Tunnelling and Underground Space Technology 143 (2024) 105368

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

IFC concepts in the execution phase of conventional tunneling projects

Marco Huymajer [a,*], Galina Paskaleva [b], Robert Wenighofer [a], Christian Huemer [b], Alexandra Mazak-Huemer [c]

[a] Chair of Subsurface Engineering, Montanuniversität Leoben, Erzherzog-Johann-Straße 3/III, Leoben, 8700, Austria
[b] Research Unit of Business Informatics, TU Wien, Favoritenstraße 9, Vienna, 1040, Austria
[c] Department of Business Informatics – Software Engineering, Johannes Kepler University Linz, Altenberger Straße 69, Linz, 4040, Austria

ARTICLE INFO

Keywords:
BIM
IFC
Tunneling
Construction phase
Process
Labor
Equipment
Material
Digitalization

ABSTRACT

The documentation process of conventional tunneling projects is time-consuming and costly. Building Information Modeling (BIM) has enabled substantial productivity gains in the Architecture, Engineering, & Construction (AEC) sector. However, BIM has only been marginally adopted in the execution phase of conventional tunneling projects. For this purpose, we propose a BIM model that facilitates fully digital and automated data exchange between project stakeholders. We use the Industry Foundation Classes (IFC) as a basis and identify concepts potentially useful to represent data from the execution phase of construction projects. We demonstrate how IFC concepts are utilized to represent a shift report of a conventional tunneling project. Thereby, we deliver a reference model as an implementation guide for software developers in this domain. This may serve as a blueprint for handling construction management data in a machine-readable format, laying the foundations for Big Open BIM in the execution phase of construction projects.

1. Introduction

In conventional tunneling, process efficiency has a high impact due to the overall volume of the market. The International Tunnelling and Underground Space Association (ITA) reported investments of € 125 billion in tunneling projects worldwide in 2019 (ITA, 2019). On average, 5200 km of tunnels are constructed annually. Although there is a trend toward off-site construction in general and specifically toward mechanized methods in tunneling, there is unquestionably a continuing demand for tunneling projects employing the conventional tunneling method.

Here, we explicitly focus on the execution phase, which involves much work documenting costs, progress, quality, and safety. The resulting documents are typically exchanged among different departments within the contractor company, and a subset of data is shared with the project owner or the construction supervisor. The data exchange of today's tunneling projects still heavily relies on paper-based documents or the exchange of unstructured digital data or proprietary data formats (Kvasina, 2018; Sabanovic et al., 2022; Sharafat et al., 2021). Such solutions are cost-intensive and time-consuming because they are not machine-readable and hinder the seamless data flow between stakeholders. Another drawback is the time delay between the generation of the data and its subsequent processing, which complicates the management of tunneling projects.

An efficient data flow is relevant both within the company infrastructure of the contractor and for the information exchange between the contractor, supervisor, project owner, and other involved parties. The exchanged information includes, among others, data on the process, labor, equipment, and material.

This data must be expressed in an international open standard to achieve interoperability. The Industry Foundation Classes (IFC) is the most commonly adopted open Building Information Modeling (BIM) standard in multiple subdomains of the Architecture, Engineering, & Construction (AEC) sector (Jiang et al., 2019). IFC serves as a machine-readable, semantically rich, and vendor-neutral data exchange format. Our main objective is to demonstrate that IFC can be applied to the execution phase of a conventional tunneling project.

Since the IFC data model is very flexible, the same semantics can be expressed by different IFC constructs, causing interoperability issues. Therefore, we propose an implementation guide showing how to express domain concepts by a specific subset of IFC constructs. This implementation guideline is meant to help software solution providers to develop interoperable tools for conventional tunneling. Implementation guides are a well-established approach in business data exchanges based on standards such as UN/EDIFACT published by the United Nations Center for Trade Facilitation and e-Business[1] (UN/CEFACT).

---

* Corresponding author.
E-mail addresses: marco.huymajer@unileoben.ac.at (M. Huymajer), christian.huemer@tuwien.ac.at (C. Huemer).

[1] https://unece.org

https://doi.org/10.1016/j.tust.2023.105368
Received 30 January 2023; Received in revised form 5 August 2023; Accepted 15 August 2023

In this paper, we propose an IFC model allowing fully automated data exchange in the execution phase of tunneling projects. Although we focus on data originating from conventional tunnel drives, the model was left sufficiently generic by design to be easily employed in different contexts.

The remainder of the paper is structured as follows: A brief overview of related work is compiled in Section 2. Section 3 touches upon the contractual foundation of executing conventional tunneling projects and introduces the shift report as the key document in such projects. IFC concepts potentially suitable to digitally represent the shift report are discussed in Section 4. Section 5 presents a reference model for a digital counterpart of a shift report based on a simplified example. Section 6 discusses our lessons learned, and Section 7 concludes this paper.

2. Related work

Rothenberg (1989) defines a model as a simplified representation of the reality of an intended purpose and modeling as the process of developing and using a model. This representation could be a verbal description, a diagram, a mathematical equation, or a technical drawing. BIM can be seen as a particular manifestation of modeling, which, in line with other AEC subdomains, is increasingly discussed within the tunneling community (Huang et al., 2021). In this article, we follow the concept of BIM as an activity rather than an object (Eastman et al., 2011; Borrmann et al., 2021). Possible applications of BIM in tunneling range from predicting the settlement risk due to tunnel construction (Providakis et al., 2019) to the maintenance management of utility tunnels (Lee et al., 2018).

To overcome the shortcomings of file-based BIM data exchange, Afsari et al. (2016b) proposed a web-based data exchange mechanism for BIM applications. Compared to conventional exchange methods, this has the advantage that the data consumer can initiate a data exchange in real time. Therefore, the receiver manages the data requests, and an intermediate, file-based integration technology becomes optional. The authors suggest the Hypertext Transfer Protocol (HTTP) and IFC or JavaScript Object Notation (JSON) as data serialization formats. A specific protocol and serialization format allows two parties to exchange data more efficiently. However, to have an unambiguous understanding of the data between two parties, the data must be based on a common data model such as IFC.

IFC is a data model for the AEC sector maintained by buildingSMART International[2] (bSI) and has been broadly discussed as a suitable approach to exchange semantically rich design data of buildings (Borrmann et al., 2021; Jiang et al., 2019). The International Organization for Standardization (ISO) has approved IFC Version 4 as the standard ISO 16739 (ISO, 2013). In many countries, including Norway, Finland, and Spain, state-owned agencies mandate IFC for data exchange (Panteli et al., 2020). Afsari et al. (2016a) consider IFC the most suitable file format for interoperable cloud-based BIM.

IFC is based on the Standard for the Exchange of Product model data (STEP) and uses EXPRESS as a data modeling language for its schema definition (Anderl and Trippner, 2000). The most common serialization format for a STEP model is the STEP Physical File Format (SPFF), which has been approved as ISO 10303-21 (ISO, 2016). Apart from SPFF, other serialization formats, such as ifcXML, ifcOWL, and ifcJSON, have been proposed for IFC models (Shelden et al., 2020). In addition, using linked data and mapping IFC to Resource Description Framework (RDF) was identified as a possibility to cope with interoperability issues in a cross-domain setting (Shelden et al., 2020; Curry et al., 2013). IFC was initially conceived as a file-based approach to data exchange. However, bSI acknowledged the necessity for a standardized application programming interface (API) to allow dynamic object-based queries on IFC data (bSI, 2020b; van Berlo et al., 2021).

The IFC data model has a modular structure. Its root lies in the IFC core module, which houses the most generic elements. IFC's capabilities to model cost and scheduling information are part of the `IfcProcessExtension` module. Version 1.0. of the IFC specification includes the `IfcWorkTask` entity, which was later renamed to `IfcTask`. The process-related semantics were extended by introducing `IfcProcedure` with version 2 × 2 (bSI, 1999) and `IfcEvent` with version 4 (bSI, 2021). Multiple authors discussed `IfcProcessExtension` in the context of project management. By modeling a simple test case scenario, Froese et al. (1999) confirmed the ability of IFC to capture project management data. Xue et al. (2015) extended the IFC data model by different entities intending to use IFC for construction schedule management. Yang et al. (2021) showed that IFC is viable for capturing construction management information on prefabricated buildings. Furthermore, IFC defines entities and types representing employed resources, such as labor (`IfcLaborResource`), construction equipment (`IfcConstructionEquipmentResource`), and materials (`IfcConstructionMaterialResource`). In summary, IFC gives comprehensive support for process-related concepts. Nevertheless, there seems to be no commercially available software using those concepts. Apart from that, no publication addresses conventional tunneling projects' specifics employing those concepts.

Other domains adopted their standards for exchanging information related to processes, including standards based on ISA-95 popular in manufacturing (IEC, 2013a,b). Regateiro and Spínola (2014) analyzed BIM in Portuguese public works contracts and identified IFC entities as presumably valuable during the cost estimation.

Our research effort consists of applying IFC-based modeling techniques to tunnel construction. In tunnel construction, we distinguish between conventional tunneling (also called the cyclic method) and mechanized tunneling (also called the continuous method) (Girmscheid, 2013; Maidl et al., 2013). A particular variety of the former method, which allows a certain amount of rock deformation and uses shotcrete as a support measure, is called the New Austrian Tunneling Method (NATM). Using explosives for excavation is often referred to as drill and blast tunneling. Despite the growing importance of mechanized tunneling, NATM plays a crucial role in tunnel construction due to its high flexibility. However, Kvasina et al. (2018) showed that the documentation process of NATM tunneling is complex. For this reason, this process harbors a high potential for saving both costs and time by transitioning out of the paper-based data exchange and into the fully automated digital one.

Different IFC extensions for the tunnel design have been proposed covering both conventional (Lee et al., 2016; Sharafat et al., 2021; Huang et al., 2022) and mechanized tunneling (Yabuki, 2008; Hegemann et al., 2012; Jubierre and Borrmann, 2014; Yabuki et al., 2013; Vilgertshofer et al., 2016). Sharafat et al. (2021) proposed a model to capture different aspects of drill and blast tunnels. However, their proposal seems hardly aligned with IFC concepts, and it appears challenging to extend to other excavation methods like excavation with roadheaders. Despite the high number of suggestions for tunneling-specific IFC extensions, official support is not expected to be included before version 4.4 of the standard. As of today, only the final draft of the IFC-Tunnel "Requirements Analysis Report" (bSI, 2020a) is available.

Only a few studies have reported on using IFC in the execution phase of tunneling projects. Lensing (2016) serialized data from a tunnel boring machine (TBM) process into JSON to compare data with a BIM model. Consolidated digital documentation and straightforward data exchange have been identified by Winkler et al. (2022) as the cornerstones of digital invoicing for NATM projects. Huymajer et al. (2022a) presented an architecture and a data model of a Tunneling Information Management System (TIMS) capable of capturing invoicing-relevant information about conventional tunnels. Similarly, Sabanovic

---

[2] https://buildingsmart.org/

et al. (2022) reported on a prototype of a data entry tool for mobile devices employed at conventional tunnel drives.

Tunneling is closely linked to other domains, such as geology, hydrogeology, and geotechnical engineering, supported by multiple standards. Examples are GeoSciML (OGC, 2022a) and WaterML (OGC, 2022b), published by the Open Geospatial Consortium (OGC).

3. Documenting the conventional tunneling process

In this section, we outline the documentation process of conventional tunneling projects. The documentation of such projects includes many aspects common to construction projects in general. Nevertheless, tunneling exhibits some peculiarities compared to other construction domains, which are reflected in the documentation accordingly. One peculiarity is the inherent uncertainty of the subsurface physical conditions, such as geology and hydrology. Another one is the extensive use of structural elements, which are not part of the final tunnel but serve as temporary support measures and are removed during a subsequent excavation step. These peculiarities affect the documentation process and have contractual implications, as discussed in the following.

3.1. Contractual foundation

There are two significant contractual aspects affecting the documentation of conventional tunneling projects. The first aspect is that the documentation serves as the basis for the remuneration of the contractor's work. In this case, tunneling documentation heavily depends on the type of contracts, such as lump sum and unit price contracts. The contracts differ regarding ground-related risk due to unforeseeable ground conditions. The International Federation of Consulting Engineers (FIDIC) issued a contractual guidance document (FIDIC, 2019c) in an attempt to harmonize various contracts. The amount of ground support depends on the changing ground conditions, thus affecting the completion time and associated time-related costs. Implementing a unit price contract for construction measures is acknowledged to support the management of such risks (ITA, 2021). Additionally, the FIDIC advises using unit price contracts for quantity-related support measures to reimburse the amount of ground support appropriately. Therefore, adequately detailed documentation of quantity-related support measures is necessary for invoicing those tunneling projects (FIDIC, 2019b). In addition to this relatively new international standard of FIDIC, there are various local standards. For example, the contractor's remuneration in Austria is governed by the standards ÖNORM B 2118 (Austrian Standards, 2021) and B 2203-1 (Austrian Standards, 2001), which are agreed on in the contract. The remuneration model, both the FIDIC and Austrian Standards International, require appropriately detailed documentation of constructional service.

The second contractual aspect is that the building contract can mandate employing BIM during the construction phase. Despite the evident requirement of a digital document exchange, there are additional constraints, frequently stated in two documents, the so-called Employer's Information Requirements (EIR) and the BIM Execution Plan (BEP) (Borrmann et al., 2021; Daller et al., 2016). These two documents are typically part of the building contract and contain detailed specifications on when, how, and what exact information to exchange.

3.2. Status quo

This subsection discusses the state-of-the-art documentation in conventional tunneling construction sites. We illustrate this in the use case of a shift report, the information of which is of paramount importance in the execution phase of conventional tunneling projects. Fig. 1 shows a shift report of a conventional tunneling project. The following main information categories can be identified in the figure: (i) information about the process, including the exact time of each task, shown in blue ●; (ii) information about the labor, including the role of each person during the shift, shown in turquoise ●; (iii) information about the employed equipment, such as wheel loaders, etc., shown in purple ●; (iv) information about consumed materials, including support measures and explosives, shown in red ●; and (v) general information, such as the tunnel section, date, approvals, etc., shown in gray ●.

Depending on the contractor and the project, the shift report might be named differently, e.g., excavation report (Winkler et al., 2022), or the document could be structured differently. The data could also be spread over multiple documents, possibly in a more detailed form, such as support logs, round sheets, and daily diagrams. The information is used in different business units within the contractor, and a subset of the information is shared with the project owner (Kvasina, 2018). The information flow is often accomplished by exchanging scanned documents or spreadsheet tables, requiring considerable manual work. Therefore, an exchange method that allows for automated data processing is desirable.

3.3. Features of a BIM-based data exchange

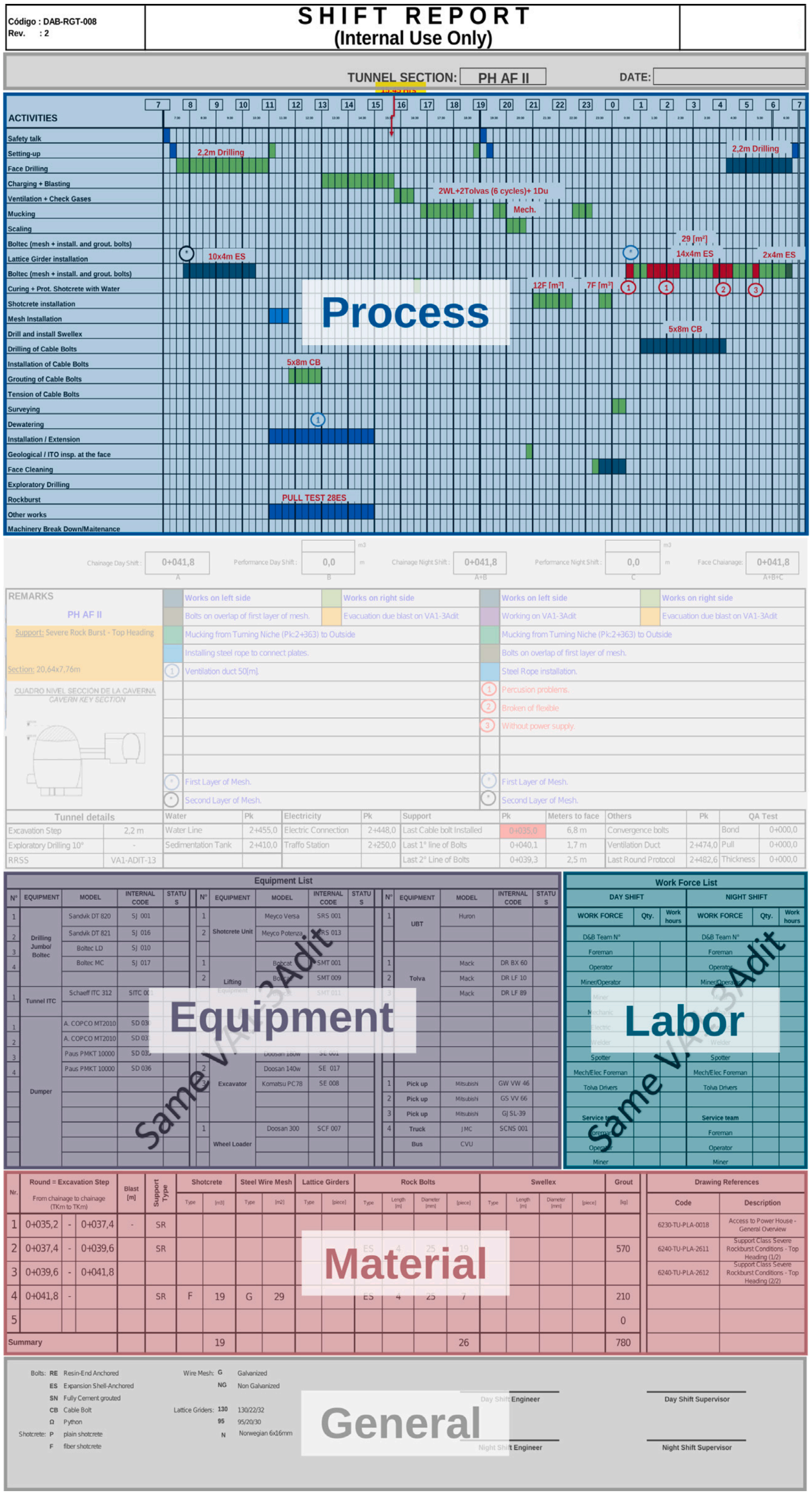
Based on the use case of the shift report presented above, we outline the most relevant features for the next-generation data exchange in conventional tunneling projects. A BIM-based data exchange should be capable of semantically describing complex processes in conventional tunneling projects. Such semantically rich models are machine-readable and facilitate automated processing. The data exchange workflow should support different levels of detail, ranging from today's coarse representations to future comprehensive representations, which enable advanced analyses. Furthermore, multiple stakeholders of tunnel construction projects utilize some or all of the data generated in a shift report, possibly using different software solutions, which suggests an interoperable and vendor-neutral solution. Considering the features of modern heavy equipment, the advances in sensor technology, and novel technologies, such as the Internet of Things (IoT), a real-time data exchange would be beneficial. In light of all this, the data exchange mechanism must provide a smooth transition from the prevailing documents and legacy software systems to reduce the disruptive effect of complete digitalization.

In addition to these general data exchange features, there are features of particular significance to conventional tunneling projects. Not all information in a shift report has a geometric representation or can be sensibly attributed to a single tunnel element. Nevertheless, many practitioners use their authoring software to attribute certain information to geometrical objects to which it does not belong. These workarounds run counter to seamless data exchange. The data exchange mechanism should therefore provide the means to model this type of information explicitly and independently. Despite having to make certain domain-related assumptions in our reference model, the proposed solution should be generic enough to be suitable as a framework for other types of construction projects.

4. Relevant IFC concepts

In the following, we discuss the parts of the IFC data model (bSI, 2021) capable of capturing the most crucial information from the construction phase of conventional tunneling projects. In addition, we identify the entities and types that potentially fulfill the requirements in the previous section.

The EXPRESS modeling language used to define IFC provides its standardized graphical notation, EXPRESS-G. The Unified Modeling Language (UML) (Seidl et al., 2015) is the dominating modeling standard in the area of software engineering, which has long been embraced by the AEC sector (Hiremath and Skibniewski, 2004). Arnold and Podehl (1999) showed that "*complete and consistent mapping can be realised*" between EXPRESS-G and UML. As UML is the more widely used and concise of the two, we presented the relevant mappings in



Código : DAB-RGT-008
Rev. : 2

SHIFT REPORT
(Internal Use Only)

TUNNEL SECTION: PH AF II DATE:

Chainage Day Shift : 0+041,8 (A)
Performance Day Shift : 0,0 m (B) m3
Chainage Night Shift : 0+041,8 (A+B)
Performance Night Shift : 0,0 m (C) m3
Face Chainage: 0+041,8 (A+B+C)

REMARKS

PH AF II

Support: Severe Rock Burst - Top Heading

Section: 20,64x7,76m

CUADRO NIVEL SECCIÓN DE LA CAVERNA
CAVERN KEY SECTION

	Day shift		Night shift
	Works on left side		Works on left side
	Works on right side		Works on right side
	Bolts on overlap of first layer of mesh.		Working on VA1-3Adit
	Evacuation due blast on VA1-3Adit		Evacuation due blast on VA1-3Adit
	Mucking from Turning Niche (Pk:2+363) to Outside		Mucking from Turning Niche (Pk:2+363) to Outside
	Installing steel rope to connect plates.		Bolts on overlap of first layer of mesh.
①	Ventilation duct 50[m].		Steel Rope installation.
		①	Percusion problems.
		②	Broken of flexible
		③	Without power supply.
*	First Layer of Mesh.	*	First Layer of Mesh.
*	Second Layer of Mesh.	*	Second Layer of Mesh.

Tunnel details		Water	Pk	Electricity	Pk	Support	Pk	Meters to face	Others	Pk	QA Test	
Excavation Step	2,2 m	Water Line	2+455,0	Electric Connection	2+448,0	Last Cable bolt Installed	0+035,0	6,8 m	Convergence bolts		Bond	0+000,0
Exploratory Drilling 10°	-	Sedimentation Tank	2+410,0	Traffo Station	2+250,0	Last 1° line of Bolts	0+040,1	1,7 m	Ventilation Duct	2+474,0	Pull	0+000,0
RRSS	VA1-ADIT-13					Last 2° Line of Bolts	0+039,3	2,5 m	Last Round Protocol	2+482,6	Thickness	0+000,0

Equipment List

N°	EQUIPMENT	MODEL	INTERNAL CODE	STATUS
1	Drilling Jumbo/ Boltec	Sandvik DT 820	SJ 001	
2		Sandvik DT 821	SJ 016	
3		Boltec LD	SJ 010	
4		Boltec MC	SJ 017	
1	Tunnel ITC	Schaeff ITC 312	SITC 0	
1	Dumper	A. COPCO MT2010	SD 03	
2		A. COPCO MT2010	SD 03	
3		Paus PMKT 10000	SD 03	
4		Paus PMKT 10000	SD 036	

N°	EQUIPMENT	MODEL	INTERNAL CODE	STATUS
1	Shotcrete Unit	Meyco Versa	SRS 001	
2		Meyco Potenza	RS 013	
1	Lifting Equipment	Bobcat	SMT 001	
2		Bo	SMT 009	
3		Bobcat	SMT 011	
1	Excavator	Doosan 180w	SE 001	
2		Doosan 140w	SE 017	
3		Komatsu PC78	SE 008	
1	Wheel Loader	Doosan 300	SCF 007	

N°	EQUIPMENT	MODEL	INTERNAL CODE	STATUS
1	UBT	Huron		
1	Tolva	Mack	DR BX 60	
2		Mack	DR LF 10	
3		Mack	DR LF 89	
1	Pick up	Mitsubishi	GW VW 46	
2	Pick up	Mitsubishi	GS VV 66	
3	Pick up	Mitsubishi	GJ SL-39	
4	Truck	JMC	SCNS 001	
	Bus	CVU		

Work Force List

DAY SHIFT			NIGHT SHIFT		
WORK FORCE	Qty.	Work hours	WORK FORCE	Qty.	Work hours
D&B Team N°			D&B Team N°		
Foreman			Foreman		
Operator			Operator		
Miner/Operator			Miner/Operator		
Miner			Miner		
Mechanic			Mechanic		
Electric			Electric		
Welder			Welder		
Spotter			Spotter		
Mech/Elec Foreman			Mech/Elec Foreman		
Tolva Drivers			Tolva Drivers		
Service team			Service team		
Foreman			Foreman		
Operator			Operator		
Miner			Miner		

Nr.	Round = Excavation Step From chainage to chainage (TKm to TKm)			Blast [m]	Support Type	Shotcrete		Steel Wire Mesh		Lattice Girders		Rock Bolts				Swellex				Grout
						Type	[m3]	Type	[m2]	Type	[piece]	Type	Length [m]	Diameter [mm]	[piece]	Type	Length [m]	Diameter [mm]	[piece]	[kg]
1	0+035,2	-	0+037,4	-	SR															
2	0+037,4	-	0+039,6		SR							ES	4	25	19					570
3	0+039,6	-	0+041,8																	
4	0+041,8	-			SR	F	19	G	29			ES	4	25	7					210
5																				0
Summary							19								26					780

Drawing References

Code	Description
6230-TU-PLA-0018	Access to Power House - General Overview
6240-TU-PLA-2611	Support Class Severe Rockburst Conditions - Top Heading (1/2)
6240-TU-PLA-2612	Support Class Severe Rockburst Conditions - Top Heading (2/2)

Bolts: RE Resin-End Anchored
ES Expansion Shell-Anchored
SN Fully Cement grouted
CB Cable Bolt
Ω Python
Shotcrete: P plain shotcrete
F fiber shotcrete

Wire Mesh: G Galvanized
NG Non Galvanized
Lattice Griders: 130 130/22/32
95 95/20/30
N Norwegian 6x16mm

Day Shift Engineer
Night Shift Engineer
Day Shift Supervisor
Night Shift Supervisor

Fig. 1. Shift report of a conventional tunneling project (Kvasina, 2018).

the UML graphical notation. Specifically, we use UML class diagrams to formally describe relevant parts of the IFC data model and a UML object diagram to describe our reference model.

For the sake of simplicity, we omit details that do not provide insights into the proposed reference model from the class and object diagrams. For example, we only discuss those aspects of the IFC model that could facilitate the digital documentation of construction sites. We use the UML classifier `interface` to represent an express TYPE and `class` to represent an express ENTITY. Our proposed reference model is based on IFC 4.3 (bSI, 2021). For interoperability reasons, we aim to exploit concepts that IFC offers out of the box instead of introducing new concepts which are unlikely to be implemented in any proprietary

Table 1
Overview of the mapping between concepts found in a shift report to IFC entities.

Concept	IFC Entities
● Process	`IfcTask`
● Labor	`IfcLaborResource`, `IfcPerson`
● Equipment	`IfcConstructionEquipmentResource`
● Material	`IfcConstructionMaterialResource`

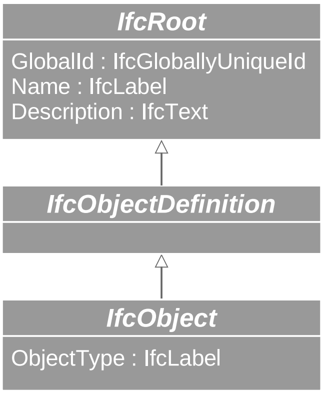


Fig. 2. An excerpt from the IFC data model: A class diagram of `IfcObject` in the core layer.

software in the foreseeable future. This means we base our proposal exclusively on entities, types, property sets, and quantity sets defined by bSI.

Table 1 gives an overview of how concepts in a shift report (c.f. Fig. 1) relate to IFC entities. The relevant entities have been identified by analyzing shift reports and other documents from the construction phase of “Zentrum am Berg” (ZaB) (Galler, 2016). ZaB is an underground research, development, education, and training facility. The table shows that IFC provides the necessary concepts to represent the information blocks of a shift report digitally. In the subsequent figures, we apply the color scheme introduced in Fig. 1.

In the remainder of this section, we analyze the IFC entities listed in Table 1 and their relevant specializations and associations. Section 4.1 presents some general characteristics of the IFC data model. IFC has comprehensive support for describing processes described in Section 4.3. In Section 4.4, we discuss labor, equipment, and material as specializations of a resource. Section 4.5 demonstrates the concept of actors used to represent concrete labor utilization. Finally, Section 4.6 outlines IFC’s capabilities to refer to external data, such as legacy documents.

4.1. Basics

Before we go into details about different parts of the IFC data model (bSI, 2021), we want to discuss some common characteristics of IFC. The basic building blocks of the IFC data model are classes or so-called entities, the names of which are prefixed with `Ifc` by convention. Many IFC entities in the core, shared, and domain-specific layers are derived from `IfcObject`, which equips them with some basic features. The inheritance hierarchy of `IfcObject` is shown in Fig. 2. All objects derived from `IfcRoot` provide `GlobalId` containing an encoded Globally Unique Identifier (GUID). The GUID of a specific object is an identifier that should not change over time. In addition, `IfcObject` instances have a `Description` and a `Name` attribute.

Typing, i.e., assigning one or more (additional) types, allows the user to specify an object’s semantics or meaning in more detail. IFC has provisions for dynamic typing of some of the specializations of `IfcObject`, which is a complementary concept to static typing via the common object-class relationship. In contrast to the static entities defined by the IFC data model, dynamic types can be defined by the user. In the simplest case, all instances of `IfcObject` can be assigned a dynamic type by setting a custom `IfcLabel` value to the attribute `ObjectType`. Objects derived from `IfcProcess`, `IfcResource`, and `IfcProduct` offer a second option for typing. Multiple objects of those entities can be typed by associating them with an `IfcRelDefinesByType` relation to a corresponding `IfcTypeObject` instance. `IfcTypeObject` instances could be collected in project-specific libraries and reused in other projects. The concept behind `IfcClassification` and `IfcClassificationReference` is orthogonal but very similar to dynamic typing, which is out of the scope of this work.

Another powerful mechanism for dynamic semantic enrichment of IFC entities is the usage of property sets, which extend the existing types by adding specialized attributes. Property sets can be declared by instances of the type `IfcPropertySetTemplate`. By convention, the name of property sets is prefixed with `Pset_`. `IfcPropertySet` instances can be attached to any object derived from `IfcObjectDefinition`. Quantities are a particular type of property aggregated in `IfcQuantitySet` instances, the name of which is prefixed with `Qto_` by convention. We do not go into details here, but we will mention all predefined property and quantity sets potentially useful for our reference model in the following sections.

4.2. Geometric representation

Another remarkable feature of IFC is the strict separation between semantics and geometry (bSI, 2021; Borrmann et al., 2021). Fig. 3 gives an overview of IFC entities for geometric modeling. All instances derived from `IfcProduct` can optionally have one or multiple geometric representations associated with it by an `IfcProductRepresentation` instance. This approach is chosen to meet the model requirements of different use cases. For example, simulation tools generally require decomposing volumetric elements into a discrete number of “simple” volumes. However, this only allows approximate curved surfaces, which does not fulfill the visual requirements of complex architectural models. On the other hand, the same representation instance could even be shared among different products. Instances of `IfcProduct` are also perfectly valid without any geometric representation. This case is motivated by Fig. 1, which contains no geometric information. Nevertheless, all instances derived from `IfcObjectDefinition` can be associated with `IfcProduct` instances – and therefore with geometric objects – utilizing the `IfcRelAssignsToProduct` relationship. This will become particularly relevant as soon as the planned IFC-Tunnel extension is released. According to bSI, “*`IfcShapeRepresentation` represents the concept of a particular geometric representation of a product or a product component within a specific geometric representation context.*” `IfcRepresentationContext` defines characteristics, such as the numeric precision, the offset of the project coordinate system, and the true north direction. Ninić et al. (2020) point out that this attribute could also be used to include different levels of geometric detail within the same IFC model. The attribute `RepresentationIdentifier` distinguishes between representations, such as bounding box representations, axis representations, or 3D body representations. One or more instances derived from `IfcGeometricRepresentationItem` make up the actual geometric representation. Fig. 3 shows only a few of those entities to illustrate the general capabilities of IFC. For example, at a low level of detail, an `IfcProduct` instance could be represented only by a point or its bounding box. In contrast, the same instance could be represented by a complex 3D shape at a high level of detail.

4.3. Process

Fig. 4 shows a class diagram of the IFC process model. According to bSI, `IfcProcess` is an abstract base class for the three process-related classes `IfcTask`, `IfcEvent`, and `IfcProcedure`.

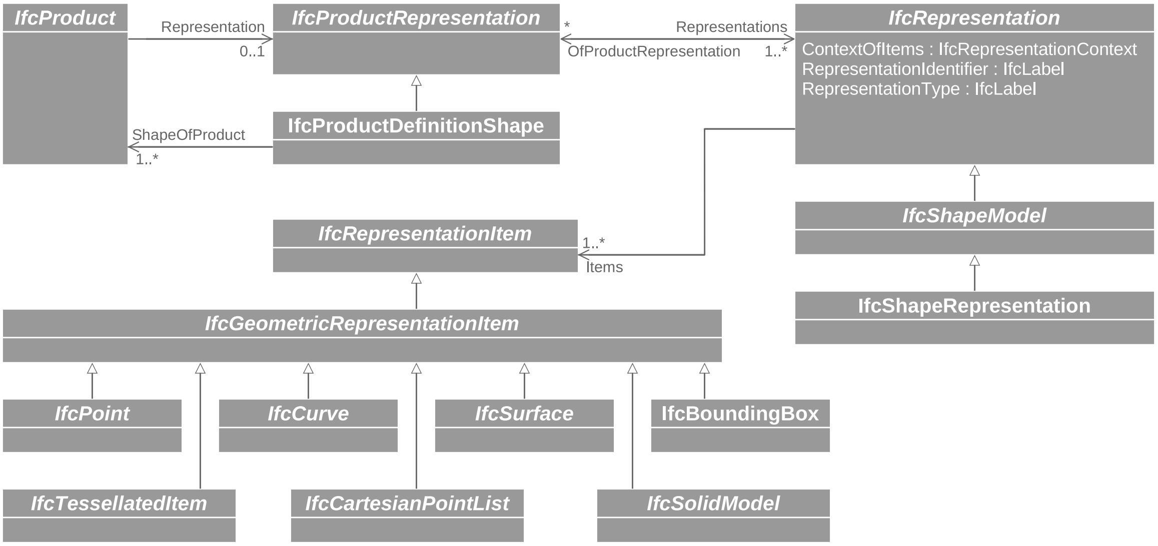


Fig. 3. An excerpt of the IFC model for representing geometric characteristics.

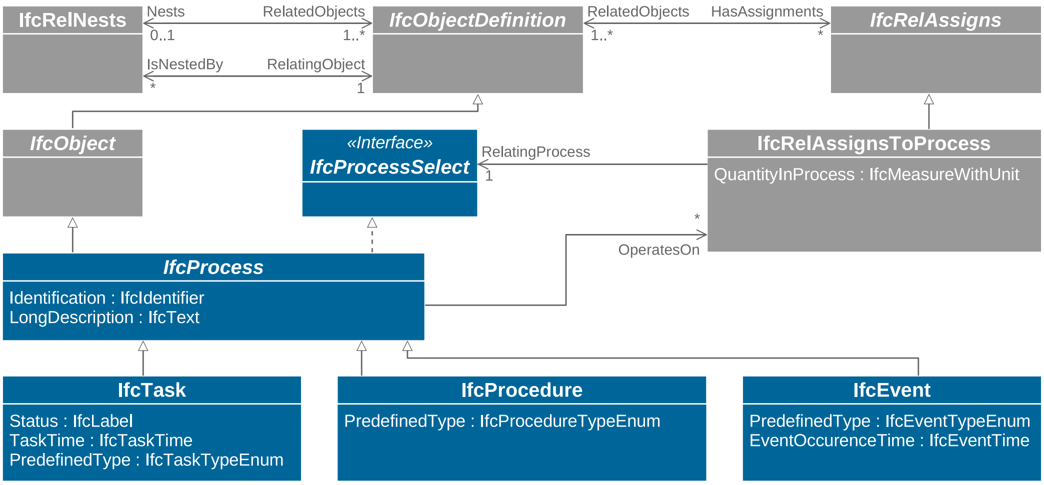


Fig. 4. An excerpt of the IFC process model in the core layer.

`IfcTask` represents an "*identifiable unit of work to be carried out.*" In a conventional tunnel drive, such a task could be, e.g., drilling blasting holes to be later filled with explosives. The attribute `Status` allows one to specify if a task is scheduled, started, or completed. The attribute `TaskTime` is an `IfcTaskTime` entity, which defines a time period. The entity combines multiple `IfcDateTime` attributes specifying start and end, multiple `IfcDuration` attributes, and other attributes representing project management-specific information. Moreover, the entity has dedicated attributes for planned and actual timings. `IfcDateTime` combines a calendar date and the time of day. `IfcDateTime` instances do not have time zone information, which does not constitute a restriction as most tunnel projects are located within a single time zone or could agree on a project-wide time zone. `IfcDateTime` instances offer a time resolution of one second, sufficient for replacing paper-based documentation. However, it could become an obstacle to using IFC as a data format for construction equipment and sensor usage.

bSI describes `IfcProcedure` as a "*logical set of actions to be taken in response to an event or to cause an event to occur.*" Fig. 4 illustrates that procedures do not have any timing information attached. A potential use case would be a project owner defining a set of tasks to be carried out by the contractor to comply with the Exchange Information Requirements (EIR) (ISO, 2018).

An `IfcEvent` "*is something that happens that triggers an action or response.*" Compared to `TaskTime`, the attribute `EventOccurenceTime` evidently describes a point in time. This entity could, e.g., express the event of blasting.

In addition to the typing mechanisms inherited from `IfcObject`, it is possible to assign a predefined enumerable type to the attribute `PredefinedType` of instances of the subclasses of `IfcProcess`. For the `IfcTask`, the attribute `PredefinedType` can, e.g., be set to one of the literals defined by the enumeration `IfcTaskTypeEnum`, including `CONSTRUCTION`, `OPERATION`, `MAINTENANCE`, `DEMOLITION`, or `USERDEFINED`, to name a few. In this way, the task can be specified further if necessary. The attributes `Name` and `Description` are inherited from the parent classes. Additionally, `IfcProcess` introduces the attribute `LongDescription`, which can carry verbose information about the instance. `IfcProcess` instances can be related by nesting or chaining, achieved through `IfcRelNests` and `IfcRelSequence` instances, respectively.

4.4. Resources

A class diagram of the IFC resource model is depicted in Fig. 5. Its subtype `IfcConstructionResource` in the domain-specific layer of

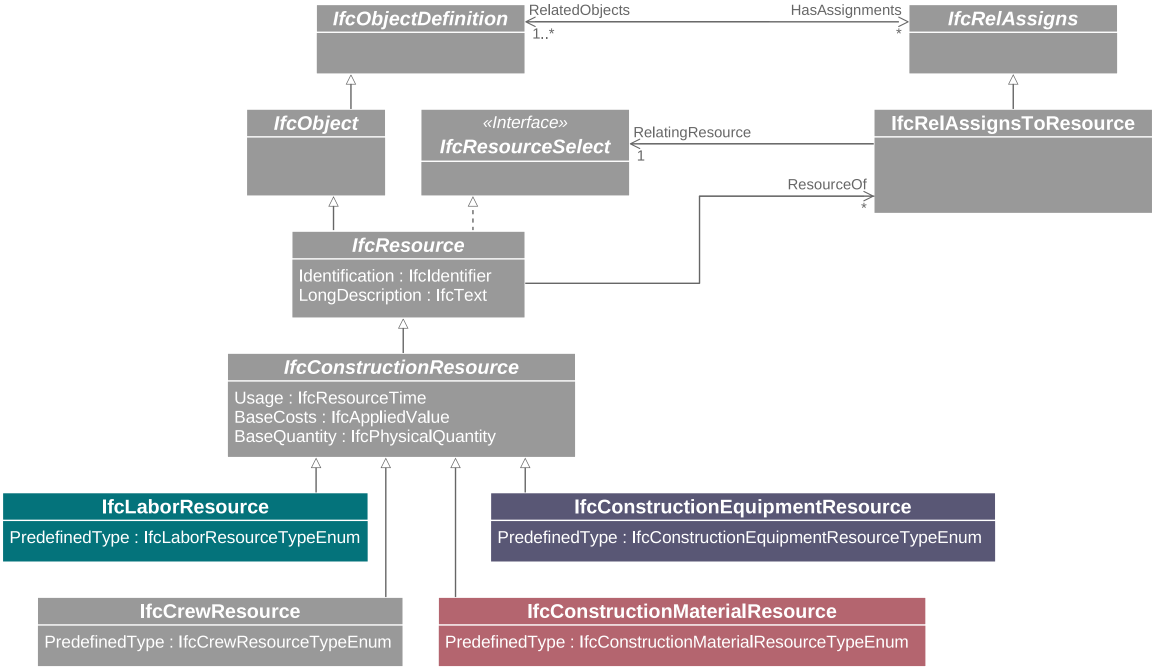


Fig. 5. An excerpt of the IFC resource model in the core and domain-specific layers.

IFC serves as a base class for various construction resources, including labor, equipment, and materials.

`IfcLaborResource` represents "*particular skills or crafts required to perform certain types of construction or management related work.*" Tunneling-related skills could include miner, foreman, site manager, geologist, geotechnical engineer, or surveyor. `Qto_LaborResourceBaseQuantities` can extend labor resources to differentiate between regular working time and overtime.

Heavy equipment is modeled with `IfcConstructionEquipmentResource` instances. Drilling jumbos, wheel loaders, and shotcrete robotic arms are conventional tunneling equipment typically used in conventional tunneling. `Qto_ConstructionEquipmentResourceBaseQuantities` allows distinguishing between the productive and idle operating time.

`IfcCrewResource` represents a "*collection of internal resources used in construction processes.*" A crew can consist of both labor and equipment resources. According to bSI, labor, and equipment resources are associated with crew instances through `IfcRelNests` relationships. It has also been suggested that labor and construction equipment could be related to the crew by utilizing the `IfcRelAggregates` relationship (Regateiro and Spínola, 2014).

Material usage is represented by `IfcConstructionMaterialResource`, whose instances are defined to be "*consumed (wholly or partially), or occupied during a construction work task.*" On the other hand, `IfcConstructionProductResource` can be instantiated in cases where the material is the product of another action, such as 100 kg of gravel excavated in a previous task. Construction materials in conventional tunneling drives are generally used as support measures, such as shotcrete, steel meshes, and anchors. A second important class of materials is the explosives used in the drill and blast method. The quantity set `Qto_ConstructionMaterialResourceBaseQuantities` specifies the volume and weight of the corresponding resource.

As in the case of the process model, resources provide the attributes `Description`, `LongDescription`, `Name`, and `Identification`. Concerning additional typing, subclasses of `IfcResource` can have the attribute `PredefinedType` set to a predefined enumerable literal, in addition to all other typing mechanisms inherited from `IfcObject`, just as we described for the entity `IfcTask`. All construction resources have a common property set `Pset_ConstructionResource`, capturing the temporal evolution of costs and scheduling data.

There are two ways of specifying the amount of resources employed: (i) Using the `QuantityInProcess` attribute of `IfcRelAssignsToProcess` (c.f. Fig. 4); or (ii) the `BaseQuantity` attribute of `IfcConstructionResource`. We opted for the second alternative, allowing different quantities without instantiating multiple `IfcRelAssignsToProcess`. Furthermore, all construction resources have a `BaseCosts` attribute, which could provide further information on the quantity. This detail supports the idea of keeping all the information in one place — in the same instance.

A set of `IfcResource` instances can be assigned to one `IfcProcess` through an `IfcRelAssignsToProcess` instance (c.f. Fig. 4). The bSI specification advises the usage of `IfcRelAssignsToProcess` to indicate that a resource is consumed by the process or acts as a mechanism to facilitate a process. This association is distinct from `IfcRelAssignsToResource`, depicted in Fig. 5, which allows associating a set of other objects with one resource. According to bSI, the semantics of this association is to model the "*assignment of a resource usage to a construction resource.*" An example is identifying a product as part of a resource, e.g., a material produced as part of a material resource. We will elaborate on another example in the following subsection.

4.5. *Actors*

An overview of IFC's actor model is depicted in Fig. 6. An Actor is a concept that abstracts persons and organizations. IFC defines three types of actors: `IfcPerson`, `IfcOrganization`, and `IfcPersonAndOrganization`. Evidently, `IfcPerson` is meant for human beings, whereas `IfcOrganization` is a generic type representing companies and other organizational units. `IfcPersonAndOrganization` addresses cases where a person acts on behalf of an organization. The three aforementioned classes are not specializations of `IfcActor` but can be assigned to the attribute `TheActor` of class `IfcActor` instead.

Compared to processes and resources, using the attribute `ObjectType` is the only mechanism for dynamically typing actors. Actors can refer to the property sets `Pset_ActorCommon` and `Pset_Address`, which allow for additional categorization and specification of the postal address, respectively.

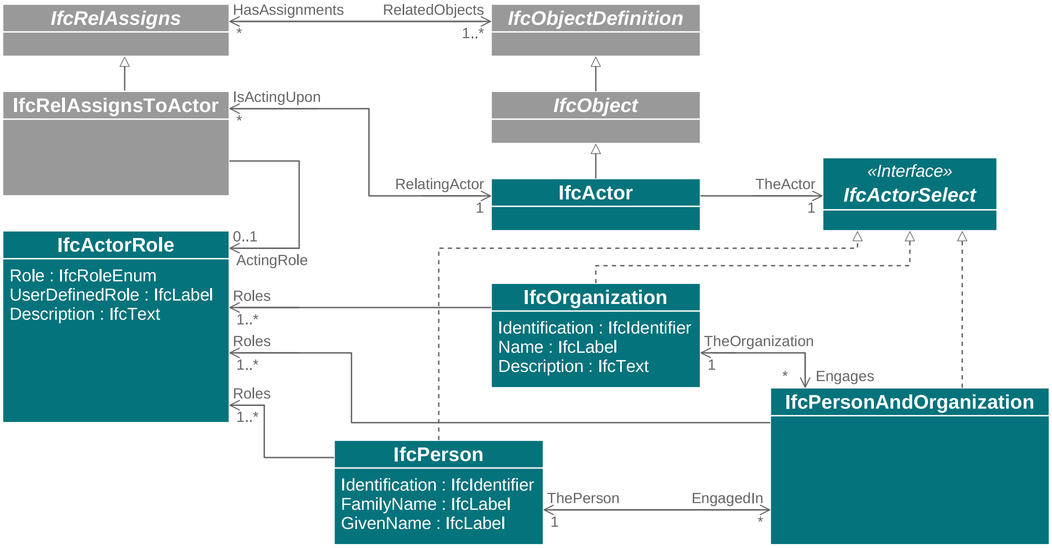


Fig. 6. An excerpt of the IFC actor model in the core layer.

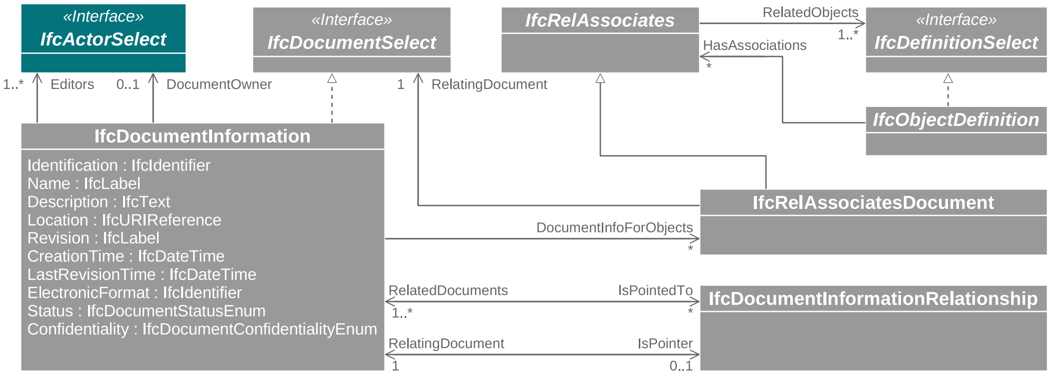


Fig. 7. An excerpt of the IFC document model.

According to bSI, `IfcRelAssignsToResource` (Fig. 5) is used to indicate that a work is performed by a specific actor. This association should be distinct from `IfcRelAssignsToActor`, shown in Fig. 6. `IfcRelAssignsToActor` has the semantics that an actor is "*responsible for allocating the resource such as partitioning into task-specific allocations, delegating to other actors, and/or scheduling over time.*" Because `IfcRelAssignsToResource` lacks an attribute to designate the role, one actor cannot take a specific role when assigned to a resource.

4.6. External data

IFC provides a means to refer to data external to the model. This is especially useful when referring to files, such as scanned documents, text documents, spreadsheets, audio and video data, monitoring data, and proprietary binary files. The possibility of referring to external data opens the opportunity for a smooth transition from legacy documents to BIM models. Apart from that, referencing other models provides a mechanism for building multi-models (Fuchs et al., 2010). We believe that this machinery should not be used to circumvent IFC concepts and therefore run counter to the ideas of BIM.

Fig. 7 gives an overview of how IFC can refer to legacy data. `IfcDocumentInformation` serves as storage for the metadata of external documents. It is important to note that the actual content of the referenced document is not contained in the IFC model. The attributes `Identification`, `Name`, and `Description` are attributes we have already encountered in other parts of the data model. `Location` holds the document's Uniform Resource Locator (URL). The document owner and editors can be supplied by referring to, e.g., an `IfcPerson`. The attributes `Revision`, `CreationTime`, and `LastRevisionTime` allow some rudimentary version control of external documents. `ElectronicFormat` defines the media type (formerly known as MIME types) (IANA, 2022), and enumerations permit setting the status and confidentiality of the referenced document.

A potential usage of this concept is to refer to the photo documentation of a tunneling round. The photos can be stored as raster graphics files on the project's common data environment (CDE). In this case, `ElectronicFormat` is, e.g., `image/jpeg`, and `Location` is set to the photo URL on the CDE.

Two relation types exist for `IfcDocumentInformation` instances. `IfcRelAssociatesDocument` defines relations to any object derived from `IfcObjectDefinition`. On the other hand, `IfcDocumentInformationRelationship` provides a way to associate one document with a set of other documents. The cardinalities in Fig. 7 make it clear that no document can have more than one parent document; therefore, only tree-like structures can be represented.

For completeness, it should be mentioned that the type `IfcDocumentReference` provides a second option to refer to external content. `IfcDocumentReference` differs from `IfcDocumentInformation` in that it has only limited metadata capabilities. The second difference is that they can be associated with different elements within the IFC data model. Appendix lists essential IFC concepts used in this paper.

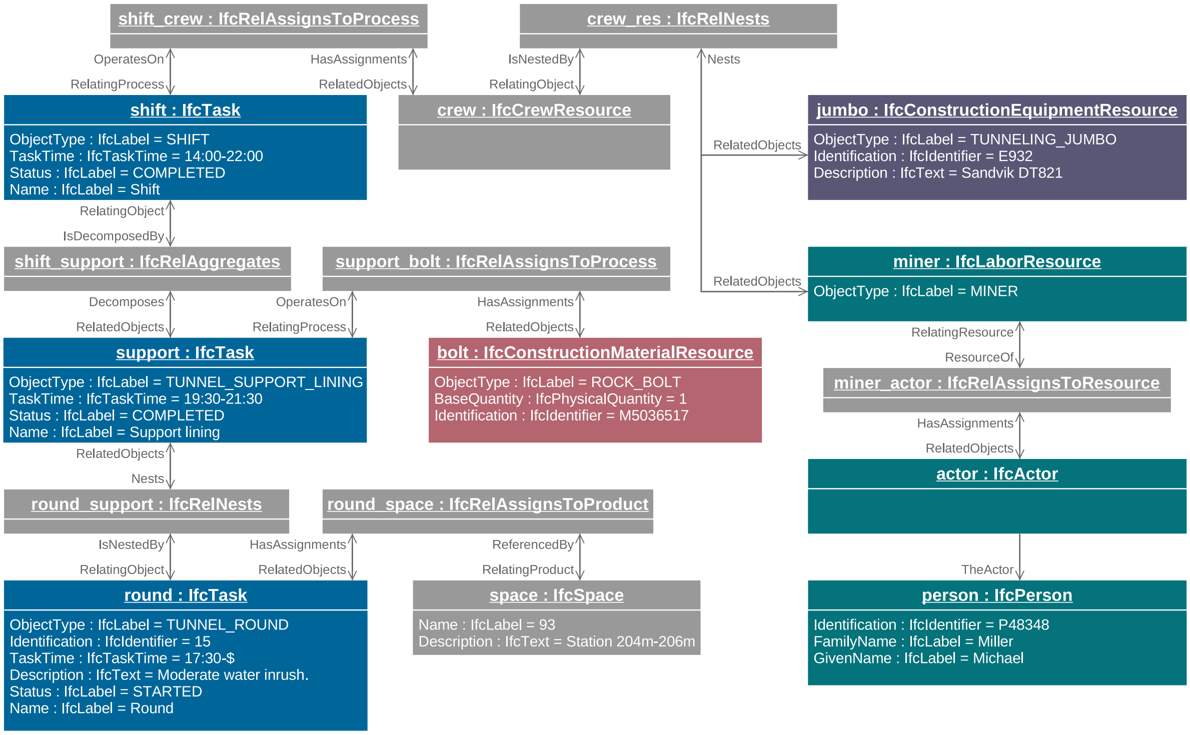


Fig. 8. An object diagram representing a minimal example of IFC-based documentation of a conventional tunneling drive.

Table 2
Data of an exemplary shift report.

Concept	Specification
● Process	shift: 2022-10-01 14:00-22:00 round: started 2022-10-01 17:30 activity: lining support, 2022-10-01 19:30-21:30
● Labor	Michael Miller, miner, id: P48348
● Equipment	tunneling jumbo, id: E932
● Material	rock bolt, id: M5036517

5. Case study

Based on the discussion in the previous sections, we propose an IFC instance model of a typical shift report of a conventional tunneling project. We keep the example simple while retaining all concepts relevant to a real-world shift report. In our example, we assume that a miner installs one rock bolt to support the tunnel face using a tunneling jumbo. The data we wish to input into the model is summarized in Table 2. Fig. 8 shows the corresponding object diagram as an instantiation of the IFC model. Due to space constraints, we have to omit some details from the figure. The complete model is serialized as a STEP file at the end of the section.

In the previous section, we outlined multiple possibilities for object typing. We employ the attribute `ObjectType` (c.f. Fig. 2) instead of the association with `IfcRelDefinesByType` to avoid visual clutter. The attribute `Identification` allows matching the model data with data in another software system, such as an enterprise resource planning (ERP) system, according to its identifier. The second possibility is the `GlobalId`, which requires the generating system to generate “stable” GUIDs and the receiving system to track those.

The process is modeled by three tasks: One for the shift (`ObjectType=SHIFT`), one for the tunnel round (`ObjectType=TUNNEL_ROUND`), and one for the particular activity in the tunneling cycle (`ObjectType=TUNNEL_SUPPORT_FACE`). We denote any concrete task performed during the excavation work, e.g., ground support, surveying, dewatering, and installation, as a construction activity. A construction activity is a task performed during the tunneling round and, therefore, nested within a tunneling round through `IfcRelNests`. Activities could be further broken down into subactivities by nesting using `IfcRelNests`. This technique allows modeling the process at different levels of development (LOD), from the coarse round level to a subactivity level. The same construction activity is also performed during a shift. However, the cardinalities in Fig. 4 show that `IfcRelNests` does not allow more than one parent element. We, therefore, resort to `IfcRelAggregates` to connect an activity to a shift. In the unlikely scenario of a construction activity crossing the shift boundary, one could represent it by two tasks of the same type without information loss. By contrast, a shift can involve multiple tunneling rounds; conversely, a tunneling round can generally span multiple shifts. Thus, tunneling rounds cannot be nested within shifts and vice versa. For embedding the round within the remaining model, the round could be further nested within a task for the tunnel drive. This task, in turn, could be nested within a top-level task for the whole project. Our simplified example assumes a shift of 8 h. A tunnel round starts during this shift but does not finish until the end of the shift. The construction activity is performed during the shift and can be attributed to the round. Table 2 shows the exact timing of the tasks. The location of tunnel rounds is crucial during both the construction and operation phases. As pointed out in Section 2, IFC currently lacks dedicated entities for semantically representing tunnel rounds. We, therefore, fall back to an `IfcSpace` entity to represent the location of a tunnel round. As this entity is derived from `IfcProduct`, it can optionally have one or more geometric representations, including the placement along the tunnel axis. The `IfcSpace` entity is associated with the task utilizing an `IfcRelAssignsToProduct` association.

In our simplified example, we assume that the crew consists of the miner Michael Miller (`IfcLaborResource`) and a tunneling jumbo (`IfcConstructionEquipmentResource`), where the crew members are assigned to the `IfcCrewResource` by nesting them with `IfcRelNests`. The labor resource is then associated with a concrete `IfcActor` by an `IfcRelAssignsToResource` instance. The actual person (`IfcPerson`) is represented by the reference `TheActor`. In cases where data protection regulations require it, this personal data can be omitted

```
 1 ISO-10303-21;
 2 HEADER;
 3 FILE_DESCRIPTION(('ViewDefinition␣[CoordinationView]'),'2;1');
 4 FILE_NAME('','2023-08-01T15:17:26',(),(),'IfcOpenShell␣0.6.0b0','IfcOpenShell␣0.6.0b0','');
 5 FILE_SCHEMA(('IFC4'));
 6 ENDSEC;
 7 DATA;
 8 #1=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2022-10-01T14:00:00','2022-10-01T22:00:00',$,$);
 9 #2=IFCTASK('2d5BbAB7eHx0196V3uqQVi',$,'Shift',$,'SHIFT',$,$,'COMPLETED',$,.F.,$,#1,$);
10 #3=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2022-10-01T19:30:00','2022-10-01T21:30:00',$,$);
11 #4=IFCTASK('2vH8ZeB7eHx0196V3uqQVi',$,'Support␣lining',$,'TUNNEL_SUPPORT_LINING',$,$,'COMPLETED',$,.F
       .,$,#3,$);
12 #5=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2022-10-01T17:30:00',$,$,$);
13 #6=IFCTASK('3A04cmB7eHx0196V3uqQVi',$,'Round','Moderate␣water␣inrush.','TUNNEL_ROUND','15',$,'STARTED
       ',$,.F.,$,#5,$);
14 #7=IFCRELNESTS('3eYvkKDF4HxRUjKEjnNbKG',$,$,$,#6,(#4));
15 #8=IFCRELAGGREGATES('2hunZeDF4HxRUjKEjnNbKG',$,$,$,#2,(#4));
16 #9=IFCPROJECT('2NEAtCC6qHxeHpKEjnNbKG',$,'Project',$,$,$,$,$,$);
17 #10=IFCSPACE('1mW7R_BvCHxeHpKEjnNbKG',$,'93','Station␣204m-206m',$,$,$,$,$,$,$);
18 #11=IFCRELASSIGNSTOPRODUCT('1n_j9UC6eHxeHpKEjnNbKG',$,$,$,(#6),$,#10);
19 #12=IFCRELAGGREGATES('21J_2wC6qHxeHpKEjnNbKG',$,$,$,#9,(#10));
20 #13=IFCQUANTITYCOUNT('Count',$,$,1.,$);
21 #14=IFCCONSTRUCTIONMATERIALRESOURCE('3mnb2yB7eHx0196V3uqQVi',$,$,$,'ROCK_BOLT','M5036517',$,$,$,#13,$
       );
22 #15=IFCRELASSIGNSTOPROCESS('3msjIaDF4HxRUjKEjnNbKG',$,$,$,(#14),$,#4,$);
23 #16=IFCCONSTRUCTIONEQUIPMENTRESOURCE('0fSgyeB7iHx0196V3uqQVi',$,$,'Sandvik␣DT821','TUNNELING_JUMBO','
       E932',$,$,$,$,$);
24 #17=IFCPERSON('P48348','Miller','Michael',$,$,$,$,$);
25 #18=IFCACTOR('3bYMWSD58HxRUjKEjnNbKG',$,$,$,$,#17);
26 #19=IFCLABORRESOURCE('3fTjJwDF8HxRUjKEjnNbKG',$,$,$,'MINER',$,$,$,$,$,$);
27 #20=IFCRELASSIGNSTORESOURCE('01ZX$CDF8HxRUjKEjnNbKG',$,$,$,(#18),$,#19);
28 #21=IFCCREWRESOURCE('1WMdwKB7iHx0196V3uqQVi',$,$,$,$,$,$,$,$,$,$);
29 #22=IFCRELASSIGNSTOPROCESS('08XjXuDF8HxRUjKEjnNbKG',$,$,$,(#21),$,#2,$);
30 #23=IFCRELNESTS('0HF8DGDF8HxRUjKEjnNbKG',$,$,$,#21,(#19,#16));
31 ENDSEC;
32 END-ISO-10303-21;
```

Fig. 9. An IFC STEP file of the reference model.

without affecting the rest of the model. Because the crew composition is generally not altered during a shift, we assign the crew instance to the shift task with `IfcRelAssignsToProcess`. Another option would be to assign the equipment to individual activities. Although this information is not available in current paper-based documentation, this may change in the future because of the increasing usage of equipment-generated data.

Material usage can generally be attributed to a specific activity in a construction process. This connection is necessary for the contractor to assess the construction process. For example, it is of the contractor's interest if shotcrete is used as a support measure or if it is used to fill up excavation volumes. Furthermore, this connection allows locating the corresponding item in a bill of quantities. For example, generally, a rock bolt securing the tunnel face corresponds to a different item than a rock bolt securing the tunnel lining. For these reasons, we use an `IfcRelAssignsToProcess` to assign the `IfcConstructionMaterialResource` instances to the related task.

Now, after describing the reference model, we demonstrate the most common form of serialization for such models – a STEP file. STEP files were initially designed as "*clear text encoding of product data for which the conceptual model is specified in the EXPRESS language*" (ISO, 2016). Fig. 9 shows the serialized counterpart to the graphical representation of the reference model in Fig. 8. Serialization refers to transforming a data structure into a sequence of bytes to save or transfer it. The file was generated with the Python implementation of IfcOpenShell[3] version 0.6.0b0. The semantic and syntactic correctness of the generated file has been checked with IfcCheckingTool[4] version 2.2. As discussed previously, there are other serialization formats for IFC files, apart from STEP files, but they are outside the scope of this work.

One can identify two sections within the STEP file: A header (lines 2 to 6) and a data section (lines 7 to 29). Predefined keywords encapsulate the whole file and every section in it. The data section comprises lines of entity instantiations (lines 8 to 28) corresponding to the instances in Fig. 8. For clarity, however, we represented `IfcTaskTime` and `IfcQuantityCount` in Fig. 8 "inline". For example, line 9 of the STEP file corresponds to the top left blue `IfcTask` instance named `shift` in Fig. 8. One can further identify, e.g., lines 8 to 13 as process-related definitions, line 19 as related to the material, line 21 as related to the equipment, and lines 22 to 24 as related to labor. Unlike the alphanumeric instance names in Fig. 8, instances in the STEP file have numeric names that can be referenced in other instantiations in the same model. The instances' attributes are instantiated as part of the input parameter list of the constructor call.

Even though we did not include all details of a real shift report in the simplified example, the serialization presented in Fig. 9 shows that it is possible to transform the shift report into exchangeable data.

6. Discussion

Section 3.3 lists the must-have features of the BIM-based data exchange. We will now assess how the proposed reference model could address those features. IFC offers multiple beneficial properties. There is no doubt that it is capable of creating semantically rich models. The previous sections showed that IFC is also capable of representing complex tunnel construction processes. IFC's strict separation of semantics and geometry allows for the unambiguous representation even of non-geometric information. Relations and property sets enable the gradual enhancement of a model with further details. IFC is an open standard already well-established within the construction sector and the research community (Jiang et al., 2019), which generally has a positive effect on interoperability.

On the other hand, it also comes with certain disadvantages. For example, the lack of a subsecond time specification makes the standard unsuitable for real-time data exchange in modern technologies, such as IoT. This, however, is not an issue, as dedicated standards exist addressing this use case (OGC, 2023). Furthermore, in line with other authors (Shelden et al., 2020), we consider IFC to be highly complex, significantly impacting the completeness and correctness of its implementation in domain tools. On top of that, IFC leaves much room

---

[3] http://www.ifcopenshell.org/

[4] https://www.iai.kit.edu/english/1302.php

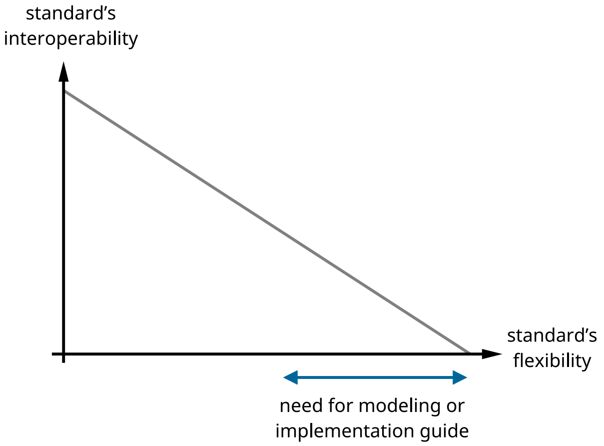


Fig. 10. Qualitative relationship between flexibility and interoperability of data standards.

for flexibility, i.e., the same semantics can be expressed by different IFC concepts. For example, the attribute `Status` of type `IfcLabel` can be set to a custom value, potentially leading to an undefined behavior during data exchange and harming interoperability. However, this inherent trade-off between interoperability and flexibility in data standards, shown in Fig. 10, is not unique to IFC.

Interoperability itself has multiple aspects. For example, the European interoperability model defines four layers of interoperability: legal, organizational, semantic, and technical (European Commission, 2017). The proposed IFC reference model contributes to semantic and technical interoperability within this conceptual framework. The publication of the Emerald Book we mentioned in Section 3 is a significant step toward legal interoperability (FIDIC, 2019b). On the other hand, organizational interoperability requires the stakeholders involved in tunnel construction projects to align their business processes.

In Section 5, we presented an IFC reference model for a use case during the construction phase in a conventional tunneling project. This model could become the basis for automated data exchange in conventional tunneling projects.

To keep the case study lean and straightforward, we focused on the main elements of a shift report, i.e., process, labor, equipment, and material. In our future work, we will show how our proposal could be practically embedded in conventional tunneling projects. It might also be beneficial to develop a tunneling-specific project library of reference models containing `IfcTaskType`, `IfcConstructionEquipmentResourceType`, `IfcLaborResourceType`, and `IfcConstructionMaterialResourceType`. Alternatively, one could design a classification scheme using `IfcClassification`. However, to achieve full interoperability, further specification through an Information Delivery Manual (IDM) and a Model View Definitions (MVD) is necessary (Eastman et al., 2010), which we plan for our future work.

There are further aspects the proposed reference model still needs to address. Despite covering all information relevant to a shift report, it does not include many other documents generated during the construction phase of conventional tunnel drives, such as geological surveys or quality checks. Therefore, the model should also be extended to deal with this data. Furthermore, energy usage is highly significant in tunneling (Huymajer et al., 2022b). While this work has shown how to represent the amount of used material digitally, future work should consider exploring the possibilities of representing the energy usage of construction processes.

The upcoming tunneling extension of IFC will provide new opportunities for modeling tunnels. Further research is necessary on how this future extension could complement our proposal to generate semantically rich models for the execution phase of conventional tunneling projects.

We applied our model in the tunneling domain, but the model is designed such that it could easily be extended to the execution phase of other kinds of construction projects. Future work should also investigate how the model leverages technology such as IoT, Augmented Reality (AR), or autonomous construction equipment.

7. Conclusion

We examined the IFC standard for elements useful for representing key information from the construction phase of conventional tunneling projects. UML models were derived to capture information about the process, labor, equipment, material, and external data. Based on these results, we presented an IFC reference model of an exemplary shift report of a conventional tunneling project. This model was serialized to an IFC STEP file as a proof of concept.

The proposed reference model could serve as an implementation guide for software developers to achieve a fully automated data exchange in conventional tunneling. Future software tools represent a substantial improvement compared to the paper and unstructured data exchange prevailing in the construction phase of conventional tunneling projects. This could bring us a step closer to the goal of Big Open BIM in tunneling projects. Because of the generic nature of our model, we see a high potential in its utilization in the construction phase of construction projects in general. A well-designed data model will pave the way for applying other technologies, such as IoT, AR, and digital twins, to tunneling projects.

CRediT authorship contribution statement

Marco Huymajer: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Galina Paskaleva:** Formal analysis, Investigation, Writing – review & editing. **Robert Wenighofer:** Investigation, Writing – review & editing. **Christian Huemer:** Project administration, Funding acquisition, Writing – review & editing. **Alexandra Mazak-Huemer:** Project administration, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

This research was funded by the Austrian Federal Ministry of Education, Science and Research under grant number BMBWF-11.102/0033-IV/8/2019.

This research was funded by the Austrian Research Promotion Agency (FFG) under grant number 879573.

Appendix. Excerpt of IFC concepts used

Entity/Attribute	Type
● IfcTask	
GlobalId	IfcGloballyUniqueId
Name	IfcLabel
Description	IfcText
ObjectType	IfcLabel
Identification	IfcIdentifier
LongDescription	IfcText
Status	IfcLabel
TaskTime	IfcTaskTime
PredefinedType	IfcTaskTypeEnum
● IfcLaborResource	
GlobalId	IfcGloballyUniqueId
Name	IfcLabel
Description	IfcText
ObjectType	IfcLabel
Identification	IfcIdentifier
LongDescription	IfcText
Usage	IfcResourceTime
BaseCosts	IfcAppliedValue
BaseQuantity	IfcPhysicalQuantity
PredefinedType	IfcLaborResourceTypeEnum
● IfcPerson	
Identification	IfcIdentifier
FamilyName	IfcLabel
GivenName	IfcLabel
● IfcConstructionEquipmentResource	
GlobalId	IfcGloballyUniqueId
Name	IfcLabel
Description	IfcText
ObjectType	IfcLabel
Identification	IfcIdentifier
LongDescription	IfcText
Usage	IfcResourceTime
BaseCosts	IfcAppliedValue
BaseQuantity	IfcPhysicalQuantity
PredefinedType	IfcConstructionEquipmentResourceTypeEnum
● IfcConstructionMaterialResource	
GlobalId	IfcGloballyUniqueId
Name	IfcLabel
Description	IfcText
ObjectType	IfcLabel
Identification	IfcIdentifier
LongDescription	IfcText
Usage	IfcResourceTime
BaseCosts	IfcAppliedValue
BaseQuantity	IfcPhysicalQuantity
PredefinedType	IfcConstructionMaterialResourceTypeEnum
● IfcDocumentInformation	
Identification	IfcIdentifier
Name	IfcLabel
Description	IfcText
Location	IfcURIReference
Revision	IfcLabel
CreationTime	IfcDateTime
LastRevisionTime	IfcDateTime
ElectronicFormat	IfcIdentifier
Status	IfcDocumentStatusEnum
Confidentiality	IfcDocumentConfidentialityEnum

References

Afsari, K., Eastman, C.M., Shelden, D.R., 2016a. Cloud-based BIM data transmission: Current status and challenges. In: Sattineni, A., Azhar, S., Castro, D. (Eds.), 33rd International Symposium on Automation and Robotics in Construction. ISARC 2016, International Association for Automation and Robotics in Construction (IAARC), pp. 1073–1080. http://dx.doi.org/10.22260/isarc2016/0129.

Afsari, K., Eastman, C.M., Shelden, D.R., 2016b. Data transmission opportunities for collaborative cloud-based building information modeling. In: XX Congress of the Iberoamerican Society of Digital Graphics. In: Blucher Design Proceedings, vol.3, pp. 907–913. http://dx.doi.org/10.5151/despro-sigradi2016-448.

Anderl, R., Trippner, D., 2000. STEP – STandard for the Exchange of Product Model Data, Eine Einführung in Die Entwicklung, Implementierung Und Industrielle Nutzung Der Normenreihe ISO 10303 (STEP). Teubner, Stuttgart, Leipzig, http://dx.doi.org/10.1007/978-3-322-89096-2.

Arnold, F., Podehl, G., 1999. Best of both worlds – a mapping from EXPRESS-G to UML. In: Bézivin, J., Muller, P.-A. (Eds.), The Unified Modeling Language. In: Lecture Notes in Computer Science, Springer, Berlin, Heidelberg, pp. 49–63. http://dx.doi.org/10.1007/978-3-540-48480-6_5.

Austrian Standards, 2001. ÖNORM B 2203-1:2001-12-01. In: Untertagebauarbeiten – Werkvertragsnorm. Zyklischer Vortrieb, Teil 1.

Austrian Standards, 2021. ÖNORM B 2118:2021-12-01. In: Allgemeine Vertragsbestimmungen für Bauleistungen unter Anwendung des Partnerschaftsmodells, insbesondere bei Großprojekten – Werkvertragsnorm.

Borrmann, A., König, M., Koch, C., Beetz, J. (Eds.), 2021. Building information modeling, technologische grundlagen und industrielle praxis, Second ed. VDI-Buch, Springer Vieweg, Wiesbaden, http://dx.doi.org/10.1007/978-3-658-33361-4.

BuildingSMART International (bSI), 1999. Industry foundation classes 2x specification. URL https://standards.buildingsmart.org/IFC/RELEASE/IFC2x/FINAL/.

BuildingSMART International (bSI), 2020a. IFC-Tunnel Project, Report WP2: Requirements analysis report (RAR). techreport, buildingSMART International, URL https://app.box.com/s/3p28520cgser0sa1bvunhc99bt4qhuza.

BuildingSMART International (bSI), 2020b. Technical Roadmap buildingSMART, Getting ready for the future. techreport, buildingSMART International, URL https://www.buildingsmart.org/wp-content/uploads/2020/09/20200430_buildingSMART_Technical_Roadmap.pdf.

BuildingSMART International (bSI), 2021. Industry foundation classes 4.3 specification. URL https://standards.buildingsmart.org/IFC/RELEASE/IFC4_3_0_0/.

Curry, E., O'Donnell, J., Corry, E., Hasan, S., Keane, M., O'Riain, S., 2013. Linking building data in the cloud: Integrating cross-domain building data using linked data. Adv. Eng. Inform. 27 (2), 206–219. http://dx.doi.org/10.1016/j.aei.2012.10.003.

Daller, J., Žibert, M., Exinger, C., Lah, M., 2016. Implementation of BIM in the tunnel design – engineering consultant's aspect. Geomech. Tunn. 9 (6), 674–683. http://dx.doi.org/10.1002/geot.201600054.

Eastman, C.M., Jeong, Y.-S., Sacks, R., Kaner, I., 2010. Exchange model and exchange object concepts for implementation of national BIM standards. J. Comput. Civ. Eng. 24 (1), 25–34. http://dx.doi.org/10.1061/(ASCE)0887-3801(2010)24:1(25).

Eastman, C., Teicholz, P., Sacks, R., Liston, K., 2011. BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, second ed. John Wiley & Sons.

European Commission, 2017. New European Interoperability Framework, Promoting Seamless Services and Data Flows for European Public Administrations. Publications Office, Luxembourg, http://dx.doi.org/10.2799/78681.

Froese, T., Grobler, F., Ritzenthaler, J., Yu, K., Akinci, B., Akbas, R., Koo, B., Barron, A., Kunz, J., 1999. Industry foundation classes for project management — A trial implementation. ITcon 4, 17–36, URL http://www.itcon.org/1999/2.

Fuchs, S., Katranuschkov, P., Scherer, R., 2010. A framework for multi-model collaboration and visualisation. In: Menzel, K., Scherer, R. (Eds.), EWork and EBusiness in Architecture, Engineering and Construction. CRC Press, London, UK, pp. 115–120. http://dx.doi.org/10.1201/b10527.

Galler, R., 2016. Research@ZaB – Start of construction of the "ZaB – Zentrum am Berg" research and development, training and education centre / Research@ZaB – Baubeginn für das Forschungs- und Entwicklungs- sowie Trainings- und Schulungszentrum Zentrum am Berg. Geomech. Tunn. 9 (6), 715–725. http://dx.doi.org/10.1002/geot.201620062.

Girmscheid, G., 2013. Bauprozesse und Bauverfahren des Tunnelbaus, third ed. Ernst & Sohn, Berlin, Germany.

Hegemann, F., Lehner, K., König, M., 2012. IFC-based product modeling for tunnel boring machines. In: Gudnason, G., Scherer, R. (Eds.), EWork and EBusiness in Architecture, Engineering and Construction. CRC Press, London, UK, pp. 289–296. http://dx.doi.org/10.1201/b12516-47.

Hiremath, H.R., Skibniewski, M.J., 2004. Object-oriented modeling of construction processes by unified modeling language. Autom. Constr. 13 (4), 447–468. http://dx.doi.org/10.1016/j.autcon.2003.09.011.

Huang, M., Ninić, J., Zhang, Q., 2021. BIM, machine learning and computer vision techniques in underground construction: Current status and future perspectives. Tunn. Undergr. Space Technol. 108, 103677. http://dx.doi.org/10.1016/j.tust.2020.103677.

Huang, M., Zhu, H., Ninić, J., Zhang, Q., 2022. Multi-LOD bim for underground metro station: Interoperability and design-to-design enhancement. Tunn. Undergr. Space Technol. 119, 104232. http://dx.doi.org/10.1016/j.tust.2021.104232.

Huymajer, M., Operta, D., Mazak-Huemer, A., Huemer, C., 2022a. The tunneling information management system – a tool for documenting the tunneling process in NATM projects. Geomech. Tunn. 15 (3), 259–264. http://dx.doi.org/10.1002/geot.202100064.

Huymajer, M., Woegerbauer, M., Winkler, L., Mazak-Huemer, A., Biedermann, H., 2022b. An interdisciplinary systematic review on sustainability in tunneling—Bibliometrics, challenges, and solutions. Sustainabil. 14 (4), http://dx.doi.org/10.3390/su14042275.

International Electrotechnical Commission (IEC), 2013a. IEC 62264-1:2013, enterprise-control system integration – part 1: Models and terminology.

International Electrotechnical Commission (IEC), 2013b. IEC 62264-2:2013, enterprise-control system integration – part 2: Objects and attributes for enterprise-control system integration.

International Federation of Consulting Engineers (FIDIC), 2019b. General Conditions. International Federation of Consulting Engineers (FIDIC), pp. 1–138.

International Federation of Consulting Engineers (FIDIC), 2019c. Guidance for the Preparation of Particular Conditions. International Federation of Consulting Engineers (FIDIC), pp. 1–95.

International Organization for Standardization (ISO), 2013. ISO 16739, industry foundation classes (IFC) for data sharing in the construction and facility management industries.

International Organization for Standardization (ISO), 2016. ISO 10303-21, industrial automation systems and integration – product data representation and exchange – part 21: Implementation methods: Clear text encoding of the exchange structure.

International Organization for Standardization (ISO), 2018. EN ISO 19650-1, organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 1: Concepts and principles.

International Tunneling and Underground Space Association (ITA), 2019. Tunnel Market Survey 2019. resreport, International Tunneling and Underground Space Association, URL http://www.societaitalianagallerie.it/notizia/1618/global-market-survey-ita/download/5820/.

International Tunneling and Underground Space Association (ITA), 2021. The ITA Contractual Framework Checklist for Subsurface Construction Contracts, techreport, Second Edition International Tunneling and Underground Space Association, URL https://about.ita-aites.org/news/download/1903_96d66759e8ac241eb6b320718c7f867c.

Internet Assigned Numbers Authority (IANA), 2022. Media types. URL https://www.iana.org/assignments/media-types/media-types.xhtml.

Jiang, S., Jiang, L., Han, Y., Wu, Z., Wang, N., 2019. OpenBIM: An enabling solution for information interoperability. Appl. Sci. 9 (24), http://dx.doi.org/10.3390/app9245358.

Jubierre, J.R., Borrmann, A., 2014. A multi-scale product model for shield tunnels based on the Industry Foundation Classes. techreport, Technische Universität München, https://www.cms.bgu.tum.de/images/forschung/IfcTunnel/IFC-Tunnel%20Documentation.pdf.

Kvasina, G., 2018. Dokumentation bei zyklischem Tunnelvortrieb, Erhebung von wesentlichen Parametern von Bauzeit und Kosten als Grundlage für ein digitales Modell. (Master's thesis). TU Wien, http://dx.doi.org/10.34726/hss.2018.43926.

Kvasina, G., Goger, G., Huymajer, M., 2018. Dokumentation bei zyklischem Tunnelvortrieb, Wesentliche Parameter als Grundlage für ein digitales Modell. bau aktuell 9 (4), 155–161, URL http://www.lindedigital.at/doc-id/art-bauaktuell-2018-04-155a.

Lee, S.-H., Park, S.I., Park, J., 2016. Development of an IFC-based data schema for the design information representation of the NATM tunnel. KSCE J. Civ. Eng. 20 (6), 2112–2123. http://dx.doi.org/10.1007/s12205-015-0123-8.

Lee, P.-C., Wang, Y., Lo, T.-P., Long, D., 2018. An integrated system framework of building information modelling and geographical information system for utility tunnel maintenance management. Tunn. Undergr. Space Technol. 79, 263–273. http://dx.doi.org/10.1016/j.tust.2018.05.010.

Lensing, R., 2016. BIM and Construction Process Data in Mechanized Tunnel Construction, Milestone Control for Tunnel Construction Sites Using Automatically Created Process Data in Comparison With 4D BIM. (Master's thesis). Universität Salzburg, http://unigis.sbg.ac.at/files/Mastertheses/Full/103255.pdf.

Maidl, B., Thewes, M., Maidl, U., 2013. Handbook of Tunnel Engineering, Structures and Methods, Vol. 1. Ernst & Sohn, Berlin, http://dx.doi.org/10.1002/9783433603499.

Ninić, J., Koch, C., Vonthron, A., Tizani, W., König, M., 2020. Integrated parametric multi-level information and numerical modelling of mechanised tunnelling projects. Adv. Eng. Inform. 43, 101011. http://dx.doi.org/10.1016/j.aei.2019.101011.

Open Geospatial Consortium (OGC), 2022a. OGC geoscience markup language (GeoSciML). URL https://www.ogc.org/standards/geosciml.

Open Geospatial Consortium (OGC), 2022b. OGC WaterML. URL https://www.ogc.org/standards/waterml.

Open Geospatial Consortium (OGC), 2023. Sensor model language (SensorML). URL https://www.ogc.org/standards/sensorml.

Panteli, C., Polycarpou, K., Morsink-Georgalli, F., Stasiuliene, L., Pupeikis, D., Jurelionis, A., Fokaides, P., 2020. Overview of BIM integration into the construction sector in European member states and European union acquis. IOP Conf. Series: Earth Environ. Sci. 410, http://dx.doi.org/10.1088/1755-1315/410/1/012073.

Providakis, S., Rogers, C.D., Chapman, D.N., 2019. Predictions of settlement risk induced by tunnelling using BIM and 3D visualization tools. Tunn. Undergr. Space Technol. 92, 103049. http://dx.doi.org/10.1016/j.tust.2019.103049.

Regateiro, F., Spínola, R., 2014. Challenges of building information modeling (BIM) in Portuguese public works contracts. In: 2nd European Conference on E-Public Procurement. ECPP, Observatório de Prospectiva da Engenharia e Tecnologia, pp. 209–220, URL http://www.opet.pt/index.php?option=com_content&task=view&id=60&Itemid=1.

Rothenberg, J., 1989. The nature of modeling. In: Widman, L.E., Loparo, K.A., Nielsen, N.R. (Eds.), Artificial Intelligence, Simulation, and Modeling. John Wiley & Sons, pp. 75–92.

Sabanovic, N., Wannenmacher, H., Stauch, F., Fentzloff, W., 2022. Demands on digital data capturing of TBM and conventional tunnel drives. Geomech. Tunn. 15 (2), 207–214. http://dx.doi.org/10.1002/geot.202100077.

Seidl, M., Scholz, M., Huemer, C., Kappel, G., 2015. UML @ classroom: An introduction to object-oriented modeling. In: UML @ Classroom. In: Undergraduate topics in computer science, Springer International Publishing, Cham, Switzerland, http://dx.doi.org/10.1007/978-3-319-12742-2.

Sharafat, A., Khan, M.S., Latif, K., Seo, J., 2021. BIM-based tunnel information modeling framework for visualization, management, and simulation of drill-and-blast tunneling projects. J. Comput. Civ. Eng. 35 (2), 04020068. http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000955.

Shelden, D.R., Pauwels, P., Pishdad-Bozorgi, P., Tang, S., 2020. Data standards and data exchange for construction 4.0. In: Sawhney, A., Riley, M., Irizarry, J. (Eds.), Construction 4.0. Routledge, Abingdon-on-Thames, Oxfordshire, England, UK, pp. 222–239. http://dx.doi.org/10.1201/9780429398100.

van Berlo, L.A., Krijnen, T., Tauscher, H., Liebich, T., van Kranenburg, A., Paasiala, P., 2021. Future of the industry foundation classes: Towards IFC 5. In: Proceedings of the 38th International Conference of CIB W78. pp. 1–15, URL https://itc.scix.net/pdfs/w78-2021-paper-013.pdf.

Vilgertshofer, S., Jubierre, J.R., Borrmann, A., 2016. IfcTunnel – a proposal for a multi-scale extension of the IFC data model for shield tunnels under consideration of downward compatibility aspects. In: Christodoulou, S.E., Scherer, R. (Eds.), EWork and EBusiness in Architecture, Engineering and Construction. CRC Press, London, UK, pp. 175–182. http://dx.doi.org/10.1201/9781315386904.

Winkler, L., Melnyk, O., Goger, G., 2022. Prerequisites for BIM-based invoicing in NATM projects. Geomech. Tunn. 15 (3), 279–283. http://dx.doi.org/10.1002/geot.202100067.

Xue, W., Wang, Y., Man, Q., 2015. Research on information models for the construction schedule management based on the IFC standard. J. Ind. Eng. Manag. 8 (3), http://dx.doi.org/10.3926/jiem.1283.

Yabuki, N., 2008. Representation of caves in a shield tunnel product model. In: Zarli, A., Scherer, R. (Eds.), EWork and EBusiness in Architecture, Engineering and Construction. CRC Press, London, UK, pp. 545–550. http://dx.doi.org/10.1201/9780203883327.

Yabuki, N., Aruga, T., Furuya, H., 2013. Development and application of a product model for shield tunnels. In: Hassani, F., Moselhi, O., Haas, C. (Eds.), Proceedings of the 30th International Symposium on Automation and Robotics in Construction. International Association for Automation and Robotics in Construction (IAARC), pp. 435–447. http://dx.doi.org/10.22260/ISARC2013/0047.

Yang, B., Dong, M., Wang, C., Liu, B., Wang, Z., Zhang, B., 2021. IFC-based 4D construction management information model of prefabricated buildings and its application in graph database. Appl. Sci. 11 (16), http://dx.doi.org/10.3390/app11167270.

Further reading

International Federation of Consulting Engineers (FIDIC), 2019a. Conditions of Contract for Underground Works (Emerald book). International Federation of Consulting Engineers (FIDIC).