to promote cost and schedule properties of the tunnel entities. Consequently, the scattered information packages can be incorporated into a single three-dimensional (3D) data model to support decision making and address lack of interoperability in the tunneling process. The resulting framework can be used as the primary component for developing an object-oriented application interface.

1 Introduction

The congested network of routes in today's big cities necessitates focusing on efficient usage of the available area and 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. Tunnel projects are associated with higher risks during project lifespan compared to other civil engineering projects (Thomas and Banyai, 2007). Higher demands, modern techniques, and extra complexity in tunneling projects contribute to challenges in the management process (Reilly, 2000). Meanwhile, new construction techniques necessitate dealing with an overwhelming amount of information and require close collaboration among multiple professional teams to analyze and interpret the data throughout the project lifespan.

A robust medium to deal with the great amount of information is information systems. Information systems provide unbounded structured frameworks to capture, store, and recall information. Case-Base Reasoning (CBR), data warehousing techniques, and anthologies for cost estimation are examples of efforts to develop structured information in construction projects to enhance the decision-making process (Lee et al., 2009). In this regard, collaboration among different participants to employ and assess the data is a substantial factor to successfully implementation of the tunneling process. The project participants, from dissociated disciplines, employ robust software applications to implement specific fragments of the tunneling design and management. The results of these processes must be combined and interpreted to present a pragmatic background for the decision making process. Despite the great advantages of Information Technology (IT) tools in AEC industry, the incompatibility of standalone applications along with inefficient information flow between project participants causes cost/time overruns (Halfawy and Froese, 2005). Lack of integration and collaboration between a project's down streams necessitates duplicating information to implement the isolated project processes.

An IT collaborative working environment promotes information sharing and compensates for the information gaps among distributed project participants. According to Xue et al. (2012), the collaborative Integrated Inter-organizational Management Information Systems (IIMIS) facilitates management of project information throughout a project’s lifecycle. Data transfer among project parties is the most important enabler in IIMIS systems. Consistency of data format and data structure plays a prominent role in performing successful data transfer between project segments. Seeking standard data models can help to achieve a universal product model. Utilizing this unique product model in the tunneling sub-processes will enhance interoperability among heterogeneous computer applications, and therefore, promote effective collaboration among project parties.

2 Integrated Project Systems - Potentials via Interoperable Solutions for Tunneling Projects

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 as 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 and relationship in/between different components of the model (Howell and Batcheler, 2005). Building Information Modeling (BIM) concept is the latest interpretation of object-oriented notion in the building area of the AEC industry.

Infrastructure projects consist of heterogeneous data sources and applications performed by an 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 the project lifecycle (Froese, 2003). Recent developments in Information and Communication Technology (ICT) in the construction industry encouraged using three-dimensional and visualization technologies to improve integration of project information in a single database or project view. Multi-dimensional (nD) project models offer a collaborative environment to incorporate diverse information in a single project model based on a universal data model which can be easily recognized by all project parties. Multi-dimensional project models are based on 3D models with added information packages such as cost, schedule, resource, logistics, assets and quality. nD models proved to be capable of improving interoperability among project parties and applications (Ding et al., 2012).

According to Kymmel (2008), in general construction projects, the efforts to generate integrated project systems have produced significant improvements in capturing and processing project data, and as a result, new collaborative solutions such as BIM emerged. 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 that helped the participating parties to incorporate diverse information and create an integrated project model. BIM represents multiple dimensions of a real project by incorporating project data in a single project database (Graphisoft, 2003).

Successful implementation of integrated project systems is enabled by establishing interoperability among disparate data and software applications across project departments (Halfawy, 2010). Eastman et al. (2008) defined interoperability as a catalyst for a collaborative work environment, which plays a prominent role in establishing data exchanges between applications, eliminates the need to replicate data input, and facilitates workflow and automation among contributing project segments. A study conducted by the Turkish construction industry showed that most of the construction phase problems stem from the lack of interaction and communication between project participants (Ding et al., 2012). Tunnel projects are not an exception in this regard; project results are affected by lack of interoperability.

In an integrated project model, data exchange and seamless interoperability is not possible with traditional ad-hoc methods (i.e., paper-based drawings, file-based documents, proprietary translators). The conventional methods are usually associated with a great amount of "non-value adding activities" and the risk of information inaccuracy and loss. A standard information structure assists in achieving interoperability between project participants. A dominant standard data structure requires a neutral file format to exchange information and address the interoperability issue effectively (Eastman et al., 2008). Industry Foundation Classes (IFC), the mainstream data architecture of BIM technology, has significantly contributed to information interactions in building construction projects. The IFC standard is a neutral data format developed by the International Alliance for Interoperability (IAI) around two decades ago to introduce a standard project data model for building construction projects. It has become the most common data format for exchanging BIM information. IFC supports multiple domains and plenty of software vendors support IFC data structure (BuildingSMART, 2011).

There is a significant lag in employing standardized product models in civil infrastructures, compared to building construction projects (Yabuki, 2010). Lack of an official standardized product model is the most important barrier to adopting integrated project systems for civil infrastructure projects. The IFC data model does not provide specific classes, in particular, for tunnel construction projects, to capture the infrastructure project data (Froese, 2003). 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 proposed by Yabuki and Shitani (2003) for a prestressed concrete bridge, as an extension of the IFC data model. Further, multi-agent systems were developed to support the design process in the CAD system. The collection of multi-agents, prestressed 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 proposed by the IAI French Chapter. Finally, a combination of the J-IFC-Bridge and French bridge product models, called IFC-Bridge, was developed in collaboration with IAI (Yabuki and Li, 2006). Ji et al. (2011) proposed an object-oriented data model to capture parametric design of bridge geometry to improve the IFC-Bridge data model. Furthermore, according to Yabuki (2008), an IFC-based product model for tunneling projects is under development. Hegemann et al. (2012) defined new IFC classes to model specific classes for earth pressure balance (EPB) tunnel boring machines (TBM). Moreover, Lee et al. (2009) developed a 3D-based information model for road structures by extending the existing IFC classes. However, the information system includes only a general representation of the tunnel components and falls short in covering the properties associated with various segments of the tunnel structure. Ding et al. (2012) developed an information management system for a city rail transit system in China. This study is focused on a proprietary nD development process based on the Chinese information exchange procedure among project parties and falls short in adopting a standardized product model. Hence, the resulting process is solely effective in China or other construction communities with similar common data exchange practices.

Based on the aforementioned reviews, the proposed framework in this study aims at providing a step-by-step procedure, firstly, to form an integrated tunnel information system, and secondly, to extend the existing IFC standard to cover tunnel-specific elements and properties. The existing classes in the current IFC architecture provide a platform for adding new domain-specific classes. A Tunnel Information Modeling (TIM) framework is proposed in this study which aims at enhancing the information exchanges among dissociated segments of the project management process by creating an integrated project model. TIM is an abstraction of the BIM concept in the tunneling construction projects domain. The scope of this study is initially to establish a framework to define the TIM system architecture, and then to introduce a hierarchical framework to drive and implement a standard data model based on the official IFC data model, rather than introducing a final applicable IFC data model for tunneling projects. The proposed step-by-step procedure to form the extended classes, called TIM-IFC classes, assists to cover all the information and avoid jeopardizing the integration process in a typical tunnel project. The resulting framework can be used in future works to form an integrated tunnel project model and acts as the primary component for developing an object-oriented application interface. The proposed TIM-IFC classes in this study were developed by adding new classes to the IFC 2x3 data structure and employing property set objects. Therefore, by implementing the resulting tunnel information model, lack of interoperability and integration in tunneling projects can be addressed. The integrated project system is presented with a 3D tunnel model incorporated with project information. Each 3D component is associated with a set of TIM classes defined in the tunnel information model.

3 Tunnel Information Modeling System (TIM)

TIM concept was first introduced by Zhang et al. (2010) as an integrated project system to support the distributed simulation environment for tunneling projects. The proposed system incorporated 3D modeling and process simulation to achieve a higher semantics in visualizing the actual processes in the project environment. Although the TIM system proposed in this paper is similar to the one introduced by Zhang et al. (2010), it concentrates on enriching a comprehensive framework for a multi-dimensional tunnel model and encapsulating the project data in an integrated system to facilitate management processes. In other words, it intends to identify the key requirements to provide a non-proprietary framework which could be used to develop an information model for a typical tunnel project.

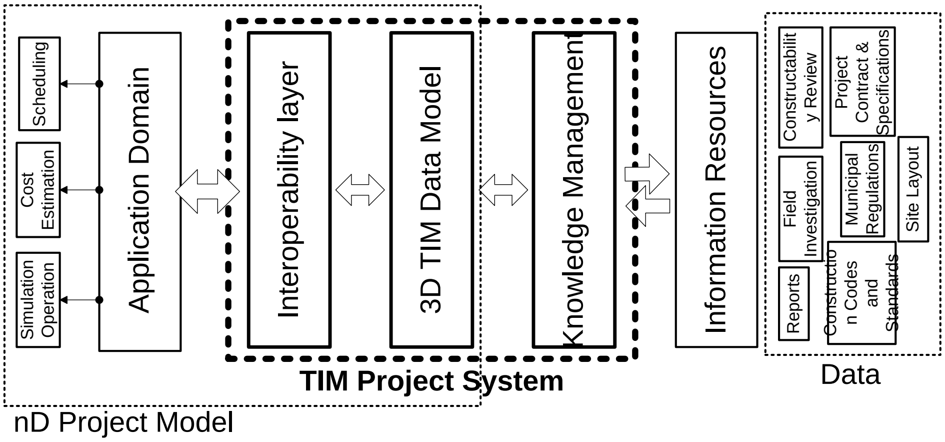


Figure 1: TIM system architecture

TIM project system is an integrated project model facilitating efficient cooperation between management processes. It consists of three major tiers: a multi-dimensional object-oriented project model, knowledge management services, and interoperability layer. Figure 1 shows the architecture of the TIM project system. The nD project model consists of a core intelligent 3D object-oriented model representing shape, geometry, and coordination of the tunnel elements. The 3D model also includes project meta data (i.e., time, cost, quality, resources) which is used to enrich the tunnel object models. Multiple resources may contribute to the nD model. The knowledge management layer consists of tools to store, modify, and record the information, history of transactions, and modifications. 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 contributing to the project. The TIM-IFC model allows the tunnel information to be operated and viewed in any specific domain used by different participants. Therefore, the standard structure assists in exchanging data with a wide range of management application tools. Exchanges and communications with function-specific tools would add extra dimension to the 3D model and assist in creation of a central nD project model environment. Hence, TIM-IFC model exploits new insights for an efficient definition of tunnel information which otherwise would be lost, misinterpreted, or redundantly stated multiple times in different contexts. Designers and project managers can use their own application. However, they no longer need to reconstruct the model from scratch, since the information added to their model can be transferred and shown in other applications using the unified TIM-IFC semantics. In the following sections, first the possibility of creating tunnel-specific classes is studied, and then the proposed framework to develop such classes is described. Meanwhile, the implementation process is described for a TBM rail tunnel project.

4 TIM Interoperability Enabler

4.1 IFC Origin, Architecture and Extension Potential

Until the mid-1980s, various file formats were used to exchange design and construction information in all engineering domains (i.e., DXF, IGES). Generally, application providers prefer direct linking to prevent consumers from switching to their competitors. Direct linking employs the Application Programming Interface (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 specifically for an application. This proprietary format functions as an interface to represent the data model in its corresponding application. However, the most desirable form of exchange is via public formats. The International Standard Organization (ISO) initiated a TC184 committee to develop STEP (Standard for the Exchange of Product Model Data) (Halfawy et al., 2006). 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 (for steel), AP225, and AP241. However, only IFC and CIS/2 are recognized as international public standards today. IFC has become de-facto in the AEC industry to exchange building information between participating applications and platforms (Eastman et al., 2008).

The architecture of the IFC data model consists of four conceptual layers: core layer (Kernel), domain/application layer, interoperability layer, and resource layer. The IFC kernel provides independent information objects which 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 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 defining new extended classes (Weise et al., 2000). IFC standard offers a generalized definition for project information, and therefore, specific use case scenarios could be defined to include a particular project workflow (Eastman et al., 2008). EXPRESS-G is the visual representation of the EXPRESS language and is frequently used to show the hierarchal distribution of 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 directly related information, useful for implementing 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 general description provides the project participants with a unique representation of the tunnel project and eventually prevents different portrayals of the actual project boundaries. 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 while it is possible to reach that information directly by importing the required cost information already generated in the 3D TIM model.

4.2 TIM- IFC Development phases

The tunnel construction process involves technical and usually complex work packages which 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, shown in Table 1, 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 Science.

Table 1: TIM-IFC development 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

The methodology to develop the TIM-IFC classes as an extension of the original IFC classes is composed of two major parts. The first part is generating a conceptual product model consisting of all geometric and non-geometric components of the tunnel and its environment. 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. Required information objects which build the tunnel product model can be identified by organizing and documenting ongoing processes, required resources, participating actors, and finally the embedded relationship among them. This tunnel information is gathered based on a comprehensive investigation in previous studies and field documents of tunnel projects. 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 which are significantly hard to handle and implement. The resulting conceptual tunnel product model is presented in Table 2.

Table 2: Conceptual tunnel product model

Physical and Spatial Elements	Processes	Resources	Knowledge	Measure Data
Shaft Shaft section Tail tunnel Tunnel Undercut Borehole Ground and underground barriers Primary liner Secondary liner Soil layer in borehole Temporary structures	Tunnel excavation Tunnel lining Shaft excavation Shaft lining Geographic survey Pre-design studies Ground stabilization TBM installation TBM removal Temporary structure removal	Labour Equipment Material	Material type Site layout Contract documents Construction method Equipment specification Site topography Plans and drawings	Cost data Scheduling data

In the second part of the TIM-IFC development, creating the Process Map (PM) assists in identifying the processes, responsible parties, and information flow through different stages of the tunnel project. A PM for tunneling projects is composed of different business processes and project phases. It also represents the general work flow in a typical tunneling project utilizing the TIM concept. A comprehensive PM is shown in Figure 2, which illustrates all the undergoing processes and actors from pre-design phase through the construction phase. However, only the management processes during the design process are studied in this work. The requirements of each task, known as Exchange Requirements (ER), need to be captured and stored. Documentation of these exchange requirements assists in understanding and providing people/organization/application needs. Moreover, according to Lee et al. (2009) informal requirements are collected by the model developer based on common terms of 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 relationship. The next step would be the creation of Model View Definitions (MVD) for tunneling elements. These views specify the information that need to be exchanged and the IFC entities that need to be involved in the MVD structure. MVDs are comparable only if they follow a particular pattern which also makes the future developments feasible for new elements or modifications. The particular pattern defines a basic structure for view definitions to have a comparable data set. A pattern of MVD for tunnel elements is composed of different classes to include attributes, kind of material, covering, geometry, and connection to other tunnel elements. Figure 3 shows the general pattern of the common MVD for tunnel components. Documenting the resulting TIM-IFC model schema helps to define the hierarchical sequence of IFC entities and clarify the associated relationships.

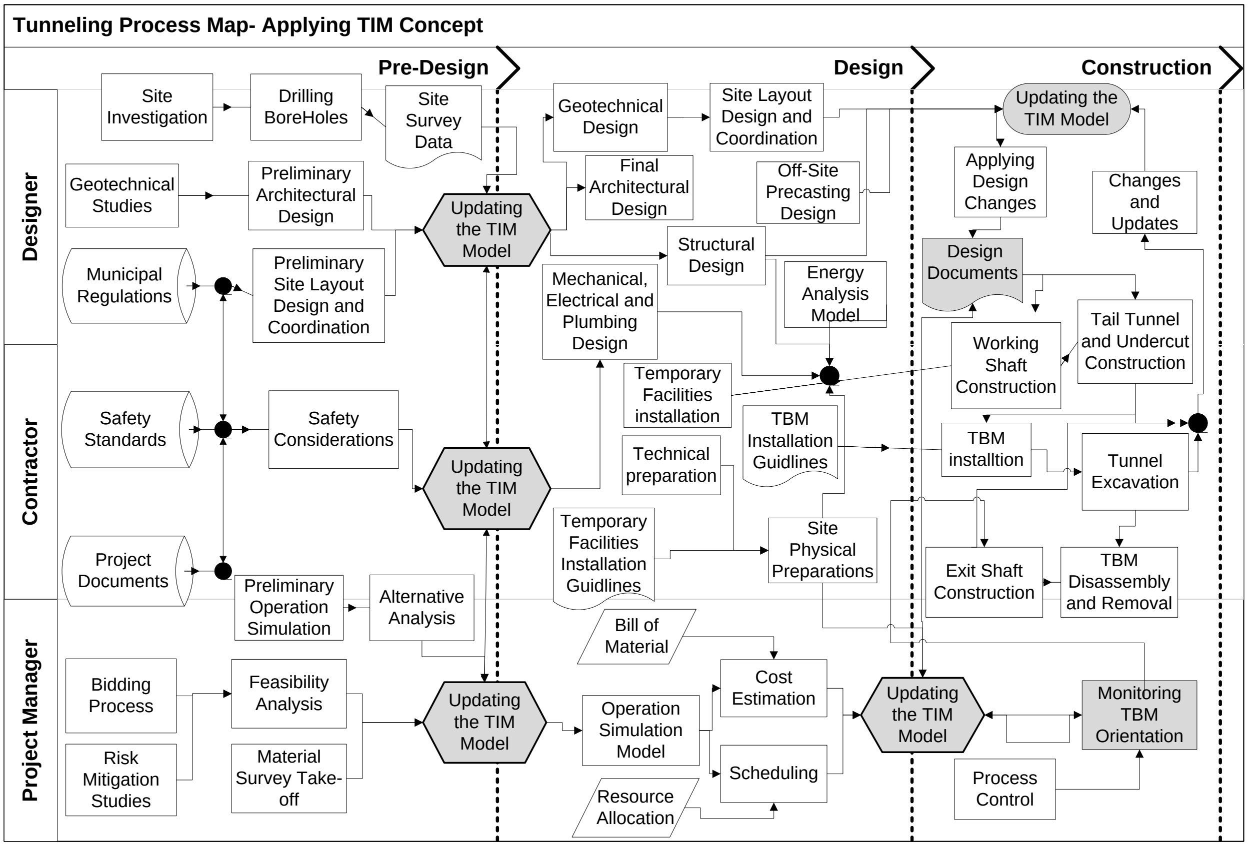


Figure 2: A process map for tunneling project from preliminary design to construction completion

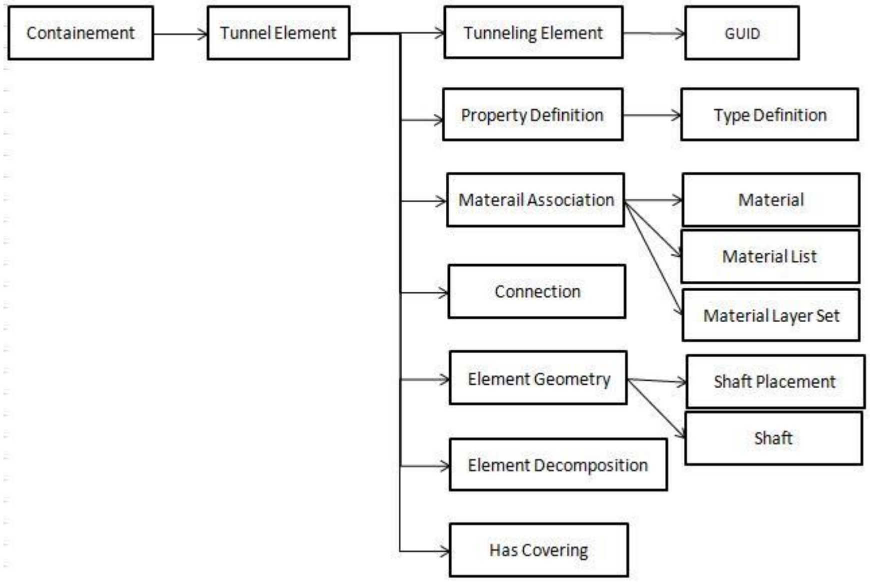
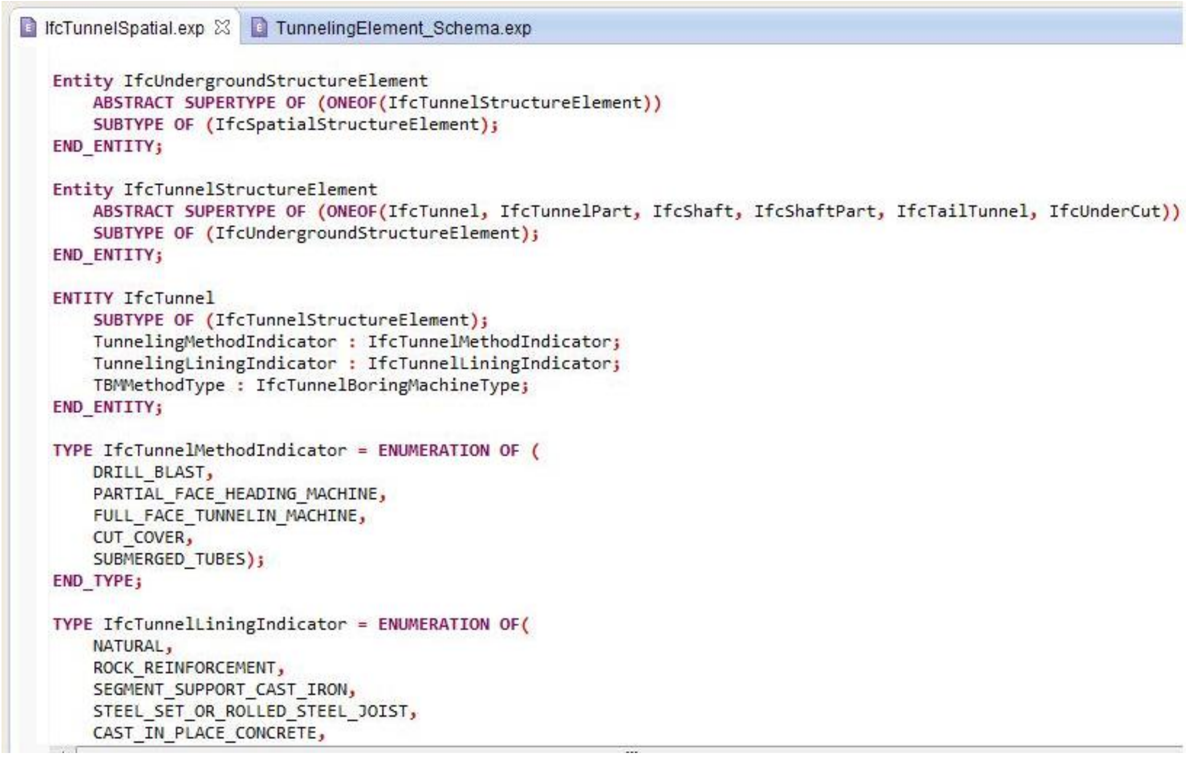


Figure 3: Common model view definition pattern for tunnel elements

In order to extend the original IFC 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). JSDAI is an open source API to work with EXPRESS data models. This platform provides an environment to define the TIM-IFC classes. These classes are then presented by EXPRESS-G diagram in the EXG layout.



```
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,
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Figure 4: Implementing in JSDAI for Eclipse platform

The tunnel components are divided into subparts and smaller units for a better breakdown of multiple related data. For instance, the mass of the general tunnel may divide into shorter segments in length (Figure 5). Furthermore, such division into smaller parts helps to imitate the actual exploitation of the tunnel boring and lining processes which additionally contributes to better handling of information for the intended segments.

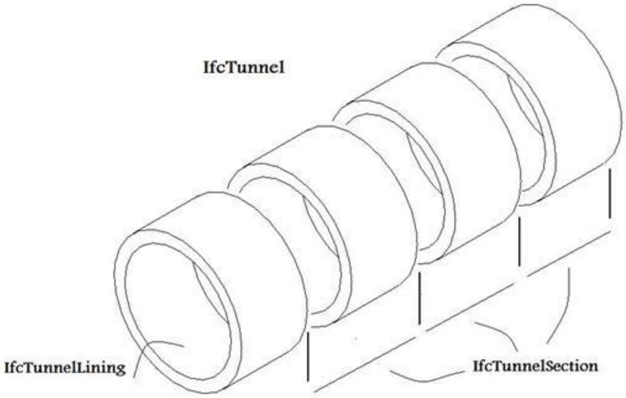

Figure 5: Division of the main tunnel and related IFC classes

The TIM-IFC entities are divided into 2 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 IfcRelSpatialToPhysical entity. 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 IfcRelNests and IfcRelGroup 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**.** The subtypes of the IfcRepresentation entity are the medium for defining the geometric and topological representation of the tunnel components. A part of the extended TIM-IFC classes for the IfcSpatialStructureElemet are shown in Figure 6.

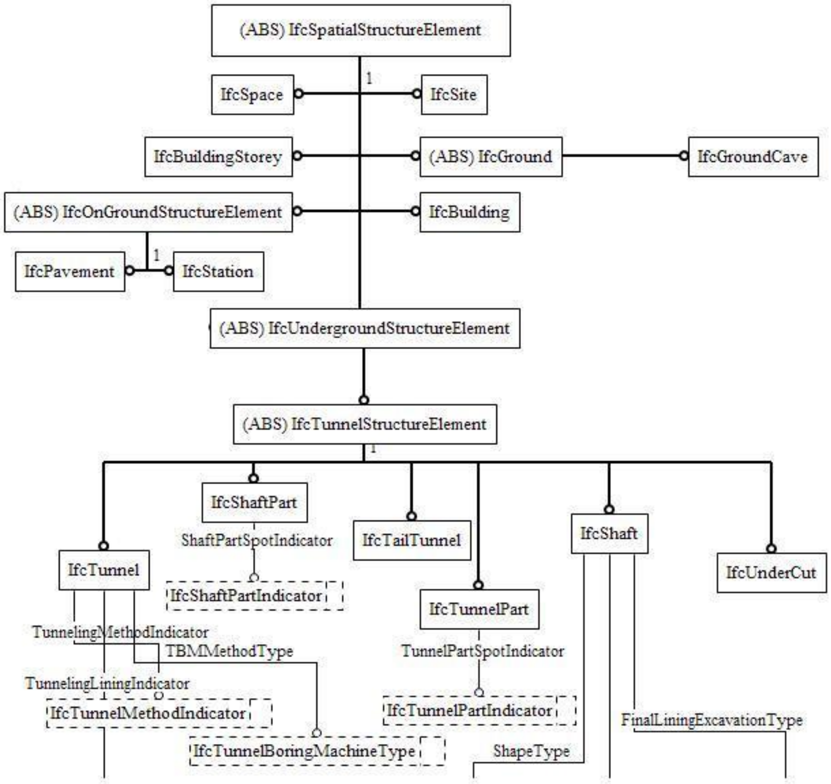

Figure 6: Part of the EXPRESS-G representation for IfcSpatialStructureElement

The implementation of the resulting TIM-IFC data model includes employing the extended IFC definitions to facilitate importing and exporting 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 convertor which 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 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 convertor 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 which 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 7).

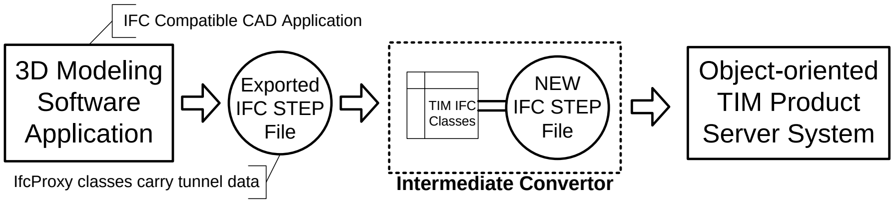

Figure 7: Using the TIM-IFC data model

5 Summary and Conclusion

The aim of this paper was to provide a framework to extend and apply the IFC standard data model to tunneling construction projects with the incentive of obtaining a unique standard structure to describe information packages in tunnel projects. As one of the major civil infrastructures, tunnel construction projects are a potential target for adopting collaborative project solutions. 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 and ultimately eliminates the data and domain fragmentation during 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 other than merely building structures. However, tunneling specific classes have not been considered in the IFC data model structure. In this paper, the potentials of IFC data model to generate tunnel-specific classes were examined and the hierarchical step-by-step framework was described. First, the general concept of the TIM modeling system and its embedded architecture was described. Then, the original IFC structure and its extension potentials were studied. Finally, the proposed framework to develop the TIM-IFC classes, as the extension of the original IFC 2x Extension 3, was presented.

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