Digital Design, Building and Operation of Underground Structures

BIM in Tunnelling

DAUB-Working Group
Index

Preamble........................................................................... 5

1 General constraints .................................................. 5
  1.1 Initial situation and objective of the recommendation.................................. 5
  1.2 Validity and target audience.............................. 6
  1.3 The life cycle of underground structures...... 6
  1.4 Special features of underground construction........................................... 7
  1.5 Project development as partners............ 8
  1.6 Contract and tendering specifications...... 8
   1.6.1 Contractual aspects................................. 8
   1.6.2 Procurement aspects............................... 9

2 BIM basics ................................................................... 10
  2.1 Building Information Modeling (BIM)..... 10
  2.2 Multi-dimensional design (from 2D to xD)........................................... 10
  2.3 Models ......................................................... 12
  2.4 Data management and interfaces........ 12
  2.5 Model granularity (LoX) ......................... 13
   2.5.1 Level of Geometry (LoG)...................... 13
   2.5.2 Level of Information (LoI)................... 14
   2.5.3 Level of Detail (LoD)......................... 14
   2.5.4 Level of Development (LoD).............. 15
  2.6 Limits to the informative value of digital models................................. 16
  2.7 Roles and responsibilities ....................... 16
  2.8 Exchange Information Requirements (EIR) 17
  2.9 BIM project execution plan (BEP)........ 17
  2.10 Modelling rules..................................... 17
  2.11 Use cases for underground construction...20

3 Design preparation.................................................... 20
  3.1 Surveying the existing situation............. 20
  3.2 3D ground modelling................................. 21

4 Design..................................................................... 22
  4.1 Design variant investigation.................. 22
  4.2 Visualisations (public relations work).... 23
  4.3 Surveying / gathering of evidence........ 23
  4.4 Coordination of the specialist disciplines...24
  4.5 Progress control of design.................... 24
  4.6 Preparation of plans for design and approval........................................ 24
  4.7 Health and safety and environmental protection........................................ 24
  4.8 Design approval........................................ 26

5 Construction preparation ....................................... 27
  5.1 Bill of quantities, tender, award......... 27
   5.1.1 Object-based measurement ................. 27
   5.1.2 Partially automated BOQ production (taking off)...................................... 27
   5.1.3 Model-based tendering....................... 30

6 Construction ........................................................ 30
  6.1 Construction scheduling ....................... 30
  6.2 Logistics planning .................................. 31
  6.3 Production of construction drawings..... 31
  6.4 Construction progress controls............. 33
   6.4.1 Monitoring of the process sequence (Process controlling).......................... 33
   6.4.2 Recording of the actual ground-process interaction................................ 34
   6.4.3 Construction supervision.......................... 35
  6.5 Change management............................. 35
  6.6 Payment of construction works............. 36
   6.6.1 General ............................................. 36
   6.6.2 Payment according to item types .... 36
   6.6.3 Lump sum items................................. 36
   6.6.4 Items for time-related costs............... 36
   6.6.5 Remeasured items.............................. 36
   6.6.6 Lump sum quantity items.................. 36
   6.6.7 Items for non-localised additional works or services.............................. 36
   6.6.8 Items derived from existing construction elements................................ 37
  6.7 Defects management............................. 37
  6.8 Tunnel documentation........................... 37

7 Operation............................................................. 37
  7.1 Use for operation and maintenance...... 38
   7.1.1 The digital facility owner’s manual as a starting basis............................ 38
   7.1.2 Operation, maintenance and renewal ....38
   7.1.3 Occupational health and safety.......... 39
   7.1.4 Requirements for the operator model....39

8 Outlook .................................................................. 39

9 Glossary.................................................................... 40

10 References ............................................................ 41

Appendix 1..................................................................... 43
Appendix 2..................................................................... 44
Preamble

Digitalisation is currently having a great effect on many branches of industry, while also being an important current theme in the construction industry, with the aim of achieving sustainable use for all involved parties and society overall. Information about construction works, in this recommendation particularly underground works, should be provided to decision makers more quickly and with a consistently high quality and in easily readable form for individual decisions.

Digitalisation arrived in construction and particularly in infrastructure rather late when compared to other branches of industry. To a significant extent, this is due to the very high complexity in the value added chain in construction. Now however, the gap to the other industry branches should be closed.

Recommendations of the German Tunnelling Committee DAUB normally provide „best practice” solutions for underground construction in Germany, but none is yet available for the subject of „Building Information Modelling” (BIM). Many first isolated solutions have been developed in the course of pilot projects, but the required degree of standardisation is still lacking. The hereby present document therefore describes solutions that are possible today based on projects known to DAUB. In the final chapter, recommendations are also given for expert bodies and politicians in order for the necessary constraints related to the subject to be created so that the standardisation necessary for the next stages of digitalisation can be achieved. It is to be expected that this recommendation will have to be adapted to future conditions in a few years.

This document should contribute to orienting and accelerating the forthcoming steps of development.

1 General constraints

1.1 Initial situation and objective of the recommendation

Digitalisation of our environment in general and specifically concerning construction is making great strides. This will lead to the activation of a great upheaval in the economy and society. Value added chains and production processes will change, also in the field of underground construction.

The challenges we are facing offer a great opportunity to further organise processes and forms of collaboration so that underground construction projects can be implemented in the future

- with consistently better design quality
- with increased acceptance of the project stakeholders
- with improved schedule and budget security
- more efficiently and with less disputes for all project parties
- with central and transparent documentation for the operator.

Is there however a need for yet another document specifically for underground construction right next to the many already existing documents concerned with digital design, build and operation?

The German Tunnelling Committee has answered this question with a clear “yes” because underground construction significantly differs from building and other disciplines of construction in many cases. Underground structures have two essential special features:

1) Underground construction predominantly consists of a combination of long, linear structures (tunnels, headings, shafts) with construction sections with complex geometries (caverns, enlargements, branches etc.).

2) Underground structures are built in and with a special material – the ground, which despite all the preliminary investigations regarding strength and deformation properties is seldom completely known.

The objective of this recommendation is to show how the complex geometry and uncertainty of ground conditions can be handled in a digitalised world and how digital methods provide the available information to the project parties in an adequate form.
1.2 Validity and target audience

The present document is basically intended for all project parties. Since the client is normally the first to be involved with a project, the recommendation is intended especially for client organisations and their partners, since the foundations of an efficient project structure are laid here. The success of a project depends quite significantly on whether the requirements and constraints are successfully formulated in a clear, transparent and comprehensive way, in every project phase and for all project parties.

This recommendation may also serve to support the development of national and international standards.

1.3 The life cycle of underground structures

Underground structures are long-lasting, as is shown by the current stock of tunnels in Germany. The digital models must reflect this durability, for example through the use of open data formats.

Digital methods should be used from the preparation of design work and support the structure during its entire lifecycle from design through preparation for construction, construction process and on to operation, maintenance, refurbishment and any demolition (see Figure 1-1).

Figure 1-1 Lifecycle of a structure

Figure 1-2 Geometrical complexity of underground structures
1.4 Special features of underground construction

Underground construction works are usually structures with complex geometries, often of great length. For the understanding of the project parties and also for collision detection with existing underground infrastructure (e.g. inner-city), the use of digital design methods (at least 3D) promises great advantages compared to the 2D design used until now. The detection of clashes and questions to be solved in the design process will be considerably simplified if all specialist design work is merged into a coordination model (see Figure 1-2).

In order to completely deploy the potential of BIM with regard to the special requirements of underground construction, additional software tools will have to be developed further. Nonetheless, practical solutions can already be found today with the current available tools.

The special challenges of underground construction are the consequence of the construction material used for the opening and supporting of cavities – the surrounding ground, the physical properties and time-dependent behaviour of which can never be completely known in advance due to its natural characteristics.

Digital models also have to be capable of representing the state of knowledge or rather the state of uncertain knowledge – a challenge, which is not faced in other fields of construction to this extent and with the same consequences.

Therefore, one of the major challenges for BIM in underground construction projects is the representation of the ground at each specific project phase taking into account all its relevant and time-dependent properties. The applicable standards, particularly statements about the degree of precision and reliability in each case, still have to be produced on the basis of already available solution approaches and conventional forms of representation (Figure 1-3).

The model requirements are very varied and should always be derived from defined use cases. This leads to the application of special purpose models related to specific problems, parts of which can be assembled to a structured coordination model.

Further special features of underground construction are:

- laborious approval procedures / public interest
- handling of tax proceeds / public money; comparatively high costs
- large share of time-related costs in construction costs (cost-intensive site facilities), therefore particular risks from the disruption of construction progress
- extensive auxiliary construction measures (e.g. support measures, launching construction) with considerable effects on construction time and costs
- complex logistics / linear construction site
- occupational health and safety
- environmental protection: groundwater treatment, handling of excavated material

At the same time, these special features also mean that the application of BIM has a particular potential for efficiency improvement and thus risk minimisation for all parties.
1.5 Project development as partners

Building Information Modelling can develop its full potential when the idea “first virtual construction, then real construction” is followed. For example, it would be completely reasonable to run through the virtual construction process with all project parties, also for example with the contractor responsible for the real construction, since conflicts of constructional feasibility can be detected earlier from the viewpoint of the contractor. Clarification of the contractual framework for this purpose would then gain significance.

Then new forms of collaboration and finally also contract models between client, consultant and contractor could even develop as far as to permit the viewpoint of the contractor to be integrated as part of partnership models that still have to be developed.

An approach during which phase or into which processes which project parties should be involved in this manner, is shown in Figure 1-4.

For public works, the federal government, the responsible client organisation, the consultant and the contractor are required to prepare the corresponding models, which should take into account the characteristics of the German construction market. The simple copying of foreign partnership models will not be practical, even though international experience is very valuable for these considerations.

1.6 Contract and tendering specifications

Procurement and the design of contracts for public sector clients in Germany is regulated by regulations and laws. For the contract values of common underground constructions, European procurement law also have to be observed. At the moment, it is not foreseeable whether and if so, how this legal framework could be changed regarding BIM requirements. In order to successfully introduce BIM working methods for project implementation, the currently available possibilities of procurement law should be used creatively. Any expense for the tendering authority should not be avoided considering the potential for successful contract implementation.

1.6.1 Contractual aspects

The requirements for digital working methods are to be unambiguously and comprehensively defined by the client as the basis for a contract for project implementation with BIM. This is dealt with through the development of the Information Requirements Documents:

- Organisational Information Requirements (OIR),
- Exchange (Employer) Information Requirements (EIR),
- Project Information Requirements (PIR)
- Asset Information Requirements (AIR),

which are also known as the BIM requirement specification and supplement the conventional specification with specific BIM aspects. In these, the client lays down the minimum requirements for the application of BIM in design and construction and also, if appropriate, for operation and maintenance. In particular, the client discloses in the CIR what objectives should be achieved with the method and which use cases are intended.

![Figure 1-4 Possible organisation structure for service performance](image-url)
The other contract party, whether consultant or contractor, answers this performance query with the development of a BIM execution plan (BEP). This is agreed with the client in the contract execution phase and updated together, if necessary over several phases.

While the EIR is part of the contract, the BEP is preferably a mutual agreement of the project execution strategy, updated at regular intervals in the course of the project and supplemented if necessary.

**Responsibility and liability**
BIM is a working method or a tool to carry out the project execution more efficiently and economically. In principle, this does not change anything regarding the liability and the object of liability compared to traditional project execution. Every consultant and contractor bears responsibility for their own services.

Generally, the same regulations apply to the services specified in the EIR as for design services and construction works including acceptance, defects liability etc. The checking and notification duties of the consultant and the contracting company correspondingly apply in just the same way.

**Variations / variation orders**
It is imperative that the intended changes to the design or the construction works are implemented as quickly as possible in the models (3D, 4D and 5D) in order to ensure and to maintain the information value of the model in the application of BIM. For this purpose, unbureaucratic provisions should be agreed (agreement of transparent workflows), which avoid delays due to time-wasting wrangling over the contractual agreement of the variation.

**Geological risk**
The ground information is normally investigated by geologists for the client. A ground model is produced on the basis of information gained at single points, geological reports and mapping. This normally includes interpolation or extrapolation of the determined ground information. This can lead to a false impression of exactness in the digital (3D) display. The ground model locally deviates from reality as depicted before, with the geological risk remaining with the client as on a traditional contract.

In the future, lawmakers should regulate whether and how the ground data and the data regarding underground infrastructure should, if possible, be made available to a central authority. Corresponding efforts have already been noticed in individual German states (e.g. Hamburg with the Drilling Data Portal). The advantages of this for future evaluation are evident.

**Copyright and information basis**
Each model producer fundamentally owns the copyright to their created model, if the model is subject to copyright. This cannot be transferred by contract. Therefore it is necessary to make contractual agreements about the right of use and the data formats to be handed over.

Despite the delineation of the data rights, each producer of information must undertake to provide the data needed out of the project requirements for the BIM coordination model.

Requirements for the data rights are also to be specified in the EIR. It is useful if the model is specified as decisive in the sense of a single source of truth. If several models exist, it is necessary to determine which model is the leading model.

**1.6.2 Procurement aspects**
Also BIM projects must be awarded to the most economically advantageous tender according to procurement law, i.e. the best price/performance ratio. Especially in the phase of the introduction of BIM in planning and construction work, it should be ensured that the price alone does not become the only criterion for awarding the contract, but that the increased quality of the project resulting from the use of BIM allows a reasonable price.

In order to guarantee further project success through the application of BIM, all involved parties must possess a given minimum competences, which applies to both the client and the contractor. For the bidder, this can be achieved by defining minimum requirements for participation in the competition in the tendering process, with, during the initial phase of BIM implementation, more emphasis being placed on evidence of training than on project references, since the latter can be intransparent.

For the assessment of bids, BIM-specific evaluation criteria are to be clearly and comprehensively specified in the tender documents including the judging system. General information in this regard are provided, for example, in „Empfehlungen für die Verwendung qualitativer Zuschlagskriterien im Bundesfernstraßenbau“ (recommendations for the use of qualitative evaluation criteria in main road building) in combination with the ARS 14/2018.

It can be assumed that application of minimum requirements and selection criteria will increase the cost-effectiveness of construction projects and reduce construction time. For BIM projects in underground construction, the two following award types are currently suitable:

- Negotiated process with participant competition,
- Competitive dialogue.
The client can also decide from which phase on he wants to involve the contracting company. It would appear advantageous to already involve the contractor in an early design phase since the input of the contractor can provide construction time savings and resource-efficient working.

2 BIM basics

2.1 Building Information Modeling (BIM)

BIM in the terms of this recommendation is to be understood as a collaborative method based on digital models for the design, implementation and operation of facilities over their entire life cycle.

The requirements for the digital models are very diverse and should always be derived from defined use cases. This provides an incentive to use problem-related partial and specialised models stock of already existing infrastructure, ground conditions, environment, tunnel, portal structures, station buildings, road building, earthworks, specialised civil engineering, drainage, mechanical and electrical, overhead with earthing, 50Hz installation, control and safety systems etc.), which can be combined in structured coordination models.

Thanks to the access to the same digital data (single-source-of-truth concept) being provided to all project parties, information losses are minimised and a platform is created, which permits more parallel and thus efficiently processing of the project.

With regard to the long-term aim of introducing holistic data-based solutions for the information management of infrastructure projects and plants, the introduction of BIM is only a first important step. The solutions intended for model-based collaboration today should always consider the long-term aims of the post-BIM era (Figure 2-1).

For the final implementation of BIM in underground construction, it is recommended to observe and implement the following key elements in a first step:

1) Specify project-specific BIM aims and derive use cases from them
2) Produce Exchange Information Requirements (EIR)
3) Mutually produce BIM execution plan (BEP)
4) Design multi-dimensionally

To provide support, the use of a common data environment (CDE) and virtual methods are recommended, for example at design meetings.

2.2 Multi-dimensional design (from 2D to xD)

2D CAD design has been the state of the technology for a long time. At the moment, we are at the transition from the 2D CAD world into 3D model-based design.

The 3D model is developed into a 4D or 5D model with the additional integration of the factors time and cost. Especially in the field of tunnel building, 4D and 5D models must be capable of representing the variability of scheduled dates due to geological conditions and the resulting cost consequences.

In the future, there may be additional information available, which is written in separate dimensions (xD). In case of the handover of the model for the operat-
During phase, it will be sensible to adapt the information collected to this point in time to the necessary magnitude for operations and reduce it again if necessary (Figure 2-2).

There are a range of advantages if in the course of multi-dimensional design work, it is clarified before the production of the model what information should be integrated into the BIM model. This also includes buildings that are relevant for the construction state but not for the completed tunnel. It is recommended to include these in the model since other processes like collision detection, both in 3D and in 4D, would otherwise work with incomplete data and this could lead to false results. The costs associated with (intermediate) construction states (5D) would then remain unconsidered. In addition, extracted 2D plans may be incomplete and thus unusable. The client should carry out the integration of all objects incrementally with the collaboration of the consultant and the contractor in the course of the project (early contractor approach), since the exact position of these buildings mostly results in the further course of construction design and scheduling.

Project structure
Objects (model element, activity, BOQ item) are normally provided in the relevant authoring tool with a Globally Unique Identifier – GUID and administered through it. In order to implement use cases such as for example 4D simulation, it is necessary to link objects with various dimensions to each other, which creates a relationship between at least two GUIDs. At this point, manual linking is very laborious, so automated and rule-based alternatives should be preferred.

The usual solution approach is to use a project work breakdown structure. This normally consists of several planes (frequently discipline, structure, construction element group, construction element, location, identifier), which are linked as attributes to the model elements as well as activities and BOQ items. Based on this structure, a unique code can be generated for each object, and using this code, linking of several objects can be generated based on rules.

Figure 2-3 shows as a diagram how the code is used for multi-dimensional design.

An object (e.g. a partition wall in a cross passage) is created in the authoring program and assigned the relevant code in the attributes corresponding to the location in the model. Using the codes, the 3D model can be filtered for individual objects, object groups or construction elements.
This code is also assigned to the activity in the construction schedule for the relevant object, as well as to the item in the BOQ, which contains the costs of constructing the object. In this way, the necessary links between 3D, 4D and 5D can be set up. This also enables the performance of corresponding simulations based on consistent data.

Figure 2-4 shows an example of a 5D implementation with the program RIB iTWO, in which the linked dimensions 3D (geometry), 4D (time) and 5D (costs) can be seen in the individual windows.

All further information, which is produced in the course of the project and is assigned to an object (protocols, certificates, data sheets, photos, surveying data etc.), is referenced using the code on the relevant object.

2.3 Models

While producing the model, it is practical to assemble overall models out of part models in order to save IT resources. Part models can be, for example, finalised standard solutions (cross passage, breakdown bay, niche, tunnelling class) or locally complex structures (portal structures, stops).

Specialist models are derived for one discipline from the intended use cases and have to be arranged to be compatible with each other (especially with the same geometrical basis). Examples of such models are for existing buildings, ground, stripping or excavation, structure, tunnelling class distributions, track and road building, equipment etc.

The gain of information for all involved parties lies in assembling of part and specialist models in a coordination model. Thus conflicts between “independent” specialist designers can be detected early and remedied. Oriented towards the use cases, it can also be sensible to lay down several purpose-based coordination models (e.g. public relations, tendering) (Figure 2-5).

2.4 Data management and interfaces

One elementary aspect of the BIM methodology is the central provision and administration of information as a single source of truth. Therefore, the use of a common data environment CDE in the project is necessary. For efficient and secure data management, the CDE is provided with role-based rules for access rights and workflow-controlled data administration adapted for the individual project. The maintenance and updating (workflow) of the models in BIM projects does not differ from the procedure for the production of plans and documents in conventional projects. With digital workflows and the consistent access to the CDE, however, there is better information and process security.

The permission and approval process should be extended to changes to the 3D model. This must still be agreed with all parties (e.g. client, consultant, contractor, authorities, councils, third parties etc.).

Through the use of a CDE, information exchange between the project parties is thus ensured. For the implementation of nearly all BIM use cases, the exchange of model data (geometrical and alphanumerical information) between various software products is also necessary. Basically, it should be the intention to implement this data exchange through open and manufacturer-neutral data exchange formats. In the construction industry, the data exchange format “Industry Foundation Classes” (IFC) can be mentioned. For building, the IFC data structure is already very well
developed. The particular challenges for infrastructure construction (e.g. stationing and transition curve development) are currently being integrated into the data format. At the moment, there is no (ISO-certified) standard exchange format. Until there is, project-specific provisions will have to be worked out and in case it is necessary, proprietary data formats or compatible software products agreed. Such agreements are to be documented in the BEP.

2.5 Model granularity (LoX)

The information depth of models is greatly dependent on the project requirements being followed. Detailed modelling is not always sensible or can even limit the usability of the model. Thus the minimum requirements for geometrical and semantic information should be defined at the start of a project. For the description of the individual information levels, international terms like Level of Geometry/Information/Detail/Development have become established. The individual detailing steps can increase with the progress of a project and are thus analogous to the increased detailing of drawings at larger scales.

Because various terms have become established in the (international) literature with nuanced variations, the following categorisation is followed in this DAUB recommendation:

- **LoG: Level of Geometry**
  Degree of geometrical detailing of the model with reference to the modelled content of the construction elements

- **LoI: Level of Information**
  Information content of each construction element provided through attributes

- **LoD: Level of Detail**
  Combination of LoG and LoI

- **LOD: Level of Development**
  Degree of readiness of a model to fulfil the requirements for the model from various use cases in different project phases

2.5.1 Level of Geometry (LoG)

In the BIM literature, LoGs have until now been described with examples from building (e.g. frame corner of a steel construction, window in a wall).

This DAUB recommendation provides examples of definitions of geometries that occur in tunnel building according to various degrees of detailing (Level of Geometry – LoG) in Appendix 1 and Appendix 2. Appendix 1 deals with tunnelling with conventional excavation and support methods and Appendix 2 deals with tunnelling with mechanised full-face excavation using segments.

The different degrees of detail are each shown in a matrix with the degrees of detail from 100 – 400 using the activities relevant for tunnel construction

- Excavation
- Excavation support (support layer and further support measures)
- Waterproofing
- Inner lining
- Fitting out
**Figure 2-6** shows an overview of LoG 100 to LoG 400. Details can be found in the Appendix.

In addition to the volume bodies for construction elements, “spaceholder bodies” can be included in the model showing the structure gauges to be kept free for the traffic space and for mechanical/electrical/drainage or operation.

It remains for the project parties to decide which LoG is to be introduced as useful for which use case in which project phase and for which construction elements. In order to provide a guide, a few descriptions are shown in the matrix in the Appendix. It also remains for the project parties to decide whether to introduce intermediate stages for special use cases.

The use of a LoG for each use case and project phase should be laid down transparently for all project parties in the EIRs, if appropriate additionally in the BEP or the modelling guidelines.

### 2.5.2 Level of Information (LoI)

The information content of the objects to be used in the 3D model is determined from the requirements for the object for each use case. The statements are in the form of semantic information, as calculation formulas or simple geometrical information about the relevant construction element.

In every case, the unique identifier or also simulation code (see Section 2.2) is to be assigned as an attribute. In underground construction, for example, the following information can be set as attributes (see Table 2-1).

### 2.5.3 Level of Detail (LoD)

The term Level of Detail (LoD) is normally understood as a combination of LoG and LoI. At the current state, applications for underground construction do not need any separate definition in this context.

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<table>
<thead>
<tr>
<th>LoG</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
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<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
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</tbody>
</table>

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**Figure 2-6** Overview of Levels of Geometry in conventional tunnelling (see also Appendix 1)
It is practical to document the assignment of attributes (LoI) and geometrical level of detail (LoG) in the modelling guideline with reference to the use case followed for each construction element.

It should be noted that a LoD 500 for the as-built model as described in the BIM literature is not recommended since the term “as-built model” rather describes the degree of maturity of the model and is to be defined as in Section 2.5.4.

### 2.5.4 Level of Development (LOD)

The LOD (note the writing of the abbreviation with capital “O”), describes the degree of completion or degree of maturity of the model. It is based on the requirements for individual project phases in the life cycle of a construction work and thus the associated BIM aims.

The requirements could be, for example in the project planning and preliminary design phase, aimed at approval procedures and thus concentrated on budgeting and legal content related to approval. From the tunnelling viewpoint, it is conceivable that the models should be capable of making statements about:

- the most economical alignment
- the discharge quantities and quality of water discharged from the site
- the transport of excavated material (quantities, landfill sites, transport routes, recycling)
- preliminary dimensions of construction elements (preliminary structural design, specification of support measures)
- collisions with existing buildings and infrastructure

After further design work, the model could be described as:

- concept model (overviews before construction)
- construction model (degree of maturity for 2D plan derivation)

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<table>
<thead>
<tr>
<th>Conventional tunnelling</th>
<th>Mechanised tunnelling (with segments)</th>
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</thead>
<tbody>
<tr>
<td>Structure number</td>
<td>Ring number</td>
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<tr>
<td>Round/block number</td>
<td>External diameter</td>
</tr>
<tr>
<td>Length</td>
<td>Ring type</td>
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<tr>
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<td>Volume</td>
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<td></td>
</tr>
</tbody>
</table>

**Table 2-1 Example of attributes (semantics)**

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[Figure 2-7 Example of the attributes of an object in the model](image)
production model (integration of actually completed services such as e.g. geology and tunnelling classes)

“As built” model (model for handover to the operator, from the as-built or operator model)

The LODs described in this way refer not only to the purely 3D, but also if appropriate to the 4D and 5D models.

The descriptions of the LODs are not separately categorised, as for example with the LoGs, but are freely formulated and agreed in the EIRs.

2.6 Limits to the informative value of digital models

The phase-specific degree of uncertainty, which is typical for underground construction work, should also be reflected in the digital models. This uncertainty is due to possible incidents (risks) and also matters, that are neither known nor could be known (unknown). These have to be overcome with the methods of project risk management, whether BIM is used or not.

Significant hazards like the geological risk in underground construction cannot be ruled out, despite risk management and the use of BIM in the design phase.

Improved model considerations can, however, contribute to detecting risks more easily so that a suitable catalogue of countermeasures can be produced at an earlier stage, which can contribute to reducing the extent of damage in case of an incident. Despite the use of digital methods, the specification of a catalogue of measures to counter hazards and to exploit opportunities remains the most important thinking task for the responsible engineers, and cannot be delegated to digital models.

BIM thus in no way replaces risk management and the planning of measures for underground construction projects. In contrast, BIM can only effect an improvement in project quality in combination with professionally operated project risk management. If implemented successfully, BIM can have a strong risk-reducing effect (Figure 2-8).

2.7 Roles and responsibilities

The client has to determine the BIM roles, their responsibilities and interfaces for BIM processing. These new roles do not change the existing project roles but rather supplement them. It has become established that the roles described below are to be specified in underground construction as in other branches of the construction industry.

BIM manager

The BIM manager is responsible for the structuring, maintenance and administration of the digital data models of construction works and for checking the correct implementation of BIM components.

BIM coordinator

The BIM coordinator in the project team ensures coordinated BIM design and control of the individual part models in order to then be able to assemble these into a common consistent overall mode. He or she is then responsible that models from various project parties and specialist fields with different IT environments can be coordinated, evaluated and analysed.
The task of overall coordination should for many of the involved professions be supported or prepared by specialist coordinators, who ensure the complete representation of their specialist design work in the specialist models.

It seems appropriate to set up the BIM organisation and the forms of collaboration in a form, such as is shown as an example in Figure 2-9.

### 2.8 Exchange Information Requirements (EIR)

The EIR is the central document used by the client to control the success of a BIM-designed project. The EIR corresponds to a BIM specification and is thus to be understood as a requirement specification. Clients must clearly communicate their requirements and needs to the contractor and make clear statements about at least the aspects shown in Table 2-2.

### 2.9 BIM project execution plan (BEP)

Execution of the EIR is organised in the BIM project execution plan (BEP). It provides the binding agreement of a route to achieving the project requirements. The BEP is first created by the client and then collaboratively further developed by the client and contractor.

The first rough draft of the BEP may be used as part of the award process for the evaluation of the bids.

### 2.10 Modelling rules

The modelling rules should be specified in the form of a modelling guideline. This can already be under-
taken by the client in the EIR, more specific in the PIT and AIRs or through discussions at the proposal of the contractor as part of the production of the BEP.

There are currently no generally valid modelling standards for building or for tunnelling. At the moment, these are drawn up based on the experience of the project parties as project-specific modelling rules. Up until now, it has turned out that due to the changing modelling requirements over the project phases, the modelling rules have to be extended in subsequent project phases, although it has to be taken into account that fundamental rules like for example the coordinate origin at the start of the project have to remain unchanged. Adaptation of the LoGs or the assignment of attributes can however be appropriate as long as this is necessary for the fulfilment of the use cases. It can also be sensible to draw up specifications of the modelling rules for individual specialist models.

Concerning modelling, at least the following points are to be regulated:

- Model structure
- Coordinate origin (overall and part models)
- Construction elements and their attributes
- Naming convention of the construction elements and models
- Introduction of unique identification codes for the construction elements
- Specification of the LoGs for each construction element
- Colour scheme
- Definition of the situations to be modelled (construction and completed states)
- Modelling of tolerances, pre-camber etc.
- Use of the alignment as a reference element

In underground construction, the following should be considered for the modelling in order to be able to serve the defined use cases of a project over the entire life cycle:

- The structure of the model with its construction elements and objects follows the project structure. Division into portal areas, tunnel branches, intermediate starting points, caverns etc. is recommended.
- It is also possible to represent areas of particular interest/attention in their own coordination models (Figure 2-10), which unify the individual specialist models (for each profession) in this area. In order to aid orientation, sections of adjacent construction elements can be shown.

Figure 2-10 Example of a coordination model of a tunnel apron
These coordination models can have their own coordinate origin and can represent the following areas:
- Portal areas
- Shafts
- Caverns
- Station structures
- Cross passages
- Main tunnel

- It will probably be correct not to model the individual driving classes with their numerous support measures over the entire tunnel length. This would demand a high LoD over the entire length of the tunnel, which would unnecessarily increase the data volume of the model. It is more appropriate to show the individual tunnelling classes in detail models (Figure 2-11), which include all the relevant quantities and information for excavation and support. These detail models are assigned to an overall tunnel modelled at a relatively low LoD (e.g. 200) in accordance with a realistic estimation of the possible probabilities of occurrence. In order to estimate the distribution of the tunnelling classes, the ground model can provide essential orientation.

- For the modelling of the inner lining, an analogous procedure can be applied for the representation of standard blocks, special blocks, niches etc.

- It should be clarified what auxiliary construction measures, both temporary and those which remain permanently, such as for example ground freezing, grout bodies, temporary contrivances, temporary structures, launching constructions, special formwork or temporary props are relevant for the BIM use cases and to what extent they are included in the 3D model.

- Specific underground construction requirements for the 3D model in order to be able to derive any 2D plans (e.g. longitudinal sections from the ground or structure model).

- It makes sense for underground construction projects to integrate the surveying of existing objects (buildings, environment, geology, ...) into the 3D model (see Section 3.1). The type and manner of modelling existing objects is to be included in the modelling guidelines. If there are existing models, then the use of those can also be regulated in the guideline as well as the integration of (digital) data about existing objects from third parties.

**Figure 2-11** Detail models of the tunnelling classes referenced on an overall tunnel model
Furthermore, in conventional tunnelling there is a fundamental need for agreement about the geometry to be represented. It is necessary to differentiate excavation as designed and as actually excavated. Depending on the priorities placed on model-based construction design and tender-conforming models, a decision should be made (BEP) which excavated section is to be shown.

2.11 Use cases for underground construction

The Table 2-3 lists use cases (UC), which could be relevant for underground construction. The descriptions and order of the use cases are based on those prepared by the working group “BIM4INFRA2020” appointed by the Federal Ministry of Transport and Digital Infrastructure for the implementation of the “Stufenplan Digitales Planen und Bauen” (staged plan for digital design and building). The listing is not to be regarded as a checklist but as an itemisation of possible use cases without claiming to be exhaustive. Project-specific adaptations of the use cases in this paper can be found in the Sections listed in the left-hand column.

3 Design preparation

The project phase of design preparation is a not unimportant part of the BIM methodology. The fundamentals and the constraints for the actual design phase have to be prepared based on models. This includes in particular the recording and appropriate provision of the existing situation in the course of surveying the existing situation. Naturally the ground and the resulting interaction with the structure are of particular significance in underground construction. This interaction is the essential difference between underground construction and all other construction disciplines.

3.1 Surveying the existing situation

<table>
<thead>
<tr>
<th>Description</th>
<th>Aims</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model-based preparation of all (relevant) existing documents</td>
<td>Creation of the basis for further project processing</td>
</tr>
<tr>
<td>Preparation of a 3D model of the existing situation incl. representation</td>
<td>Creation of the input quantities for subsequent use cases (e.g. design coordination)</td>
</tr>
<tr>
<td>of above-ground building, foundation situation of structures and underground infrastructure</td>
<td></td>
</tr>
</tbody>
</table>
Any existing building situation can be recorded above ground by laser scanning or drone flights and integrated into the coordinated model of the existing situation, for example in the form of point clouds. As soon as 3D models have been derived from point clouds, these are also to be integrated. The foundation situation of the structures can, depending on its relevance, be remodelled if there is no existing model of the existing situation. The project-specific requirements resulting from the evaluation of settlement susceptibility are to be considered in the modelling.

Furthermore, underground infrastructure such as pipes and cables, wells, anchors, support residues etc. are to be exhaustively represented in the three-dimensional development (Figure 3-1).

The granularity of the model of the existing situation created in this way is to be chosen to suit further BIM use cases.

### 3.2 3D ground modelling

The ground-structure-process interaction is so important in tunnelling that the recording of ground conditions is distinguished with its own use case in the course of surveying the existing situation.

The information from the recording of ground conditions is assembled into a 3D ground model. The layer structure – each layer represents a volume body – enables assignment of ground parameters and other semantic information for the use cases based on it. The layer structure of the 3D ground model can, for example, be carried out with direct interpolation of strata boundaries between individual investigation boreholes. The connection of boreholes to form strata boundaries by interpolation should however as until now only be carried out by a specialist engineer. The derivation of a 3D ground model from a limited number of boreholes may create a subjective accuracy, which is not real. The remaining intrinsic imprecision of the model is to be taken into account with appropriate measures during the entire project processing.

![Figure 3-1 Visualisation of existing infrastructure under London (source: Crossrail London)](image-url)
since the ground model is relevant as an input quantity for almost all use cases.

It is recommended that the project parties agree on the parameters relevant to each use case. In addition to the characteristic ground parameters determined according to standards and the data required for simulation investigations, particular attention should be paid to groundwater. The challenge of modelling the groundwater lies in the fluctuations of the groundwater table over time.

One elementary aspect of the preparation of the ground model is the creation of an updating scheme. This should answer questions including:
- What data is updated (geometry, semantic information)?
- How are various version states saved and documented?
- Who may undertake and approve changes?
- In what timeframe do changes to the model have to be inputted and approved?

The updating scheme, which serves as a basis for various processes, should be produced in collaboration between the project parties, since all benefit from a consistent, current ground model accepted by all.

4 Design

The BIM use cases for the design phase of underground construction projects do not differ fundamentally from those for other fields of construction. Specific requirements for underground construction are emphasised in the following descriptions of the relevant use cases.

4.1 Design variant investigation

<table>
<thead>
<tr>
<th>Description</th>
<th>Aims</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variant investigations based on 3D models of the existing situation</td>
<td>Comparison of various design options based on the 3D model to aid decision making</td>
</tr>
<tr>
<td>Conflict analysis</td>
<td>Variant decision for further detailing in subsequent design phases</td>
</tr>
<tr>
<td>- geometrical, e.g. with underground infrastructure</td>
<td></td>
</tr>
<tr>
<td>- affecting several specialist models, e.g. protection areas</td>
<td></td>
</tr>
</tbody>
</table>

Based on the 3D models of the existing situation, particularly the existing underground infrastructure and the 3D ground model, alignments and variants of the underground structure can be investigated and evaluated (Figure 4-1).

The linking of deadlines and costs enables rapid, meaningful and transparent decision criteria for each variant. This does however require the resilient assignment of construction time and cost-relevant data in the models of the existing situation, such as for example groundwater effects, solubility of the ground, tunnelling classes etc.

Here, the BIM methodology permits rapid adaptability of the variants to any changes in the 3D models based on the existing situation, for example through more detailed geological investigations and the corresponding updating of the ground model.

For all investigated variants, clash detection can be performed, for example with existing or planned underground infrastructure, protection areas or fault zones in the ground. The associated uncertainties that affect the actual location and tolerances of planned

![Figure 4-1 Settlement effects of underground alignment variants](image-url)
construction elements (e.g. anchors, structure etc.) have to be represented in the model.

Section 5.1.1 applies analogously for the object-based quantity determination to be prepared in a design variant investigation.

4.2 Visualisations (public relations work)

Even though underground structures are essentially invisible in the completed state in contrast to an above-ground alignment, they still represent an encroachment on the existing situation. Parts that are visible later, such as tunnel portals and starting cuts, emergency exits and sensitive parts of the alignment such as sections passing beneath buildings, and near approaches to existing infrastructure can be visualised on the basis of the 3D models (cf. Figure 4-2). Involved and affected parties gain a realistic picture of the planned tunnel, an optimal three-dimensional representation and even the option of seeing various viewing angles.

Even very long construction-time interventions, such as temporary cuts, starting pits and construction site furnishings can be visualized and optimized in this way as part of the involvement of the public and decision-makers.

4.3 Surveying / gathering of evidence

The intention is to create interfaces to enable the transfer of the geometrical constraints (geometry and dimensions of the tunnel structure, overburden) and the input parameters for calculations (construction material and ground characteristics, ground/tunnel interaction, ground water conditions, construction and tunnelling states etc.) into the structural calculation program, with both 2D strut-and-tie models and 3D FEM calculations being used.

![Figure 4-2 Example of a visualisation](image)
Since structures generally have to be designed to resist the least favourable combination of parameters that are relevant for the calculation, the interface must also be capable of taking into account the upper and lower limits of input parameters such as ground parameters (E-modulus, cohesion, friction angle, lateral pressure ratio etc.) or various groundwater states.

After calculation, it should be possible to feed relevant results of the structural verifications, calculated and forecast deformation at the surface or to the structure back into the 3D model (e.g. through attributes) for the further course of the project and the other project parties.

Even with automated verifications and model-based simulations, the experience and knowledge of the structural engineer will still remain essential in the future for the calculated representation of the structural system and interpretation of the results.

The same applies for the transfer of data from the 3D models into the programs, e.g. for noise protection investigations (construction noise, portal areas), aerodynamic calculations (cross-sectional analyses, sonic boom effect), ventilation calculations and smoke clearance and evacuation simulations.

### 4.4 Coordination of the specialist disciplines

**Description**
- Assembly of each specialist model to one coordination model
- Checking of the specialist models for collisions with other disciplines

**Aims**
- Risk minimisation through early coordination of all disciplines
- Minimisation of design and construction conflicts

The coordination of specialist disciplines in the context of BIM is dealt with as an use case, which is generally valid for all areas of construction.

### 4.5 Progress control of design

**Description**
- Representation of the progress of design work in the model

**Aims**
- Transparency of design progress in the project or structure
- Use in project management to compare with schedule

The control of the progress of design work in the context of BIM is dealt with as an use case, which is generally valid for all areas of construction.

### 4.6 Preparation of plans for design and approval

**Description**
- Design plans and plans for approval are derived in 2D from the structure model

**Aims**
- To ensure consistent design documents
- To ensure design to standards and with the appropriate quality

The production of plans for design and approval in the context of BIM is dealt with as an use case, which is generally valid for all areas of construction.

### 4.7 Health and safety and environmental protection

**Description**
- Consideration of all safety-relevant aspects in the model, especially through the representation of the construction sequence with time
- Rule-based checking of escape routes, bottlenecks, closed zones, escape and rescue possibilities
- Analyses of working conditions
- Consideration of environmentally relevant aspects (closed areas, hazardous substances) in the models (especially in the 4D simulation of the working sequence)

**Aims**
- Identification and representation of spatial and time dependencies of safety-relevant aspects
- Plausibility checking of safety plans
- Support of communication with emergency services and inhabitants
- Improvement of the level of safety

The subject of occupational safety is to be considered in the BIM model and should be separately addressed in the BEP. Aspects of occupational health and safety can be addressed during the design phase particularly by model-based, holistic representation of the changing construction states (4D simulation of working sequence) and the resulting identification of activities associated with risk. Safety aspects of the construction progress represented in the model are always to be investigated by linking closed zones, temporary support elements as well as an adapted access control. In the course of the obligatory hazard analyses, aspects such as the rule-based analysis of escape and rescue routes, bottlenecks, lighting sources and visibility or the availability and location of rescue facilities (fire extinguishers, first aid stations, helicopter pad, assembly points, rescue container, ...
are to be considered based on the model and documented. The visualisation of haul roads and footpaths enables a minimisation of accident risks by avoiding bottlenecks in advance by adapting construction operations or the use of traffic control or access control systems. The working conditions, which can often change during the construction phase (dust exposure, gas content etc.) can also be simulated in the model and appropriate measures taken. In the course of construction, it has to be expected that improved health and safety coordination and more accurate accident analyses can succeed due to the use of models and simulations of working sequences – both can lead to an improvement of safety (Figure 4-3).

With the constant updating of the ground model, the resulting adaptation of logistic processes and the categorisation of the suitability for tipping and environmental acceptability of excavated material based on the actually excavated geology, there is great potential for aspects of environmental protection. During the design phase, special concepts and compatibility studies can be performed using the provision of

Figure 4-3 Model-supported planning of working safety (protection zones)
information from the models in order to investigate the possible effects of deviations from the expected conditions. Critical times (e.g. bird breeding times, repelling of lizards, clearance seasons) can be taken into account, which may contribute to keeping the project on schedule. Furthermore, information linking (e.g. of safety data sheets) in the models and simulations of working sequences, both in the design and also in the construction and operation phases, can simplify dealing with hazardous substances and their environmental impact. Appropriately structured models also permit more accurate analyses of energy efficiency in advance and prompt adaptation or changes during the construction period.

4.8 Design approval

<table>
<thead>
<tr>
<th>Description</th>
<th>Approval processes are not currently implemented with models, therefore 2D plans are still necessary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aims</td>
<td>Approval of models with digital signatures</td>
</tr>
</tbody>
</table>

Due to the current legal and structural framework of the approval authorities and their employees, approval processes cannot yet be performed using models. This means that the derivation of 2D plans from the information stored in the models will continue to be necessary in the near future. The aim has to be consistent digital project processing, with the model providing all information and 2D plans only being produced in exceptional situations. For this purpose, however, all project parties will have to use consistent digital workflows and model signatures in all phases. The subject is not absolutely specific to underground construction but affects all branches of construction.

4.9 Cost estimation and cost calculation

<table>
<thead>
<tr>
<th>Description</th>
<th>Model-based and structured quantity determination, Linking of the 3D model with cost data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aims</td>
<td>Transparent quantity determination, Identification or representation of geometrical and time dependencies or constraints (ground-structure interaction), Improved analysis of project risks through transparency, Improvement of cost security, Comparison of various design variants based on the corresponding 5D model for decision making</td>
</tr>
</tbody>
</table>

Model-based cost estimation becomes possible through the linking of 3D geometry and cost data. The number or the geometry of the 3D objects is calculated with the assistance of the program and assigned to the corresponding cost item. Firming up the construction elements at attribute level makes rule-based assignment possible. Quantities or works, which have not been explicitly geometrically modelled, can be determined, for example, through derivation from existing construction elements or virtual areas or bodies. If this is not possible either (for example for lump sum quantities or items), then the quantity figures can still be entered manually. Evaluation of total costs and certain cost groups is possible at any time by linking. In this way, changes to the 3D model can be integrated directly into the cost estimation so that this is also updated.

In order for a 3D model to be used for cost estimation, the question of cost estimation (e.g. DIN 276, DIN 276-4, AKVS, DB cost group catalogue) has to be clarified before producing the model. This affects the LoX of the construction elements in particular, whose granularity has to suit the cost structure. For example a bored tunnel can be represented as a “worm”, as a sequence of rings or as individual segments depending on the cost structure.

If cost estimation is also understood as 5D modeling, then the granularity of the schedule for the current phase also has to be considered. The resulting costs for interventions during the construction period, like temporary cuttings, various construction states (e.g. excavation depths) can be transparently recorded by model-based cost estimation. In addition, various design scenarios (e.g. construction sequence), design variants (e.g. alignments, extension of tunnel structure or shortening of trough structure), and construction processes (cut-and-cover or mechanised tunnelling) can be efficiently evaluated.

The ground-structure interaction in underground construction also poses special requirements for model-based cost estimation. The ground model should contain all parameters that are relevant for cost estimation (e.g. cuttability of the ground or division into tunnelling classes). The lack of precision of the actual strata should also be considered sensibly and efficiently in order that the spread of possible final costs and completion dates is as small as possible and reliable.
5 Construction preparation

Model-based project progress, as described in the previous sections considering the individual use cases, puts the project team in a position to prepare the construction implementation of the project based on models. This is a decisive step, which should absolutely be taken in order to carry into the next phase the results of the wide variety of relevant information, coordination and discussions, which have been produced during the long design phase.

5.1 Bill of quantities, tender, award

5.1.1 Object-based measurement

| Description | • Taking off of relevant quantities on the basis of model-based design and geological forecasts, which are represented in the ground model  
• Use of the model for variant studies and determination of the variant-dependent quantities for decision-making purposes |
| Aims | • Preparation of structure and ground models with a realistic estimation of the probably occurring interactions  
• Correctness, transparency and capability of checking of the quantities to be expected |

The following descriptions refer both to object-based measurement (taking off) in the course of preparation for construction and also the quantity determinations to be produced in earlier design phases, for example for a variant investigation.

Taking off the quantities for each construction element or its objects provides the basis for numerous use cases in 3D, 4D and 5D models. They are based on the geometrical data of the modelled objects, which are calculated from the parameters used. Furthermore, quantity statements entered in the attributes can also be used in calculations (e.g. number of rock bolts per tunnel metre, degree of reinforcement etc.).

Quantity changes resulting from the investigation of various variants (alignment, cross-section, geology etc.) in the course of the design and implementation process are quickly and correctly available.

In underground construction, differences can arise between the actual remeasured quantities and the quantities in the bill of quantities, for example from loosening of the excavation, overcut to be considered, precamber from deformation, invoicing rules of the VOB (German conditions of contract) etc.

This situation is to be taken into account and a uniform understanding of the calculated quantities and their basis should be created with all project parties.

5.1.2 Partially automated BOQ production (taking off)

| Description | • Use of structure and ground models to produce quantity-related items in the bill of quantities for tunnelling, inner lining and equipment  
• Use of standard bills suitable for underground construction  
• Representation of familiar construction time models from traditional methods in BIM (4D and 5D)  
• Addition of items, which cannot be directly derived from the model |
| Aims | • Production of a bill of quantities, which complies with the requirements of BIM and the intended use cases  
• Rapid production of bills of quantities |

The process of model-based BOQ production demands a transparent handover of information between modelling and cost planning. Starting with the control of model quality, the cost or BOQ structure is then set up for cost and quantity calculation. After the subsequent partially automated taking off, the result is a bill of quantities including the planned construction quantities and serves for subsequent cost calculation.

Underground construction has its own constraints, which significantly differ from building and classic civil engineering, so special consideration is required, which is described below.

5.1.2.1 Structuring of the BOQ

It is recommended that a standard BOQ intended for tunnelling is developed, that should sufficiently accurately describe the works independent of a particular project. The

• project structure,  
• the structure of the 3D model and  
• the structure of the BOQs

should ideally have the same coverage as far as possible and be continuously generated. For example, it is recommended to separate the BOQ into individual project areas or part models like, for example,

• cut-and-cover and mined construction  
• portal areas (north, south, …)  
• tunnel branches

Otherwise, this continuous structure is to be used to the same extent on the construction schedule (see Figure 2-3).
For the structure of the BOQs, the items are to be matched to the existing project and model constraints in order to then link them to the modelled construction elements. Links between a construction element and several items and vice-versa are also possible.

The items, which cannot be derived in the model due to the existing level of detailing are, like connection details (e.g. segment tubes to station structure), to be supplemented with items from the standard BOQ or separately freely formulated in order to then link them to the corresponding construction element.

### 5.1.2.2 Types of items

Model-based BOQ production intends that the structure of the costs or the BOQ structure in the tendering, award and invoicing program is carried out using generally valid work items from the standard BOQ. The following types of item are generally used:

#### 5.1.2.3 Lump sum items

This type of item describes works or services, which normally arise steadily over a certain time period. It is possible to generate these as fictitious construction elements such as e.g. areas in LoD 50 in the model in order to use them as an “envelope” for the information. In any case, they should be included in the 4D and 5D models and thus be linked to the 3D model (linking of assigned times and costs to the “envelope”).

Process-independent costs are works such as technical processing or gathering of evidence, which normally arise steadily over a certain time period. Therefore these costs can either be assumed to be linear over the entire construction period or an appropriate part of the construction period, linked with the relevant construction start and end in the 4D model. Process-dependent costs on the other hand are works or services such as e.g. setting up the construction site, investment costs for tunnelling machinery or preliminary measures, which must be dependent on the construction process. Therefore these costs show direct dependency on the construction process and are thus to be linked to the corresponding activity in the 4D model. Setting up links between lump sum items and the activity in the constructions schedule makes it possible to distribute the virtual construction costs in the 4D model as realistically as possible.

#### 5.1.2.4 Items for time-dependent costs

These items cover overheads, which are necessary for operation of the construction site and construction of the works. They cannot be directly assigned to any work item and are dependent on the forthcoming construction period.

In underground construction, the construction period depends essentially on the actual ground conditions (geology) encountered and the associated expenses for the safe driving of the tunnel using the corresponding tunnelling classes. Thus the construction period is variable and can only be determined or estimated in the construction preparation phase from the distribution of the forecast tunnelling classes.

The three dimensions of the models interact as follows:

- **3D:** Representation of the forecast tunnelling classes and those actually encountered during construction and other geologically caused expenses
- **4D:** Linking of the tunnelling classes and other geologically caused expenses to the assigned time figures
- **5D:** Linking of the tunnelling classes and other geologically caused expenses to the assigned costs

In this context, reference is made to the “Leitfaden für die Behandlung von zeitgebundenen Kosten (ZGK) im Tunnelbau” (Guideline for the handling of time-dependent costs in tunnelling) published by the Federal Highway Research Institute (BASf) in the version from 13/03/2017. The flexible construction time model from the guideline is included here for illustration as Figure 5-1.

For the application of BIM in the field of underground construction, the representation of the construction time model, which is now current practice with the assistance of the so-called “construction time tables” together with the relevant items for time-dependent costs, is of great significance.

Time and cost data for the individual tunnelling classes and any necessary auxiliary measures (e.g. overcut due to geological conditions, additional support measures, ...) are included in the 4D and 5D models and can be referenced to the 3Ds model (structure and ground).

#### 5.1.2.5 Remeasured items

These items cover work items such as shotcrete, carriageway or excavation, which are remeasured in accordance with the applicable payment agreement (e.g. VOB) and invoicing units (e.g. m, m², m³, t, kg). With this type of item, BOQ quantities are taken off from the 3D model and the costs can be determined from the modelled construction elements. The calculation results are dependent on the model quality (degree of detailing, geometry and information attributes) (see Section 2.10 “Modelling rules”).
Support measures in the course of tunnelling, which extend over several rounds such as probe drilling, drainage drilling, face anchors or pipe screens, should be correspondingly taken into account in the 3D, 4D, and 5D models.

If (temporary) auxiliary construction measures such as ground freezing and operation, grouting, construction equipment, temporary constructions, launching constructions, special formwork or temporary props are represented in the model, their quantities can be taken off from the 3D model. Another approach is to supplement these works with additional items and reference them in the 4D model according to their occurrence in the course of construction.

It should be noted that variation of the BOQ quantities due to geological conditions in the course of construction is possible.

5.1.2.6 Lump sum quantity items
Lump sum quantity items cover works, which are tendered according to quantity units but can contain numerous work items. Lump sum items containing several work items, which arise at various times in the course of construction, are to be avoided with the use of BIM since a realistic construction sequence (place, time and finance flow) can no longer be represented due to the lack of transparency; this counters the basic idea of BIM.

5.1.2.7 Items for non-localised additional works or services
The affected works include plus-minus quantities for support measures, extra or less thickness of the shotcrete, overcut due to geological reasons and its filling, obstructions due to water ingress, stoppage costs for the mining crew or obstructions due to restricted tunnelling times.

These items are a special case in model-based BOQ production and the later model-based payment or project control. The performance and thus the associated time and cost shares of these items are uncertain before the start of the project and dependent on the encountered geology. In order to be able to react to the existing conditions, these items therefore have to be taken into account in the formation of 4D and 5D model structures. Then it is possible to transparently represent changes of conditions. Attention should be paid to realistically estimating the number and quantity of the works in order to ensure truthful cost planning and scheduling for the project.

5.1.2.8 Items derived from existing construction elements
It is possible to take off quantities for works, which are not explicitly modelled, from the 3D model. This is carried out by derivation from the existing geometry of the construction element. It is possible, for example in conventional tunnelling, to measure the waterstop from the length of the block or the block joints without the waterstop itself being modelled.

The reinforcement for an inner lining block is according to current practice not explicitly shown and would unnecessarily swell the data volume for a long tunnel tube. The solution would be the statement of a degree of reinforcement as semantic information to the inner lining block. Using this information, the quantity of reinforcement can be determined from the sum of the inner lining blocks (or their concrete volumes) and either assigned to an additionally introduced or automatically generated item (see Figure 5-1 Flexible construction time model).
Section 5.1.2.1 last paragraph). Alternatively, if there are various different inner lining blocks and reinforcement contents, standard blocks could be produced as detail models containing detailed information and linked to the overall tunnel tube according to their planned locations (compare the procedure for different tunnelling classes in Figure 2-11). Another example is the handling of material excavated from the tunnel starting from the portal area. In general, transport to the landfill site (if appropriate according to various tipping classes and locations) and/or reuse are differentiated. Appropriate links should be provided representing proper assignment of the disposal or reuse costs for excavated material at the correct time. These links should sensibly be made in the ground model, since this should include information about rock properties and the individual strata and thus an indication of suitability for reuse or disposal.

Effective model-based BOQ production is generally only practical if the necessary information parameters for the corresponding construction elements are specified before the start of modelling (see Section 2.10 “Modelling rules”).

5.1.3 Model-based tendering

<table>
<thead>
<tr>
<th>Description</th>
<th>Aims</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of the 3D models produced in the preliminary design phase and updated for the process of tendering the works in underground construction</td>
<td>Avoidance of information losses through the use of updated models</td>
</tr>
<tr>
<td>Standardisation of the tendering process</td>
<td>Support for general and technical construction descriptions through the model</td>
</tr>
<tr>
<td></td>
<td>Improvement of the efficiency of bid preparation by contractors</td>
</tr>
</tbody>
</table>

The models (structure and ground), which grow in their degree of detailing through the design process, are used for BOQ production from a certain maturity of design and detail. The model and the BOQ are handed over from client to contractor in addition to additional documents (contract conditions, construction description etc.). Both the models and the BOQ undergo revision inside the client organisation to their needs regarding model standards and cost estimation structures. The model revised in this way can be used for the investigation of optimisation variants. The revised BOQ is used for cost estimation in the estimation program; the calculated prices are imported into the BOQ of the client and sent to contractors with the tender documents.

Scheduling takes over the structures from the model and develops a construction schedule, which is also sent to contractors with the tender documents. 4D simulations of the construction sequence can also be produced at this stage. Scheduling of underground construction works is significantly based on the estimation of excavation, support and inner lining works. The results of this estimation have until now been entered into “construction time tables”. With BIM, these results can now be located in the model according to the tunnelling classes to be driven and the inner lining to be constructed.

It is recommended to apply uniform standards for the structure of the models and the BOQs in order to ensure their use without interruptions as far as possible without requiring great expense on the contractor’s side.

6 Construction

In the project phase of construction, BIM can lead to simplification of the sometimes-complex processes in various use cases. The emphasis during the construction phase must be the consistent and thorough application and continuous updating of the existing data basis. Only digital information that continuously represents construction progress can be used for progress control, defects management or for the payment of construction works. With regard to the ground-structure-process interaction, BIM can be an important step toward objective consideration of dispute situations and thus contribute to an improvement of construction culture.

6.1 Construction scheduling

<table>
<thead>
<tr>
<th>Description</th>
<th>Aims</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model-based scheduling of construction</td>
<td>Production of tunnelling forecasts taking into account the natural spread of the ground parameters that the ground model is based on</td>
</tr>
<tr>
<td>Linking of individual construction elements from the structure model with the associated activities in the schedule</td>
<td>Simulation of construction sequences taking into account the interaction with the ground behaviour and various logistic approaches</td>
</tr>
<tr>
<td>Representation of the project structure in the schedule structure and the BOQ structure</td>
<td></td>
</tr>
</tbody>
</table>

The following statements apply analogously both for the schedule during construction and also for the schedule in the preliminary design and design.
Scheduling of construction works is model-based. The three dimensions of the structure model are extended with construction time as the fourth dimension. The linking of individual objects or construction elements from the 3D model with the associated activities from the schedule should be carried out with an unambiguous code generated out of the common project structure (see Section 2.2). This should be identical with the associated BOQ item for linking with the fifth dimension (cf. Figure 2-3).

Since tunnels are normally extended linear structures, it will still be sensible in the future to use the time-distance diagram (Figure 6-1), which is usual in tunnelling, in parallel. This applies generally for proven forms of display, although it is always important to ensure linking with the models (single source of truth approach).

The special feature of scheduling in underground construction is that uncertainties and imprecision resulting from incomplete knowledge of the ground conditions do not permit any forecast of the exact duration of individual processes. This is seen as an advantage of model-based (5D) scheduling, to run through various simulations in advance with various combinations of the spread due to natural conditions and the construction processes that come into question. This should finally lead to an improvement of adherence to the schedule.

### 6.2 Logistics planning

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Digital planning and checking of space management, delivery possibilities, supply and disposal etc. with the model</td>
</tr>
<tr>
<td>- Determination of the effects on logistic capacity of changes to the model</td>
</tr>
<tr>
<td>- Simulations / variant studies of various logistic solutions incl. representation of the requirements of health and safety and environmental protection as well as time and cost effects</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aims</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Improvement of the potential for lean production in the advance and back areas</td>
</tr>
<tr>
<td>- Optimisation of processes before and during construction</td>
</tr>
<tr>
<td>- Support of construction progress control or process controlling</td>
</tr>
<tr>
<td>- (Partially) automated construction production</td>
</tr>
</tbody>
</table>

Logistics is important in tunnelling and often determines the performance of the overall system due to the fact that tunnel sites are normally linear and frequently with restricted space. Digital, model-based logistics planning through the direct linking of time and costs promises to be advantageous compared to the methods that have been usual until now. For this purpose, all constraints that are significant for logistic planning are to be extracted from the model and transferred to a separate logistics model for evaluation.

The structure model can be used, for example, for planning or checking of space management and possible changes (material, personnel). This also included capacity planning for supply and disposal (concrete transport, site water supply etc.). By assigning parameters, the individual logistics processes (e.g. muck clearance) can be represented in the model. This makes it possible to directly determine the effects on capacity of changes or adaptations of the model and assign them to causes. By linking to a logistics simulation, investigation and assessment of optimisation ideas for the logistics process (e.g. the use of an invert bridge, checking of minimum sections) can be undertaken. This improves the potential for lean production in the advance area and behind. The requirements of health and safety and environmental protection can also be taken into account.

Linking of model-based progress control with current traffic data can reduce the risk of delayed deliveries. If such information, which is already available today, is used, model-based logistics planning can provide part of the basis for construction progress control or process controlling.

Similarly to pure logistics companies, at least partially automated construction production is conceivable in the future, if all information and data regarding the logistic processes are linked to the BIM model of the underground structure and can thus be used (Figure 6-2).

### 6.3 Production of construction drawings

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Working drawings, also in 2D, are generated from the structure model</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aims</th>
</tr>
</thead>
<tbody>
<tr>
<td>- To ensure construction in compliance with standards and quality requirements</td>
</tr>
<tr>
<td>- Serving the traditional and lapsing approval process with checking engineers, authorities and client-side specialist departments</td>
</tr>
</tbody>
</table>

The production of working drawings in the context of BIM is dealt with as an use case, which is generally valid for all areas of construction. The special feature of underground construction in this regard is the fact that the behaviour of the construction material around the cavity on the one hand is dependant on the selected tunnelling process, and on the other hand that the deformation and strength properties of the ground is often not fully understood. This leads to
Figure 6-1  Time-distance diagram
the situation that in many cases, especially however for tunnels under deep overburden, the constructional and structural design of the inner lining can only be undertaken with knowledge of the behaviour of the excavated cavity. The BIM methodology enables all information over long distances of driven tunnel to be made available in a simply interpreted form for the responsible tunnel engineers, so the project can be optimised with little effort (e.g. reduction of the fill concrete if deformation has not occurred in squeezing rock mass thanks to optimisation of the formwork construction for the inner lining).

6.4 Construction progress controls

<table>
<thead>
<tr>
<th>Description</th>
<th>Aims</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording of the actual progress of construction and prompt comparison and adjustment to the intended situation</td>
<td>Prompt, in the best case immediate, identification of changes</td>
</tr>
<tr>
<td>Digital documentation and stepwise recording or acceptance of construction activity by official inspector or client’s construction supervisor</td>
<td>Creation of the basis for tunnel documentation and thus for the handover of the tunnel to the operator</td>
</tr>
<tr>
<td></td>
<td>Creation of the basis for payment of the construction works</td>
</tr>
<tr>
<td></td>
<td>Performance of an earned value analysis regarding the quality, deadlines and costs (complete process controlling)</td>
</tr>
</tbody>
</table>

The control of construction progress on the basis of BIM models is a complex process sequence supported by various digitalisation tools, which are to be agreed between the involved parties in advance. Tools include, for example, CAD systems in combination with BIM viewers, estimation programs, geotechnical sensors, and suitable data platforms for the saving and evaluation of machine and plant data.

It is sensible to be able to display the current state of the project in the BIM model. For this purpose, completed objects can be linked with a completion date. Based on this date, just the objects with this parameter and whose date lies before the given date can be displayed.

6.4.1 Monitoring of the process sequence (Process controlling)

The process sequence is monitored in particular to enable the early identification of changes to the actual state of progress against the intended state and for consistent documentation. For this purpose information systems can be used, which are capable of networking planned construction processes and the resulting data with the produced BIM models. The information recorded includes the entire underground construction process and can be called up at any time. This includes mechanically recorded sensor data, manually entered information from the production process, which is documented in shift protocols, and information imported from external data sources such as a separating plant. In mechanised tunnelling, data from the sensors of the tunnel boring machine are especially relevant for process monitoring; in con-
6.4.2 Recording of the actual ground-process interaction

Continuous updating of the ground model (cf. Section 3.2) is one of the greatest challenges for BIM in underground construction. Above all, the updating of the 3-dimensional body is difficult since there is normally only indirect data, for example from the separating plant or belt weigher). If homogeneous ground is being driven through, then the relevant ground parameters can be updated without having to update the geometry (except perhaps for cutting out the excavated area). In an inhomogeneous area, this is however not possible and therefore largely impractical. On a hard rock tunnel drive, detailed ground information can be gathered from face images, which can be used both for exact updating of the geometry and also as ground parameters. From this new documentation, the ground conditions can be compared with the initial ground model in order to evaluate deviations.

Considering the intention to provide uninterrupted use of material from the model, it seems sensible to use the ground model produced during the design phase and the derived excavation/tunnelling classes (both in mechanised and in conventional tunnelling) as the basis for the routine tunnelling forecast and excavation specification. Findings from already driven sections of tunnel are inputted into the evaluation of the following sections of tunnel.

6.4.2.1 Mechanised tunnelling

The geotechnical longitudinal section should be divided and contractually fixed into process sections, in which a specified tunnelling mode is driven. The process sections are to be entered into the BIM model and continuously documented and updated through comparison of the actual with the planned situation.

Updating of the ground model can normally only be carried out using the planned taking of samples and performance of simulation tests. It is recommended to specify the taking of samples and performance of tests in the contract and carry them out at regular (continuous) intervals in the presence of both contract partners and ideally also an expert commission. The results are to be documented and entered into the BIM model/ground model. Independent of the project constraints, it needs to be agreed what data are to be documented and how precisely.

During a mechanised tunnel drive, ground conditions can cause many and varied problems like water ingress, clogging or other disturbances. These events are normally documented in a process controlling program as tunnelling proceeds. There is therefore no urgent necessity to save the same data in the BIM model. It is sufficient to store links to the events in the model. The data produced in this connection has
to be filtered and analysed and the model provides a suitable medium for visualisation.

The same applies for wear to the cutting wheel tools, which varies according to the soil or rock being driven through. This is documented in a process controlling program and can be linked to this in the model. However, it is recommended to save a summary of the abrasiveness of the ground directly in the model for future tunnel sections or projects.

6.4.2.2 Conventional tunnelling

In conventional tunnelling, the advance rate is heavily influenced by the geological and stand-up properties of the rock mass (excavation classes). Time- and money-related changes are to be entered into the model promptly. This can also be provided, for example, by links in the model.

In conventional tunnelling, the encountered geology is to be mapped and documented after each round. Based on this continuous documentation carried out at very short intervals, the forecast tunnelling class distribution is to be updated and if necessary corrected with the actually encountered distribution (passed through) and displayed in the BIM model. Based on the updated ground model, the time- and money-related effects resulting from the changes of support specification that have become necessary are to be decided.

Based on the updated ground model, the extra or reduced expenses related to support measures, time-related changes, and consumption of material (wear to drill bits...) are to be displayed and the effects in terms of time and money are to be updated in the BIM model and recorded.

Difficulties and extra expenses due, for example to unforeseen water ingress, are to be documented.

6.4.3 Construction supervision

Generally the supervision of construction can be differentiated into a) the supervision of the design for construction and b) the supervision of construction operations themselves. Therefore a part of the tasks can be undertaken by external checkers, although the site supervision is in charge of the process and decides (also furthermore) in what form checks and approvals are to take place. Currently, collaborative working between supervision authorities and the client side in a common data environment is in the test phase. The result is that, at least in the medium term, a fixed interface between the client side and the supervision authorities will continue to be available. Furthermore the applicable legal regulations lay down a closer formal framework here than what is the case with other use cases. This applies, for example, to the derivation of 2D plans from BIM models, since rules sometimes have to be hereby adapted to enable an efficient workflow.

One first step towards a BIM working method could be the use of a common data environment. Adaptation of the rules for the plan documents could be a further step until finally only models are used for construction supervision. Generally however the responsible construction supervision authorities will have to work out a procedure or a timetable for the use of 3D models.

6.5 Change management

<table>
<thead>
<tr>
<th>Description</th>
<th>Handling of deviations identified in construction progress controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aims</td>
<td>Daily support of decisions, especially regarding changes due to ground conditions</td>
</tr>
<tr>
<td></td>
<td>Documentation of the derivation, justification and implementation of changes</td>
</tr>
</tbody>
</table>

The use case “change management” is essentially the handling of deviations identified in the construction progress control. A process is to be set up between the project parties to define the communication routes or notification of changes when they are detected, to provide support for decisions related to changes and ensure the corresponding necessary documentation of the agreed procedure.

In underground construction, above all changes due to ground conditions are problematic, although also to be expected regularly. Uncertainty about the composition and the behaviour of the ground is therefore a problem independent of BIM. However, BIM can enable a reduction of this uncertainty in order to permit decisions on a technically founded and up-to-date basis.

In the process of change management, it should be considered that a rapid approval process for changes is essential since the drive advances continuously and information is required for the current section. The structure of the approval process including the distribution of rights and the final authority to issue an approval should therefore be defined from the beginning so that the implementation and approval of changes can be carried out as quickly as possible.
## 6.6 Payment of construction works

### Description
- Use of the model, which is promptly updated with the actually encountered excavation classes and any additional and/or reduced quantities of support measures, as the basis for the payment of excavation works, taking into account the associated time-related costs
- Use of the “construction time model” in BIM

### Aims
- Improvement of transparency and cost security
- Descriptive documentation in the model
- Improvement of forecasting security for time and cost to the end of the construction period

### 6.6.1 General
Model-based payment makes use of the information saved in the model, in particular the geometry (3D), from which the quantities can be derived, the linking with the schedule (4D), from which time-dependent components can be derived, and the BOQ (5D), which prescribes the structure for measurement and includes monetary components (invoicing, interim payment application, controlling, finance flow plans etc.). Furthermore, it is possible to link further documents such as delivery notes, acceptance or tunnelling protocols, excavation decisions etc. digitally to the construction elements to be invoiced in order to document the corresponding verification of the works carried out.

Ideally, information relevant to invoicing from tunnelling is already digitally recorded and saved in a database, from which the 3D model or the (updated) schedule is supplied with data.

In principle, payment quantities are
- either recorded in the 3D model by marking the completed objects. The payment quantities are calculated from the stored dimensions of the construction element, and it will be the case that several items are linked to one object.
- derived from links in the updated schedule (cf. Section 6.4), in case the relevant items are time-dependent or lump sum items with payment plan.

Constant updating of the 3D model and the linked schedule to reflect the construction works actually carried out is decisive for realistic model-based invoicing. In tunnelling, this applies in particular to entering of the actually driven tunnelling classes and any additionally necessary or omitted works as the tunnel is driven.

### 6.6.2 Payment according to item types
The payment of the individual types of items described in Section 5.1.2 can be undertaken as follows:

#### 6.6.3 Lump sum items
Items with process-independent costs are either paid according to a defined payment plan or as work uniformly distributed over a certain period. In each case the information for the payment quantity is fed from the updated schedule.

Items with process-dependent costs are assigned to their own activities from the schedule and receive their valuation through activation of the relevant activity in the updated schedule. If a percentage work performance is to be paid in an invoicing period, then this can be defined using degrees of completion of the activity. Visualisation of the degrees of completion is possible using the “envelope” added to the model for assistance.

#### 6.6.4 Items for time-related costs
These items are to be paid according to the construction time model represented in the model. The value to be paid is determined by taking into account the actually driven tunnelling classes and the work rates stored in the construction time model.

#### 6.6.5 Remeasured items
Payment is carried out directly from the updated 3D model. The individual payment quantities for tunnelling come from the detail models of the relevant tunnelling classes. The same applies for construction contrivances, if detail models have been produced for them.

#### 6.6.6 Lump sum quantity items
This type of item, as described in Section 5.1.2.6 should not even be part of a BOQ since they do not have the necessary transparency of work items. Also for payment purposes, it would be necessary to work with great effort using various aids (e.g. degrees of completion), which would considerably reduce the intended information value and accuracy of the works carried out.

#### 6.6.7 Items for non-localised additional works or services
The occurrence of these works is to be assigned to the model (structure/ground) through the tunnelling documentation and located to the associated chainage, so that payment of the works is connected to the chainage driven in the payment period.

The optimal method of working would be to record the tunnelling documentation with digital protocols of forms, whose data are referenced to the structure and/or the ground model thus ensuring un-
interrupted information transfer. If this is not the case, then the encountered ground conditions have to be entered manually and the thus specified tunnelling classes including any extra or reduced quantities of support measures or tunnelling obstructions.

6.6.8 Items derived from existing construction elements

Objects created in the model contain geometrical and semantic information, which can be used for the payment of construction elements associated with the construction elements, which are not explicitly modelled. For example, with designation of an inner lining block, the waterstop and the reinforcement can be paid.

Payment for the handling of tunnel excavation material outside the tunnel (reuse and/or tipping) can be carried out using the linking to the structure and/or ground model as explained in Section 5.1.2.8.

If necessary auxiliary construction measures or contrivances are not explicitly modelled in the 3D model (see in this regard Section 5.1.2.5) but were tendered with their own items to be paid according to quantities (m², t, kg, h, ...), then these items are to be linked to the relevant objects in the model according to the cause. Time-dependent works or services (keeping ready, operation, waiting times, ...) can be called up for payment through the activities for them in the schedule.

6.7 Defects management

| Description | • Complete coverage of defects and the measures to remedy them in the digital model |
| Aims | • To ensure the construction of the tunnel in compliance with standards and quality |

Defects management in the context of BIM is dealt with as an use case, which is generally valid for all areas of construction. No special features of underground construction can currently be stated. The essential tunnelling specifics, which should also be taken into account in defects management, are listed under Section 6.4 “Construction progress controls”.

6.8 Tunnel documentation

| Description | • Creation of „as built“ BIM models  
• Documentation of the construction process with comprehensible defects management |
| Aims | • Handover of BIM models in a suitable form to the operator and the responsible authorities |

Tunnel documentation in the context of BIM is dealt with as an use case, which is generally valid for all areas of construction. According to the user requirements, several types of “as built” model may be appropriate. The essential underground construction specifics, which should also be taken into account in tunnel documentation, relate to the documentation of the actually encountered ground conditions and their consequences (see also Section 6.4 “Construction progress controls”). The requirements resulting from operation are described in Section 7.1.4.

7 Operation

The infrastructure operator should ideally be provided with a “digital twin” of his assets on the day of handover containing the necessary information for operation. From commissioning, the operator has to operate the facilities safely and considering the economic requirements.

With a typical period of use of 80 to 100 years, the operating phase dominates the life cycle of a tunnel. In this phase, facilities have to be operated and maintained. Individual systems and components will be replaced once or more time during the period of use. Cumulated over the entire use of an infrastructure facility, the nominal costs for operation, maintenance and renewal, depending on the type of use of an underground cavity, reach a similar magnitude to the initial investment. The infrastructure operator correspondingly has a great interest in minimising operating and maintenance costs over the entire life cycle. For such minimisation, the operator needs exact knowledge about the existing facility, the behaviour of the plant (e.g. drainage systems, deformation) and the associated expense of operation, maintenance and renewal.

Currently, such optimisation is only possible to a limited extent because for one, there is often a lack of consistent data about the existing plant and its behaviour after a certain period of operation. Data about costs in the required structure is also often lacking.

The operation of underground infrastructure for regular operation or in the case of an incident needs appropriately trained personnel. Digital information and models can be of great assistance for the operator, if

- the as-built documentation is handed over to the operator according to his requirements and completely
- changes to the facility can be updated continuously and promptly using mobile devices
- Results from monitoring systems (e.g. fibre optic sensing, laser scans, etc.) and linked with a georeference to the virtual facility model.
Digital information and digital models are used in the operating phase for operational management, the planning and optimisation of maintenance and renewal measures as well as for training.

The integration of the ground and its behaviour as well as the representation of temporary support measures are specific requirements for underground construction.

7.1 Use for operation and maintenance

<table>
<thead>
<tr>
<th>Description</th>
<th>Aims</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Provision of a facility model with all relevant data for operation</td>
<td>• Quicker and more intuitive access to available information</td>
</tr>
<tr>
<td>• Data administration and updating at a central location (database)</td>
<td>• Support for operation (e.g. maintenance intervals)</td>
</tr>
<tr>
<td></td>
<td>• Updating and documentation using mobile devices</td>
</tr>
<tr>
<td></td>
<td>• Enabling of systematic analyses according to selected criteria</td>
</tr>
</tbody>
</table>

7.1.1 The digital facility owner’s manual as a starting basis

The digital information from the design and construction phases represents great material and ideal values and should be provided to the operator in a suitable form in order that necessary information for operation and maintenance is available in a homogeneous and consistent machine-readable form. The “suitable form” is to be defined by the operator according to his needs and the state of the technology in his employer’s information requirements. For underground works, clients should define what data from construction (ground structure, ground behaviour, groundwater conditions, temporary support, auxiliary construction measures etc.) they want to hand over in his digital facility owner’s manual.

Experience shows that the operator should be recommended to secure in the long term all information about the ground and its behaviour, as well as temporary excavation support and auxiliary construction measures (if they remain in the ground).

7.1.2 Operation, maintenance and renewal

From the point of view of the operator, the digital model should provide the following improvements:

- Ensure fully up-to-date as-built documentation
- Quicker recording of the actual state of the facility and model-based representation of the actual state (fibre optic sensing, laser scans, etc.) with georeferencing.
- Enable optimised maintenance over the entire facility portfolio thanks to considerably better information and uniform data structure.
- Enabling systematic and comprehensive analyses using selected criteria (e.g. product-specific search for installations)

![Homogeneous and consistent data flows (no media breaks)](image)

**Figure 7-1** Input of the requirements from operation and maintenance
Simulation of constructional effects on running operations in case further construction works have to be carried out with continued operation.

7.1.3 Occupational health and safety
Restricted areas, access restrictions, escape routes, fire fighting equipment, operational processes etc. are displayed in the model. Such models can help make training courses more instructive and efficient.

Safety-relevant documentation and control processes are recorded and saved as digital forms on mobile devices.

7.1.4 Requirements for the operator model
At the moment, digital methods are mostly being introduced in design and partially in construction. The forthcoming potential mostly still has to be communicated to facility operators. The following points can be noted:
- In the design and construction phases, great quantities of data are recorded and documents created.
- It is not practical to save these data and documents directly into the model since the necessary storage space could impair the performance of the models. In contrast, it would seem ideal to link the data with objects in the model in order to keep the model itself slender.
- The purposeful selection of suitable objects prepares the way for reduced models, which then provide intuitive access to structurally saved information.
- This would also open the possibility of keeping the great quantity of data centrally and only transmitting the necessary information to the local user.

8 Outlook

The present recommendation is a first reference work concerning the introduction of BIM in the tunnelling industry, which is currently still in its early stages. Best practice experience, which is usually described in DAUB recommendations, is largely lacking at the moment for underground construction.

The following fields of action should be given priority for a beneficial application of BIM in underground construction
- Standardisation of ground modelling
- Standard catalogue of components for underground construction
- Conditions of contract (collaborative partnership)
- Contract award practice
- Soft- and hardware (modelling, project management, CDE)
- Training for young professionals and users

For underground construction, extensive recording and processing of ground information relevant for construction is of central importance if the full potential of this method is to be exploited. The handling of ground data and the resulting requirements for central data storage of the digital underground infrastructure also demands the assistance of lawmakers.

It is already understood that standardisation is an essential precondition for the application of digital working methods. Standardisation of bill items shows advantages for both contract parties in contract security, error reduction, simplification and transparency of estimation. A standard catalogue of work items for underground construction in Germany, which is lacking until now, should be produced urgently.

In addition, new forms of collaboration between client, consultant and contractor are high on the list of constraints in need of clarification.

Various examples in the European periphery show that the awarding of underground construction contracts using BIM methods does not demand any adaptation of procurement law. In order however to deploy the full potential of the method, the possibilities of existing law should be fully exhausted, e.g. in bid evaluation.

The application of BIM in underground construction presumes that all the necessary tools are available in order to be able to handle the (extensive) digital data. The appeal to the software companies is to answer the specific challenges of underground construction. Particularly with regard to the linear extent of tunnels, the constraints of programs are often intended for building projects. The usual representation of the construction schedule in underground construction in the form of time-distance diagrams must also be made available for selection in addition to Gantt charts.

For the successful introduction of BIM in tunnelling, the human factor is central as with all digitalisation. The opportunity to use innovative digital working methods is frequently a motivation as such for young professionals. Support for all those involved according to their individual needs – underground construction and IT – is an essential precondition for successful collaboration.
## 9 Glossary

<table>
<thead>
<tr>
<th>Specialist term:</th>
<th>Description:</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;As built&quot; model</td>
<td>One or more models as a virtual representation of a structure after completion of construction works. In the course of later construction works, this becomes a model of the existing situation.</td>
</tr>
<tr>
<td>Asset Information Requirements (AIR)</td>
<td>Asset Information Requirements answer the requirements of the OIR. AIR should be expressed in such a way that they can incorporated into asset management works.</td>
</tr>
<tr>
<td>Exchange (Employer) Information Requirements (EIR)</td>
<td>A contract document, which prescribes the information requirements of the client in the tender in order to specify the framework conditions of BIM application. This information serves as the basis for the preparation of project-specific BEPs.</td>
</tr>
<tr>
<td>Use case</td>
<td>Special service performance or use of BIM methodology derived from the BIM aims.</td>
</tr>
<tr>
<td>Attribute</td>
<td>Alphanumeric information of a 3D object.</td>
</tr>
<tr>
<td>Existing model</td>
<td>Model of the existing situation and building as the basis for digital design.</td>
</tr>
<tr>
<td>BIM execution plan (BEP)</td>
<td>A contract document, which describes the possible BIM application of the bidder and is cyclically extended in the course of the project. It also specifies the level of detailing.</td>
</tr>
<tr>
<td>Building Information Modelling (BIM)</td>
<td>Cooperative working method based on digital models for the consistent provision of all the information relevant for the project over the entire lifecycle (design, construction, operation and maintenance).</td>
</tr>
<tr>
<td>BIM (overall) coordinator</td>
<td>Responsible for the coordinated planning of BIM over all specialist models. Responsible for the implementation of the aims agreed in the BEP for the specific case or use case.</td>
</tr>
<tr>
<td>BIM manager</td>
<td>Central post for the handling of the requirements defined in the BEP and also responsible for the application of the BIM methodology on the project.</td>
</tr>
<tr>
<td>Common Data Environment (CDE)</td>
<td>Project-specific common data environment for the central storage and provision of documents and information.</td>
</tr>
<tr>
<td>Specialist model</td>
<td>BIM model which delivers the information for a specialist expert discipline or has been produced by a specialist designer.</td>
</tr>
<tr>
<td>Coordination model/overall model</td>
<td>A model consisting of the various specialist models and used for coordination of specialist design work.</td>
</tr>
<tr>
<td>Industry Foundation Classes (IFC)</td>
<td>Open and software-independent data exchange format.</td>
</tr>
<tr>
<td>Level of Detail (LoD)</td>
<td>Describes the phase-related level of detailing of the models. It consists of LoI and LoG.</td>
</tr>
<tr>
<td>Level of Development (LOD)</td>
<td>Describes the degree of maturity of a model to fulfil the requirements.</td>
</tr>
<tr>
<td>Level of Geometry (LoG)</td>
<td>Describes the phase-related state of development of the model geometry.</td>
</tr>
<tr>
<td>Level of Information (LoI)</td>
<td>Describes the phase-related information content (attributes) of the models</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Organisational Information Requirements (OIR)</td>
<td>Organisational Information Requirements represent a specification for data and information by the asset owner achieve their organisational objectives (e.g. strategic asset management, portfolio planning, life cycle costs reduction).</td>
</tr>
<tr>
<td>Project Information Requirements (PIR)</td>
<td>Project Information Requirements aim at supporting the strategic objectives within the involved organization. They are generated from the client and asset owner’s perspective.</td>
</tr>
<tr>
<td>Single-source-of-truth concept (SSOT)</td>
<td>Organisation concept to ensure central information storage.</td>
</tr>
<tr>
<td>3D model</td>
<td>Three-dimensional model of a structure containing physical, geometrical and functional attributes.</td>
</tr>
<tr>
<td>4D model</td>
<td>A 3D model, which is linked to the schedule of the construction processes with the component time, with which 4D construction sequence animations can be produced.</td>
</tr>
<tr>
<td>5D model</td>
<td>An extension of the 4D model with cost planning. Enables simulation of cost development against project duration.</td>
</tr>
</tbody>
</table>

### 10 References

The following literature list delivers further information about the subject of Building Information Modeling and should help to achieve a founded understanding of the current themes, intentionally concentrated on the requirements and themes of underground construction. The list does not claim to be complete but should serve as an entry and impetus for further research.

#### BIM-Basics


#### Data formats/Data exchange
Roles/scope of services


Contractual aspects


Standardisations/standards/committees

VDI 2552 Building Information Modeling: Blatt 2 - Terms and definitions; Blatt 3 - Model-based quantity determination for budgeting, time scheduling, contracting and accounting; Blatt 4 - Requirements for data exchange; Blatt 5 – Data management; Blatt 7 – Processes (2018)


DIN EN ISO 16739 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries (2017)


Experience reports and further literature


Appendix 1:

Proposal for the use of a „Level of Geometry“ (LoG) in conventional tunnelling

<table>
<thead>
<tr>
<th></th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
<td>Conceptual illustration of the tunnel tube as a structure in the form of an idealized shell. The outer edge of the structure describes the theoretical excavation line.</td>
<td>Illustration of the excavation, the outer shell and the inner shell as separate model elements (according to the planning state). Separate illustration of the securing means by an encasing. Separate illustration of the securing means as an idealized body. Modeling of the sealing system as a separate element. Inner shell separated by vault, invert, shoulder, filling concrete and false ceiling. Illustration of the interior fittings (street / track superstructure) separated from shoulder and filling concrete by means of an encasing. Modeling the cross-passages with inner walls.</td>
<td>Excavation with exact dimensions, material and position. Excavated body and outer shell separated by partial cross-sections, plus other additional required components such as niches, shafts or pumping stations.</td>
<td>Detailed and accurate illustration required for the execution phase dimensions incl. superimpositions. Excavation and outer shell divided into partial cross-sections and advance lengths. Securing means as individual objects. Modeling of the sealing system divided into the individual components (sealing carrier, fleece and sealing foil). Assignment of the joint tapes to the respective model elements according to the method of installation. Inner shell analogous to LoG 300. Separate modeling of cross-passages with doors and interior fittings (cable conduit, wiring, road construction or track systems (side or central) and built-in components).</td>
</tr>
<tr>
<td><strong>Excavation</strong></td>
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<td>Excavation</td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Excavation support</strong></td>
<td>Outer shell</td>
<td>Outer shell</td>
<td>Outer shell</td>
<td>Outer shell</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Support means of support</strong></td>
<td>Pipe screen</td>
<td>Pipe screen</td>
<td>Pipe screen</td>
<td>Pipe screen</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Support means of support</strong></td>
<td>Reinforcement</td>
<td>Reinforcement</td>
<td>Reinforcement</td>
<td>Reinforcement</td>
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<td></td>
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<tr>
<td><strong>Inner shell</strong></td>
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</tr>
<tr>
<td><strong>Interior fittings</strong></td>
<td>Interior fittings</td>
<td>Interior fittings</td>
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<td>Interior fittings</td>
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</tr>
<tr>
<td><strong>Diameter change</strong></td>
<td>Diameter change</td>
<td>Diameter change</td>
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<tr>
<td></td>
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</tr>
</tbody>
</table>

Ehrbar, H.: Building Information Modelling – A new tool for the successful implementation of major projects of German railways. DOI: 10.1002/geot.201600053 (2016)
## Appendix 2:

### Proposal for the use of a „Level of Geometry“ (LoG) in mechanised tunnelling

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Conceptual illustration of the tunnel tube as a structure in the form of an idealized shell. The outer edge of the structure describes the theoretical excavation line.</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>200</td>
<td>Illustration of the excavation and the segment ring as separate model elements (approximate geometry). Modeling the annular gap grouting and sealing system as a separate element. Separate modeling of the inner shell and interior fittings.</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>300</td>
<td>Illustration with exact dimensions, materials and position. Segment ring divided into individual segment stones. If necessary, annular gap grouting with different materials (mortar, pea gravel) is to be illustrated. Inner shell separated by vault, invert, shoulders, filling concrete and false ceiling. Illustration of the interior fittings (street / track superstructure) separated from shoulders and filling concrete by means of an encasing. Modeling the cross-passages with inner walls.</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>400</td>
<td>Detailed and accurate illustration required for the execution phase. Modeling the segment stones with seals and bolting connections. Modeling of the sealing system divided into the individual components (sealing carrier, fleece and sealing foil). Assignment of the joint tapes to the respective model elements according to the method of installation. Inner shell analogous to LoG 300. Separate modeling of cross-passages with doors and interior fittings (cable conduits, wiring, road construction or track systems (slab or ballast) and built-in components).</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**Reference:**