

## IMPLEMENTING BIM FOR CONVENTIONAL TUNNELS - A PROPOSED METHODOLOGY AND CASE STUDY

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**SUMMARY:** *The topic of Building Information Modelling (BIM) adoption by public organizations has become a central subject of research, and a significant amount of BIM documents, guidelines, and standards have been created to meet different organizational purposes. Compared to the building industry, the application of BIM tools for tunnel project management is lagging far behind. This paper proposes a methodology for integrating BIM tools for conventional tunnelling. A fundamental distinction is made between the tunnel internal architectural domain and the external structural domain. For the former, BIM methodology can be applied similarly to the building industry. For the latter, it is suggested that a BIM model be built according to the essential information generated during tunnelling excavation. The proposed methodology was put to test for an actual tunneling project. A routine was established where the supervisor on behalf of the owner was responsible for gathering and reporting essential data in tabular form. Via REVIT's Application Programming Interface (API), a code was developed so that a BIM model was built and updated automatic to data insertion. Ultimately, the final BIM model allows managing up-to-date qualitative and quantitative information visually. Thus, human understanding and interpretation are enhanced for future uses, such as maintenance, future renovations and project post-analysis.*

**KEYWORDS:** *Building Information Modelling, Tunnelling, NATM, BIM Adoption, Tunnel Maintenance, Knowledge Management.*

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# 1. INTRODUCTION

BIM is defined as a shared digital representation of a built asset to facilitate design, construction, and operation processes to form a reliable basis for decisions (ISO 19650/1). At the current state of practice, it is generally accepted that BIM technology is the future for design and construction; the question of why to adopt BIM has gradually shifted to how to adopt BIM. Public construction procurement agencies are increasingly demanding the use of BIM, and the topic of BIM adoption has become a central subject of research in the field of construction management (Gurevich and Sacks, 2020). For this purpose, a significant amount of BIM documents, guidelines, and standards have been created by different construction organizations (Chae & Kang, 2015; Cheng & Lu, 2015). These documents require organizations to create Organizational Information Requirements (OIR), and to define the Level of Detailing (LOD), and Level of Information (LOI). The Employer Information Requirement (EIR) for each project is derived according to the OIR, and lists the model objects and their LOD and LOI.

Compared to the building industry, the application of BIM technology in tunnel engineering is lagging far behind and is still in the exploratory stage (Xing *et al.*, 2020). Zhou *et al.* (2017) conducted a systematic study of projects to analyse BIM applications in China's tunnel engineering industry. There, they found that the application of BIM technology for tunnel engineering is limited and mainly applied during the design stage rather than during the construction and operation stages.

Tunnels can be constructed using either conventional excavation methods or with a fully mechanized operation using a Tunnel Boring Machine (TBM). Conventional tunnels are most often constructed using an approach referred to as New Austrian Tunnelling Method (NATM). Generally speaking, in these projects ground conditions are assessed during construction and engineering solutions are selected accordingly. A brief review of some of the basic principles for conventional tunnelling approaches is given in the literature review hereinafter. From an organizational perspective, it is obvious that tunnels require the development of special BIM guidelines that consider their unique characteristics and address the full project life cycle.

This paper discusses the integration of BIM tools for conventional tunnel practice from the perspective of a public organization. The Department of Engineering and Construction (DEC) is a large governmental procurement agency of the Israeli ministry of defence. A longitudinal study of the adoption of BIM by DEC for the building industry and other public procurement agencies for construction works in the UK is given by Gurevich and Sacks (2020). Amid the efforts for BIM adoption for buildings, DEC management debated the application of BIM for a large tunnelling project. The methodology proposed by the authors, as well as the implementation process and lessons learned throughout, are discussed in detail.

## 2. LITERATURE REVIEW

### 2.1 Organizational Information Requirements for BIM projects

During the last decade, public procurement agencies for construction works became more aware of the benefits and the potential for requiring Building Information Modeling (BIM) within their projects, mainly due to their financial value. Nevertheless, in many cases, the information gathered within the different models remained poor (Gurevich and Sacks, 2020).

The architecture, engineering, and construction industry has recognized the fundamental change in how the industry functions and communicates. Using BIM allowed changing the work place environment and culture during the design stage. However, whereas transformation of BIM models became common, the human form of thinking about project management has yet to adapt to this technological change. One typical example is the practical aspect of gathering information during actual construction, as this process is not automated and requires a change in human working habits.

The importance of gathering information for the whole life-cycle of buildings, from conceptual design to the operation and maintenance, has been acknowledged by researchers (e.g. Xu *et al.*, 2014), but seems to be underestimated by practitioners. The demand for information within the BIM model is fundamentally different from the traditional way construction organizations receive tender documentation. A better definition of information requirements might enable closer cooperation and coordination between the owners, designers, contractors, operators, and suppliers. At the current state of practice, there are differences in BIM requirements

between various public procurement agencies. Moreover, BIM is often demanded without proper definition of requirements and tasks.

ISO 19650 (ISO/DIS 19650 2018 p. 1), which became one of the most common standard documents, is calling for organizations to create an OIR, which will include different organizational requirements and will consist of LOI, LOD, and other documents. Ashworth et al. (2019) studied the influence of EIR documentation on facility management. There, they found that planning an EIR in an early stage is highly beneficial as at the completion of the project all structural objects and mechanical equipment are properly listed and linked to the corresponding object in the BIM model. Still, to the authors' knowledge, there is a lack of research that investigates the actual value of preventing potential errors (e.g. conflicts between the data in a specific object and actual installed equipment) due to the lack of reliable information gathered from the construction stage.

## 2.2 Conventional Tunnelling

Perhaps the greatest challenge in underground engineering is dealing with the inherent uncertainty that stems from the heterogeneous nature of geological formations. For a successful tunnelling project, it is essential to conduct site investigations prior to the design stage. However, it is acknowledged that even under the most rigorous investigation plan, geological unpredictability is guaranteed to provide some surprises during tunnel excavation (Heok, 1982). Tunnels can be constructed using conventional excavation methods, often referred to as the New Austrian Tunneling Method (NATM), or with a fully mechanized operation using a Tunnel Boring Machine (TBM). As opposed to TBM tunnels, which require rigorous planning and detailed design prior to construction, for NATM tunnelling a "design as you monitor" approach is applied. A comprehensive review of conventional tunnel approaches and their historical origin is given by Tonon (2010).

In his abstract to the first paper on NATM, Rabcewicz (1964) refers to the NATM as: "a new method consisting of a thin sprayed concrete lining, closed at the earliest possible moment by an invert to a complete ring, called an auxiliary arc, the deformation of which is measured as a function of time until equilibrium." Rabcewicz favoured full-face excavation whenever possible. However, under poor ground conditions the tunnel cross section is commonly divided into subsections and a sequence of excavation and support is applied (see example shown in Fig. 3).

In conventional tunnelling the strength characteristics of the rock or soil dictate the magnitude of support required for stabilization. Consequently, conventional tunnels consist of varying support classes (Hemphill, 2012). Studies have shown that the extent of support has a significant impact on the overall project budget (Paraskevopoulou and Benardos, 2012). In contrast, TBM tunnels generally consist of a constant support made of precast concrete segments, designed to accommodate the most severe ground conditions.

During the design stage of NATM tunnels, the tunnel engineer is traditionally in charge of designing a number of support classes with varying structural capacity. For fair to good geological conditions, support classes regularly consist of a combination of sprayed concrete and bolts. For poorer rock mass quality, thicker concrete liner and denser rock bolt patterns are necessary. Under even more severe ground conditions, additional means of support may be installed, such as steel sets and steel fore-poles. During tunnel construction, rock mass quality is assessed after each step of advance. Geotechnical engineers that specialize in tunnels observe and assess the exposed rock mass and select the appropriate support class according to empirical classification systems and expert qualitative judgment (Hemphill, 2012). In addition, in-situ displacement measurements and core drilling during construction are often used in conjunction with the qualitative observations, in order to provide engineers with quantitative data, and to compare actual values with the predicted ones.

## 2.3 BIM use in Tunnelling

Different researchers have proposed utilizing BIM technology for different aspects of tunnelling. Due to their simple geometry, tunnels have been traditionally modelled and represented primarily by two-dimensional views (i.e. plans, elevations, and cross-sections); hence, the advantage of 3D visualization capabilities is seemingly minor compared to buildings. However, some preliminary works have demonstrated the advantages of 3D capabilities for tunnelling projects. For example, Providakis et al. (2020) presented an integrated 3D BIM-geology interaction methodology to assess tunnelling-induced settlements and their effect on an aboveground urban environment. For this purpose, empirical formulae for settlement assessment were used in conjunction with a 3D model, which includes the ground, tunnel, and aboveground structures. Their tool provides an efficient

method for visualizing and assessing risk to structures during the preliminary design phase. However, the use of this method will not provide additional information for the design team. When attempting to create a full 3D model that includes the aboveground features such as topography and buildings, long tunnels pose a challenge upon computer visualization. Currently, performance issues have been reported, and data has been limited accordingly (Žibert et al., 2018).

Sorge et al. (2019) presented various BIM applications implemented for the Brenner Base tunnel project to be constructed primarily by Tunnel Boring Machines. They found that BIM technology aids in managing the design process of such a big project, with unique workflows developed to improve the collaboration and data sharing between all parties involved, from designer to contractor and client. Also, BIM was used to design and visualize detailed support elements; this was achieved via BIM design software using adaptive parametric objects, capable of representing their real position on the alignment. In tunnel projects that require complex details (e.g. in intersections between main tunnels and cross passages) this capability can be highly useful for better communication and clash detection.

As BIM provides easy-to-read 3D map data and visualization for various stakeholders, Yin et al. (2020) proposed a framework for the operation and maintenance of underground utility tunnels. The BIM platform can be used as a data source that contains rich information about the tunnel utility, equipment, and pipelines. Indeed, similar to building design, BIM is well suited for coordinating the systems within the tunnel.

It is important to note that alongside the known capabilities of BIM, it is safe to assume that there are many benefits yet to be realized. The growing interest of the tech community in BIM technology is anticipated to yield additional technological developments (Tang et al., 2019). These will change the cost-value balance in favour of promoting BIM implementation. Furthermore, they suggest the importance of information management (IM) in the BIM platform, as it increases the possibility of enjoying future BIM-related applications.

## 2.4 Tunnel Information Management

Tunnelling projects produce a large volume of information. Preserving and storing information effectively can significantly contribute to saving costs, improving performance, and preventing future errors. Over the past decades, forms of IM have advanced considerably, and evolved from reliance on human memory and paper documents, to digital intranets and web-based databases. Currently, the majority of systems developed for IM in the realm of construction are text-based and focus less on visual information (Forcada et al., 2010). This issue is a major drawback, as survey results have shown that engineers are easier to understand data when presented in 3D visual form (Lin, 2014). In this regard, BIM is an efficient means of IM, as it allows information to be managed visually (Deshpande et al., 2014).

When a tunnel project has been completed, information can be useful for different uses. Three main uses identified by the authors are: 1) maintenance, 2) renovations, and 3) project post-analysis. These are briefly discussed in the following paragraphs.

During the maintenance stage various standards require periodic inspection of the tunnel (Ai et al., 2020). Over time, as the tunnel degrades, different problems may arise. For example, a common phenomenon encountered is cracking of the concrete liners. Published literature of lining damage demonstrates that failure can occur due to various causes (Sandrone and Labiouse, 2011). Proper diagnoses of the underlying cause may be challenging, and even require costly investigative actions and analysis (Zhao et al., 2019). Clearly, when the relevant information tied to the location of failure is simple to obtain and interpret, understanding the root cause and finding the optimal solution is extremely important. The relevant information is predominantly collected during tunnelling, when the rock face is assessed and supported. Similarly, other problems such as rockfall, leakage, deformation analysis, can be better understood according to the relevant geological information generated during the construction stage. With respect to operation and maintenance in utility tunnels, a framework for BIM integration has been proposed by Yin et al., (2020).

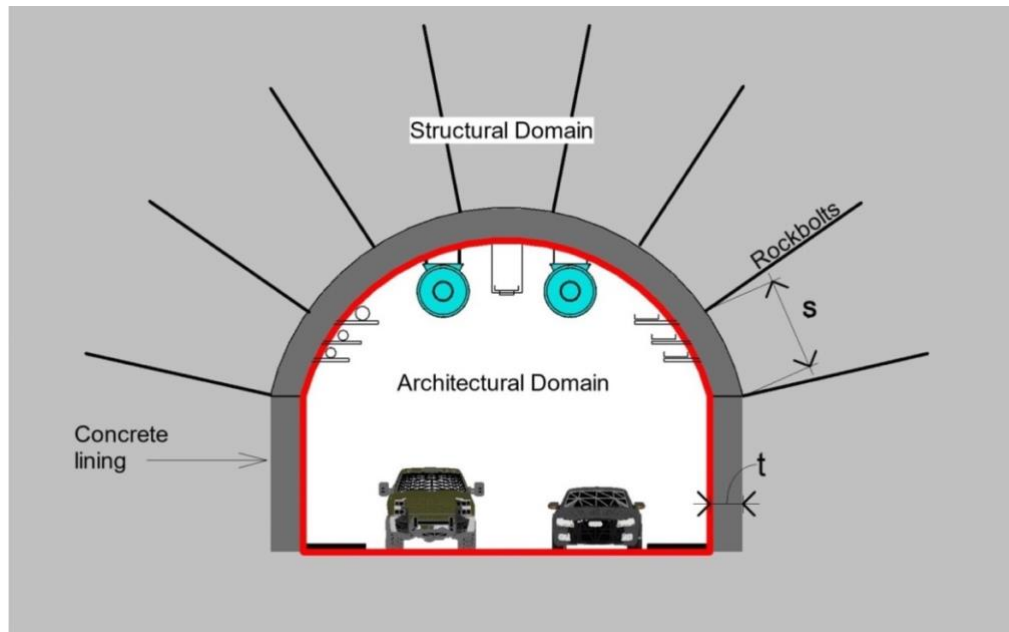
In addition to maintenance operations, it is possible that in the future, renovations will be required. As described in the previous paragraph with respect to maintenance, the quality and availability of the relevant information is crucial for the successful design of renovations. Finally, information gathered during tunnel construction can serve as a highly valuable source for project post-analysis and research. It is argued that it is imperative for future standards developed for BIM integration for tunnelling to define data collection, classification, and storage for this objective. It is noted that with the current emergence of novel and powerful machine learning

tools, preserving data according to widely accepted standards can significantly contribute to the advance of tunnelling practice (Elmo and Stead, 2020).

### 3. BIM CAPABILITIES AND TUNNELLING PRACTICE

As mentioned, BIM has been originally developed and implemented for the building industry. In buildings, the architectural and structural components are not separable, as many elements (e.g. walls, columns, floors, etc.) share both architectural and structural functions.

In tunnels, however, this is not the case. When discussing the integration of BIM to tunnelling practice, it is instructive to make a distinction between what is termed here as the 'Architectural domain' (AD) and 'Structural domain' (SD) of a tunnel. The tunnel's internal space can be referred to as the AD, whereas the external space can be referred to as the SD. FIG. 1 shows a typical road tunnel cross-section. In this figure, a clear boundary (marked in red) can be identified between the tunnel AD and SD.



**FIG. 1:** Typical tunnel cross-section demonstrating the boundary (marked red) between the 'Architectural Domain' and the 'Structural domain'.

The AD must be designed according to the functionality and operation of the final underground space. In this domain, the well-recognized advantages of BIM during the design stage are apparent, and may include:

- Collaboration and communication- BIM tools allow for the various consulting disciplines (traffic, electricity, water, drainage, etc.) to coordinate design and make optimal use of the tunnel internal space to meet all engineering requirements. In this process, clashes are detected and mistakes are prevented.
- Visualization- the model ecosystem provides stakeholders to gain insight and adequately supervise the project throughout the design stages.
- Model-based cost estimation- BIM tools allow precise and automatic translation of the 3D models into accurate cost estimates and bills of quantities. Note that at the current state the quantity computation process requires preliminary preparations (i.e. manual setup with dynamic filters), and has yet to be fully automated.
- Improved scheduling and sequencing- as the tunnel's internal space frequently involves several different contractors and operations, BIM tools allow for better planning and sequencing of construction operations. Furthermore, through this process, increased safety may be achieved, and disputes between contractors that work simultaneously may be avoided.
- Enriched data- BIM can serve as a repository of all the required information for the total project life cycle. Asset profiles can be created for each object of the model, including technical data, essential documents, performance data, etc. (Yin *et al.*, 2020). This data is highly relevant for equipment and utilities within the AD.



In contrast, it seems that the above advantages do not apply to the tunnel SD. The magnitude of support in NATM projects is a function of the ground conditions determined during actual construction. Therefore, it is impossible to model the SD during the design stage, as this data does not yet exist. In order to overcome this information gap, other methods, such as probabilistic analyses, must be used for the purpose of cost and schedule estimation (Mitelman and Elmo, 2018).

It is emphasized that although the thickness of the liner (denoted "t" in FIG. 1) and the spacing of the bolts (denoted "S" in Figure 1) may vary considerably along the length of the tunnel, these regularly have no impact on the AD. This is because any additional excavation required to install thicker linings and denser bolting patterns consistently extends beyond the contour of the inner space. Thus, the advantages of visualization, communication, and clash detection do not fully apply to the tunnel SD. However, it is noted that there are some exceptions to this general rule. For example, tunnel intersections are an example where 3D visualization and clash detection capabilities may be useful for better detailed support planning.

For the structural analysis and design of buildings, BIM technology is especially useful, as the architectural model already contains the structural design elements at global aspects (Chi et al., 2015). In contrast to building structural analysis, tunnel structural analysis is independent of the AD. Furthermore, rock engineering differs from other engineering disciplines as design must be completed based on severely limited information collected during the preliminary site investigation. The natural variability of the rock mass, coupled with the limited knowledge available in the early phases of a project, renders the creation of a virtual twin (i.e., an accurate digital representation of the physical world) unattainable (Elmo and Stead, 2020). Hence, rather than carrying out precise simulations, tunnel designers are advised to use a combination of different stability assessment methods and support design (Oreste, 2009).

Finally, with respect to enriched data, during the maintenance stage, it is usually not important to have knowledge of the exact location of support elements, such as bolts. In addition, the technical data relevant to the SD (e.g. bolt type) is usually identical throughout the tunnel and can be readily inferred from general 2D cross-sections which present the support classes. Support class plans can be stored separately from the BIM model in analogue form (e.g. PDF files).

For these reasons, it is clear that the adoption of BIM for NATM projects is not a straightforward process and that any proposed methodology must consider the distinction between tunnel AD and SD.

#### **4. RESEARCH METHODOLOGY AND LIMITATIONS**

The primary research question was: From the perspective of a public procurement agency, how should BIM tools best be applied to NATM projects?

To address this question, the authors developed a methodology and put it to test in an actual NATM project. In order for the proposed methodology to best satisfy organizational needs, the authors held several discussions with officials, project managers, consultants, and other key members related to the project. These discussions greatly contributed to the process, as each member added valuable comments from their personal experience and perspective.

Through this process, a number of secondary research questions were identified:

- What is the role of BIM modeling with respect to project stage (i.e. design, procurement, construction, maintenance)?
- What is the essential information for better IM at the organizational level, and how should this information be collected?
- How can this information best be integrated into BIM environment?

The proposed methodology for BIM integration into NATM projects is summarized in Table 1. In the table, BIM activity is presented according to project stage and according to the distinction between tunnel AD and SD. In Section 5, a firsthand account of the case study and implementation process is brought. This account serves to illustrate the methodology and highlight some of the important lessons learned.

Table 1 Summary of the proposed methodology with respect to project stage

Project stage	BIM activity	
	Tunnel AD	Tunnel SD
Design	Applied similar to building industry.	Modelling is not applicable, as data does not yet exist. The essential information to be collected must be established by project management.
Procurement	Arrangements to guarantee BIM activity during SD and AD construction.	
NATM tunnel construction (SD)	-	BIM model construction according to systematic data collection.
Construction of internal elements (AD)	Applied similar to building. Industry	-
Maintenance	Management of information via the unified BIM model	

Our work has a number of limitations. First, compared to buildings, the number of tunnelling projects is considerably smaller, a fact which hinders upon gathering data from multiple case studies. Furthermore, NATM projects among themselves are diverse, and can differ by various parameters (project scale, complexity, excavation methods, etc.). Second, the construction of the current case study has yet to be completed and therefore no feedback has been received from the maintenance stage. Nevertheless, it is assumed that decades of experience gained in DEC from the maintenance of other underground facilities served as a valuable source for establishing the essential information to be collected during construction.

Finally, public agencies can differ greatly by organizational structure, goals, cultural environment, and more. These features pose a limitation on establishing generalized guidelines based on the success or failure of a single case study. Undoubtedly, it is important for additional researchers and practicing engineers to share initiatives and findings for the purpose of developing generalized BIM guidelines for tunnels. Nevertheless, tunneling projects are repetitive by nature, as they involve cycles of excavation and support. As such, a learning curve can be established in the course of a single project (Srouf et al., 2016). Similarly, during a lengthy implementation process, the proposed methodology was modified and refined. Hence, although limited to a single case, it is argued that the general conclusions drawn from this work are valid for other projects and organizations. Moreover, other researchers and organizations can further modify the proposed methodology according to their specific needs.

## 5. CASE REVIEW

DEC is a large governmental agency responsible for the design, construction, and maintenance of several facilities in the jurisdiction of the Israeli ministry of defence. DEC plays a key role in the national construction industry, with a very large annual budget for construction. Following the design and procurement stages, the construction of the case study tunnelling project began in 2018.

Within the case study project, underground road tunnels are excavated in mountainous terrain. The geological medium consists mainly of dolomitic limestone with varying strength. Different geological risks were identified during the site investigation conducted prior to design, including fault zones, karst, and perched water. The Q system proposed by Barton (1988) was used as the classification system for the assessment of rock mass quality and support selection. The rock was excavated mechanically, via roadheaders. Project geometry enabled tunnelling simultaneously through a number of fronts.

Project procurement was divided by DEC into two tenders. The first tender called for tunnel SD operations, i.e. excavation and support. The second tender included all AD operations, i.e. construction of roads, installation of utilities, etc. During the design process, it was determined by the project management staff that BIM technology would be used solely for the second tender, i.e., for the design of the AD. Accordingly, the 3D BIM model was used mainly for the purposes of visualization, as well as utility clash detection and automatic quantity

calculation. The Organizational Information Requirement from the design team was to reach LOD 350 (as to be defined by the American Institute of Architects (AIA 2013))

For the initial tunnelling tender, the contractual documents published by DEC did not include any demands for BIM modeling during construction. At that time, the potential benefits discussed in this paper were yet to be realized. However, a year after construction had already begun it was decided by the project management to attempt to utilize BIM for tunnel construction in order to investigate its potential for the current project, as well as for future projects.

Fig. 2 shows a schematic summary of the various reports and documents that are generated during a typical NATM project in DEC, relevant to the current case study. Clearly, all information can be stored in a single BIM model, which can serve as a single unified platform for project management and supervision. However, it was decided that the BIM model would serve as an additional platform alongside the traditional means of project management.

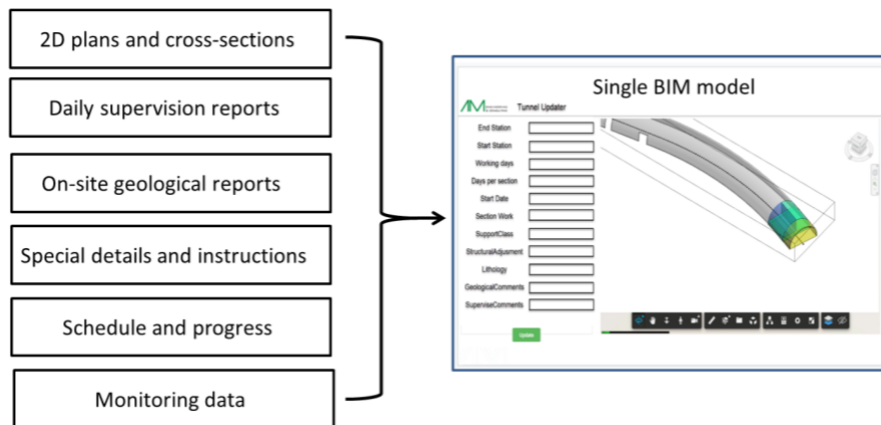


FIG. 2: The reports and documents integrated into the BIM model.

According to the National Building Information Modeling Standard Committee, a building information model (BIM) is defined as "a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward" (NIMBS Committee, 2007). As discussed, creating a fully accurate digital representation for an NATM project is superfluous. Hence, the fundamental assumption here was that the BIM model would serve as a means of recording and preserving only essential information. This was because future uses of the information would not require precise knowledge.

As discussed in Section 2.4, data such as the exact location and technical information of structural object (e.g. bolts) are regularly not a matter of interest in the maintenance phase. Accordingly, it was decided that the BIM model should attempt to capture the essential and useful information. Consequently, any effort invested in collecting and representing data beyond this purpose would be redundant.

To identify and pinpoint the essential information, discussions were conducted with various personnel to determine which data should be fed into the BIM model. As mentioned, DEC is responsible not only for the construction but for the maintenance of facilities as well. Experience from maintenance of previous underground facilities has showed that for the assessment of problems at the operation phase (e.g. cracking, leakage, etc.) the relevant geological and structural information that may explain the problems is difficult to obtain. This has led to unnecessary and costly physical data collection operations such as core drilling and laboratory testing in order to reassess the nature and quality of the rock and support. In other cases, conservative measures were undertaken in light of the lack of reliable information (e.g. installing a highly dense configuration of rock bolts in response to support failure and rock fall). Accordingly, the following key features and parameters of data to be collected for each segment were decided upon:

*Excavation date-* excavation dates allow an analysis of schedule issues and performance comparison of different excavation methods.



*Support installation date-* In addition to schedule and performance issues, support installation date delays between excavation and support installation may have implications upon tunnel deformation and stability.

*Rock mass classification-* according to the final decision regarding rock mass quality, each segment classification was reported ("good", "fair", "poor", etc.). The BIM model contour was assigned colors correspondingly, as shown in Fig. 4. The rock mass quality dictates the support class to be installed, predetermined by the structural engineer in the design stage. Note that occasionally, different segments from a single cross-section slice can be assigned other classes, as rock mass quality may vary even along small distances.

*Structural adjustments-* for cases where the actual support installed was different than the support class. Examples include fore-poling under extremely poor, additional bolting of an individual wedge, etc.

*Lithology-* a description of rock lithology was reported by the geologist for each segment prior to support installation. This provides the future engineers with knowledge of distinct geological features (e.g. faults, perched groundwater, etc.) that may adversely affect support and tunnel performance. In addition to the verbal description, photos of the rock face prior to support installation were added to this rubric.

*Special comments-* in cases where there are special findings, instructions, or events, these are reported and added to the model. Such special comments may include stop stop-work orders, safety events, poor in-situ and laboratory test results, etc.

In addition to the listed features, all data recorded from rod and convergence extensometers were added to the model's data points corresponding to their in-situ location. This allows the engineer to interpret displacement data with greater clarity.

According to the NATM tunnelling principle, excavation was sequenced and divided into three parts: main (right) pilot, left shoulder, and bench (see FIG. 2). Full face excavation was applied when rock mass quality permitted so. The BIM model was divided and numbered, corresponding to tunnel sequencing. This point was crucial, as different tunnel segments may be excavated months apart, consisting of unique geological features, and even be classified and supported differently.

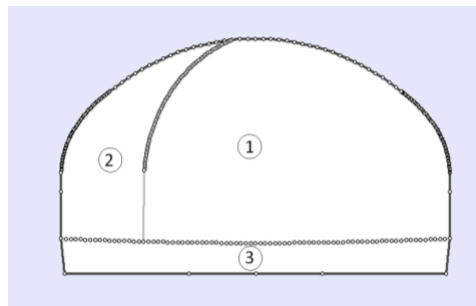


FIG. 3: Excavation sequence of 1) pilot, 2) left shoulder, and 3) bench.

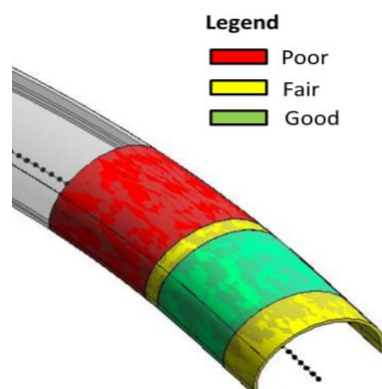


FIG. 4: BIM Model contour according to rock mass classification.

It is acknowledged that the essential information can vary from project to project. For example, in a project where a combination of excavation methods are used (e.g., drill and blast, mechanical excavation, cut and cover, etc.), it would undoubtedly be useful to record this parameter, as it could prove to be useful for post-analysis purposes. On the other hand, when deciding upon which information is essential, it is argued that the risk of information overload must be considered. Specifically for maintenance, it is vital to guarantee that the users will not be overwhelmed by unnecessary data, which can be stored separately.

Discussions revealed that it is important to establish a strict routine for data collection and insertion, as there are various members (supervisor, geologist, contractor, designer, etc.) that create data, each with their distinct perspective and interests. On behalf of DEC, the principal supervisor was designated responsible for gathering the data and filling in the Excel table daily.

The BIM model was setup so that it would be automatically updated according to the data entered into the Excel table (see Fig. 5). For future purposes, a meter unit scale was found to sufficient in terms of precision and accuracy. Hence, via Dynamo coding, the model was divided into 1-meter slices, whereas each slice was divided into the partial excavation segments (see Fig 3). This code tied each geometric segment to the corresponding tunnel cross section plan numbering along with its empty row inputs. An additional script was written via Revit's API to allow the BIM model to be updated according to the Excel table update. The BIM model and Excel table were stored on a cloud-based platform made accessible to all parties (i.e., project management personnel, relevant consultants, contractor and BIM modeler). Following this initial setup, the BIM modeler was not required to actively update the model, but was assigned to assist with any technical issues that may rise. The main issues are summarized in Table 2. Naturally, these issues were encountered predominantly at the initial implementation process and gradually diminished as a learning curve was established.

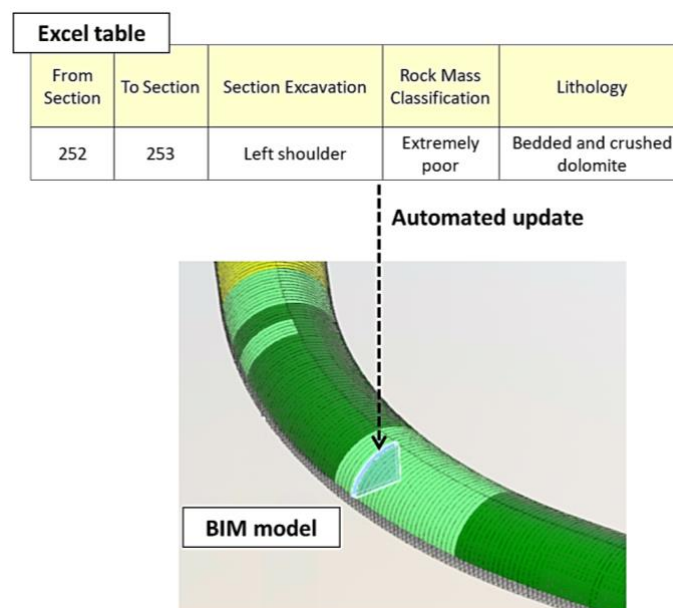


Fig. 5: Illustration of data model updating process

Initially, an attempt was made to complete the BIM model so it would include the information from sections already constructed. This required examining several data and documents (as illustrated in FIG. 2). Building a BIM model that reflects upon work carried out only months before proved to be a highly cumbersome task for a number of reasons:

Many documents contained an overload of information and used different terminology. Thus, sorting the relevant information was difficult and time-consuming.

The various documents are most commonly sequenced according to their date of execution. However, tunnelling progress was not aligned with model geometry, as it involved construction at simultaneous fronts and the adoption of partial excavation.

Through the process of data collection, conflicts between different sources were detected. For example, a certain cross-section could be recorded as “good” in the geological report and referred to as "fair" in the supervisory report. Attempts to resolve such conflicts based on memory or comparison to other data records did not always prove successful.

These issues can be viewed as a demonstration of the importance of the proposed methodology. If it were difficult to reproduce data during construction, doing so years after the project has been completed would be increasingly more difficult, and possibly even unfeasible.

In contrast, when data was collected during actual construction, conflicts between reports were quickly resolved. In cases where such conflicts stemmed from a difference in opinion rather than human error, these were added to the model as additional comments.

*Table 2 Problems and corrective measures*

#	Problem	Corrective measure
1	Data from portions constructed prior to initiation was difficult to obtain.	For future projects, proper contractual arrangements for this task must be made beforehand.
2	Lack of full cooperation from the supervisor.	
3	Reports contained improper information.	The report spreadsheet code was adjusted to constrain the supervisor to report appropriately and thoroughly.
4	Special comment section was left empty.	A list of important issues that require being reported was established and added to the spreadsheet as part of a drop-down menu.

The costs of BIM implementation during the construction stage as described can be regarded as negligible. The process of data collection demanded relatively little time and effort and did not disrupt the regular construction and management routine.

## 6. RECOMMENDATIONS FOR FUTURE WORKS

From a technical standpoint, the proposed methodology is rather simple, and can be readily implemented by others who wish to use the current framework. Additionally, the data to be collected during tunnel construction according to specific organizational needs and project characteristics can be easily modified. However, much technical and methodological work is required in order to increase automated collection of quantitative data. As discussed in the literature review, the current practice of the assessment of ground conditions is inherently qualitative by nature. Nevertheless, the rapid technological advance can allow integrating novel tools for automated collection of quantitative data.

One such idea discussed by Cheng et al. (2019), is coupling terrestrial laser scanning (TLS) technology with a BIM tunnel model. The use of TLS poses significant advantages for engineering applications as millions of 3D points can quickly be scanned and interpreted. For tunnelling projects, readings from TLS can be used for a number of purposes, such as creating an accurate as-is model of the tunnel, monitoring ground deformations, and accurately measuring the quantity of shotcrete applied by the contractor. In order to tie the data from TLS to the BIM model, it is required to develop a code that transfers and interprets the information according to the application requirements. Subsequently, the information gathered can be analyzed with novel tools from the realm of data science, potentially leading to insights beyond the reach of regular human intuition.

## 7. SUMMARY AND CONCLUSIONS

For conventional tunnelling projects that consist of varying excavation and support methods, a methodology for the integration of BIM tools is proposed. For this purpose, a distinction is made between tunnel internal architectural domain (AD) and external structural domain (SD). For tunnel AD, BIM can be applied similar to

building projects, whereas tunnel SD requires a methodology for the integration of BIM tools to be used during tunnel construction.

The methodology presented here was implemented upon an actual tunneling project managed by a governmental procurement agency. In this process, the essential information necessary for future IM was established beforehand. The data was collected and reported daily by the supervisor on behalf of the owner. Via REVIT's API, a code was developed so that a geometric BIM model was updated automatically to data insertion into an Excel table.

The implementation process was initiated in delay to the beginning of construction. It was found that collecting reliable data generated only months prior is a complicated and sometimes even unfeasible task. This finding suggests that it is vital to collect the essential information during actual construction. As different project members were forced to subscribe to a concise tabular format, conflicts between reports were reduced and transparency was increased. In addition, it is assumed that future erroneous interpretation of information due to overdetailed technical reports can be prevented.

According to experience gained from the maintenance and operation of previous underground facilities, increasing the availability and reliability of relevant information has the potential for significant savings. The final BIM model allows data to be accessed easily and visually. Hence, when structural problems (e.g. liner cracking, rock fall, excessive deformations, etc.) are encountered during the operation and maintenance phase, the underlying geological causes can be readily inferred from the information stored in the BIM model.

Although not practiced in the current study case, it is clear that the BIM model could be a handy tool for IM during the construction stage itself. Available and concise information could contribute to activities such as performance assessment, design modifications and conflict settlement.

The current methodology was adopted by the organization (DEC) as guidance for future projects and the EIR was updated accordingly. As there is a wide range of diversity both in tunneling projects and public organizations, it is important for additional researchers and practicing engineers to share initiatives and findings of BIM adoption for tunneling projects for developing generalized BIM guidelines for this purpose. Such guidelines may assist procurement agencies in better defining the modeling and data collection procedure. In addition, other future technological developments (e.g. automated data collection devices) can be integrated into this process.

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