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Building Information Modeling in the execution phase of conventional tunneling projects

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ABSTRACT

Building Information Modeling (BIM) has become the key technology for the digital transformation of the architecture, engineering, and construction (AEC) sector. The Industry Foundation Classes (IFC), as an open and vendor-neutral data model, play an essential role in this transformation. Despite all the recent advances of BIM, tunneling needs to catch up with other AEC sectors adopting digital technologies. Currently, IFC is mainly used to capture information directly connected to the structural elements of the final tunnel but rarely as a means to document the tunnel excavation and support. This article proposes an IFC-driven process for the execution phase of conventional tunneling projects by extending the usage of IFC to information about the process, labor, equipment, and employed material. The proposed process is evaluated by a case study demonstrating how to represent data from a conventional tunneling project by IFC. The results show that IFC provides the necessary concepts to express the data of the execution phase of conventional tunneling projects. Implementing an IFC-driven process in this phase significantly contributes to the digital transformation of tunneling projects.

1. Introduction

An average of 5200 km of tunnels are being built annually worth an investment of € 125 billion (ITA, 2019). Tunneling is crucial to modern infrastructure, providing essential transportation and utility services. Tunnels are used for road, rail, and subway systems, water supply, sewage systems, power generation, and transmission networks (ITA, 2012). As such, tunneling technology has become increasingly sophisticated, focusing on sustainability, safety, and efficiency (Galler, 2014; Huymajer et al., 2022b). The importance of tunneling in modern infrastructure is likely to increase as population growth and urbanization continue to drive the demand for improved transportation and utility systems.

Tunnel construction is a complex and highly technical process involving various stakeholders, including owners, engineers, contractors, suppliers, and regulators (ITA, 2012). The process also involves many documents containing geotechnical, structural, mechanical, electrical, and safety information. These stakeholders often use different software applications that may not be compatible, leading to inefficiencies, miscommunications, and errors. Open standards, such as the Industry Foundation Classes (IFC), can help address these issues by providing an interoperable format, thus enabling data exchange between software applications. Such data exchange alleviates the need for conversion to proprietary data formats or manual data entry, potentially saving time, reducing errors, and improving data quality.

Conventional tunneling, or the so-called cyclic method, is characterized by repeatedly performing tasks of excavation and support (Girmscheid, 2013; Maidl et al., 2013). The excavation is frequently performed by employing excavators, roadheaders, or explosives, which is why the latter case is called drill and blast tunneling. The New Austrian Tunneling Method (NATM) is a particular conventional tunneling method employing continuous monitoring and adjusting the type and amount of support measures to the local geological and hydrological conditions (Galler, 2010; Galler et al., 2009; Stipek et al., 2012). The surrounding rock is primarily supported with shotcrete and bolts.

The excavation and support documentation, including detailed records about the project's costs, progress, quality, and safety, is essential to any conventional tunneling project. Accurate and complete documentation allows for making informed decisions to optimize the project's progress continuously while maintaining the necessary safety and quality standards (Kvasina et al., 2018; Winkler et al.,

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2022; Schiefer, 2018). However, the documentation tools of today's tunneling projects are hardly standardized. Instead, every tunneling project adopts its specific approach to documentation, which negatively impacts interoperability. Beyond that, data exchange in today's tunneling projects still relies heavily on exchanging paper-based documents or unstructured digital data. Such an approach is costly and time-consuming because the data are not machine-readable and impede the smooth data flow between parties. Another drawback is the time lag between data generation and subsequent processing, which challenges tunneling project management.

Building Information Modeling (BIM) is the apparent solution to those challenges. However, applying BIM to conventional tunneling projects is not straightforward and lags behind other architecture, engineering, and construction (AEC) sectors (Mitelman and Gurevich, 2021; Costin et al., 2018). Another issue is that digital data exchange predominantly utilizes proprietary data formats. This is related to the fact that standard software tools are hardly interoperable and frequently do not fulfill functional requirements (Žibert et al., 2018).

International open standards are the basis for interoperability between different stakeholders, and IFC has become the most widely adopted open BIM standard (Jiang et al., 2019). It allows for a machine-readable, semantic-rich, and manufacturer-independent data exchange (ISO, 2018). However, IFC's flexibility makes the semantic description ambiguous, creating interoperability issues. Thus, ensuring that the data exchanged is accurate, complete, and consistent is essential. Although IFC has already been partially used in planning several tunnel construction projects, such as the Gotthard Base Tunnel in Switzerland (EBP, 2019), IFC has rarely been used in the execution phase of tunneling projects. For this reason, Huymajer et al. (2024) proposed an implementation guide to express domain concepts using a specific subset of IFC constructs to assist software solution providers in developing interoperable tools for the execution phase of conventional tunneling projects.

The current paper reports on an IFC implementation that enables automated data exchange during the execution phase of tunnel construction projects. It complements the implementation guide of Huymajer et al. (2024) and illustrates the corresponding documentation process for conventional tunneling projects enabling full IFC-based data exchange. Additionally, it evaluates the IFC model with real data from the construction of the research tunnel at the Zentrum am Berg[1] (ZaB) (Galler, 2016) and connects the model with 3D geometry.

The rest of the article is organized as follows: Section 2 provides an overview of the related work. Section 3 deals with the status quo of documentation in conventional tunneling. IFC-supported workflow used for the digital representation of the excavation and support documentation is discussed in Section 4. Section 5 presents a case study of employing an IFC reference model to data from the construction phase of the ZaB. Section 6 concludes this paper with lessons learned.

2. Related work

Compared to the overall number of publications on BIM, only a few authors have addressed the peculiarity of BIM in the execution phase of conventional tunneling. Therefore, this section discusses BIM in a broad scope, including other construction subsectors.

2.1. Building information modeling

BIM applications in tunneling are gaining attention in the research community (Huang et al., 2021). BIM has a broad range of potential applications, from predicting subsidence risk due to tunneling (Providakis et al., 2019) to managing the maintenance of public tunnels (Lee et al., 2018).

IFC is widely considered a key technology for implementing BIM (Borrmann et al., 2021; Jiang et al., 2019). IFC is a data model for the AEC sector maintained by buildingSMART International[2] (bSI), allowing semantically rich building data to be exchanged. IFC Version 4 has been approved as the ISO 16739 standard by the International Organization for Standardization (ISO, 2018), and government agencies in many countries require IFC to share data (Panteli et al., 2020). While IFC was initially conceived as a file-based approach, bSI recognizes the need for a standardized application programming interface (API) that enables object-based querying of IFC data (van Berlo et al., 2021; bSI, 2020). The most common serialization format for STEP (STandard for the Exchange of Product Model Data) models is the STEP Physical File Format (SPFF), approved as ISO 10303-21 (ISO, 2016). Besides SPFF, other serialization formats, such as ifcXML, ifcOWL, and ifcJSON, have been proposed for IFC models (Shelden et al., 2020).

The capabilities of IFC go far beyond describing only geometric characteristics. For example, `IfcCostItem` is an IFC entity used in the construction industry to represent cost information related to building and infrastructure projects (bSI, 2021). It provides a standardized way to store and exchange cost data between software applications and stakeholders involved in the project. The `IfcCostItem` entity can represent various cost items such as material, labor, equipment, and contingency costs (Cassandro et al., 2023). The entity also contains currency, date of cost calculation, and cost type classification. Xue et al. (2015) explore implementing and expanding the IFC standard in construction schedule management. The authors conclude that an extended IFC model can describe all aspects of schedule management, including cost, resource, quality, and risk management. Regateiro and Spínola (2014) found that IFC could be useful in estimating costs for a Portuguese public works contract.

Whereas BIM strives to be a process spanning the whole lifecycle of a building, more specific solutions have also been created, e.g., national standards for data exchange during tendering and invoicing have been defined (GAEB, 2023a; Austrian Standards, 2021a). Ye and König (2020) proposed utilizing smart contracts, which, together with digital construction site documentation, allow for an automated invoicing of construction projects.

2.2. Building information modeling in tunneling

Even though BIM is an established concept in AEC, many experts see the need to catch up in implementing BIM in tunneling. Costin et al. (2018) reviewed the literature on BIM for transportation infrastructure. They showed that tunnels had gained considerably less attention in the scientific community than other transportation structures, such as bridges, highways, and rail infrastructure. This is also showcased by Vrublevskaya (2021), who showed that limited case studies exist employing BIM in the execution phase of tunnel construction.

Data integration, project visualization, cost savings, planning and scheduling, building lifecycle management, and decision support can benefit from employing BIM in tunneling projects (Yin et al., 2020; Sharafat et al., 2021). On the other hand, the low level of digitalization in construction, its limited innovativeness, and human suspicion of BIM have been identified as possible barriers to BIM in tunneling.

Koch et al. (2017) proposed a model for tunneling projects using a tunnel boring machine (TBM), while Lensing (2016) serialized data from a TBM into JavaScript Object Notation (JSON) to compare it with a BIM model. Stascheit et al. (2018) discuss the application of BIM in shield tunneling projects and its benefits in the design, construction, and operation phases.

Only a few papers are available on BIM applications in the operation and maintenance phase. For instance, Lee et al. (2018) discuss

[1] https://www.zab.at/

[2] https://www.buildingsmart.org/

a maintenance management system for utility tunnels integrating BIM and geographic information system (GIS) technology.

Most publications on IFC in tunneling focus primarily on tunnel design, underscoring the requirement for a more thorough exploration of BIM's role in executing conventional tunneling projects.

2.3. Building information modeling in the execution of conventional tunneling projects

Kvasina (2018) investigated the documentation process based on two different NATM projects. She found that the documentation process is complex, and transitioning from paper-based data exchanges to a fully automated digital one can save time and money. Schiefer (2018) comes to the same conclusion in a similar work.

Baraibar et al. (2022) reported on a BIM implementation in the execution phase of a drill-and-blast tunnel. However, their results show that primarily unstructured data, such as raster graphics, vector graphics, text documents, and spreadsheets, are exchanged. Mitelman and Gurevich (2021) distinguish between the tunnel's architectural domain (AD) and structural domain (SD). The authors propose a methodology for the SD in which data from the excavation rounds are gathered in a cloud-shared spreadsheet table, and these data are later annotated in a Revit model. Their approach was designed from the perspective of a governmental procurement agency. Still, this coarse data model may not fulfill the parties' requirements in executing the excavation work. Li et al. (2021) utilize BIM to simulate a highway tunnel's construction schedule and construction costs. Despite that, they used a cloud platform to share construction management photos and quality and safety problems. The authors conclude that construction management data could not be exchanged due to the lack of a standardized data format. Fentzloff and Classen (2019) described their experience with BIM in the "Albvorland Tunnel" project. They report that a 3D model could support the planning process, and linking the model with schedule and costs could serve a reporting purpose. The analyzed literature suggests that BIM is used in the execution phase of conventional tunneling projects. However, there is no indication of a fully digital process starting at the tunnel face. Publications suggest that conventional tools are used to document the tunnel excavation and support, and these data are only later put into 3D authoring software like Revit.

Winkler et al. (2022) discuss concepts for BIM-based documentation and invoicing of tunnel construction projects using the NATM. The authors propose a workflow with a digital on-site data recording tool and a BIM-based project element list that can be integrated with invoicing software. Huymajer et al. (2022a) presented a data model of a Tunneling Information Management System (TIMS) capable of capturing invoicing-relevant information from conventional tunnel construction projects. Sabanovic et al. (2022) developed a prototype of a data entry tool for mobile devices used in conventional tunneling projects. Given the enormous volume of information, integrating the data into other systems, possibly across organization boundaries, is essential. Melnyk et al. (2023a) proposed a data model supporting a digital invoicing process for conventional tunneling projects. The authors validated their proposal with data from the ZaB.

Huymajer et al. (2024) examined the IFC standard for concepts to model essential information from the execution phase of conventional tunneling projects. They demonstrated how to employ those concepts for serializing rudimentary data of a tunnel round into an IFC STEP file.

3. Status quo of documentation in conventional tunneling

This section discusses the process of documenting conventional tunneling projects. While several aspects of this process may resemble documentation in other construction projects, tunneling projects possess unique characteristics reflected in their documentation requirements. Two notable characteristics are the inherent uncertainty associated with subsurface physical conditions, such as geology and hydrology, and the extensive utilization of temporary support structures that are subsequently removed during excavation.

3.1. Project organization

It is beneficial to acquire a preliminary understanding of the project organization typically employed in conventional tunneling projects to understand the documentation procedure associated with the tunnel excavation and support. For this purpose, we use ArchiMate, a description language for enterprise architecture (EA) released by the Open Group[3] (The Open Group, 2022; Lankhorst et al., 2010). Lankhorst (2017) defines EA as "*a coherent whole of principles, methods, and models used to design and realize an enterprise's organizational structure, business processes, information systems, and infrastructure*". Nevertheless, our intention is not to provide a comprehensive depiction of a construction company's EA but rather to employ ArchiMate to illustrate the most pertinent concepts for this paper. While ArchiMate itself does not attribute specific semantics to colors, we adopt a comparable color scheme as found in the online documentation of the ArchiMate specification (The Open Group, 2022). In Figs. 1 and 2, business layer elements are represented in orange ●, elements related to the application layer are visualized in blue ●, and elements representing a location are shown in red ●. Fig. 1 gives a highly simplified ArchiMate description of concepts related to the documentation process of the tunneling excavation and support. The entity responsible for initiating a construction project, often referred to as the *employer* or project owner, engages the services of a company, commonly known as the *contractor*, to undertake the excavation and support activities associated with a conventional tunnel. These activities are performed by dedicated tunneling divisions within a construction company or company specializing in tunneling projects. Under most contracts, the employer takes over the risk associated with unexpected ground conditions, while the contractor executes the project under the conditions stipulated in the contract (Galler et al., 2009; FIDIC, 2019b; Austrian Standards, 2021b; Melnyk et al., 2023b). During the execution phase of the tunneling project, the majority of personnel dealing with the project is located close to the construction site. The personnel consists of multiple teams of miners working at the tunnel face and performing the *excavation and support* tasks in the tunnel. The *site management* is responsible for the overall leadership and management of the tunneling project. The on-site team also includes a unit conducting the intricate *invoicing* process and a *construction cost accounting* for tasks such as material supply and payroll management. The project is usually monitored by a *project controlling* and supported by functionally organized business units, such as accounting. These business units are typically located at corporate headquarters and work in a cross-project manner. The employer has a dedicated unit or commissions a third party for the overall *site supervision* of the construction work. This roughly matches the engineer's role, as defined by the International Federation of Consulting Engineers (FIDIC) (FIDIC, 2019b). It should be noted that some projects involve other parties, such as a tunnel designer, a geologist, a geotechnical engineer, or a surveyor (Galler, 2010; Kvasina, 2018). However, these are outside the focus of this paper.

3.2. Contractual issues

Construction contracts can be distinguished into lump sum contracts, unit rates contracts, cost plus fee contracts, and turnkey contracts. With the Emerald Book (FIDIC, 2019a), the FIDIC has published a contractual framework for underground works. Depending on the type of contract, the tendering and invoicing process of construction projects is based on the so-called bill of quantities (BoQ). A BoQ is an extensive hierarchical list of materials, elements, and services together with the estimated quantity and unit prices. This structure and the specific items of the BoQ are chosen on a case-by-case for every construction project (Melnyk et al., 2023b). Standardized BoQ catalogs exist for

[3] https://www.opengroup.org/

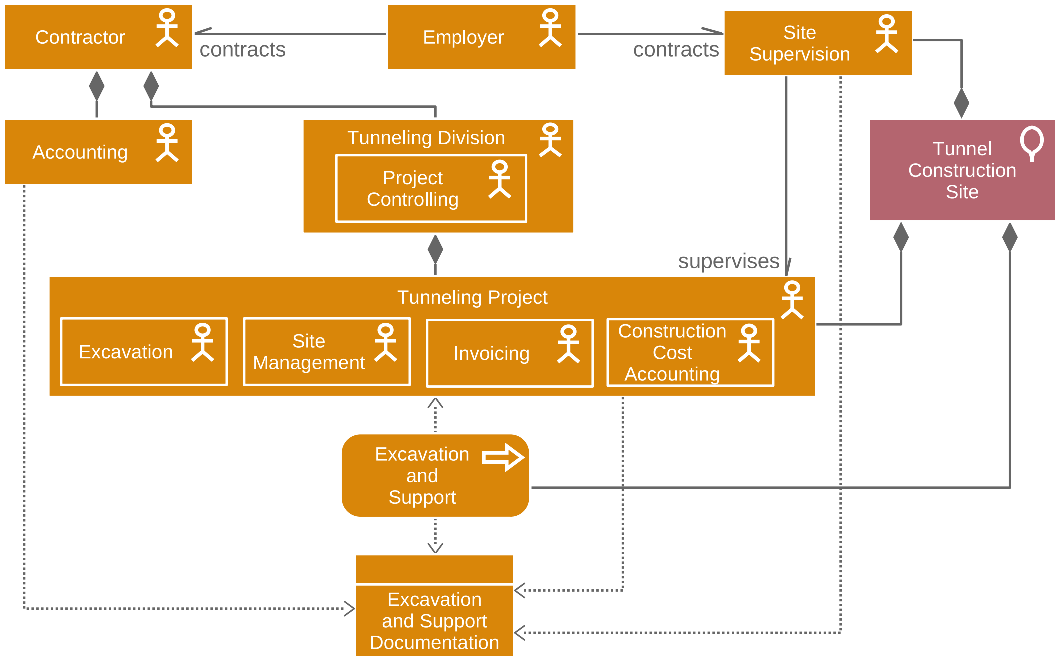

Fig. 1. ArchiMate model of concepts relevant to the documentation process of conventional tunneling projects.

the tunneling sub-sector in some countries, such as Austria (FSV, 2021). Other countries, such as Germany, have adopted standardized catalogs but do not yet include tunneling-specific items (GAEB, 2023b). The type of contract has implications on how the documentation process is implemented for a particular project, as will become apparent in the remainder of the section.

3.3. Documents

The documentation of information from the tunnel excavation and support is essential for efficiently managing conventional tunneling projects. Accordingly, this section provides an overview of the process involved in documenting such information.

Due to the complexity of conventional tunneling projects, there is not a single type of document containing all the information (Winkler et al., 2022; Wenighofer et al., 2020; Kvasina, 2018; Schiefer, 2018; Alkhaddour, 2021). Instead, the documentation often consists of many types of reports, protocols, records, notes, and multimedia, mainly serving a specific purpose. Frequently, the documents contain redundant information such that one document contains overlapping information or derived information from another document. The specific documentation setup depends on the project and is agreed upon in the contract. Even the name for a type of document often varies between different contractors. Some of these documents are illustrated in Fig. 2 as the yellow business objects ●, forming the tunnel excavation and support documentation.

The *support definition* is a document jointly created by the site supervision and the contractor. Thereby, a geologist and a geotechnical engineer play a consultant role by preparing advisory reports. In line with the principles of the NATM, it allows for flexible responses to local geological and hydrological conditions. The *shift report* is a tunneling-specific document containing records of the exact timing of the tasks performed, the involved personnel, employed material, and used equipment. The *excavation and support report* is similar to the shift report but contains data mainly used during invoicing. Both documents are based on data on the work of the tunneling crew. Most regulations require the contractor to keep a *site diary*, builder's construction diary, or daily records (Austrian Standards, 2021b; Stiftinger et al., 2019; Jochem and Kaufhold, 2016; Sawyer and Gillott, 1990). While the content of site diaries overlaps significantly with the documents mentioned above, they also include additional information such as weather conditions, communication details with subcontractors and the employer, and other relevant observations or events. The *admeasure report* or site measuring records any works to be invoiced separately from the regular tunnel invoicing based on the excavation and support report. The case study in Section 5 will present examples of some of the mentioned documents. Depending on the project, further documents, such as geological or acceptance reports, exist (Schiefer, 2018), which are not discussed in this paper. Overall, most documents include five main categories of data: process details, labor information, equipment used, consumed materials, and general data. Those categories are modeled in Fig. 2 as blue data objects ●.

The documentation of conventional tunneling projects fulfills different purposes. First, contractual obligations exist for recording and sharing specific information. For example, the FIDIC (2019b) requires the contractor to document certain information, known as the contractor's records, including the working hours of personnel and equipment, the types of temporary works utilized, the types of installed plants, and the quantities and types of materials used. Local standards, such as the Austrian standard ÖNORM B 2118 (Austrian Standards, 2021b), require the parties to document all occurrences that affect the execution of works and their invoicing. Specifically, these data are the foundation for the invoice or claim process. The contractor could also be obligated to take so-called as-built records, including the locations, amounts, and other details of the work performed (FIDIC, 2019b). In projects employing BIM, there are typically two documents: the so-called Employer's Information Requirements (EIR) (formerly known as Exchange Information Requirements) and the BIM Execution Plan (BEP) (Borrmann et al., 2021; Walker and Rowlinson, 2019). These documents are part of the building contract and contain detailed specifications on the data exchange between employer and contractor. Secondly, the documentation serves technical purposes. Continuous geotechnical monitoring is a core element of the NATM to achieve adequate support (Galler, 2010; Galler et al., 2009). The monitoring includes the measurement of displacements of the tunnel lining and surface subsidences along the constructed tunnel. These measurement data need to be appropriately documented. Thirdly, the contractor collects data beyond those objectives, enabling them to manage complex tunneling

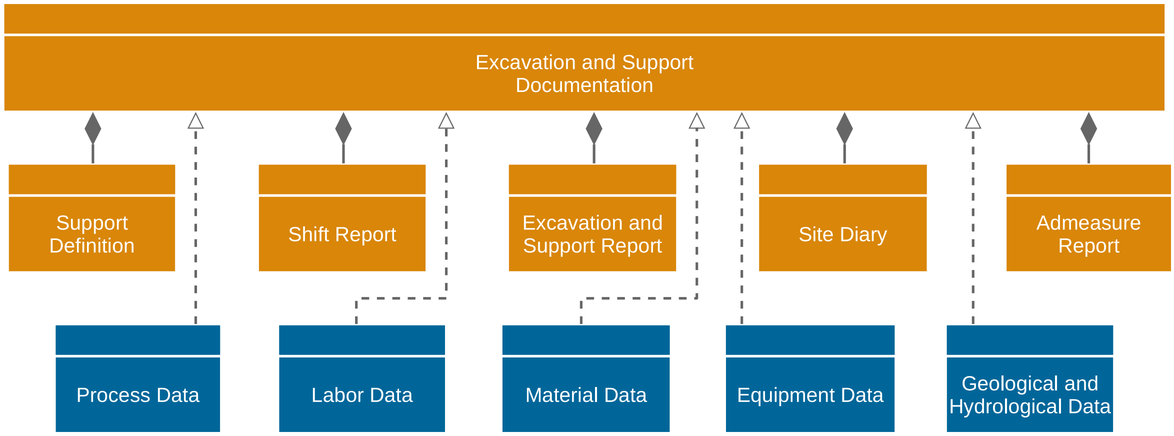

Fig. 2. An ArchiMate model of the tunnel excavation and support documentation.

projects effectively. This broader data collection gives the contractor valuable insights and information for optimizing the project's execution and overall management.

3.4. Documentation process

This subsection outlines the excavation documentation process from the data generation to different data recipients inside and outside the contractor. The process model is based on our experience as an employer during the construction of the ZaB while considering our previous research on this topic (Kvasina, 2018; Stift, 2023).

We use Business Process Model and Notation (BPMN) version 2.0 process diagrams to visualize this process (OMG, 2013; Allweyer, 2016). BPMN is a business process modeling standard released by the Object Management Group[4] (OMG). Although some issues with BPMN, such as semantic ambiguities, have been identified (Kossak et al., 2014), the number of construction and BIM-related publications show that BPMN is well-accepted in the AEC community.

Comparing previous research and the experiences at the ZaB, we conclude that the exact implementation of the documentation process varies across different contractors and even across projects within the same contractor. Hence, we present a generalized view of the documentation process involved in conventional tunneling projects as a foundation for the IFC-driven proposal outlined in Section 4. For the sake of simplicity, we only discuss the regular workflow. BPMN provides the concept of exceptions to model deviations from the regular workflow. As handling exceptional cases does not contribute to understanding the documentation process, we omit them to keep the model concise.

Fig. 3 shows a BPMN process diagram of a conventional documentation process. Circles represent start or end events, gray rectangles represent activities, and diamonds represent joining or splitting nodes, so-called gateways. Arrows with solid lines represent sequence flows, lines with dotted lines represent dataflows, and arrows with dashed lines represent message flows. Data or message flows utilizing IFC data are visualized in turquoise. The contractor and the site supervisor are the two main stakeholders in the construction, represented by the pools labeled *contractor* and *site supervision*, respectively. According to the OMG (2013), a process must be fully contained within a pool. Thus, in BPMN semantics, the diagram shows two different processes — one for the contractor and one for the site supervision. We partition the contractor process into two lanes, *on-site* and *off-site*, and further subpartition these lanes according to different business units *excavation*, *site management*, *invoicing*, *construction cost accounting*, *project controlling*, and *accounting* (c.f. Fig. 1).

The responsibility for preparing the excavation and support documentation lies primarily with the contractor. The documentation process starts in the lane *excavation*. The contractor performs the task of a tunneling round, e.g., the installation of a rock bolt according to the *support definition*. During the excavation work, the foreman manually records precise timings for each task and notes the exact quantity and type of materials used. The latter includes installed material of the final tunnel (such as a rock bolt), consumed materials (such as explosives), or temporary ground support (such as temporary shotcrete). When the shift is finished, different documents are prepared, namely the *shift report*, the *excavation and support report*, and the *admeasure report*.

Depending on the contract terms, a specific subset of the data is shared with the *site supervision*, shown in Fig. 3 as a message exchange. Creating the documents triggers an event where the site supervision receives all the data specified in the contract. Following a thorough review of the documents, a message exchange is initiated to notify the contractor about the confirmation.

The process continues in the lane *site management*. The site management keeps the site diary. The entry to the site diary is sent to the employer, which is modeled as a message exchange. The documents are also internally used by the contractor. The site management creates highly aggregated reports, periodically sent to the *project controlling* for review.

Based on the documents created during excavation, the *invoicing* unit manually maintains a spreadsheet containing all works and materials to be invoiced. All relevant invoicing data are transferred to specialized construction management (CM) software while creating the invoices at the end of the invoicing period.

The process model shows that further business units within the contractor utilize different parts of these data originating from the excavation. For instance, the *construction cost accountant* uses the shift reports to enter the working time into a project management (PM) tool, which the *accounting* department later uses to create the pay slips.

Fig. 3 and the description reveal multiple drawbacks of the current documentation process. Data are redundantly entered, manually processed, or stored, requiring considerable effort. Manual processing bears the risk of mistakes leading to inconsistencies. Furthermore, the data is not readily accessible to all relevant stakeholders. Instead, files must be transmitted through email or uploaded to a cloud service. Unstructured data, such as scanned documents or spreadsheets, impede subsequent automatic processing and make enforcing integrity checks on the data impossible. Additionally, file exchange typically does not allow a fine-grained access control or a "content-aware" workflow. Finally, the integration of equipment-generated data in this workflow is complicated. Consequently, there is a growing need for a BIM-supported documentation process, which is proposed in the subsequent section.

[4] https://www.omg.org/

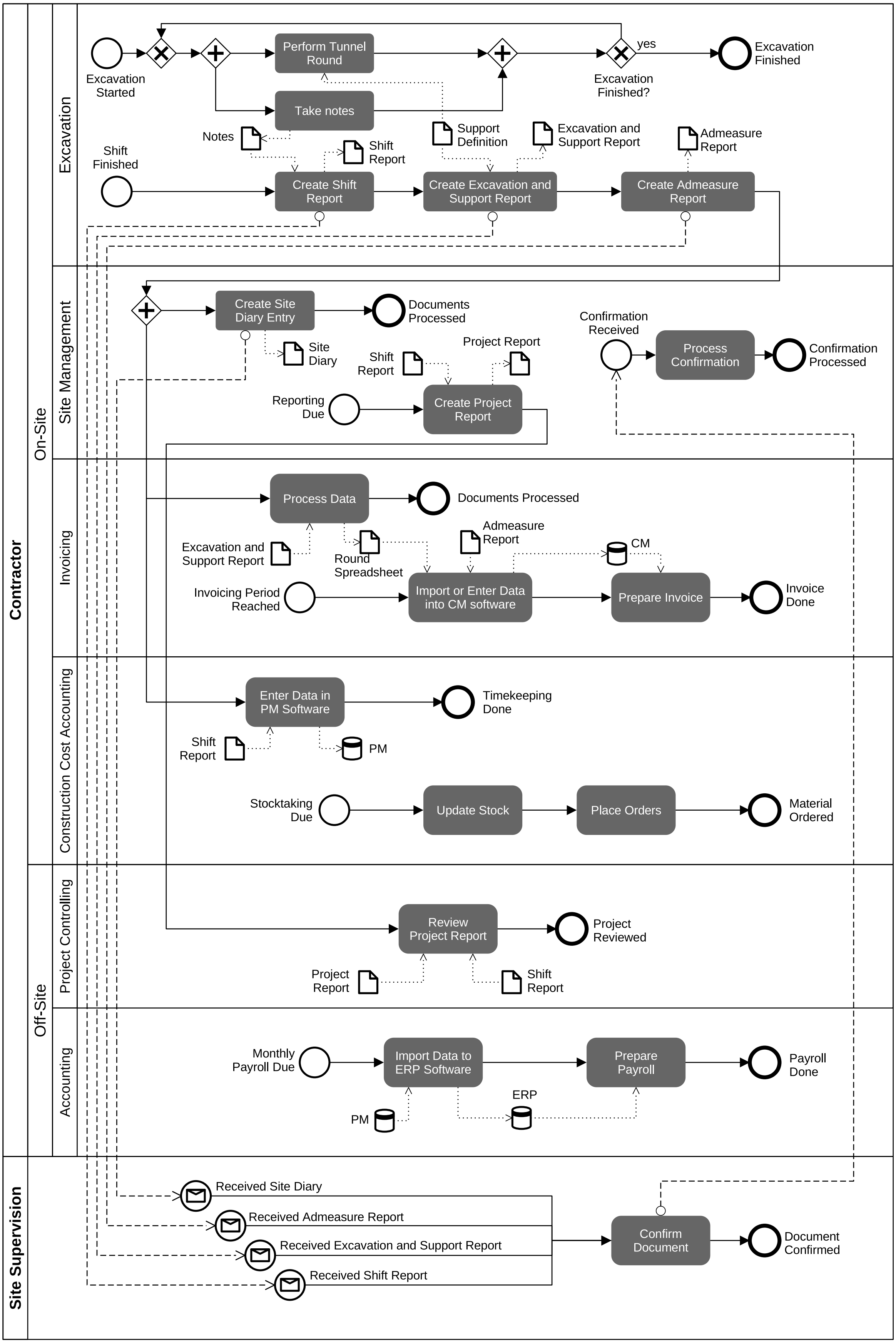

Fig. 3. A BPMN model of a conventional tunneling documentation process.

4. BIM-supported documentation process employing IFC

Based on a conventional documentation process discussed in the previous section, this section proposes a BIM-supported documentation process utilizing IFC-based data exchange. The proposed process should incorporate the guideline for IFC-based documentation in conventional tunneling projects presented by Huymajer et al. (2024).

Fig. 4 shows the model of such a process. A tunneling-aware data management tool, a TIMS (Huymajer et al., 2022a), is essential to the IFC-supported process. It allows for capturing and managing all tunneling-related data, including processes, labor deployment, equipment, and material. Compared to BIM authoring tools, it allows for swift data entry directly at the tunnel face with a mobile device. Another difference is that it understands the semantics of different construction or tunneling-specific concepts, such as shifts, tunnel rounds, support measures, and tunneling classes (Melnyk et al., 2023a). The tool enables further consistency checks, preprocessing, and exporting of the data to different consumers, such as CM or enterprise resource planning (ERP) systems.

The data originates from the *excavation* work as in the conventional case. Support tasks are performed according to the support definition available in TIMS. That means that the default values for the support measures exist, and only deviations need to be documented. Additionally, the documentation of rounds includes the details on the task performed, other consumed materials, such as explosives, and any other noteworthy occurrences. Because a tunnel round can span across multiple shifts and a single shift can involve multiple rounds, shifts are documented independently from rounds. The documentation of shifts includes the involved personnel and the equipment employed. As shift schedules are created in advance, and the equipment is rarely changed during a project, default values for personnel and equipment are also available.

The documentation process continues at the *site management* when a tunnel round or a shift is finished. The site manager can check the data and, if necessary, correct any errors. Confirming a shift triggers an automatic push of relevant shift-related data to an ERP system or PM software, which, in particular, includes the working hours of the involved personnel. Similarly, confirming a round causes relevant round-related data, such as used materials, to be pushed to an ERP system.

The confirmation also involves automatically exchanging relevant IFC data with the *site supervision*. The scope of the IFC data thereby depends on the contractual agreement. The site supervision checks the data, and a settlement is reached with the contractor in case of discrepancies.

In general, the contractor is notified when the data are confirmed. This confirmation triggers a service that pushes all invoicing-relevant data to the CM software using the IFC format. The data include the exact timing of the tasks, used materials, employed equipment, construction progress, and any noteworthy incidents.

The invoicing is performed asynchronously in a time-triggered subprocess, typically monthly, at which the settled data of the period to be invoiced are already available in the CM software. The proceeding invoice handling is not tunneling-specific but follows the same workflow within the contractor as other invoices.

By keeping track of the material consumption in every round, the current stock level is always available in the ERP system, rendering frequent manual stocktaking unnecessary. Orders are placed when the order interval is reached and the stock level is forecasted to be low.

Creating dedicated project reports can be omitted as the *project controlling* can retrieve all the relevant information from TIMS or the CM software in real-time.

Data are digitalized at the very origin, at the tunnel face, and managed with TIMS or automatically exchanged with other systems or parties. Managing the data in TIMS or an equivalent system makes data or a subset immediately available to all authorized stakeholders. The process also provides the basis for exchanging machine-readable data, which can be reused in subsequent steps without manual intervention. The system can perform integrity checks, such as whether the number of installed support measures matches the ones mandated in the support definition. Employing specialized software tools allows for fine-grained access control following the organization and project policies. The same goes for the workflows, which can depend on the data. For example, support measures surpassing the stipulated amount in the support definition could require additional confirmation from the site management. Modern heavy equipment, such as wheel loaders or shotcrete sprayers, generates large amounts of data. Another side effect is that these data could easily be integrated into the process.

5. Case study

The previous section proposed a documentation process for conventional tunneling projects solely employing IFC for data exchange. The case study in this section demonstrates the feasibility of such a documentation process. Referring to Fig. 4, we present a concrete example of IFC files provided in the message exchange visualized as turquoise arrows. We use real-world data originating from the construction of a railway tunnel at the ZaB (Galler, 2016). We consider one tunnel round performed in May 2018, specifically the excavation and support of the top heading. Relevant data of the presented documents are serialized into IFC employing the concepts introduced by Huymajer et al. (2024). The serialized data contain information on the process, employed labor, equipment, and material.

5.1. Source documents

As discussed in Section 3.3, the specific documentation setups are project-specific. The presented case study contains the essential information for managing the tunnel's excavation and support in three kinds of documents. Although the original documents are in German, we will describe all aspects necessary to follow the case study. Due to information privacy, some parts of the documents have been redacted. In the following figures, information about the process is highlighted in blue ●, information about the labor is highlighted in turquoise ●, information about the employed equipment is highlighted in purple ●, information about consumed materials is highlighted in red ●, and general information is highlighted in gray ●.

The top panel of Fig. 5 shows the *shift report* representing a 24-hour interval. The section highlighted in turquoise documents the participating personnel. As can be seen, on a 24-hour interval, five shifts occur: two foreman shifts of 12 h and three regular shifts of 8 h. The primary information of this document is the detailed recording of the performed activities highlighted in blue, also called the cycle diagram. In this diagram, similar to a Gantt chart, each line represents a specific tunneling activity, such as drilling, blasting, mucking, and supporting. Columns discretize a day into 15 min intervals. The intersection is highlighted if a specific activity took place in this interval. This diagram is of paramount importance for managing conventional tunneling projects. The diagram in Fig. 5 records five rounds performed within the 24-hour interval. It concisely visualizes the tasks of a conventional tunneling cycle, including loosening the rock and consecutively performing various support measures. For clarity, this case study only considers the first round in the preceding IFC listing. The section highlighted in red contains information on the material used and is not documented in the corresponding support definition. In the case of staged excavation, the document records the stages, such as the top heading and bench.

The bottom left panel of Fig. 5 shows an *excavation and support report* of the first round of the shift report. The section highlighted in red contains a detailed list of all used materials in the tunnel round. The material includes explosives, material for ground improvement (e.g., grouting materials), material for pre-support measures (e.g., spiling bars),

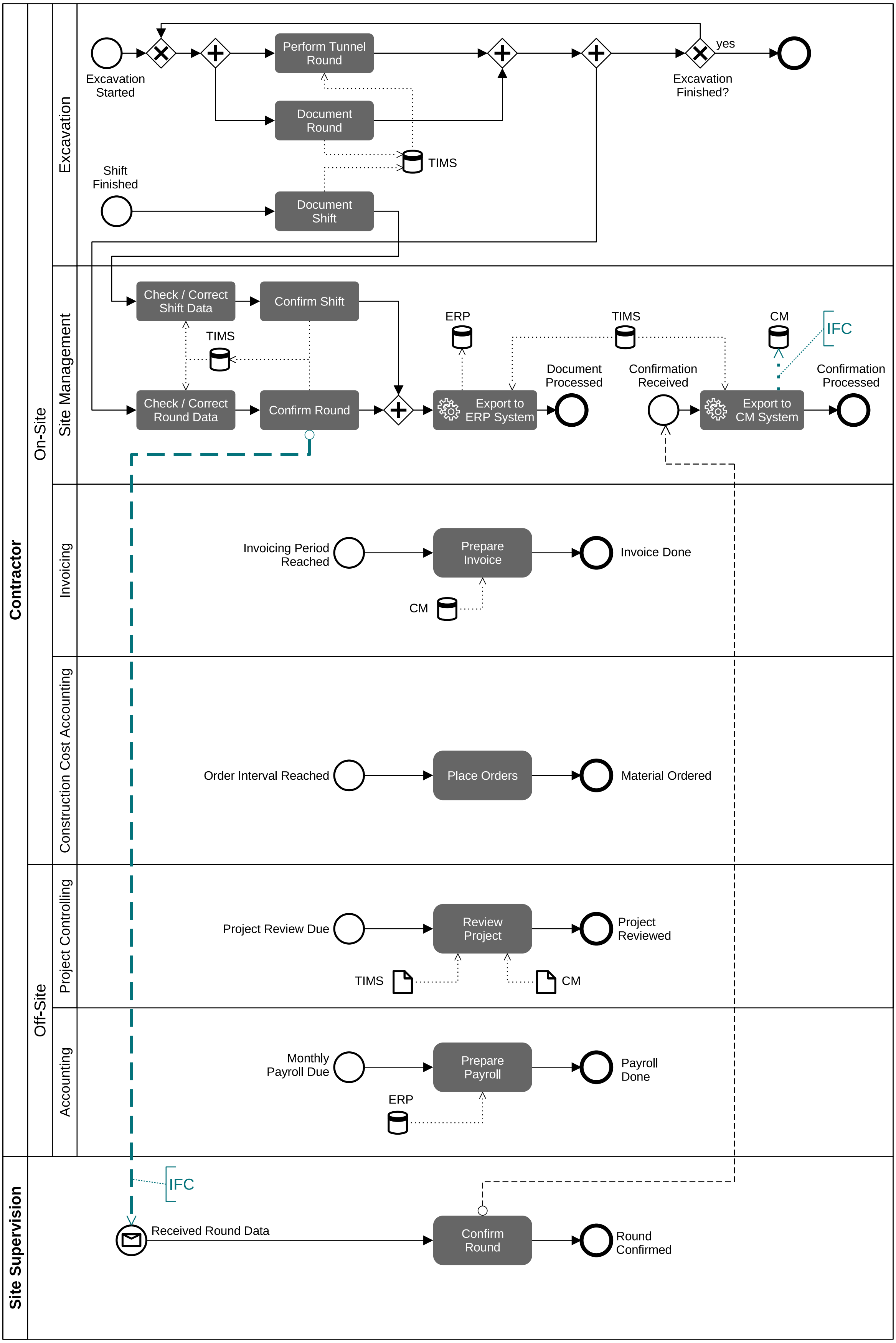

Fig. 4. A BPMN model of an IFC-supported documentation process in conventional tunneling. The IFC data exchange is represented in turquoise.

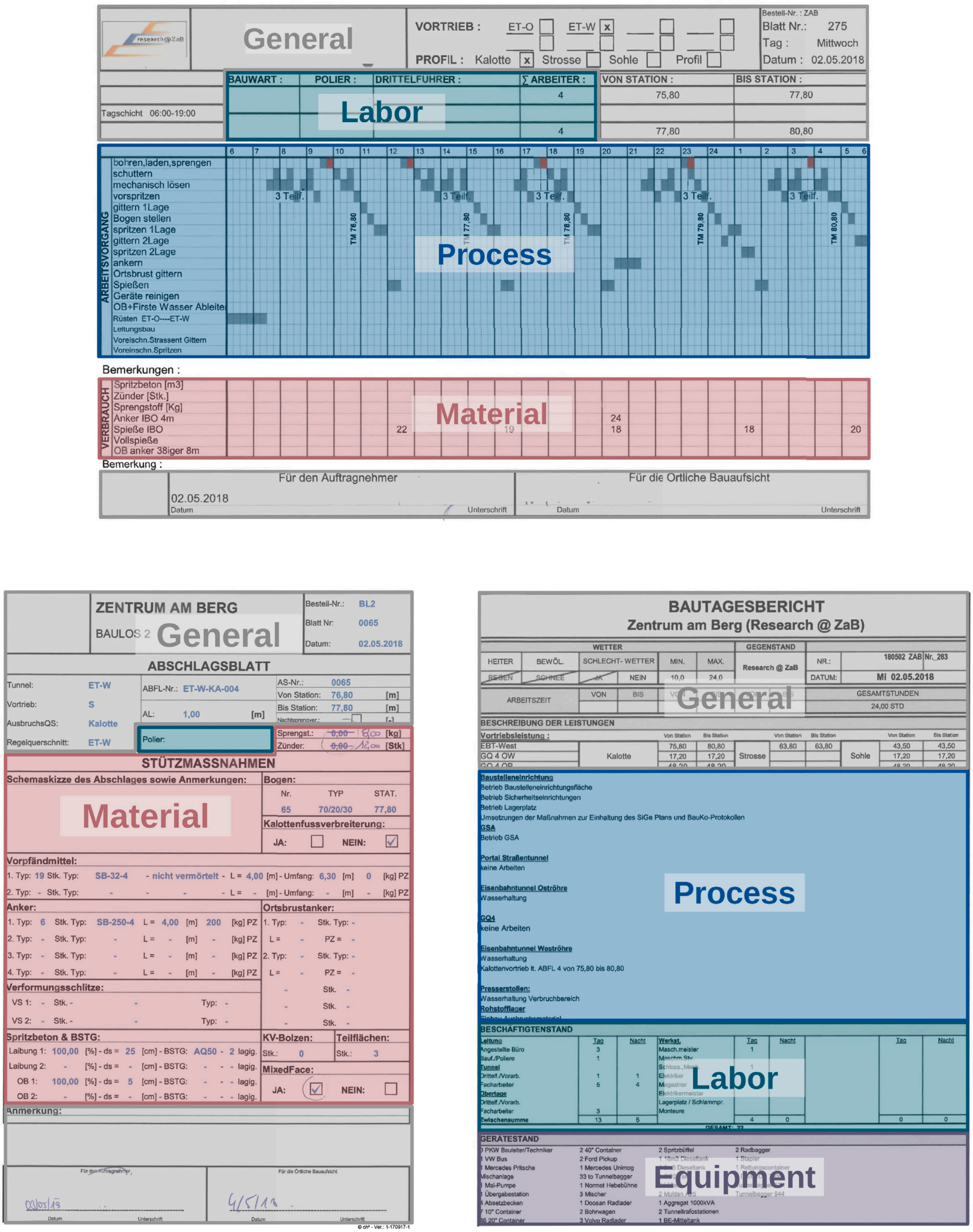

Fig. 5. Shift report of five rounds (top), an excavation and support report of round number 65 (bottom left), and the site diary at the ZaB (bottom right).

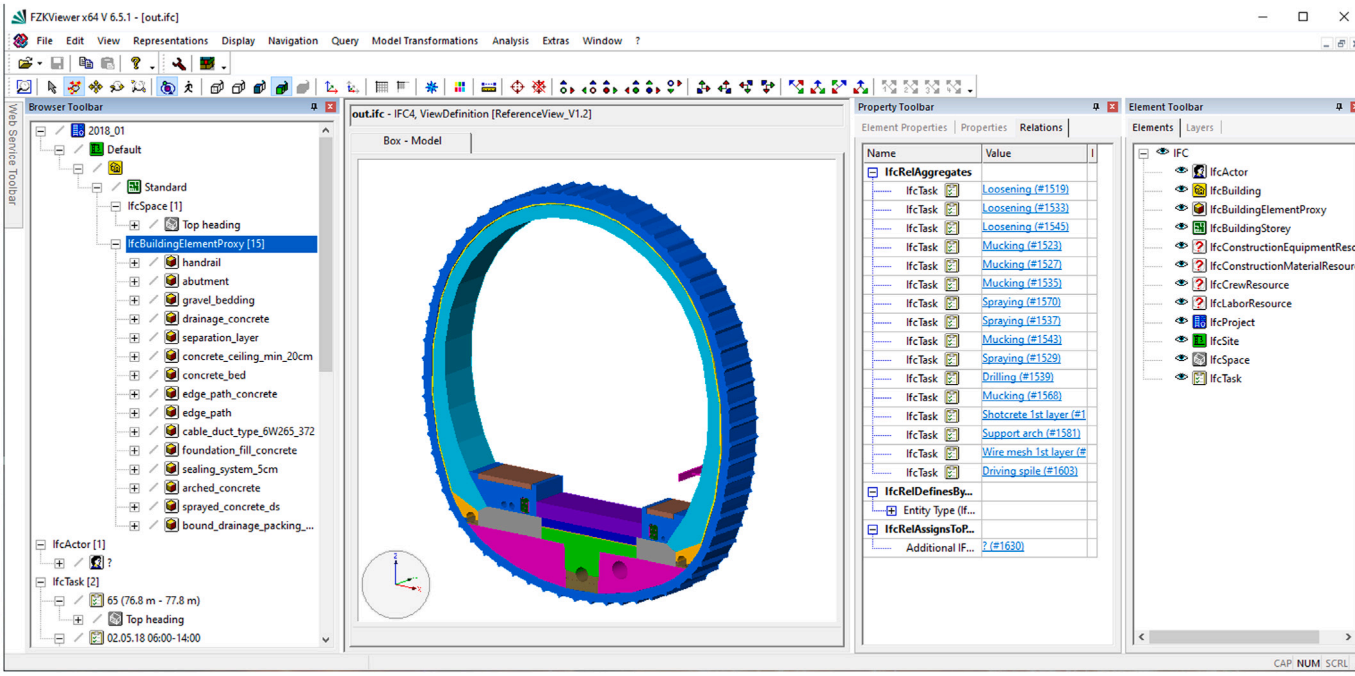

Fig. 6. Connection to the geometric representation of the round.

support material (e.g., shotcrete or reinforcement steel meshes), material to construct the tunnel lining or waterproofing of the lining. This section may contain non-material information, such as the number of partial face excavations. All the information in this document has in common that it is directly relevant to subsequent invoicing in a unit rates contract.

The bottom right panel of Fig. 5 shows one entry of the *site diary* of the day the tunnel round was performed. This document contains high-level information about the construction site, not just the excavation and support process. The data largely overlap with the former reports by summarizing the tasks performed and the number of personnel according to their role. The site diary additionally documents significant incidents. However, no notable incidents have been recorded in the given example. The document also includes information on the used equipment, highlighted in purple.

In all the documents mentioned above, the sections highlighted in gray provide general information, such as the date and details of the exact work location. As discussed in Section 3, all documents are prepared by the contractor and are sent to the employer for confirmation. Therefore, the documents contain confirmations from the entitled personnel of the contractor and the employer.

5.2. 3D model

Fig. 6 shows a 3D model of a small section of the final tunnel. Such a model resulting from the planning phase is handed over to the contractor before construction. Due to a lack of more specific elements, we must rely on `IfcBuildingElementProxy` elements to model the section. As `IfcBuildingElementProxy` is inherited from `IfcProduct` (bSI, 2021), this does not imply any restriction on the generality of the case study. In future versions of IFC, `IfcBuildingElementProxy` elements can be replaced by semantically more appropriate elements.

An accurate 3D tunnel model was created using the tender documents of the examined tunnel, which serves as the foundation for data extraction. A 2D CAD model is transformed into a 3D model using Autodesk AutoCAD and BlenderBIM software suites. During this process, various elements and components of the tunnel are accurately traced, scaled, and then assigned to their respective layers. These layers encompass the following elements of the tunneling specification plan: sprayed concrete, arched concrete, sealing system, foundation fill concrete, cable duct, parallel edge path, edge path concrete, concrete foundation, cohesive/bound drainage packing, concrete ceiling, separation layer, drainage concrete, gravel bedding, abutment, and handrail. Following the principles of the NATM, the type and amount of support measures, such as bolts, are dynamically adjusted to the local conditions and are, therefore, not included in the 3D model.

After creating these 15 elements, they are color-coded and extruded to the round length. During the export process, these 3D elements are exported into an IFC file, with the individual layers defined as `IfcBuildingElementProxy`. This approach allows for the precise model generation for each tunnel meter. The geometric tunnel model also incorporates an `IfcSpace` entity denoted as the “Top heading”. In a subsequent step, the construction data obtained during the tunnel excavation (Fig. 5) is assigned to this `IfcSpace`. The resulting enriched file comprehensively comprises all related documentation data linked to a geometric tunnel model, which is further viewed using a software tool for the visualization of semantic data models, such as *FZKViewer*, as seen in Fig. 6. The approach is discussed in the remainder of this section.

5.3. Semantic modeling

This section outlines how the tunnel excavation data of round 65 (Fig. 5) are associated with the 3D model (Fig. 6). Our tunnel excavation data modeling is based on the implementation guide proposed by Huymajer et al. (2024).

We use `IfcTaskType`, `IfcLaborResourceType`, `IfcConstructionEquipmentResourceType`, and `IfcConstructionMaterialResourceType` entities to serialize the type of tasks, employees, equipment, and material, respectively. All those types have an attribute `PredefinedType` containing the value of an IFC-defined enumeration (bSI, 2021). For example, the `Predefined-Type` attribute of an `IfcTaskType` takes one of the values defined in the `IfcTaskTypeEnum`. The most appropriate value describing a typical tunneling task is the value `CONSTRUCTION`. However, this is too coarse to describe the detailed recording of the shift report in Fig. 5. Therefore, we use the attribute `Identification` to narrow down the task type in a machine-readable way. Additionally, the attribute `Name` contains a human-readable name of the task type. `IfcLaborResourceType`, `IfcConstructionEquipmentResourceType`, and `IfcConstructionMaterialResourceType` instances are treated accordingly. For full interoperability, involved parties or systems must agree on the exact typing. To achieve this, type definitions could be organized in a project-wide template library represented by an `IfcProjectLibrary` instance (bSI, 2021).

During excavation and support of conventional tunnels, one can distinguish between three overall kinds of tasks (Huymajer et al., 2024): A task representing the whole tunnel round, a task representing a support activity during a tunnel round, and a task representing the shift. All tasks are represented with `IfcTask` instances interconnected with relationships. `IfcConstructionMaterialResource` instances are associated with the support task via `IfcRelAssignsToProcess` instances. `IfcConstructionEquipmentResource` and `IfcLaborResource` instances are associated with the shift task.

The excavation and support data are associated with the 3D representation. Precisely, an `IfcRelAssignsToProduct` instance associates the `IfcTask` (representing the tunnel round) with the `IfcSpace` (representing the top heading). The data are equally assigned to any other instance derived from `IfcProduct`, such as `IfcSpace`. On the other hand, the generated `IfcConstructionMaterialResource` instances are not associated with any geometric representation. This is consistent with the documents in Fig. 5, which do not contain any information on the exact location and orientation of the support measures. This approach adequately demonstrates a fundamental property of IFC — the separation of semantics and geometry (Borrmann et al., 2021).

5.4. Generated STEP file

It is instructive to review how the information in Fig. 5 is reflected in the generated STEP file by analyzing small file snippets. A more exhaustive file listing can be found in Appendix. The semantic and syntactic correctness of the generated file has been checked with IfcCheckingTool[5] version 2.2.

The serialization of the activity of loosening the rock, corresponding to the task from 7:30 to 8:30 in Fig. 5, is reflected by the following lines in the STEP file:

```
1 #1518=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,’2018-05-02T07:30:00+02:00’,’
      2018-05-02T08:30:00+02:00’,$,$);
2 #1519=IFCTASK(’1tOT2kCWhwklwN9foJEwdY’,$,’Loosening’,$,$,$,$,’COMPLETED’,$,.F.,
      $,#1518,$);
3 #1520=IFCTASKTYPE(’3_Sw2tOYqv09gzQbHTo_p4’,$,’Loosening’,$,$,$,’T60’,$,$,.
      NOTDEFINED.,$);
4 #1521=IFCRELDEFINESBYTYPE(’11DvXDHoJMooNiw6cJJ06a’,$,$,$,(#1519,#1533,#1545)
      ,#1520);
```

For flexibility reasons, IFC accomplishes the time definition with an `IfcTaskTime` object, which can be seen in line 1. Line 2 contains the instantiation of the `IfcTask`. The task type is defined in line 3. A so-called objectified relationship (bSI, 2021) assigns a type to one or more tasks, as seen in line 4.

The tunnel round task is represented similarly:

```
#1613=IFCTASK(’3nSYXxPpXj7naAbo$tbx9A’,$,’65␣(76.8␣m␣-␣77.8␣m)’,$,$,$,$,$,$,.F
      .,$,$,$);
#1614=IFCTASKTYPE(’1PLFOU7FMgCfvdG5GyT36f’,$,’Tunnel␣round’,$,$,$,$,$,’
      TUNNEL_ROUND’,.CONSTRUCTION.,$);
#1615=IFCRELDEFINESBYTYPE(’3DV2KTgPxGx00Af_1qCnvE’,$,$,$,(#1613),#1614);
```

This tunnel round task is associated with the geometric representation of the outer lining with an `IfcRelAssignsToProduct` relationship:

```
#1086=IFCSPACE(’1BpV9djTT5MvQ62vWuGojr’,$,’Top␣heading’,’Top␣heading’,’
      Tunnel_round’,#1517,#1506,$,.ELEMENT.,.SPACE.,$);
...
#1634=IFCRELASSIGNSTOPRODUCT(’2g24BbC1HZZQ_EqJ15ec0P’,$,$,$,(#1613),$,#1086);
```

The serialization of the tunnel shift completes the process-related information:

```
#1617=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,’2018-05-02T06:00:00+02:00’,’
      2018-05-02T14:00:00+02:00’,$,$);
#1618=IFCTASK(’2Hmo4hfj8u1dnG_s9s_sSF’,$,’02.05.18␣06:00-14:00’,$,$,$,$,’
      COMPLETED’,$,.F.,$,#1617,$);
#1619=IFCTASKTYPE(’3TvOKgOMGU76b5CliWiel9’,$,’Shift’,$,$,$,$,$,’SHIFT’,.
      ATTENDANCE.,$);
#1620=IFCRELDEFINESBYTYPE(’151HrutDp0uGbJgHwuwg7o’,$,$,$,(#1618),#1619);
```

All tasks are associated with each other, as Huymajer et al. (2024) proposed.

The STEP file also contains information on the involved personnel:

```
#1621=IFCLABORRESOURCE(’3HzN7J9S3Cx4JRM23LLfiC’,$,$,$,$,$,$,$,$,$,$);
#1622=IFCLABORRESOURCETYPE(’2NkZ1G70qICxlu2jUvIBAg’,$,’Worker’,$,$,$,$,$,$,$,$
      ,.GENERAL.);
#1623=IFCRELDEFINESBYTYPE(’1achYUYwzsF2nZcbJf3YE_’,$,$,$,(#1621),#1622);
#1624=IFCPERSON(’2’,’Mayer’,’Michael’,$,$,$,$,$);
#1625=IFCACTOR(’1JW3Bgw$clg$1XBPlYVRRZ’,$,$,$,$,#1624);
```

The following lines represent the equipment employed during the shift:

```
#1627=IFCCONSTRUCTIONEQUIPMENTRESOURCE(’3umIaz6P8dywL_6SOzKTGm’,$,$,’Wheel␣
      loader␣1’,$,$,$,$,$,$,$);
#1628=IFCCONSTRUCTIONEQUIPMENTRESOURCETYPE(’1SyWiVehsG5LgjoyNCiRpd’,$,’Wheel␣
      loader’,$,$,$,$,$,’WHEEL_LOADER’,$,$,.EARTHMOVING.);
#1629=IFCRELDEFINESBYTYPE(’2CMx4wbppmtMaqfKettGv_’,$,$,$,(#1627),#1628);
```

The employed material of six rock bolts for supporting the tunnel lining, as shown in the excavation and support report in Fig. 5, is serialized as follows:

```
#1550=IFCQUANTITYCOUNT(’Units’,$,$,6.,$);
#1551=IFCCONSTRUCTIONMATERIALRESOURCE(’0TVKgRsDs4rou8xWgfdWZC’,$,$,$,$,’Z
      .02.63.01.21.B’,$,$,$,#1550,$);
#1552=IFCCONSTRUCTIONMATERIALRESOURCETYPE(’34jcnCBgdc0zAfbevWZcVI’,$,’Bolt␣-␣
      Self-drilling␣bolt’,$,$,$,$,$,’BOLT’,$,$,.METAL.);
#1553=IFCRELDEFINESBYTYPE(’1BOVJ2YaBxtKARS17rii5i’,$,$,$,(#1551),#1552);
```

5.5. Technical implementation

The implementation of the described case study contains three major tasks: 1. Implementation of a software tool managing the tunnel data and handling IFC data. 2. Importing the relevant data from the construction of the ZaB. 3. Creation of a 3D model of a short tunnel section. The realization of the third task has been discussed in Section 5.2. This subsection focuses on the two former tasks.

Our software tool implementation is based on TIMS (Huymajer et al., 2022a) and has been enhanced with IFC input and output functionality. Generating IFC output entails developing methods returning the IFC representation of relevant objects, so-called serializers. The IFC generation involves mapping instances of TIMS to IFC instances and subsequently transforming the IFC instances into a sequence of bytes. TIMS is based on a framework[6] that adopts a software design pattern resembling the so-called model-view-controller pattern (Fowler, 2002). In this sense, the implementation has shown that for most classes in TIMS, there is a direct mapping to one IFC entity. For example, the IFC entities `IfcConstructionEquipmentResourceType` and `IfcConstructionEquipmentResource` have corresponding classes in TIMS. A notable difference between TIMS and IFC is the representation of relationships between instances. IFC employs objectified relationships using instances derived from `IfcRelationship`, whereas, in TIMS, these “intermediate” instances do not exist for many-to-one relationships. Efforts were made to ensure that the IFC serialization of each object maintains a consistent GUID. For the low-level IFC handling, the Python bindings of IfcOpenShell[7] are used.

The 3D model of a tunnel section is used as an IFC input for subsequent enrichment with tunnel excavation and support data. The import involves finding the IFC instance for attaching the round data via an `IfcRelAssignsToProduct` relationship. A property on the round has been added to allow the user to determine the IFC object to which the tunnel data should be assigned.

The case study encompasses importing relevant data into TIMS. Although we only presented the use case of a single tunnel round

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

[6] https://www.tryton.org/

[7] https://ifcopenshell.org/

in this publication, more data have been imported into TIMS. As the original documentation consisted of paper and spreadsheet documents, we had to digitalize paper documents manually. The data have been subsequently imported into TIMS using an API and checked for correctness.

5.6. Results and discussion

The tree view window in Fig. 6 visualizes the generated STEP file as an expandable tree structure of IFC instances and their relations. The window shows that the 3D model (Section 5.2) has been enriched with the essential data from the construction phase (Section 5.1). Specifically, the round task is associated with an `IfcSpace` representing the top heading. The view also shows that the support and shift tasks are associated with the round task.

We omit some general information during serialization that is not fully supported by the IFC standard or not directly related to the considered tunnel round. For example, we omit representing the weather information as the property set `Pset_SiteWeather` cannot sufficiently describe this information. Due to simplicity and information privacy, we only add one fictitious employee and one construction machine to the model.

The results show that IFC offers all the features for implementing a BIM-based data exchange for conventional tunnel excavations, as proposed by Huymajer et al. (2024). The most important feature is to semantically describe the tunnel documentation, allowing for fully automated and real-time data exchange between stakeholders in a vendor-neutral format. For a smooth transition to a BIM-based workflow, legacy documents, such as paper documents or spreadsheets, on a common data environment (CDE) can be referenced with `IfcRelAssociatesDocument` relationships. In today's conventional tunneling, the exact location of installed support measures is rarely documented. Moreover, many tunneling tasks, such as dewatering, cannot be attributed to a single structural element within the tunnel. IFC's strict separation of semantics and geometry allows one to fully capture this information without laboriously recording the exact location or "artificially" locating objects where they do not belong. IFC does not enforce any level of detail to a specific implementation, giving a high degree of flexibility. For example, if a project requires not to include information related to the shift, one could omit the serialization of the shift task and the associated `IfcLaborResource` and `IfcConstructionEquipmentResource` instances. Additionally, property sets provide an opportunity to extend the data model beyond the specification from bSI. Another advantage is that IFC is an open standard (OpenStand, 2023) already well-established within the construction sector and the research community, positively impacting interoperability.

In contrast, IFC also has some drawbacks. The listing in Appendix shows that even a relatively straightforward example results in a rather complex model. Moreover, IFC, due to its high flexibility, can lead to potential issues in data exchange and interoperability. Additionally, there are already established national data standards for tender, award, and invoicing with mostly complementary functionality to the proposed IFC-based workflow (GAEB, 2023a; Austrian Standards, 2021a). In the execution phase, those standards allow the exchange of invoicing data between the employer and the project owner. However, those standards do not aim to offer a digital alternative to documents, such as the one depicted in Fig. 5. Proper software support is the biggest challenge for the proposed methodology. External software providers must adapt their applications, or contractors must make considerable effort for an in-house implementation.

6. Conclusion

The article deals with BIM in the execution phase of conventional tunneling projects. We discussed the state-of-the-art documentation and proposed a BIM-driven process utilizing IFC as a means of data exchange. A case study demonstrates an example of applying the proposed IFC concepts to a real tunnel project.

The results confirm that the most relevant information of today's conventional tunneling project could be modeled with IFC. A generated IFC STEP file is a basis for further discussion with the community to enhance BIM in conventional tunneling. The described implementation shows that developing software tools aiding an IFC-supported data exchange is feasible. Significant parts of our proposal are generic enough to apply to other construction projects.

Implementing BIM in the execution phase of tunneling projects is a significant step towards employing BIM throughout the tunnel life cycle, bringing many benefits. IFC serves as a particular tool in this endeavor and, as an open standard, brings advantages compared to proprietary solutions. The exchange of semantic-rich data is one fundamental characteristic enabling involved stakeholders an optimized project management.

Our experience and previous research focused on international tunneling projects, mainly from Austrian contractors. Moreover, our proposal aims at conventional tunneling projects but could be extended to mechanized tunneling. The proposed implemented data model covers relevant information for a shift report and needs to be extended to include other data generated during conventional tunneling, such as geological surveys and quality checks. We are confident that the proposal is general enough to be applied to a broader scope, but further work is needed for a thorough validation. Future research should also include implementing the BIM-based process in an ongoing construction project, comparing it to the status quo. This effort requires handling any deviations from the "standard workflow". bSI made considerable advances for the eagerly awaited IFC version 4.4, extending the standard with tunneling-specific concepts. Further work is planned to adopt those concepts in our proposal. Finally, future work should also explore how data generated from heavy equipment can be integrated.

Implementing BIM forms part of the foundation for further innovation in the tunneling domain, such as AI (artificial intelligence), Internet of things (IoT), and augmented reality (AR). Time will show how standardization committees evolve the standards, how software corporations pick up those standards, and how AEC stakeholders implement future innovations.

CRediT authorship contribution statement

Marco Huymajer: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Software, Data curation. **Oleksandr Melnyk:** Writing – original draft, Visualization. **Robert Wenighofer:** Writing – review & editing, Resources. **Christian Huemer:** Project administration, Funding acquisition, Writing – review & editing. **Robert Galler:** Project administration, Funding acquisition, Writing – review & editing, Resources.

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

Data will be made available on request.

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Appendix. Excerpt of the generated IFC STEP file

Due to file length, large parts of the file needed to be omitted, as indicated by the ellipsis (...).

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(('ViewDefinition␣[ReferenceView_V1.2]'),'2;1');
FILE_NAME('EB_W_3D_Melnyk_0.0.7.ifc','2023-09-18T19:04:22+02:00',(''),(''),'IfcOpenShell␣v0.7.0-9cc1f5f0e','BlenderBIM␣0.0.230902-46cfe70','');
FILE_SCHEMA(('IFC4'));
ENDSEC;
DATA;
...
#1086=IFCSPACE('1BpV9djTT5MvQ62vWuGojr',$,'Top␣heading','Top␣heading','Tunnel_round',#1517,#1506,$,.ELEMENT.,.SPACE.,$);
...
#1518=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T07:30:00+02:00','2018-05-02T08:30:00+02:00',$,$);
#1519=IFCTASK('1tOT2kCWhwklwN9foJEwdY',$,'Loosening',$,$,$,$,'COMPLETED',$,.F.,$,#1518,$);
#1520=IFCTASKTYPE('3_Sw2tOYqvO9gzQbHTo_p4',$,'Loosening',$,$,$,'T60',$,$,.NOTDEFINED.,$);
#1521=IFCRELDEFINESBYTYPE('11DvXDHoJMooNiw6cJJ06a',$,$,$,(#1519,#1533,#1545),#1520);
#1522=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T07:45:00+02:00','2018-05-02T08:00:00+02:00',$,$);
#1523=IFCTASK('3VCva001C5BiIMa$arEFRZ',$,'Mucking',$,$,$,$,'COMPLETED',$,.F.,$,#1522,$);
#1524=IFCTASKTYPE('15c8LARINPMOApPRfqIffQ',$,'Mucking',$,$,$,'T40',$,'MUCKING',.CONSTRUCTION.,$);
#1525=IFCRELDEFINESBYTYPE('0RrnbICySeJse7LahePXZw',$,$,$,(#1523,#1527,#1535,#1543,#1568),#1524);
#1526=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T08:15:00+02:00','2018-05-02T08:30:00+02:00',$,$);
#1527=IFCTASK('3Ag717m1zhfjgdxYf3jor2',$,'Mucking',$,$,$,$,'COMPLETED',$,.F.,$,#1526,$);
#1528=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T08:30:00+02:00','2018-05-02T08:45:00+02:00',$,$);
#1529=IFCTASK('1W9sw9BYRIxhDDwNh_$bdW',$,'Spraying',$,$,$,$,'COMPLETED',$,.F.,$,#1528,$);
#1530=IFCTASKTYPE('2LGq0e9WkrXR_DFS8C1Sdc',$,'Spraying',$,$,$,'L02',$,$,.NOTDEFINED.,$);
#1531=IFCRELDEFINESBYTYPE('3UHnpR_MdAjgBCVgmpZAGx',$,$,$,(#1529,#1537,#1570),#1530);
#1532=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T08:45:00+02:00','2018-05-02T09:15:00+02:00',$,$);
#1533=IFCTASK('2KA4q3nwAkgiT30E60mPne',$,'Loosening',$,$,$,$,'COMPLETED',$,.F.,$,#1532,$);
#1534=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T09:00:00+02:00','2018-05-02T09:15:00+02:00',$,$);
#1535=IFCTASK('2rucihLLwwFkT4U$ty5uz7',$,'Mucking',$,$,$,$,'COMPLETED',$,.F.,$,#1534,$);
#1536=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T09:15:00+02:00','2018-05-02T09:30:00+02:00',$,$);
#1537=IFCTASK('0sxlNUyGhMr$DqE$pGhrM8',$,'Spraying',$,$,$,$,'COMPLETED',$,.F.,$,#1536,$);
#1538=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T09:30:00+02:00','2018-05-02T10:00:00+02:00',$,$);
#1539=IFCTASK('2n0U2g30vchw7hpY$0yUpE',$,'Drilling',$,$,$,$,'COMPLETED',$,.F.,$,#1538,$);
#1540=IFCTASKTYPE('15OM9F5zp2rJzNgLnPcX4H',$,'Drilling',$,$,$,'T10',$,'DRILLING',.CONSTRUCTION.,$);
#1541=IFCRELDEFINESBYTYPE('0xHmKm064ZoIdHIyqgJP3v',$,$,$,(#1539),#1540);
#1542=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T10:00:00+02:00','2018-05-02T10:15:00+02:00',$,$);
#1543=IFCTASK('3JaADd5xFJvXk6lVghmELt',$,'Mucking',$,$,$,$,'COMPLETED',$,.F.,$,#1542,$);
#1544=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T10:15:00+02:00','2018-05-02T10:45:00+02:00',$,$);
#1545=IFCTASK('0hVjVSl4cHnhBUwfvdgzqC',$,'Loosening',$,$,$,$,'COMPLETED',$,.F.,$,#1544,$);
#1546=IFCQUANTITYWEIGHT('Mass',$,#26,58.,$);
#1547=IFCCONSTRUCTIONMATERIALRESOURCE('1y7VxCLh3dEts1lSOJ_yCj',$,$,$,$,'Z.02.63.02.03.A',$,$,$,#1546,$);
#1548=IFCCONSTRUCTIONMATERIALRESOURCETYPE('3iRtwkdY3$XRUvpIPqZ5gK',$,'Wire␣mesh␣-␣Inside␣with␣steel␣arch',$,$,$,$,$,'WIRE_MESH',$,$,.METAL.);
#1549=IFCRELDEFINESBYTYPE('0kQoQ3$mRIvD5pirHYaTUv',$,$,$,(#1547),#1548);
#1550=IFCQUANTITYCOUNT('Units',$,$,6.,$);
#1551=IFCCONSTRUCTIONMATERIALRESOURCE('0TVKgRsDs4rou8xWgfdWZC',$,$,$,$,'Z.02.63.01.21.B',$,$,$,#1550,$);
#1552=IFCCONSTRUCTIONMATERIALRESOURCETYPE('34jcnCBgdc0zAfbevWZcVI',$,'Bolt␣-␣Self-drilling␣bolt',$,$,$,$,$,'BOLT',$,$,.METAL.);
#1553=IFCRELDEFINESBYTYPE('1BOVJ2YaBxtKARS17rii5i',$,$,$,(#1551),#1552);
#1554=IFCQUANTITYAREA('Area',$,#22,41.73,$);
#1555=IFCCONSTRUCTIONMATERIALRESOURCE('3jjW4BJOgF2sy5Jr0GB7ag',$,$,$,$,'Z.02.63.04.04.A',$,$,$,#1554,$);
#1556=IFCCONSTRUCTIONMATERIALRESOURCETYPE('0jKsUjUZqnwjFm9vL_7w78',$,'Shotcrete␣-␣Face',$,$,$,$,$,'SHOTCRETE',$,$,.CONCRETE.);
#1557=IFCRELDEFINESBYTYPE('3wadx3XOlowT6L$jfxk1rD',$,$,$,(#1555),#1556);
#1558=IFCQUANTITYAREA('Area',$,#22,4.62,$);
#1559=IFCCONSTRUCTIONMATERIALRESOURCE('0c5pQ5xIcCVkss$88qjIkb',$,$,$,$,'Z.02.63.04.04.A',$,$,$,#1558,$);
#1560=IFCCONSTRUCTIONMATERIALRESOURCETYPE('04eyCJe_qwkNzTsumewTDO',$,'Shotcrete␣-␣Partial-face␣excavation',$,$,$,$,$,'SHOTCRETE',$,$,.CONCRETE.);
#1561=IFCRELDEFINESBYTYPE('2WncLvILbNRqG5jopp0GaW',$,$,$,(#1559),#1560);
#1562=IFCQUANTITYLENGTH('Length',$,#21,2.,$);
#1563=IFCCONSTRUCTIONMATERIALRESOURCE('1BlFzgcIG4LLzUO0DAImKI',$,$,$,$,'Z.02.63.02.21.A',$,$,$,#1562,$);
#1564=IFCCONSTRUCTIONMATERIALRESOURCETYPE('1VtaP8iGoIEUjTx3lNudIT',$,'Contact␣Bench-Invert',$,$,$,$,$,'REINFORCEMENT_CONTACT',$,$,.METAL.);
#1565=IFCRELDEFINESBYTYPE('1MNSIIuYixzQpjsvec_zEM',$,$,$,(#1563),#1564);
#1566=IFCRELASSIGNSTOPROCESS('2dRRKjl$daG0WhXz5O2PLO',$,$,$,(#1547,#1551,#1555,#1559,#1563),$,#1545,$);
#1567=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T10:30:00+02:00','2018-05-02T10:45:00+02:00',$,$);
#1568=IFCTASK('0syJX3Bio$2bWhPlHv$Urz',$,'Mucking',$,$,$,$,'COMPLETED',$,.F.,$,#1567,$);
#1569=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T10:45:00+02:00','2018-05-02T11:00:00+02:00',$,$);
#1570=IFCTASK('0CUBvduYajwlI8BbsakJZa',$,'Spraying',$,$,$,$,'COMPLETED',$,.F.,$,#1569,$);
#1571=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T11:00:00+02:00','2018-05-02T11:15:00+02:00',$,$);
#1572=IFCTASK('0QW_0465YsTxcaTRFWemr4',$,'Wire␣mesh␣1st␣layer',$,$,$,$,'COMPLETED',$,.F.,$,#1571,$);
#1573=IFCTASKTYPE('3e7L7xJ9kZxHz7$MvuqsNI',$,'Wire␣mesh␣1st␣layer',$,$,$,'L10',$,'WIRE_MESH_1',.CONSTRUCTION.,$);
#1574=IFCRELDEFINESBYTYPE('3OeRMbNeYEmLfR2vsT48Y_',$,$,$,(#1572),#1573);
#1575=IFCQUANTITYWEIGHT('Mass',$,#26,58.,$);
#1576=IFCCONSTRUCTIONMATERIALRESOURCE('3BFtI_1LXs1o7bLBRCnplv',$,$,$,$,'Z.02.63.02.02.A',$,$,$,#1575,$);
#1577=IFCCONSTRUCTIONMATERIALRESOURCETYPE('31VTfkpdgkJo4hsR$ZyAXn',$,'Wire␣mesh␣-␣Outside␣with␣steel␣arch',$,$,$,$,$,'WIRE_MESH',$,$,.METAL.);
#1578=IFCRELDEFINESBYTYPE('0GPxdlmhb65fmQWEm9FoVy',$,$,$,(#1576),#1577);
#1579=IFCRELASSIGNSTOPROCESS('3eb$JS2OOBQZRBFK3_Zh5E',$,$,$,(#1576),$,#1572,$);
#1580=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T11:15:00+02:00','2018-05-02T11:30:00+02:00',$,$);
#1581=IFCTASK('2TtIDVNI$35F9jWi7CCvdY',$,'Support␣arch',$,$,$,$,'COMPLETED',$,.F.,$,#1580,$);
#1582=IFCTASKTYPE('0x9Opd8jOsoAQGFztEVSTL',$,'Support␣arch',$,$,$,'L11',$,$,.NOTDEFINED.,$);
#1583=IFCRELDEFINESBYTYPE('2Y9whRIhVPHpj4CPSOFvRH',$,$,$,(#1581),#1582);
#1584=IFCQUANTITYLENGTH('Length',$,#21,15.57,$);
#1585=IFCCONSTRUCTIONMATERIALRESOURCE('15$XOpo7LTx7NPVT4KS4Q8',$,$,$,$,'Z.02.63.03.01.A',$,$,$,#1584,$);
#1586=IFCCONSTRUCTIONMATERIALRESOURCETYPE('2L8W2apy4Ua4W3NR3YlWj2',$,'Arches␣and␣wall␣beams',$,$,$,$,$,'ARCH_BEAM',$,$,.METAL.);
#1587=IFCRELDEFINESBYTYPE('06Sjm5nbqtCpabXRTMcBU_',$,$,$,(#1585),#1586);
#1588=IFCRELASSIGNSTOPROCESS('2381j09i74zMonnFDawPhW',$,$,$,(#1585),$,#1581,$);
#1589=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T11:30:00+02:00','2018-05-02T12:00:00+02:00',$,$);
#1590=IFCTASK('03iPXUEDYeoTAA0tA59D5a',$,'Shotcrete␣1st␣layer',$,$,$,$,'COMPLETED',$,.F.,$,#1589,$);
#1591=IFCTASKTYPE('1r9YkHxgynzDhcwYtSKuQe',$,'Shotcrete␣1st␣layer',$,$,$,'L12',$,$,.NOTDEFINED.,$);
#1592=IFCRELDEFINESBYTYPE('021Vfb$MygIy4BnAg9apG4',$,$,$,(#1590),#1591);
#1593=IFCQUANTITYAREA('Area',$,#22,15.57,$);
#1594=IFCCONSTRUCTIONMATERIALRESOURCE('1bYXsiQWJdQZ5wwSwfZAgd',$,$,$,$,'Z.02.63.04.01.E',$,$,$,#1593,$);
#1595=IFCCONSTRUCTIONMATERIALRESOURCETYPE('0g8xTHdTpqzDIpGw8qxA5w',$,'Shotcrete␣-␣Top␣and␣bench␣headings',$,$,$,$,$,'SHOTCRETE',$,$,.CONCRETE.);
#1596=IFCRELDEFINESBYTYPE('1tQlf3zcPa9qs0tPI18Iha',$,$,$,(#1594),#1595);
#1597=IFCQUANTITYVOLUME('Volume',$,#23,3.518,$);
#1598=IFCCONSTRUCTIONMATERIALRESOURCE('24jgPwOMyVNpsaEyt39CjV',$,$,$,$,'Z.02.63.04.20.A',$,$,$,#1597,$);
#1599=IFCCONSTRUCTIONMATERIALRESOURCETYPE('0DLg5JqIJW_FIYRuXGFUI$',$,'Shotcrete␣-␣Filling␣spandrels␣and␣over-excavation',$,$,$,$,$,'SHOTCRETE',$,$,.CONCRETE.);
#1600=IFCRELDEFINESBYTYPE('0zabJuUZ8dY_rCzP1CTbwT',$,$,$,(#1598,#1611),#1599);
#1601=IFCRELASSIGNSTOPROCESS('2KbORqbWPMnO8Wjrk8BUXu',$,$,$,(#1594,#1598),$,#1590,$);
#1602=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T12:00:00+02:00','2018-05-02T12:30:00+02:00',$,$);
#1603=IFCTASK('35bQem9Hc7CKT5$gXhsF8R',$,'Driving␣spile',$,$,$,$,'COMPLETED',$,.F.,$,#1602,$);
#1604=IFCTASKTYPE('2NBFBiGTrMbMxIBEZpfEQy',$,'Driving␣spile',$,$,$,'A41',$,$,.NOTDEFINED.,$);
#1605=IFCRELDEFINESBYTYPE('0rwD9KaguCjyYw3S_kA5xu',$,$,$,(#1603),#1604);
#1606=IFCQUANTITYCOUNT('Units',$,$,19.,$);
#1607=IFCCONSTRUCTIONMATERIALRESOURCE('1MELPFPoGNyeDQcK_rhFfg',$,$,$,$,'Z.02.63.05.03.B',$,$,$,#1606,$);
#1608=IFCCONSTRUCTIONMATERIALRESOURCETYPE('2QNqgqXvROMCG6Bino6Iw$',$,'Spile␣-␣Self-drilling␣spile',$,$,$,$,$,'SPILE',$,$,.METAL.);
#1609=IFCRELDEFINESBYTYPE('0PtwAYpieVTjolD4HLOxB7',$,$,$,(#1607),#1608);
#1610=IFCQUANTITYVOLUME('Volume',$,#23,0.276,$);
#1611=IFCCONSTRUCTIONMATERIALRESOURCE('0VIY9G$A43stvYu_hXwa5q',$,$,$,$,'Z.02.63.04.20.A',$,$,$,#1610,$);
#1612=IFCRELASSIGNSTOPROCESS('050rxBAWOIheh2qVLEDgPf',$,$,$,(#1607,#1611),$,#1603,$);
#1613=IFCTASK('3nSYXxPpXj7naAbo$tbx9A',$,'65␣(76.8␣m␣-␣77.8␣m)',$,$,$,$,$,$,.F.,$,$,$);
#1614=IFCTASKTYPE('1PLF0U7FMgCfvdG5GyT36f',$,'Tunnel␣round',$,$,$,$,$,'TUNNEL_ROUND',.CONSTRUCTION.,$);
#1615=IFCRELDEFINESBYTYPE('3DV2KTgPxGx00Af_1qCnvE',$,$,$,(#1613),#1614);
#1616=IFCRELNESTS('0992G5qgwRZ5YxQ9DG$lyh',$,$,$,#1613,(#1519,#1523,#1527,#1529,#1533,#1535,#1537,#1539,#1543,#1545,#1568));
#1617=IFCTASKTIME($,$,$,$,$,$,$,$,$,$,$,$,$,$,$,$,'2018-05-02T06:00:00+02:00','2018-05-02T14:00:00+02:00',$,$);
#1618=IFCTASK('2Hmo4hfj8u1dnG_s9s_sSF',$,'02.05.18␣06:00-14:00',$,$,$,$,'COMPLETED',$,.F.,$,#1617,$);
#1619=IFCTASKTYPE('3TvOKgOMGU76b5CliWiel9',$,'Shift',$,$,$,$,$,'SHIFT',.ATTENDANCE.,$);
#1620=IFCRELDEFINESBYTYPE('151HrutDp0uGbJgHwuwg7o',$,$,$,(#1618),#1619);
#1621=IFCLABORRESOURCE('3HzN7J9S3Cx4JRM23LLfiC',$,$,$,$,$,$,$,$,$,$);
#1622=IFCLABORRESOURCETYPE('2NkZ1G7OqICxlu2jUvIBAg',$,'Worker',$,$,$,$,$,$,$,$,.GENERAL.);
#1623=IFCRELDEFINESBYTYPE('1achYUYwzsF2nZcbJf3YE_',$,$,$,(#1621),#1622);
#1624=IFCPERSON('2','Mayer','Michael',$,$,$,$,$);
#1625=IFCACTOR('1JW3Bgw$clg$1XBPlYVRRZ',$,$,$,$,#1624);
#1626=IFCRELASSIGNSTORESOURCE('2x3jGh1V6r5$2Y0c5F_o_R',$,$,$,(#1625),$,#1621);
#1627=IFCCONSTRUCTIONEQUIPMENTRESOURCE('3umIaz6P8dywL_6SOzKTGm',$,$,'Wheel␣loader␣1',$,$,$,$,$,$,$);
#1628=IFCCONSTRUCTIONEQUIPMENTRESOURCETYPE('1SyWiVehsG5LgjoyNCiRpd',$,'Wheel␣loader',$,$,$,$,$,'WHEEL_LOADER',$,$,.EARTHMOVING.);
#1629=IFCRELDEFINESBYTYPE('2CMx4wbppmtMaqfKettGv_',$,$,$,(#1627),#1628);
#1630=IFCCREWRESOURCE('3E1bbbjGnSF5G2TzPtzrq7',$,$,$,$,$,$,$,$,$,$);
#1631=IFCRELASSIGNSTOPROCESS('1qMddIp8dsRxZxyGv_vhEG',$,$,$,(#1630),$,#1618,$);
#1632=IFCRELNESTS('1w0zm2bDHfCGvMXT9YyWeB',$,$,$,#1630,(#1621,#1627));
#1633=IFCRELAGGREGATES('3BJXps345H_lk$Z2hBB7ZC',$,$,$,#1618,(#1519,#1523,#1527,#1529,#1533,#1535,#1537,#1539,#1543,#1545,#1568));
#1634=IFCRELASSIGNSTOPRODUCT('2g24BbC1HZZQ_EqJl5ecOP',$,$,$,(#1613),$,#1086);
ENDSEC;
END-ISO-10303-21;
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