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ENRICHMENT OF BIM WITH CONSTRUCTION PROCESS DATA IN MECHANIZED TUNNEL CONSTRUCTION

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Abstract: This paper discusses Building Information Modeling (BIM) and its use in underground, mechanized tunnel construction, as well as sensor data and data sources of Tunnel Boring Machines (TBM) and surrounding systems and installations used to create concrete lined tunnels. The BIM methodology shares data across users and platforms primarily using open file standards. As the de facto standard for open source file standards, the Industry Foundation Classes (IFC) were considered. As IFC was not yet adapted for use in underground construction, research initiatives, which focused on the adaption of IFC for use in tunnel construction were conducted. IfcShieldTunnel and IfcTunnel, each developed by researchers in Japan and Germany respectively were investigated.

Construction surveillance today uses information systems which provide near real-time information online. The availability of data resulting from the construction process makes it possible to combine and compare it with digital model files, resulting from the BIM methodology (BI models) representing the planned building. To semi-automate that comparison needs the constant dilution of the BI models (the design data, target state) and process data (as-is state, based on as-built data and more). This paper presents an experimental use case: A software tool was created to match tunneling process data with a BI model using an example tunnel model and construction meta data provided by the TBM navigation system, the tunnel ring installation software and segment management software, which is used to track the production process of concrete segments. Also, the problems faced during the project are presented: the current lack of specialization in the IFC schema and thus the need for designated IFC extensions specifically for tunnel construction.

Future use cases for the intersection of construction process data and BI models are currently being evaluated in the research community, which this paper gives an overview about.

Keywords: BIM, IFC, IfcTunnel, IfcShieldTunnel, IFC Tools Project, IFC5, Tunnel Construction, TBM, Information System

ANREICHERUNG VON BIM MIT BAUPROZESSDATEN IM MASCHINELLEN TUNNELBAU

Zusammenfassung: Dieser Beitrag beschäftigt sich mit Building Information Modeling (BIM) und dessen Einsatz untertage im maschinellen Tunnelbau. Darüber hinaus werden Sensordaten und allgemeine Datenquellen der Tunnelbohrmaschinen (TBM) betrachtet, welche zum Bau von segmentgekleideten Tunnelbauwerken eingesetzt werden. BIM geht einher mit der gemeinsamen Nutzung von Daten über Benutzergruppen und Plattformen hinweg, wobei auch offene Dateistandards verwendet werden. Als De-facto-Standard für die Open-Source-Dateistandards wurden die Industry Foundation Classes (IFC) untersucht. IFC ist noch nicht vollständig für den Einsatz im Tief- und Spezialtiefbau geeignet. Daher wurden Forschungsinitiativen untersucht, die sich auf die Erweiterung von IFC im Tunnelbau konzentriert haben: IfcTunnel und IfcShieldTunnel wurden unabhängig von Forschern in Deutschland und Japan betrieben.

Bauüberwachung geht heute Hand in Hand mit dem Einsatz von Informationssystemen, die nahezu in Echtzeit Informationen online präsentieren. Die dynamische Nutzung vorhandener Datenquellen aus dem Konstruktionsprozess ermöglicht die ständige Verschneidung von Daten aus dem BI-Modell (Designdaten) auf der einen und Prozessdaten (As-Built-Daten und mehr) auf der anderen Seite. In diesem Beitrag wurde ein praktischer Anwendungsfall näher betrachtet. Er beschreibt die Erstellung eines Softwaretools für die Verschneidung und den Vergleich von Bauprozessdaten aus dem Tunnelbau mit einem BI-Modell: Ein Beispielmodell wurde verschnitten mit Metadaten aus dem Bauprozess, wie dem TBM-Navigationssystem, der Vermessung der gebauten Tunnelringe und einer Software für die Verwaltung von Segmentdaten.

Zukünftige Anwendungsfälle für ein solches Zusammenspiel von Bauprozessdaten mit BI-Modellen werden aufgezeigt, aber auch die Probleme, welche während der Erstellung der Arbeit auftraten: Die derzeit noch fehlende Spezialisierung des IFC-Formats für den Infrastrukturbau und damit der Bedarf an ausgewiesenen IFC-Erweiterungen speziell für den Tunnelbau, welche erst für die Format-Version IFC5 anvisiert sind.

Schlüsselwörter: BIM, IFC, IfcTunnel, IfcShieldTunnel, IFC Tools Project, IFC5, Tunnelbau, TBM, Informationssystem

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1 INTRODUCTION AND RELATED WORK

This paper covers topics including Building Information Modeling (BIM), and the acquisition and aggregation of data in the specific context of tunnel construction. It also focusses on the approach to update a building model with as-built information. Updated, near real-time building information models, for instance, can be seen as necessary in a more general approach to the "digital jobsite", in concert with methods of computational engineering, augmented reality, the use of RFID technology (Radio Frequency Identification) and live construction monitoring (König et al. 2015).

1.1 BIM IN THE TUNNELING BUSINESS AND THE NEED FOR MANUAL INPUT

When researching the international use of BIM the different level of BIM rules and regulations within the different nations become apparent: In Germany, the Tunnel Rastatt, a railway project currently in development by "Deutsche Bahn" is the first big tunneling project of its kind, being executed with BIM and therefore funded by the German government's "Major Projects Reform Commission". As well, BIM has been used by construction companies in various other countries. These include the Seattle State Route 99 tunnel project (Trimble 2011), the Swedish Transport Authority "TRAFIKVERKET" in the Hallandsås tunnel project (Smith 2014), and the Crossrail Project Consortium, responsible for the construction of Europe's biggest infrastructure project, the Crossrail tunnel in London (Taylor 2013).

Within BIM, milestones of tunnel construction, as well as other goals, can be added to the design model. "As tunneling progressed, by continuously feeding the 'as-built' data from the tunneling production into the 3D model, integrating it with the latest design and engineering information, the team can effectively manage the changing conditions. The shared information empowers the design engineers to analyze the effect of, and react to, changes immediately, avoiding the risk of costly surprises during the construction as a result" (Smith 2014). Yet, currently the comparison of those construction results with the as-built (as exemplarily displayed for an imaginary tunnel project in Figure 1) still needs manual input.

1.2 PRODUCT MODELING FOR THE CONSTRUCTION INDUSTRY: IFC IN TUNNEL CONSTRUCTION

For the construction industry, BIM is also a design-methodology. It is derived from a procedure called "product modeling", the digital description and abstraction of desired products. Completed buildings are the final product, where all information may be structured in a digital manner. The goal is the usage of all information over the whole product lifecycle, saved into appropriate file formats. Buildings can last several decades and up to centuries. For a long-term usable documentation of the building to not be dependent on the existence of the specific vendors and the software with which it was created, the need for vendor and software neutral, open file formats is tremendous. Therefore, certain organizations push the creation of such file formats. One of the main actors is the "buildingSMART" organization, whose file format "Industry Foundation Classes" (IFC) is the de facto standard. Both topics, product modeling and IFC will be a necessity for a desirable tunnel product model, which is utilizable over a long period of time.

IFC was created independently by the buildingSMART organization, yet its current version IFC4 was later standardized by ISO as the norm ISO 16739:2013. Even though proprietary file formats exist, IFC is recognized as the only vendor-neutral format and is pushed as the mandatory file format by big construction companies and project developers. Its predecessor was the version IFC 2x3. An example BIM tunnel

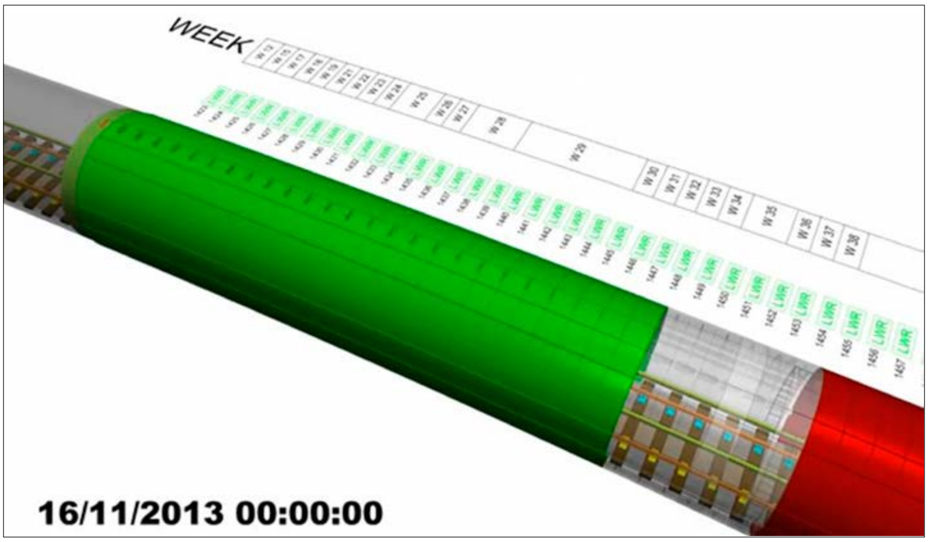

Figure 1: Visualization of a tunnel construction schedule for demonstration (Source: Paul Brown 2013, 4D BIM Tunneling Sequence Schedule, http://www.coroflot.com/PaulBrown/4D-BIM-Tunneling-Sequence-Schedule, accessed 12/2016)

model was studied, which was only available in IFC 2x3 format. This is why all references are always to be seen in relation to that version. Until now all versions of the IFC file schema, including the current version of IFC4, only focus on surface construction engineering, such as buildings. Yet, "the current version of IFC lacks the ability to comprehensively describe infrastructure facilities such as roads, bridges, railways or tunnels in detail" (Vilgertshofer et al., 2016, p. 1). This is why the next update IFC 5 (still in development) will also focus on infrastructure.

It must be stated that it is not the final goal of the format to fully describe the entirety of a built structure and its environment in every detail. A model made in any specific BIM-enabled design software will always comprise details which are not reflected in the schema. This is primarily the case with special object types of varying kinds, which are not part of the IFC schema, and for which generic entity classes – also called "proxy objects" – are made for. These act as containers to save characteristics unrepresented in the IFC schema. Today it is still necessary to use a lot of those proxy containers when saving tunnel models into an IFC file, as well as for the use of generic "space objects". This necessarily generic approach during the saving process is accompanied by information loss, which could have adverse effects later. For example, a specialized simulation software could need the detailed object type information for further calculation processes. Research initiatives, however, are working on this specific problem. A first attempt has been made by researchers in Japan, at the University of Osaka, leading to the creation of the differently structured schema adaption called "IfcShieldTunnel". Publications describing those were made in 2007 and were presented in Yabuki (2007) and Yabuki et al. (2009, 2013). The team broke down the semantic structure of a tunnel building into precise detail and subsequently created IFC classes for most of them. The resulting proposal is very rich with classes. A project funded by the German Research Foundation (DFG), originating with the universities in Bochum and Munich, also researched the necessities and made proposals for IFC extensions in relation to a better reflected tunnel model, which led to the creation of the schema adaption "IfcTunnel". Though the accom-

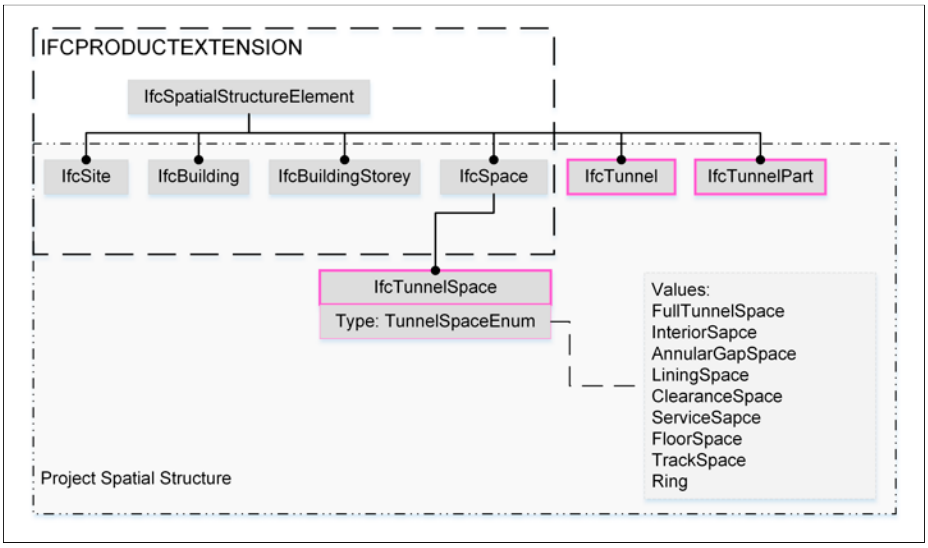

Figure 2: Extension of the spatial structure approach of the IFC Product Extension, highlighted in pink color, adding them to the existing concepts. Only tunnel buildings are considered within the publication of Amann et al. An enumeration list offers to choose from a set of attributes for the IfcTunnelSpace object to clarify the specifics of the object.

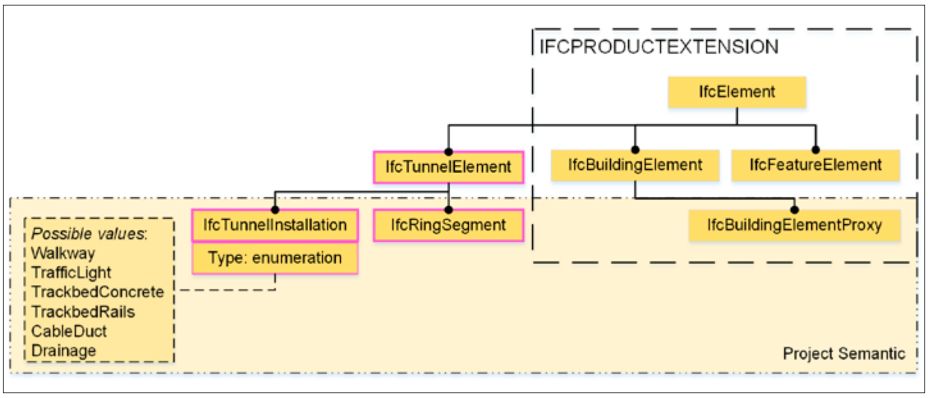

Figure 3: Extension of the element list, using enumeration classes. Newly proposed elements highlighted in pink.

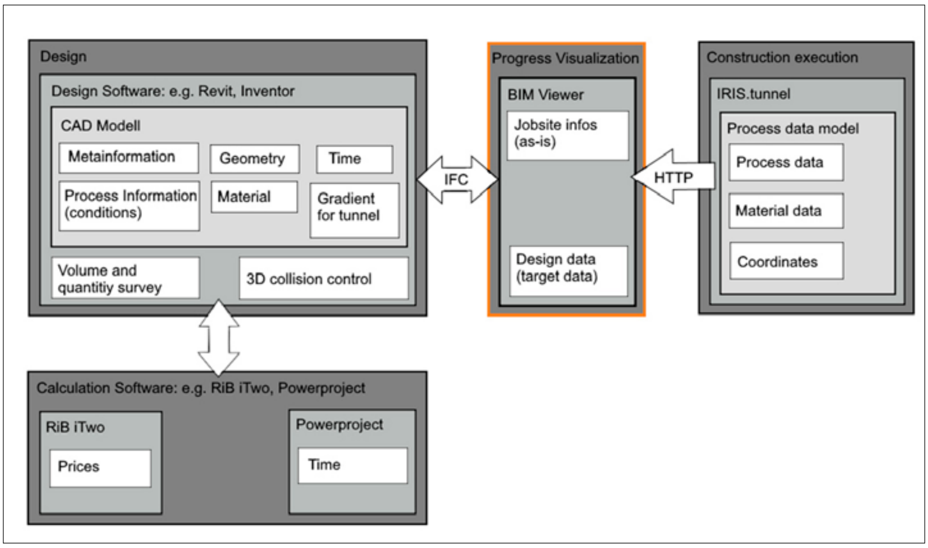

Figure 4: Concept for the integration of data from different construction phases into a visualization context / middleware software: A design model, e.g. created with a BIM software tool like Autodesk Revit, and updated with project information using e.g. RiB iTwo, is blended with construction process information from an information system – adapted from Hegemann et al. (2016)

panying publications reference the work of Yabuki et al. (2009), the team had a more generic approach to modelling. It was published first in Amann et al. (2013). Amann et al. then proposed six new classes for modelling purposes, three of which are used for the spatial structure. The specialization of certain classes was done with enumeration classes, offering a set of options from which to choose. The latter approach is displayed in Figure 2 and Figure 3, describing the extension of existing spatial and project semantic, respectively, which in IFC are completely distinct.

Both published extensions for tunnel construction are only proposals, none that have yet found reflection in any commercial software products available on the market.

1.3 TUNNEL CONSTRUCTION USING TBMS AND TUNNEL CONSTRUCTION INFORMATION SYSTEMS

Tunnel buildings of a certain diameter and length, especially when being constructed in suitable soil, are today often built using highly mechanized machines, called Tunnel Boring Machines (TBM), to which e. g. Maidl et al. (2013) gave an introduction. The most common approach to tunnel construction using these machines is to lay precast concrete segments as the inner tunnel lining.

The complex interaction of construction machinery, the ground in which they operate and other involved components and systems is described as „system behavior". The work involved in tunnel construction can be divided into subsystems, where each most often represents a single construction step. They are thus process-oriented. Tunnel construction using a TBM can be subdivided into different production-processes like advance, foam injection, grouting, segment installation, material transport and more. Every process must be controlled. Alarming values for each system and "Key Performance Indicators" (KPI) can be observed near real-time (Maidl et al. 2014, p. 355 ff.). This requires a data acquisition system which collects all necessary values of sensors and makes KPI calculation and visualization. Information of TBMs and segment production are used in this work in the context of a tunnel construction information system.

Information systems assist in aggregating data from diverse sources and structure, and merge it into a single framework. For tunnel construction, links between heterogeneous data pools are established between systems which normally operate on their own, such as the TBM, surface and sub-surface surveying systems, systems for the treatment of excavated material, including conveyor belt systems or slurry circuits with separation plants, and logistical applications. The input data from those sources to be imported into information systems are varied and diverse, and include Machine data from a TBM's central data storage, the Programmable Logic Controller (PLC), TBM position data and as-built information of the installed tunnel rings, both originating from the TBM's navigation system, and segment data from the central data storage of the precast segment production factory. In this way, the information systems like that can serve as an "aggregation layer" over the jobsite information infrastructure, which is established for the gathering of process data and subsequent analysis.

2 RESEARCH TOPIC

The topic for this work as well as its implementation originates from the desire for live observation of machine data with the purpose of adapting the construction processes, where suitable. This "observation method" is a combination of the use of geotechnical analysis, calculations, and prognosis with an ongoing metrological control of the building and the foundation soil during its construction. This characterized approach requires the ongoing adaptation of the construction process to measurement results, particularly when the prediction of the geotechnical behavior of the soil is difficult (Herten 2012, p. 11), as is also recommended by the German Tunnelling Committee "DAUB" (Breidenstein et al. 2015, p. 89 ff.).

In considering the topics of tunnel construction using TBMs, process data recording and evaluation, BIM with IFC data and in reference to the described observation method, the central question became: How can selected machine and construction-process data, which are stored in tunnel construction information systems, be utilized to semi-automatically compare them to design data from a previous construction phase? As described before, BI models can be extended with target data, adding a 4th dimension of information to the 3D construction model. In this paper, the parameter "tunnel ring installation time" was taken as an example.

A similar approach for data aggregation and matching to BI models has already been described in Hegemann et al. (2016). Apart from that, it should be stated that further experiments like these did not make their way into publication as of yet, specifically with respect to tunnel construction.

3 METHODOLOGY

The practical implementation to fulfill the goals and to answer the research question was based on a 3D tunnel model in the form of an IFC file in IFC2x3. This file was thankfully received from one of the researchers of the German IFC tunnel schema adaption initiative – thus, the influence of the "IfcTunnel" proposed structure was clearly visible in the file: The use of space objects was widely present. That for, the file first had to be adapted, to be able to actually load it into the IFC tools project software. All instances of "IfcTunnel" (e. g. classes IfcTunnelSpace) had to be replaced with "IfcSpace" classes for the common used IFC software library to load the file.

This file was then (1) imported using an adapted BIM IFC Viewer, which parsed all IFC classes into Java classes in runtime. This provided the base to (2) display the model. The software was then (3) expanded with a web interface to an existing tunnel construction information system, which was used to (4) read relevant building process information. This data was then (5) matched to the tunnel model. (6) Using an Editor, example target data (desired ring installation dates) was added to the model. That was the basis for (7) a graphical visualization of whether the process data adhered the design data. With this, the created piece of software served as a middleware between an information system and the construction design suite. The realized concept is shown in Figure 4.

The created piece of software is based on the "IFC Tools Project" as a "programming framework for accessing IFC based Building Information Models" (Tauscher & Heiler 2013), implementable in a common software development environment, such as Eclipse. The strategy was to enable the software to connect to the tunnel information system software to retrieve a meaningful set of construction meta data from an actual project. Table 1 shows an example dataset for a ring, retrieved in JSON format, originating from the information system.

This meta data in the software was matched to the tunnel ring entities of the imported IFC-based BI model. The new entities where attached to existing IFC classes. The same procedure was performed with meta data retrieved for the TBM itself and per each ring segment. Figure 5 exemplarily gives an overview of the used generic IFC classes needed to attach tunnel ring data.

4 RESULTS AND LIMITATIONS

The software provides an overview of the loaded tunnel ring model. After matching online meta data from the tunnel information system to the BI model, it can be viewed by highlighting the model entities in either the 3D viewer or in the semantic table structure next to it. An example for segment information is shown in Figure 6.

The software furthermore enables the user to manually attach construction deadlines to the model if it was not already present in the model file. That information is the basis to compare the planned installation dates (from manual input) to the realized installation dates (from the online system) and indicate the result color coded, whether the goal was met or not, as shown in Figure 7.

This attempt to work with IFC tunnel data, which used the adapted IFC model file with necessarily generic IFC classes as tunnel-specific IFC extensions, because official classes were not available yet, created additional constraints during programming. To identify whether the correct IFC entities of the imported model are used in the software, many hardcoded (thus inflexible) text string comparisons needed to be performed. An example code snippet showing the search for an object of type "Tunnel Ring" is provided in Box 1.

A similar situation occurs when loading specific attributes or meta data from the external sources. The piece of source code in Box 2 shows the loading process of an IfcPropertySet-element for each tunnel ring concrete segment, where also here text string searches must be performed, in this case for segment data from a product called "SDS".

If a use case like the shown one was to be extended further in practice, it is not realistically thinkable without available official IFC extensions for the tunneling business.


```
{
   "Ring No.": 1,
   "Date and Time (Before Installation)": "12.10.2015 14:41",
   "Date and Time (After Installation)": "20.10.2015 08:31",
   "Tunnelmeter Ring [m]": "-11,32",
   "Chainage Ring [km]": "72+985,32",
   "Chainage Cutting Edge [km]": "72+975,78",
   "Ring Type": "TN/N3",
   "Offset HZ Ringbuild End [m]": "36,1",
   "Offset VT Ringbuild End [m]": "-8,66",
   "Ring Orientation": 13
 }
```


Table 1: Example for a JSON string delivered as a response to requesting ring meta data

Box 1

```
If (element InstanceOf IfcSpace && element.getName().toString().contains(„Tunnel Ring") {

      // do something

}
```

Box 2

```
[…]
boolean check = def.getName().toString().contains("SDS Segment Data");

if (check == true) {
            IfcPropertySet properties = (IfcPropertySet) def;

            SET<IfcProperty> segmentPropertySet = properties.getHasProperties();

            return segmentPropertySet;

} // end of if-clause
[…]
```

5 USE CASES, CURRENT RESEARCH AND FUTURE WORK

For the creation of a practical software and the professional, flexible use of IFC models, it is necessary to also use tunnel-specific IFC-extensions. Having a more thorough data structure in place is also a prerequisite to a more professional approach to addressing the need of BI model updates with real-time data.

In practical use of BI models, the use of different model types differing by their depth of content won recognition. Five steps are distinguished by their "Level of Detail" (LOD) (Borrmann et al. 2014). A single modelled element can herein be linked to a growing set of meta data, depending on the LOD. This reference to the amount of meta data is called "Level of Information" (LOI). During the planning and the execution of construction works those different models could roughly be called the deliverable of specific project phases, when it comes to digital documentation. Deliverables like that are normally written out in the projects BIM Execution Plan, as

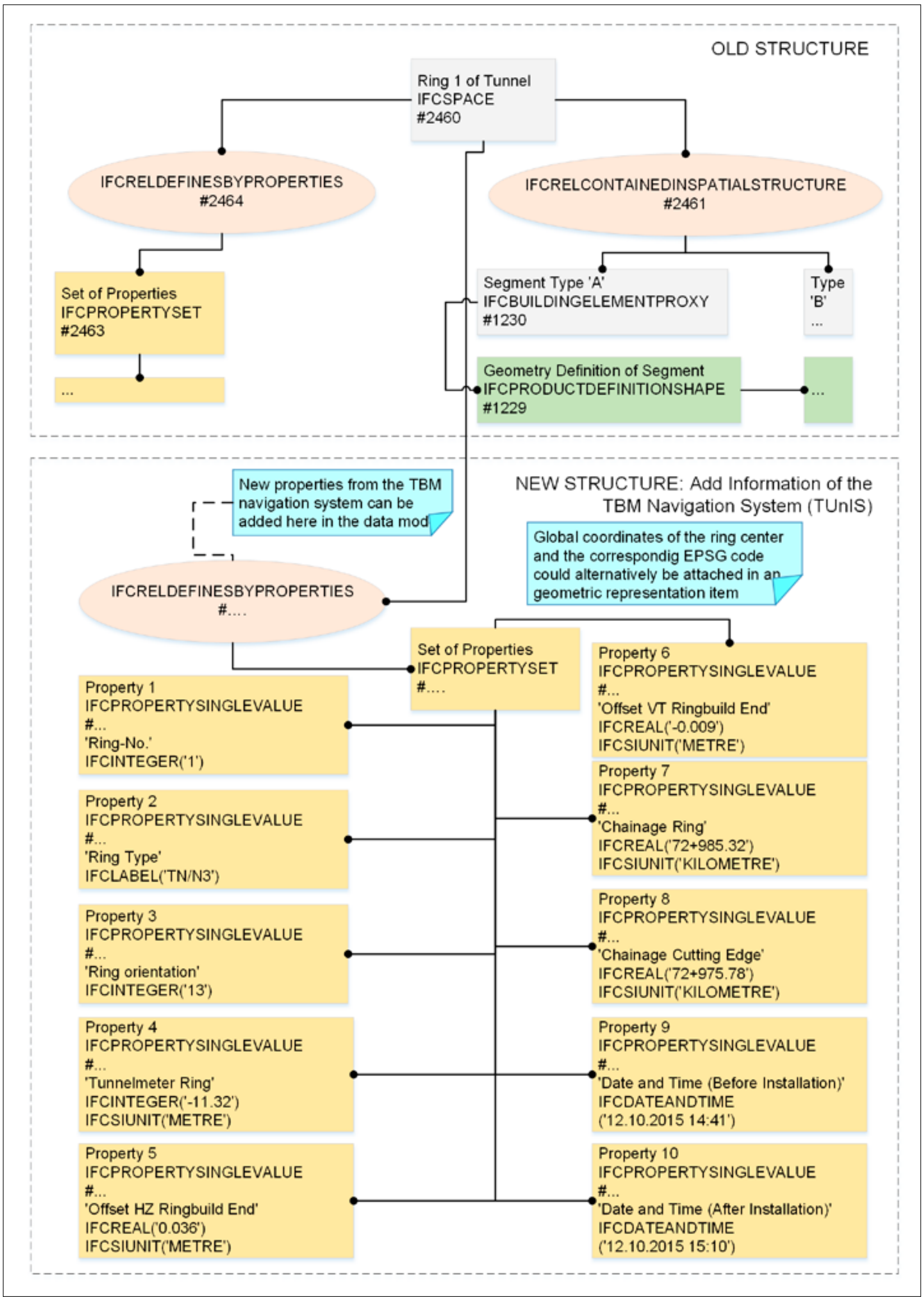

Figure 5: Matching data of the TBM navigation system to each ring

common project structures (e.g. in Germany in reference to HOAI stages) do not reflect the creation of digital models. At the end of the construction phase, in prearrangement of the operation phase, updating the design models with data of external systems can then be utilized. A piece of software to update models with as-built data from the construction, like the one evaluated in this paper, can contribute to update the model in LOD5 with LOI5. This can update model elements referred to the built as-is condition, e.g. real and precise dimensions, forms, position and geographical reference (König et al. 2016b, p. 207). It is considerations like these, which are also part of the use-case study of BIM in tunnel construction, evaluated at the Rastatt tunnel project.

During the construction phase for a building project, having machine data can also be used in the BIM context for event-based actions, e.g. the update of the tunnel building model by sending a feedback signal to the model, each time a tunnel ring was installed underground. This can further on be used for different use cases, exemplarily given in the latter.

During the construction phase:

- Model-based progress reporting for the jobsite. In addition to progress reporting on site performed by personnel using mobile devices, an automated interface can help in this stage. For example, the TBM navigation system can help in achieving a model-based schedule-review by informing the model-viewers about the progress.
- Model-based invoicing to the client, per tunnel ring, when systems are also connected to the companies' ERP systems, can assist with model-based cost-control.
- Communication purposes: Providing live updates on the state of the tunnel, including visualization, would be helpful in the context of public relations.
- Giving live feedback into linked interaction models, for simulations in settlement analysis. These simulations can take place for the ongoing improvement of the construction process, in relation to the described "observation method". Simulation of processes on the site and their influences will play a growing role in construction projects in the future.
- Alarming mechanisms, when critical levels are reached.

During the operation phase:

- Construction relevant TBM meta data should be linked, which could be of interest in any later evaluation context, like damage management of the tunnel. Those parameters could be, but are not limited to, pressure of cylinders pushing onto the segments, pressure of surrounding mortar injection, pressure of the tunnel face support or TBM advance speed values.

These and other application examples where also described in König et. al. (2017). Also, Koch, Vonthron & König (2017) thoroughly sum up the research efforts of the last years and describe an example of the dilution of several expert models for Building Information Modeling using the example of the tunnel project Wehrhahnlinie, Düsseldorf, Germany.

The next version of the IFC file format is already in development, yet no publication date is foreseeable. Currently running research projects for instance focus on the foundation of every very elongated infrastructure: The tunnel alignment. IfcAlignment is considered to be the first addendum to IFC4 (Amann & Borrmann 2015). Research projects for IfcRoad and IfcBridge are already running (König et al. 2016a), yet a project for IfcTunnel is still missing funding (Borrman et al. 2016). The website of buildingSMART dates the earliest project start for an official IfcTunnel development project to spring of 2018, whereas a consortium of project partners is already working on a first candidate standard. First technical documentation as an outcome of this project might not to be expected before early summer of 2019 (Dohmen & Eichler 2017).

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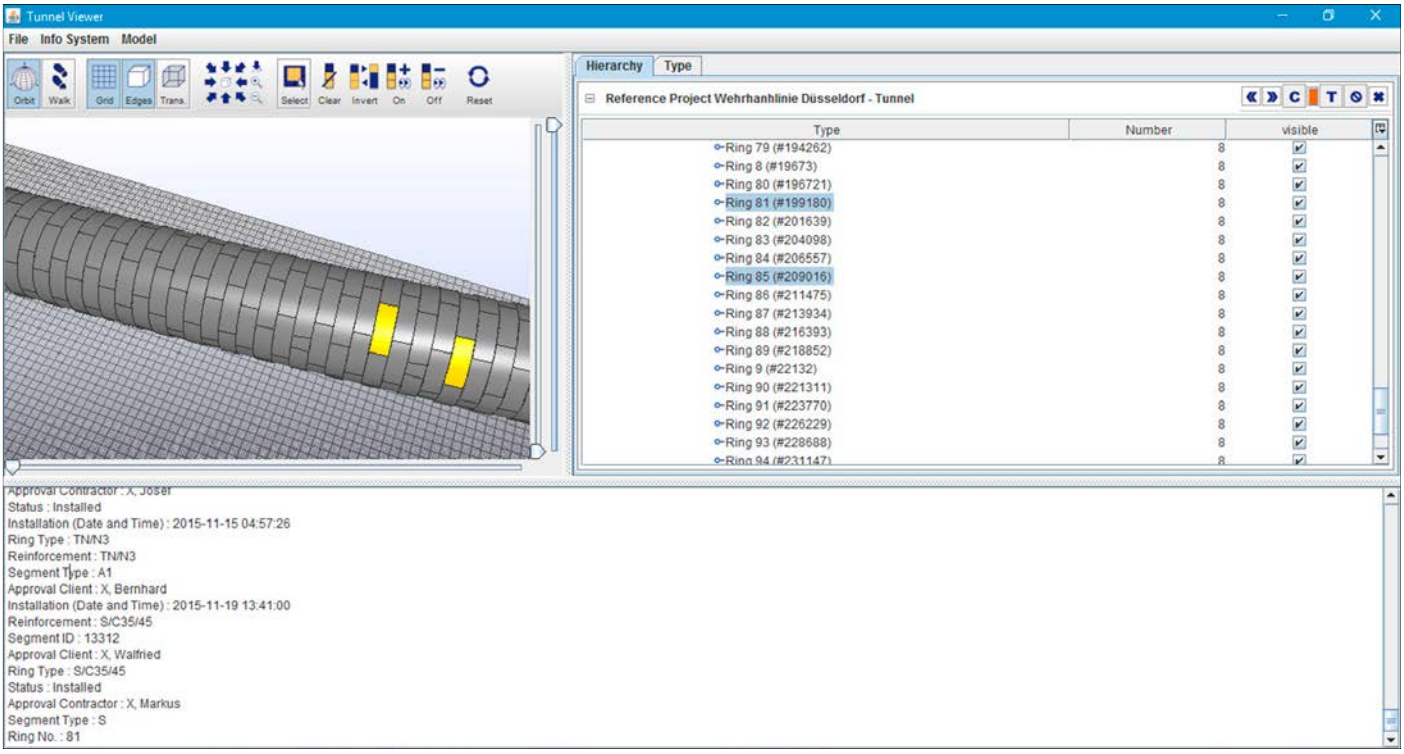

Figure 6: *Displayed segment meta data in the bottom text pane of the window after selecting a specific tunnel element*

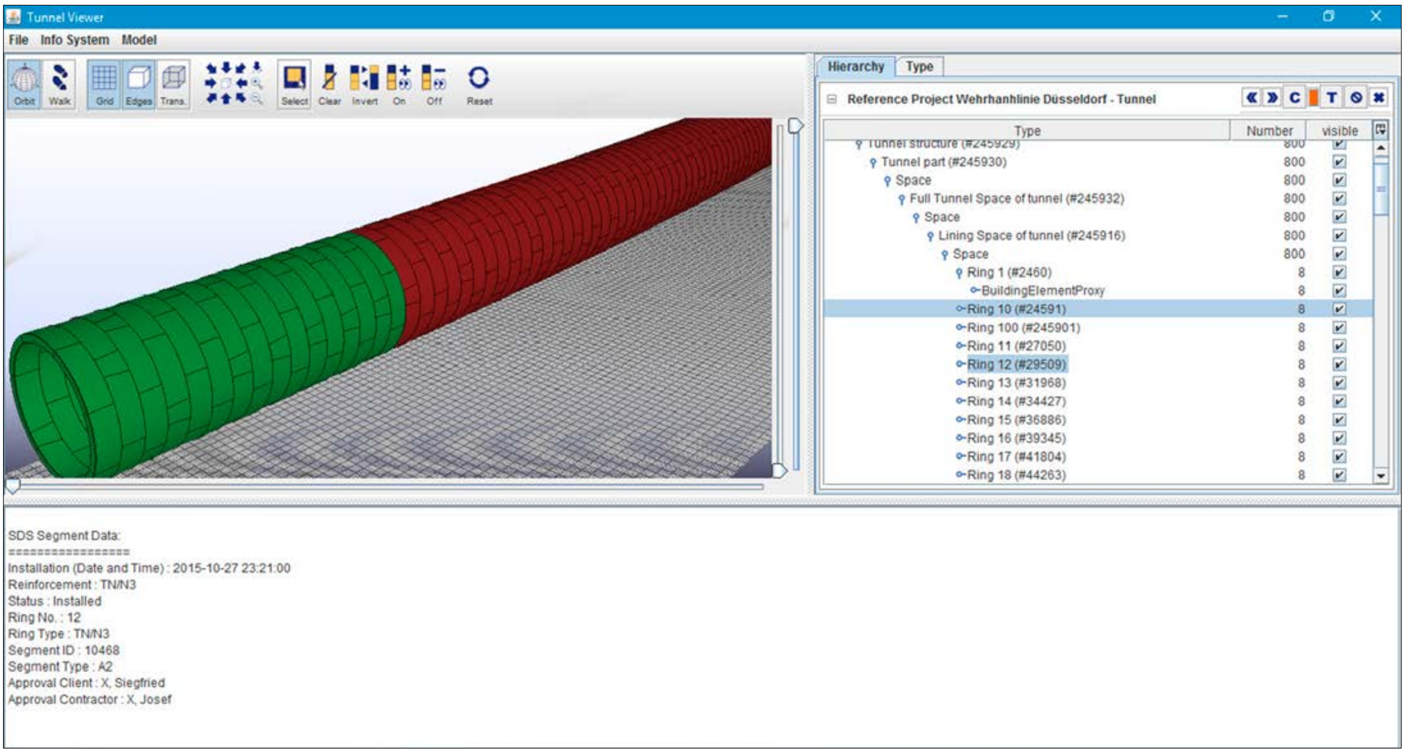

Figure 7: *Interpretation of construction success using a color-coding approach, after timeline comparison*

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