The IFC-Tunnel project – Extending the IFC standard to enable high-quality exchange of tunnel information models

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Abstract. The paper reports on the buildingSMART International project IFC-Tunnel that is developing an extension of the vendor-neutral data exchange standard Industry Foundation Classes (IFC). The paper highlights the importance of a well-defined development process and the involvement of international domain experts. It discusses in detail the requirements analysis conducted as well as its outcome in terms of the tunnel types and the use cases covered. It subsequently reports on the conceptual model that includes all proposed extensions and modifications, as well as the alpha version of the EXPRESS encoding which will evolve into version 4.4 of the IFC standard.

Keywords: BIM · Tunnel Information Modeling · Industry Foundation Classes · Geology model · Geotechnical model · Underground Constructions · Voxel Geometry

1 Introduction

The international standard Industry Foundation Classes (IFC) is a vendor-neutral BIM data exchange standard providing a comprehensive data model that allows the detailed geometric and semantic description of buildings. It is in widespread use for data exchange across different BIM software products. It is developed by the international non-profit organization buildingSMART and has been adopted as ISO 16739. Up to version 4.0, the IFC standard was mainly focused on buildings. However, due to increasing international demand, a substantial extension of the standard to support infrastructure facilities has been carried out.

To this end, the so-called Infra Room, a subdivision of buildingSMART International (bSI) with its own steering committee, was founded in 2013. It developed a roadmap and started a number of projects to develop the necessary extensions. The first project was IfcAlignment which defined extensions for describing the alignment of linear infrastructure assets [16]. On this basis, the IFC Infra Overall Architecture project was conducted in order to specify general principles to be followed by all Infrastructure extension projects. On top of that, the projects IFC-Bridge, IFC-Rail, IFC-Road and IFC-Tunnel have been initiated.

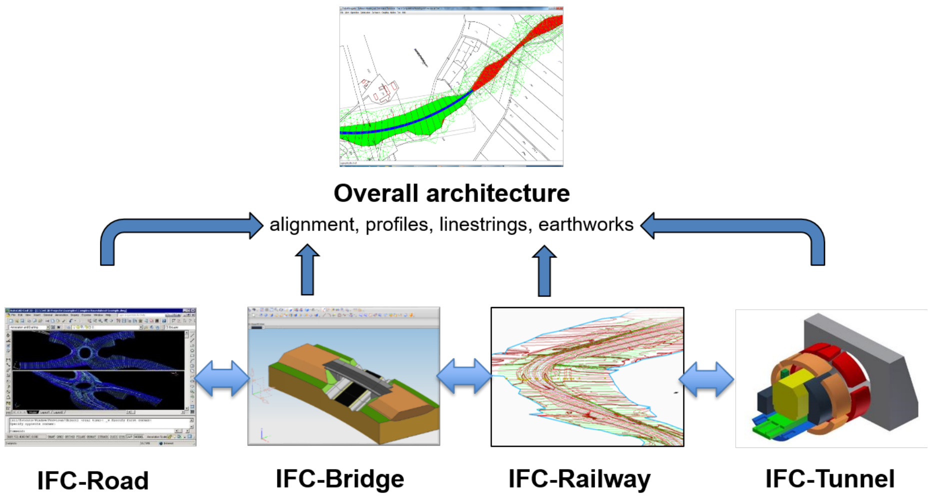

Fig. 1. Overview on the IFC-Infra extensions.

In this paper, we report on the IFC-Tunnel project; its development process and the results.

2 The IFC-Tunnel extension project

In response to the urgent demand of international infrastructure stakeholders for extending IFC for tunnels, the standard development project was initiated by bSI Infrastructure Room. It started in January 2019 and will be completed by the end of 2022. Due to the short duration and the limited resources available, it was essential that the project focused on "low hanging" fruits; i.e. selecting use cases to be supported that bring the most value to the future users of the standard.

The IFC-Tunnel extension project followed the formal project execution guidelines of bSI that came into effect in 2015 [10] specifying the organizational structure and the development process.

2.1 The organizational structure

For each IFC extension project, a project team has to be formed. It consists of a group of international experts, preferably a combination of domain experts and IFC specialists. In the case of the IFC-Tunnel project, the project team was composed of more than 40 members originating from different parts of the world, including France, Switzerland, Austria, Norway, Sweden, Italy, Germany, and Japan.

To ensure a maximum efficiency, the project team was subdivided into the following working groups:

- Geology and Geotechnics,
- Excavation and Lining,
- Equipment and Systems,
- IFC experts

The individual subteams met on a bi-weekly basis complemented by whole-team meetings in irregular intervals. The project lead reported to the Infra Room Project Steering Committee (IRPSC) on a monthly basis, which monitors project progress and funds across all bSI infrastructure projects.

Panel meetings with external domain experts were hold in 6-months intervals to discuss the use cases and verify the development results.

2.2 The development process

As demanded by bSI guidelines, the IFC-Tunnel project implements the following development phases:

1. Requirements Analysis
2. Taxonomy Analysis
3. Conceptual model development
4. IFC schema extension proposal (draft)
5. Validation / Deployme
6. IFC schema extension proposal (final)
7. Formal acceptance

The following section will report in detail on each of these phases.

3 Requirements Analysis

An important lesson learned from more than 25 years of developing the open data standard IFC [15] is that it is of utmost importance to first define the scope and use cases to be covered by any extension project. This becomes even more obvious when considering (1) the large extent of the existing data model (IFC$\tilde{4}$.1 comprises 801 entities), (2) the limited time and resources available for the developing the extensions, and (3) the goal of lowering the effort for software implementation to enable a fast uptake of the standard.

The extensive requirements analysis performed by the project team resulted in the publication of the requirements analysis report [18], the content of which is summarized in the following subsections.

3.1 Tunnel types covered

Based on discussion with the expert panel and an analysis of the most widespread tunnel types constructed worldwide, the following construction methods were considered in the IFC-Tunnel project:

- Mechanized tunneling, using Tunnel Boring Machines (TBM)
- Drill-and-blast tunneling
- Cut-and-cover tunneling

Other construction methods, such jacked, immersed, and micro tunneling were investigated with lower priority.

From a usage point of view, the following tunnel types were decided to be in scope and having high priority:

- Road Tunnels
- Railway Tunnels
- Metro Tunnels
- Access Tunnels

With lower priority, the following usage types were investigated:

- Evacuation Tunnels
- Ventilation Tunnels
- Water Tunnels
- Pedestrian Tunnels
- Service Tunnels
- Underground facilities

3.2 Use cases covered

The project team performed an in-depth analysis of the use cases for a software vendor-independent tunnel data exchange format in order to identify those that are supposed to be supported by the extension, and those that are considered out-of-scope. The analysis included specifying the sending and the receiving application, rough descriptions of the required geometry representations and the semantic data as well as an assessment of the complexity of the realization of the required data structure. In addition, the priority of individual use case support was identified through intense consulting of the expert panel.

Based on a careful analysis of the benefits of the individual use cases and the complexity and effort involved with defining the necessary data structures, the project team decided to prioritize the following use cases for explicit consideration when designing the IFC-Tunnel extension:

- Initial state modelling

- Geologic factual data
- Geologic modelling
- Geotechnical modelling for design
- Geotechnical modelling for construction
- Exchange of alignment and major road/railway parameters
- Technical visualization
- Design coordination
- Design to design w. reference models
- Quantity Take-Off (general)
- Construction sequencing (4D modeling)
- Design to tender: Construction Model
- Design to tender: Geotechnical Model
- Design to construction
- Progress monitoring
- Geological documentation
- Quantity determination for billing / payment
- Handover to GIS
- Handover to AMS

Due to overly high complexity, the following use cases were decided to be out of scope of the fast-track project, but worth to be investigated in follow-up extension projects:

- Realistic visualization
- Safety visualization
- Structural and geomechanical analysis
- Air flow simulation
- Hydraulic simulation
- Standards compliance checking
- Prefabrication
- Scanning during construction
- Machine guidance and control
- Damages recording
- Settlement monitoring
- Design to Design (Full model logic)

3.3 Process Map

In compliance with the Information Delivery Manual (IDM) standard, the process map depicted in Figure 2 has been developed to clearly identify the exchange requirements and associate them with dedicated data exchange scenarios. Its purpose is to provide a general reference workflow, i.e. deviations in national or regional processes are possible.

As processes related to geological assessment and geotechnical engineering are particularly important for tunneling projects, these processes are depicted in detail in Figure 3.

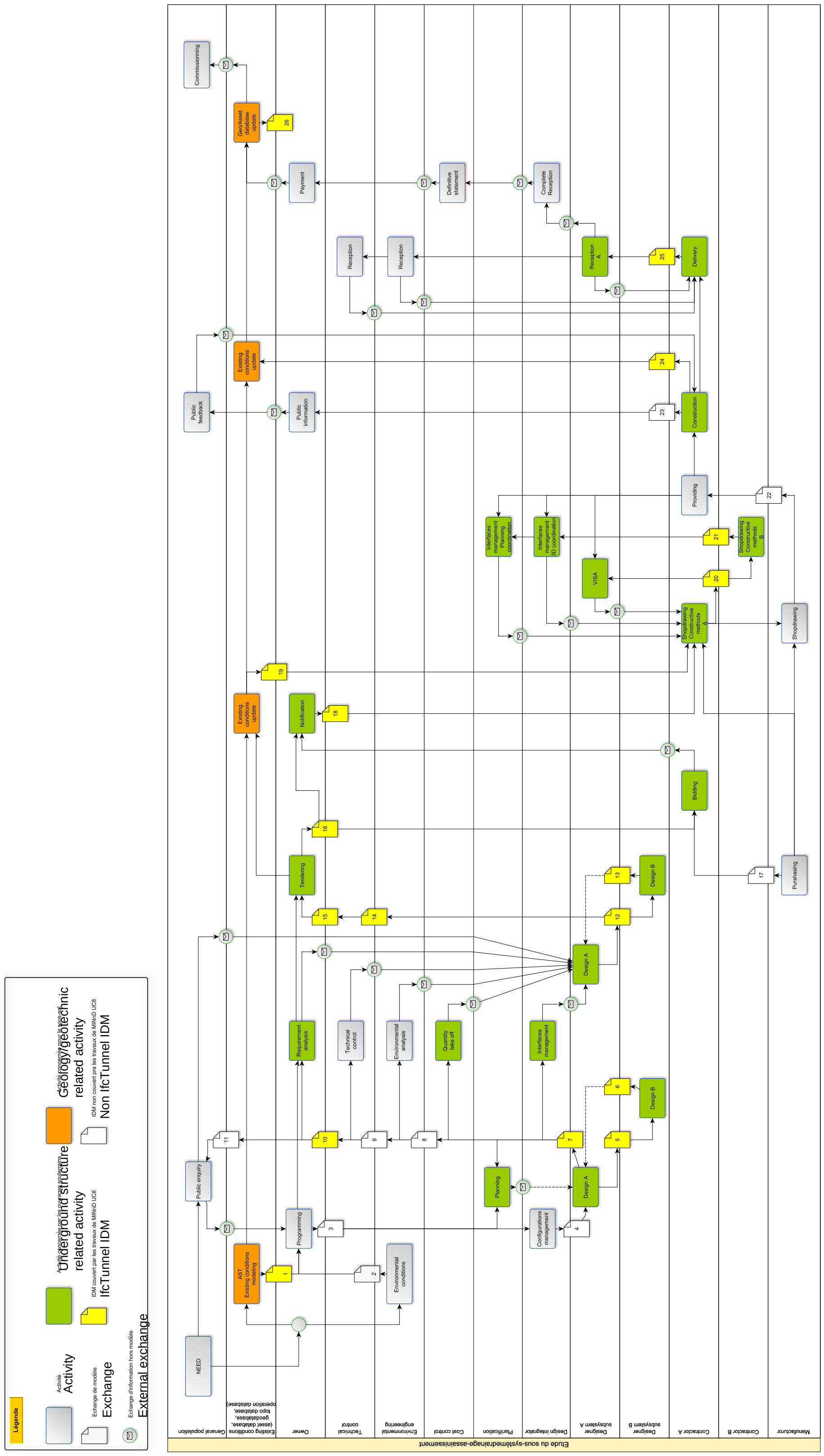

Fig. 2. BPMN Process map developed by the IFC-Tunnel project, based on prior work by the French MiND project.

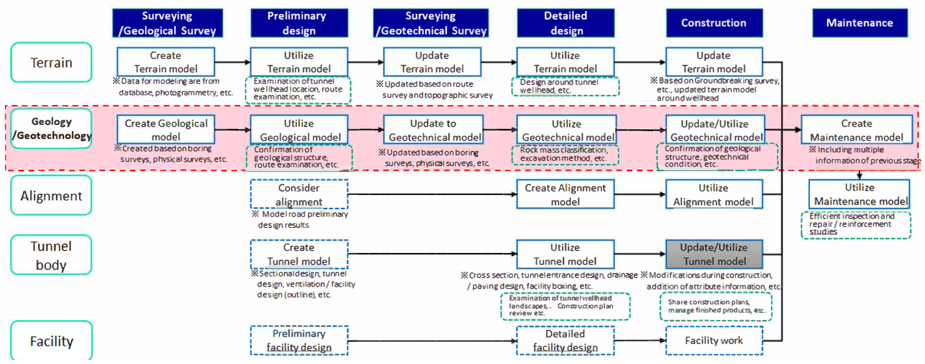

Fig. 3. The process map depicting the geotechnics-related processes.

3.4 Georeferencing

The proper usage of geodetic coordinate reference systems (CRS) plays an extraordinarily important role for the design and construction of tunnels due to their potentially very long expansions. Geodetic CRS apply a transformation to project the earth surface approximated by an ellipsoid onto a flat map (map projection). In the case of the Universal Transversal Mercator (UTM) projection, a cylindrical surface is used as projection surface. The projection and the height reduction to an ellipsoid introduces distortions in lengths (see Figure 4). These distortions depend on the coordinate reference system applied and the location on the earth surface.

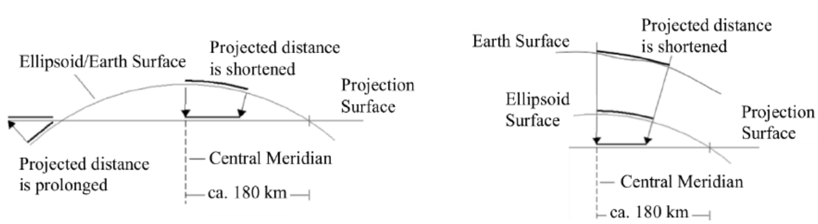

Fig. 4. The distortions induced by geodetic projection (left) and height reduction (right). Source: [13]

In consequence, tunnel models created in geodetic CRS are not 1:1 representations of the physical reality. This has to be taken into account for surveying, setting out, quantity take-off and any other kind of activity that translates model dimensions into the real world. Surveyors are experts in this field and can handle the required translations.

Data exchange standards, such as InfraGML, GeoSciML or CityGML, that are based on the Geographic Markup Language (GML) pay particular attention to the correct handling of geodetic reference systems by providing the necessary meta-data and by using exclusively coordinate values in the underlying geodetic CRS. This approach is also implemented by roadway and railway design systems.

BIM authoring systems for buildings are typically not able to handle geodetic CRS (large coordinates). For this reason, often a mere translation of the coordinate system is applied by defining a local coordinate system on a local point of origin. Typically, the geodetic coordinates are provided for this point of origin. However, if the local coordinate system is created by a mere translation (shifting in x and/or y direction by subtracting a fixed value from x and y coordinates), it remains a projected coordinate system with length distortions as described above. However, as now "small-value coordinates" are used, there is the severe risk that the tunnel model is erroneously interpreted as a distortion-free 1:1 model, potentially resulting in cost-intensive production or surveying errors on site.

Accordingly, for the proper use of the tunnel model represented by an IFC model, explicit information of the applied Coordinate Reference System is crucial. Very important is to allow the receiver of the model to unambiguously determine whether the model is distorted or not.

For short tunnels, also the use of a 1:1 modeling approach with an undistorted local coordinate system is possible. However, again this must be clearly specified in the IFC model. It is important to have in mind that for any data imported from GIS and other sources with geodetic CRS (e.g. digital terrain model), a re-projection must be applied to de-distort it.

For very large tunneling projects or for tunnels that cross national borders, project-specific CRS are applied that apply non-standard projections to minimize distortions between the projected CRS and the reality. A good example is the Brenner Base Tunnel that crosses the Austrian-Italian border and has its own CRS. This introduces the problem that for these project-specific CRS, no pre-defined EPSG codes exist.

The IFC Tunnel project analyzed the existing IFC4.3 standard that was submitted to ISO and identified a lack of this clarity of coordinate values in the IFC dataset. For this purpose, next to the IfcMapConversion entity which describes a conversion between local engineering coordinates from the IFC dataset to projected coordinates in the context of the IfcProjectedCRS as an EPSG code, three new entities were defined an proposed.

3.5 Alignment

The proper description of the alignment plays a major role for the digital representation of tunnels. A large number of use cases require the alignment to be represented as an explicit description as part of the IFC model to be exchanged. The alignment information is used for:

- procedural geometry descriptions where a cross-section is swept / extruded along an axis
- a linear reference system to position objects along the alignment

Both aspects are equally important. They are not necessarily implemented on the basis of the same geometric curve.

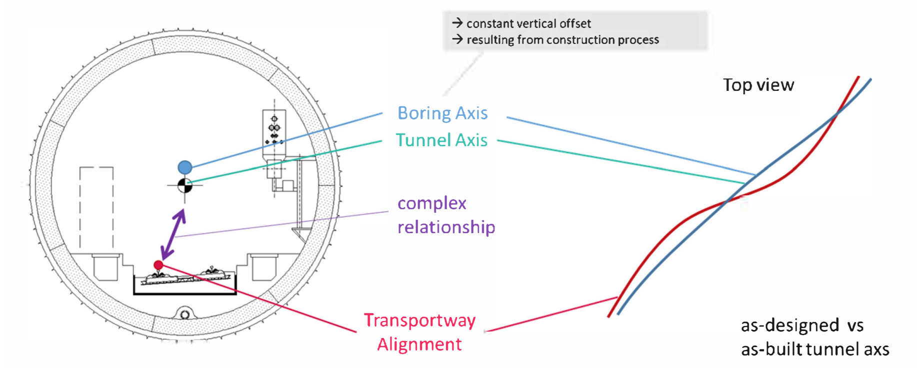

Fig. 5. Differences between the boring axis, the tunnel axis and the transport alignment.

Especially for TBM tunnels, it is important to distinguish between the different axes and underlying alignment curves (see Figure 5):

1. the alignment of the roadway or railway encased by the tunne
2. the tunnel axis ("theoretical axis")
3. the boring axis

The differences between (2) and (3) results from the fact that there is vertical displacement of the ring after it has been installed due to the gravitational forces. The tunnel accordingly must be bored in an axis that has a vertical offset from the resulting tunnel axis.

While there are dependencies between (1) and (2), they are usually too complex to be described by the IFC model in an explicit manner. For the in-scope use cases (see Section 3) it is also not necessary to express this dependency.

According to the analysis conducted, the capabilities of IFC to describe alignments as introduced with IFC 4.1 and refined with IFC 4.3 are deemed sufficient for representing the axes of tunnel models and implement the identified use cases.

3.6 Geometry

The IFC data model supports a wide range of geometry representations. They can be broadly divided into

- **explicit representations** that describe the geometry of volume objects by their surface
- **implicit representations** (also called procedural descriptions) that describe the construction history, i.e. the operations applied to create the geometry

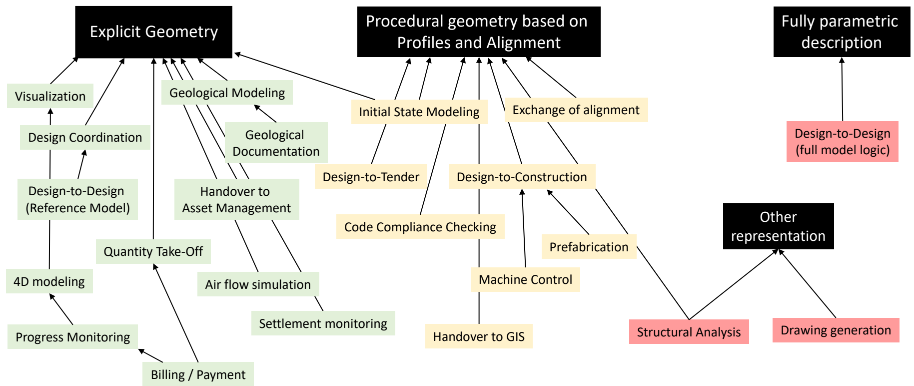

Fig. 6. Dependence of the use cases on specific geometry representations.

Both representations have their advantages and disadvantages and are suitable for different use cases. This is discussed in more detail in the following subsections.

The analysis revealed that the in-scope use cases require both, explicit BRep geometry as well as procedures geometry based on sweeps using profiles and alignment (Figure 6).

Explicit Geometry Explicit geometry representations describe the resulting geometry, but not the construction process. As such, they are well applicable for use cases that do not require the geometry to be modified after receiving it as an IFC model. By contrast, for design-to-design use cases where the (user of) the receiving application is supposed to change the model, explicit representations are of limited use.

The IFC standard provides multiple options for describing explicit geometry:

- triangle-based geometry (IfcTriangulatedFaceSet): a very common and widespread representation based only on triangles
- BRep geometry (IfcFacetedBRep): A representation that allows the proper description of non-triangular faces and the topology relations between faces, edges and vertices. All faces are planar and all edges are straight lines
- NURBS geometry (IfcAdvancedBRep): A representation that allows the description of solid objects with curved surfaces and curved edges on the basis of the mathematical description of Non-uniform rational B-Splines (NURBS).

Due to the construction methods applied, tunnel models typically have a high number of curved surfaces. This makes the application of NURBS geometry a natural choice. However, this representation is currently only to very low degree implemented by software vendors. Nevertheless, it is desirable for use cases with

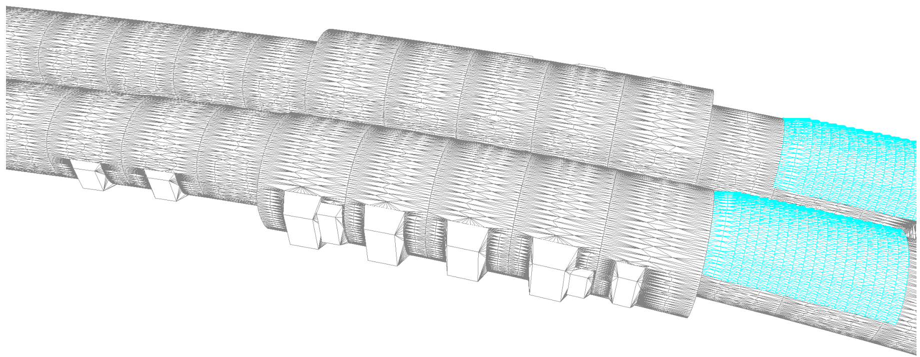

Fig. 7. A tunnel model with geometry described by IfcTriangulatedFaceSet with a large number of triangles

high accuracy demands and should be demanded from software vendors in the future.

Accordingly, in most cases an approximation using triangle-based geometry will be applied (Figure 7). It must be noted however, that due to this approximation, there are deviations between the real geometry and the one represented by the model. The size of the deviations depends on the refinement of the triangular mesh. At the same time, it must be noted that models with a large number of triangles are heavy in terms of file and storage size.

TBM tunnels are composed of a large number of repetitive (identical) elements, such as the ring segments. The geometry of these elements should be represented only once, and subsequently instantiated, placed and rotated by means of the IfcObjectType mechanism.

Procedural geometry Many of the high-priority use cases demand the usage of sweeps for representing the geometry of the tunnel, its elements and interior spaces. It was agreed by the project team that the usage of triangulated face sets is not appropriate for many use cases, due to the loss in accuracy and the excessive increase in data size.

Both, TBM tunnels as well as conventional tunnels can very well be described by procedural approaches based on the concept of sweeping a profile (cross-section) along an axis, as this reflects the typical construction methods. Many use cases accordingly depend on this notion and require the explicit description of the cross-section(s).

The use of procedural geometry is a requirement of any exchange scenarios that require the modification of the tunnel geometry at the receiving side. In comparison with a triangulated geometry description, a higher accuracy can be achieved by procedural descriptions while at the same time significantly lowering the data footprint (file size). However, the risk of diverging interpretations at the sending and the receiving application is higher, potentially resulting in erroneous geometry.

An important aspect to be considered is the fact that the profiles of conventional tunnels may change along the axis. Accordingly, the transition between the profiles must be clearly and unambiguously described by the IFC model, such that it is interpreted in the same way at both the sending and the receiving side.

For the procedural description of tunnel models, the following aspects have to be considered:

- the definition of the sweeping behavior,
- the description of the cross-section(s),
- the description of the sweeping axis,
- the description of interpolation between profiles,
- the description of spaces voiding the extrusion body

The entity IfcSectionedSolidHorizontal plays an important role. It has been introduced with IFC 4.1 as a result of the development activities in the IFC-Alignment and the IFC Infra Overall Architecture projects [16][6]. The entity allows to perform sweeps along an alignment where the cross-section's y-vector is kept pointing in the global z direction, in contrast to the conventional IfcSweptAreaSolid where the cross-section is kept perpendicular to the sweeping path at any time. IfcSectionedSolidHorizontal has been introduced for correctly modeling elements of infrastructure facilities (roadway layers, bridge decks) and will be applied in this sense in the IFC-Tunnel extensions.

In practice, both IfcSweptAreaSolid and IfcSectionedSolidHorizontal are needed to define alignment-based geometry, depending on the construction method. TBM tunnels in most cases have a sweep geometry where the profile is perpendicular to the sweeping path, mainly due to the fact that prefabricated ring segments are used. Cut-and-cover tunnels on the other hand, are more likely to make use of IfcSectionedSolidHorizontal geometry as often they require cast-in-place processes which normally are oriented along the gravity axis (global z).

A particular requirement lies in the fact tunnels often have varying cross-sections along their axis. For a correct exchange of the sweep geometry, an unambiguous description of the interpolation between the profiles is necessary. To this end, guiding curves are used (Figure 8).

Voxel grids and octrees for representing geological data There are specific use cases in the context of geological modelling [21] that require the use of voxel representations to allow for a fine-grained description of varying soil/rock properties with high spatial resolution (Figure 9). Currently, such a geometry representation is not yet available in IFC. It should be considered to extend the IFC schema accordingly.

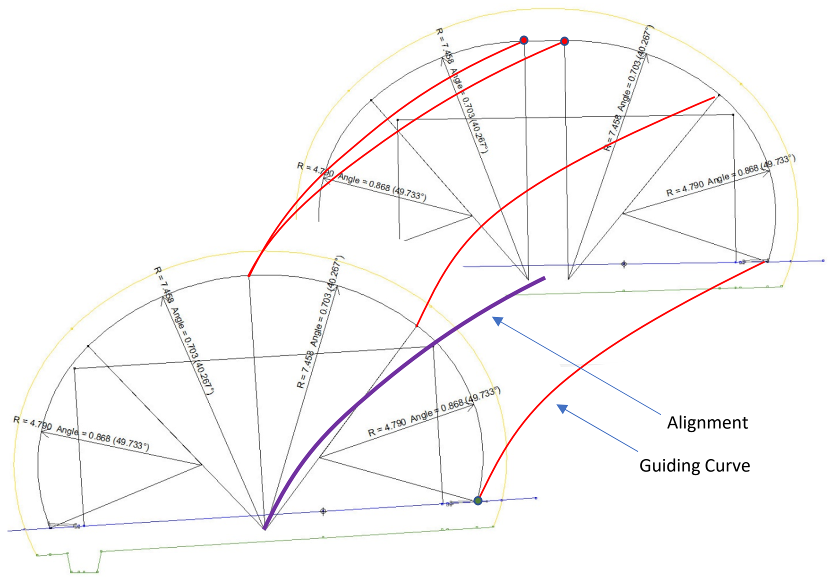

Fig. 8. A tunnel represented by a sweep with varying cross-sections. A particular challenge lies in the correct interpolation between the profiles. To this end, guiding curves are used.

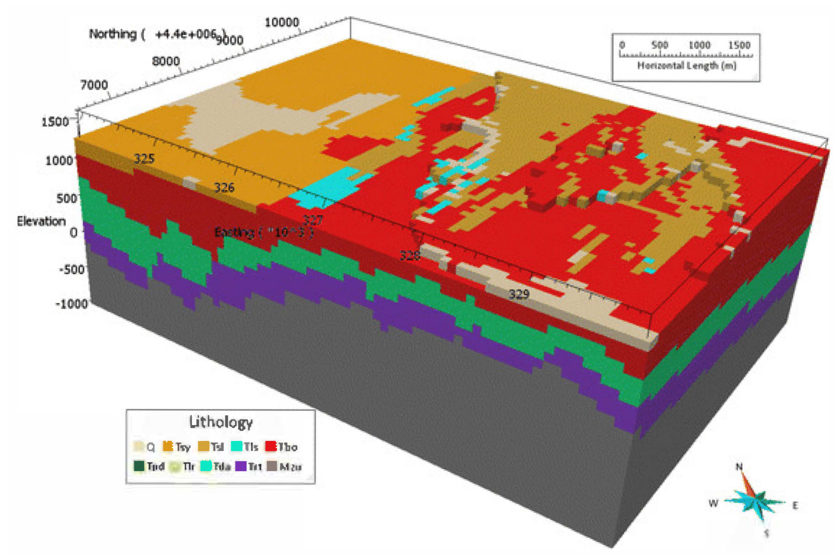

Fig. 9. Voxel representation of a geological model (Source: Witter et al. 2016 [21])

3.7 Geology and geotechnics

The geological and geotechnical modeling of the underground plays an important role throughout all phases of a tunnel project and is relevant for several decisions and design solutions.

Several kinds of risks are associated with geological conditions and uncertainties in predictions of the ground conditions (interpreted models), which have a significant impact on the costs of tunnel projects.

Furthermore, in tunneling the ground material can be seen as a part of the building. For these reasons, the geological and geotechnical information must be described and represented in a standardized way, paying attention to the compatibility with IFC and existing standards of the geology and geotechnics disciplines. As IFC has developed to a widely applied industry standard and the integration of ground models into BIM design environments is requested frequently (not only, but especially in tunneling), such models should be covered by IFC.

This creates challenges for developing the IFC-Tunnel extension as the underground is not a man-made artefact, but a natural one and thus exhibits a rather complex structure, in terms of geometry and of spatially diverging properties: In general, there are no "standard-materials", but only artificial classifications superimposed to an inhomogeneous ground material.

Such classifications can be based on geological categories like e.g. age, stratigraphy and structural-tectonic position or lithology ("Geological model") or mechanical material properties and aspects relevant for design and construction ("geotechnical design models").

These classifications depend on the purpose and requirements in a (construction) project. Precise knowledge on the underground is only given by observation points (documentation, factual data). The modeling between these observation points represents the assumptions for design and provides the base for several applications:

- structural analysis (focus on mechanical properties)
- definition of construction and excavation methods
- material management etc.

This implies that commonly, different classification systems are used in parallel in tunneling projects, and the ground can be described in by different overlapping interpreted models.

Further, an interpretational model related to the planned facility (tunnel excavation / portal cut slopes) is used to summarize the expected conditions with key properties that describe the above aspects.

The nature of interpretational models for predictions involves vagueness and uncertainty. The developed schema includes several measures to describe and quantify this uncertainty, such as:

- multiple model scenarios related to a probabilistic analysis
- definition of value ranges for e.g. mechanical parameters

– visualization of the modeller's confidence by e.g. color coding
– an overlapping voxel model that describes the distribution of uncertainty of confidence in the model

The uncertainty is reduced throughout the project time with ongoing investigation and documentation of encountered conditions. Especially during project execution, comparison of encountered conditions to the prediction is one of the most important application for ground models. A well-defined "baseline model" that describes the expected conditions with e.g. value ranges regarding mechanical properties and distribution of materials enables a very efficient model-based evaluation of observations during construction. This provides the base for clear risk allocation in contracts and reduces the potential for disputes on unexpected ground conditions.

An as-built model of the encountered ground conditions, enriched with all the documentation collected during execution, can be provided after completion of excavation and ground improvement works. Such a standardized model can be stored in a structured way, and filtered content can be integrated in existing BIM environments for maintenance.

4 Taxonomy Analysis

After completing the requirements analysis phase, the tunnel taxonomy was compiled and analyzed in a comprehensive manner. The goal was to identify concepts specific to tunnel construction and to identify commonly used English terms for them. To this end, the following sources were analyzed:

– International Tunneling and Underground Space Association
– ISO and IEC standards on tunneling
– GeoSciML standard by OGC
– French MiND project documentation
– German DAUB guidelines on Tunnel BIM models
– and many others

In addition, the published results from various research projects were taken into account [22] [23] [5] [4] [8] [1] [7] [12] [20] [19] [2] [14] [9] [17] [11].

The information from the sources was subsequently merged and harmonized, first by using spreadsheets developed among the project team (see Figure 10, later by mapping them into a UML conceptual model.

Object type inheritance hierarchy (this part is for tech-team)

Note: This is not a description of the system breakdown structure, but a definition of types and their subtypes (not parameters or attributes)

Level 0	Level 1	Level 2	Level 3 (object type)	Level 4 (properties)	Reference to RAR-report (ver	IfcMapping
Built Element						
	Tunnel Element					
		Tunnel Excavation Element				IfcExcavatior
			open excavation? Surface excavation?			IfcEarthworksC
			Open slope excavation		Page 80	IfcEarthworksC
			Confined open excavation		Page 80 & Page 85 / Fig. 9-10	IfcEarthworksC
			Braced open excavation		Page 80 & Page 85 / Fig. 9-10	IfcEarthworksC
			Anchored open excavation		Page 80	IfcEarthworksC
			underground excavation?			IfcUndergroun
			Full face excavation		Page78 & Page 84 / Fig. 9-9	IfcUndergroun
			Pilot bore		Page 84 / Fig. 9-9	IfcUndergroun
			Reaming		Page 84 / Fig. 9-9	IfcUndergroun
			Staged excavation		Page 83 / Fig. 9-7	Process/Task?
			Profile widening		Addressed on page 38 in geometry	IfcUndergroun
			Reprofiling		Cross-section?	IfcUndergroun
			Fill			IfcEarthworksF
		Ground Improvement Element				IfcGroundImp
			Injection grouting		Page 93 - Fig 10-13 & 10-14	IfcGroundImp
				Tubes à manchette (TAM)		
				Duct injection		
				Injection		
				Tube dimensions		
				TAM spacing		
				Drilling diameter		
				Length		
				Arrangement (simple, staggered)		
				longitudinal spacing		
				radial spacing		
				Grout composition		
				Injection parameters		
				Injection pressure		
				Injection duration		
				Injection mechanical strength		
				Equivalent strength		
				Deformability		

Fig. 10. A typical spreadsheet used by the project team for capturing and harmonizing the taxonomy of tunnel elements.

5 Conceptual model development

In the next step, the conceptual model was developed. The conceptual model describes the IFC extensions mostly by using UML diagrams in combination with documentation text. As opposed to the approach taken by OGC, the bSI conceptual model takes the particularities of the existing IFC data model into account and describes, for example, new sub-classes as refinements to existing IFC classes. It also defines pre-defined types, attributes and properties where appropriate.

The IFC-Tunnel project strictly followed the extension guidelines hat have been defined by the Infra Overall Architecture Project [6]. Among other restrictions, it demands to keep the number of new entities to a minimum and instead make a maximum use of existing classes. A good example is the wall of a cut-and-cover tunnel. It is not necessary to define a new class for it, instead the existing IfcWall can be used. However, it may be appropriate to extend the enumeration of the predefined types of an entity. Where necessary, the documentation was modified to include tunnel concepts.

Thanks to the principle described above, the resulting conceptual model only adds a minimum amount of new entities. At the same time however, a large number of new predefined types for a variety of entities were introduced. In the following UML diagrams the new PredefinedTypes have a cyan background color.

5.1 Spatial element extensions

In the IFC model, spatial structure elements are applied to capture the spatial hierarchy of a project. A significant extension allowing to cover not only buildings, but also infrastructure facilities was performed in Version 4.3 introducing the new entities IfcFacility and IfcFacilityPart, both as subtypes of IfcSpatialStructureElement.

The main new spatial entity introduced here is IfcTunnel, defined as subtype of IfcFacility. The PredefinedTypes defined for IfcTunnel are:

- ACCESSTUNNEL
- SHAFT
- UTILITIES
- RAILWAY
- ROAD
- PEDESTRIAN
- METRO
- BICYCLE
- BYPASS
- MAINTENANCE
- UNDERGROUND_FACILITIES
- RAMP

The existing IfcFacilityPart was extended by a new suclass IfcTunnelPart with the following predefined types:

- TUNNELSECTION
- CROSSWAY
- RINGSECTION
- PORTAL

Figures 11 and 12 illustrate these extensions by means of UML diagrams.

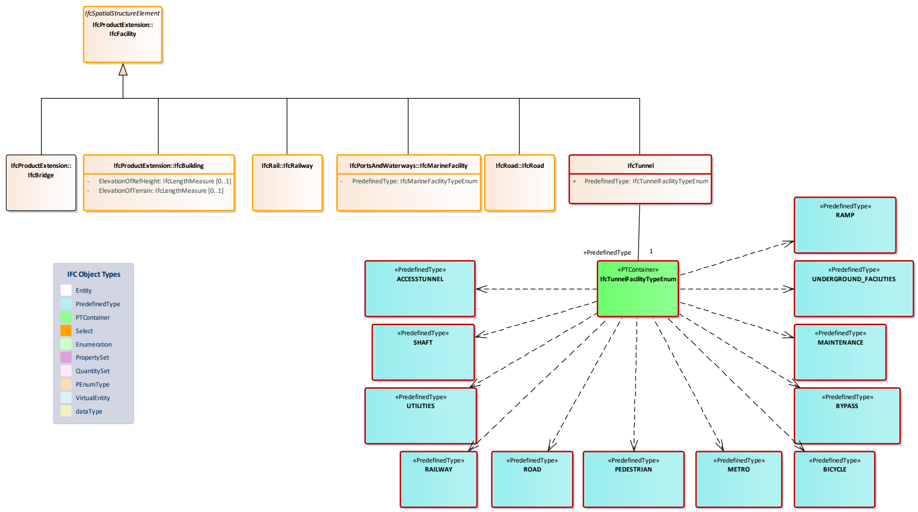

Fig. 11. Extension of the IFC model by the new class IfcTunnel depicted along with its predefined types (in cyan).

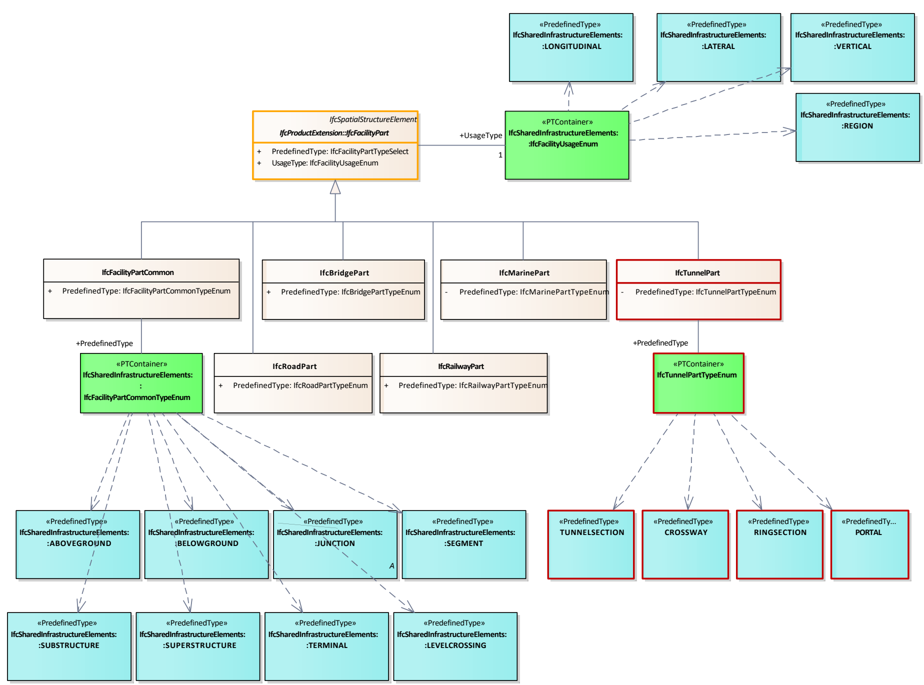

Fig. 12. Extension of the existing IfcFacilityPart by the new IfcTunnelPart (in red box) depicted with its predefined types (in cyan).

5.2 Spatial zone extensions

Spatial zones play an important role in tunneling as they are often used as placeholders or reservations spaces. In contrast to IfcSpatialElement and its subclasses, instances of IfcSpatialZone do not have to be hierarchical and can be overlapping.

The existing IfcSpatialZone was hence extended by new PredefinedTypes which are depicted in Figure 13 with a red-colored outline.

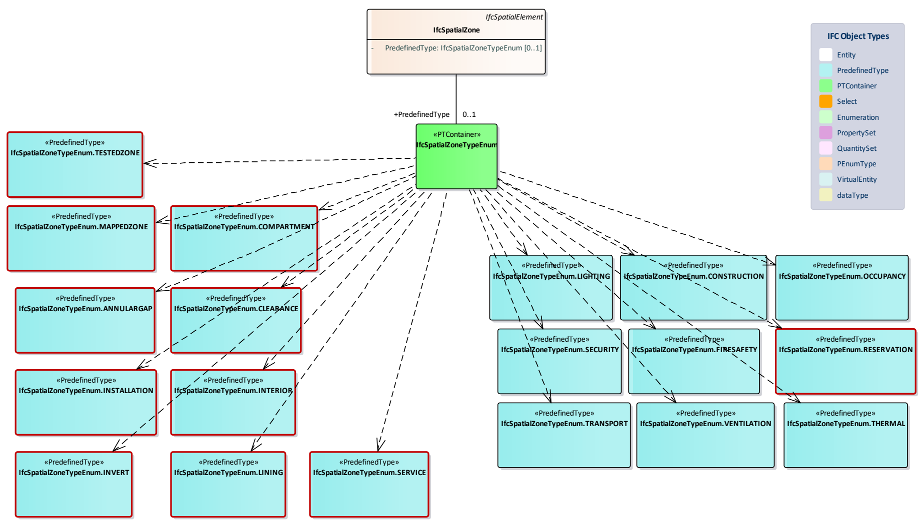

Fig. 13. Extension of the existing IfcSpatialZone by the new predefined types shown with a red box.

5.3 Systems extensions

New predefined types were defined for the existing entity IfcBuiltSystem in order to support a suitable representation of systems in tunnels:

- TUNNEL_PRESUPPORT
- TUNNEL_SUPPORT
- TUNNEL_LINING
- FIREPROTECTION
- WATERPROOFING

For the existing entity IfcDistributionSystem the new PredefinedType SAFETY was added and the semantics of MONITORINGSYSTEM were extended. Figure 14 depicts these extensions.

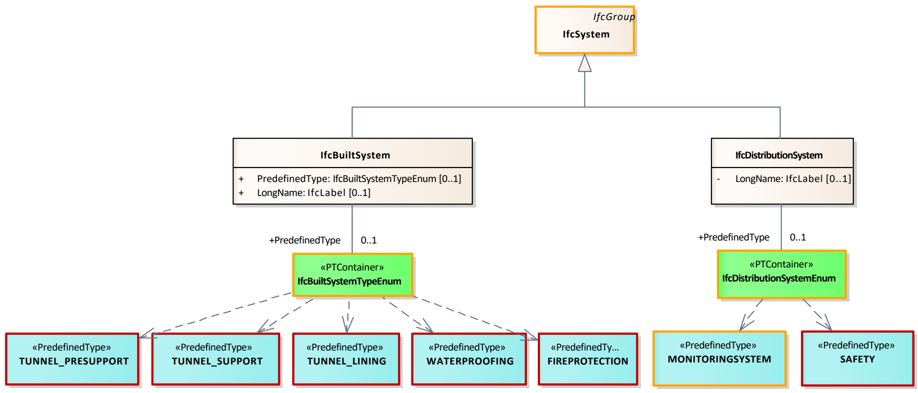

Fig. 14. The existing classes IfcBuiltSystem and IfcDistributionSystem along with their new predefined types (in cyan)

5.4 Built element extensions

The majority of the built elements of tunnels can be described by means of the existing entities. The following new entities were defined to describe tunnel-specific built elements:

- IfcFillElement
- IfcArchElement
- IfcGroundReinforcementElement

Figure 15 depicts the extensions in terms of the new entities and their predefined types. Apart from that, a large number of new predefined types were introduced for existing sub-classes of IfcBuiltElement that are not shown here.

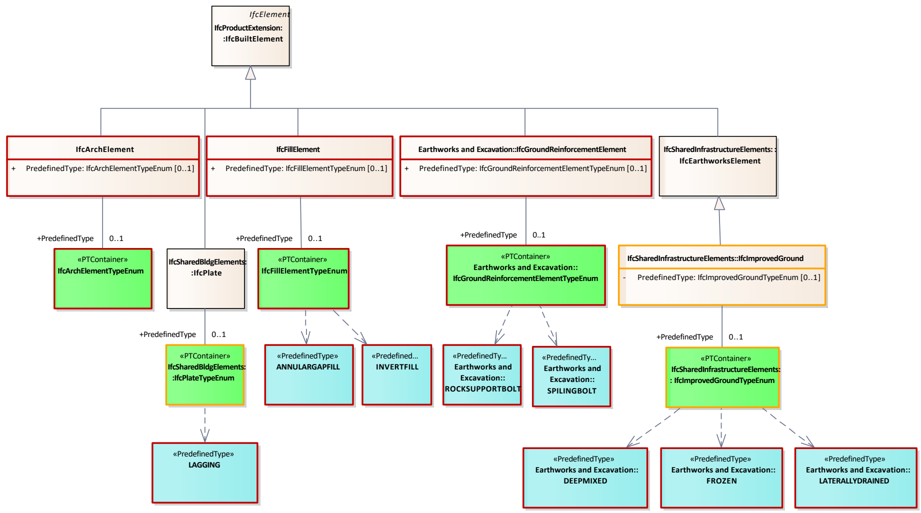

Fig. 15. Extension of the existing IfcBuiltElement by the new subclasses IfcArchElement, IfcFillElement and IfcGroundReinforcementElement depicted with their predefined types (in cyan). In addition it is proposed to modify the existing IfcImprovedGround and extend it by new PredefinedTypes.

5.5 Geology and geotechnics

To allow the integration of geological, geotechnical, hydrogeological etc. models, the umbrella term GeoScienceModel was introduced and the new class IfcGeoScienceModel was introduced. It has the following PredefinedTypes:

- GEOTECHMODEL
- HYDROGEOMODEL
- GEOLOGYMODEL
- GEOTECHSYNTHESISMODEL
- PHYSICALPROPERTYDISTRIBUTIONMODEL
- GEOHAZARDMODEL

The class IfcGeoScienceFeature was introduced to model individual features in the ground, such as folds or faults. The complete list of predefined types is shown in Figure 17.

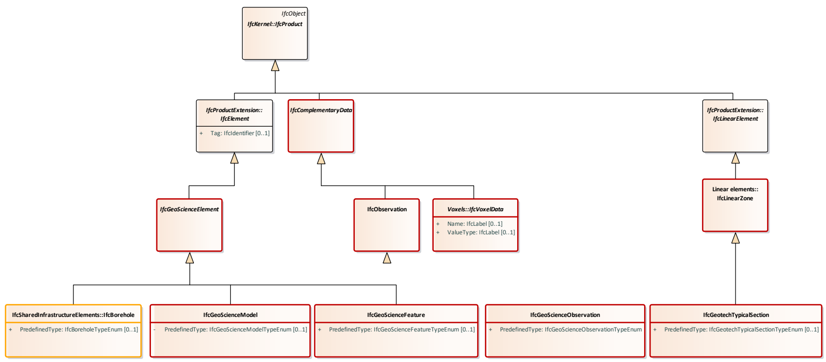

Fig. 16. Overview of the new classes introduced for describing a geological model in IFC and the associated observations.

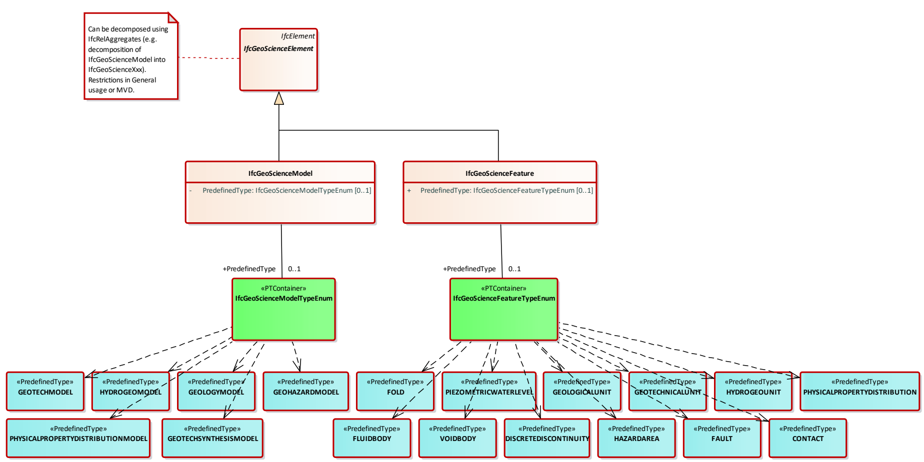

Fig. 17. The new classes IfcGeoScienceModel and IfcGeoScienceFeature and their predefined types (depicted in cyan)

5.6 Earthworks and Excavations

In order to cover the important aspect of tunnel-specific excavation the new class IfcUndergroundExcavation was introduced as subclass of the new abstract superclass IfcExcavation. The existing IfcEarthworksCut (mainly used for road and railway projects) is another subclass of IfcEarthworksCut (Figure 18). The existing IfcReinforcedSoil was renamed to IfcImprovedGround to allow a wider range of applications. Accordingly, PredefinedTypes relevant for tunneling have been defined that are shown in the diagram.

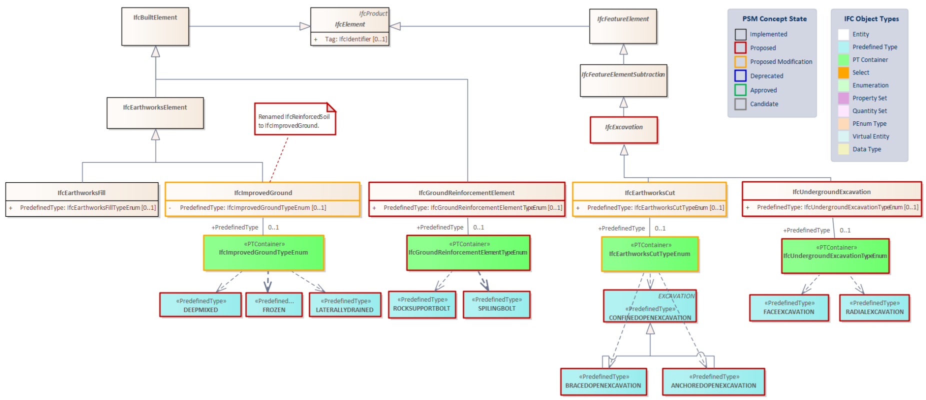

Fig. 18. The new classes IfcExcavation, IfcUndergroundExcavation and IfcGroundReinforcementElement along with their predefined types (in cyan)

5.7 Extended Georeferencing

To fulfill the requirements described in Section 3.4 the IFC data model was extended by the new class IfcRigidOperation as a subclass of IfcCoordinateOperation. When applied to a projected coordinate reference system the effect is that of truncating the "big coordinate values" which is often done in today's real-world projects. In consequence of applying a mere translation and/or rotation, the coordinate system remains distorted (projected), i.e. all model distances have to be multiplied by a scale factor to get real-world distances.

If this is not intended, an instance of IfcMapConversion has to be applied, essentially inverting the projection of projected CRS to enable real-world dimensions and distances in the model.

Besides projected CRS also geographic CRS are now supported by the new class IfcGeographicCRS. Any location on Earth can be referenced by a point with longitude and latitude coordinates and the height above or below the ellipsoid. It serves as an alternative to projected CRS, such as Gauss-Krueger or UTM.

Figure 19 depicts the extensions. More details can be found in [11].

The new entity IfcWellKnownText allows flexible definitions of site-specific coordinate reference systems outside the bounds of existing databases such as EPSG. As stated in Section 3.4, customized CRS are frequently applied in large-scale tunnel projects, especially when realized across different countries. IfcWellKnownText implements the OGC standard "Well-known text representation of coordinate reference systems", which was adopted as ISO 19162:2019. The underlying literal must be formed according to ISO/IEC 13249.

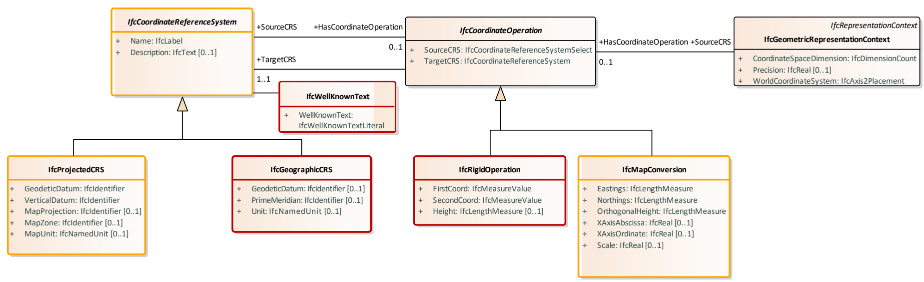

Fig. 19. The new classes IfcGeographicCRS and IfcRigidOperation. A IfcGeographicCRS is a CRS that uses a three-dimensional ellipsoid surface to determine locations on the Earth. IfcRigidOperation allows the definition of a local, yet distorted coordinated system when applied on a geodetic reference system such as UTM. This is often done in today's BIM practice to avoid large coordinates.

5.8 New voxel representation

The cover the requirements described in Section 3.7, the new entity IfcVoxelGrid has been introduced as a subclass of IfcSolidModel. It can be connected in a very flexible manner with one or multiple IfcVoxelData entities holding the actual values of the voxel grid. The classes and their connections are depicted in Figure 20.

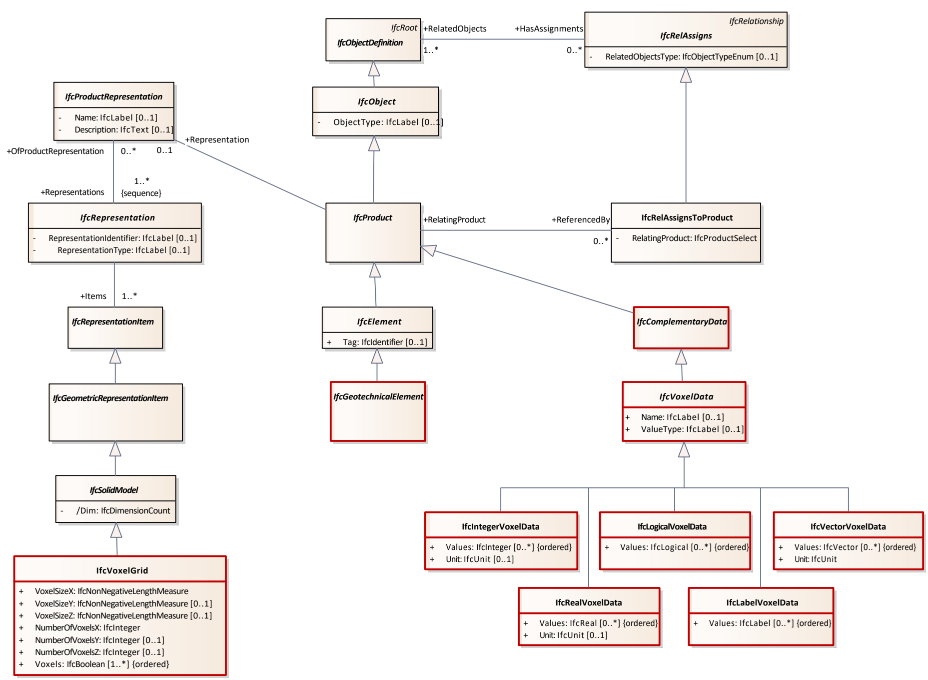

Fig. 20. The new classes IfcVoxelGrid and IfcVoxelData and their connection.

6 IFC schema extension (draft)

Based on the conceptual model, the actual extension of the IFC schema was realized. This was done by defining the corresponding EXPRESS schema. From the EXPRESS schema, all other data schemas supported by bSI are derived (ifcXML, ifcOWL, etc.). In addition, a comprehensive HTML documentation is generated. With respect to the latter, the project team created the documentation for new entities and updated those parts of the existing documentation where semantics were altered or extended.

The draft extension was published on GitHub[6] enabling direct feedback from the international community. In addition, the generated documentation was published on a dedicated website[7].

7 Validation and Deployment

To avoid ambiguities and identify deficiencies, the extension will be validated through prototypical implementations. To this end, software vendors from the tunneling domain are invited to join the deployment project that will develop and define a number of exchange scenarios and unit tests to be implemented by diverse vendors to validate the robustness of the extension.

8 IFC schema extension (final)

Once the errors and ambiguities identified in the course of the validation phase are fixed, the candidate standard of Version 4.4 will be published by buildingSMART International. It will undergo further validation before it becomes a final standard.

9 Handling of properties

Properties play an important role in IFC-based data exchange. They are not part of the schema but are defined independently by means of the PropertySet mechanism [3]. This allows for a dynamic extension of the schema and enables to fulfill the data exchange needs on a national, regional or authority level without requiring international consensus (Figure 21).

According to this principle, only a limited number of properties will be defined as international properties forming part of the final specification. However, there are well-defined mechanisms for handling national or authority-specific properties, for example by means of the buildingSMART Data Dictionary (bsDD).

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[6] `https://github.com/bSI-InfraRoom/IFC-Specification/projects/2`

[7] `https://bsi-infraroom.github.io/IFC-Documentation-Tunnel/4_4_0_0/general/HTML/`

10 Model View Definitions

As part of the deployment project, tunnel-specific Model View Definitions (MVD) will be specified that will allow software vendors to focus on those parts of the IFC schema that are relevant for their specific domain.

The following MVDs are planned to be specified:

- Tunnel Reference View (Tunnel RV)
- Tunnel Alignment-based Reference View (Tunnel ARV)
- Tunnel Design Transfer View (Tunnel DTV)
- Geology and Geotechnics View (GaGV)

11 Next steps

The development phase was finished in October 2022. It will be followed by a deployment project where interested software vendors are invited to join a coordinated early implementation effort. In the frame of the project, the software vendors are receiving intensive support and gain the opportunity to provide direct feedback on the standard. If major deficiencies are detected in this process, the standard will be revised accordingly.

After successful completion, the official bSI standards adoption process is performed. Upon approval of the standards committee, the extension becomes the official IFC 4.4 candidate standard and is subsequently set for vote by the national or regional chapters of buildingSMART International. If accepted, the standard will become the official IFC 4.4 release.

12 Discussion

The paper presented the extension of the vendor-neutral data format IFC developed in the course of the official buildingSMART International IFC-Tunnel project. The extension fulfilled a pressing request of the international BIM community to better support the data exchange of tunnel information models.

The project showed that is possible to successfully develop an extension of significant extent in a limited time of only 2 years. However, a stringent process had to be implemented to reach this goal. The most important prerequisite for the success of the project was the clear definition of the tunnel types to be included and the uses cases to be supported by the standardization effort. In this regard, it was essential to concentrate on the "low hanging fruits", i.e. on the most widespread tunnel types and the most beneficial use cases with limited complexity.

The involvement of international domain experts through frequent online workshops proved to be a very helpful resource for the development process.

For the actual extension, the guidelines laid down by the IFC-Infra Overall Architecture project were carefully followed. Most importantly, new entities were only defined where necessary, i.e. where existing entities did not provide the

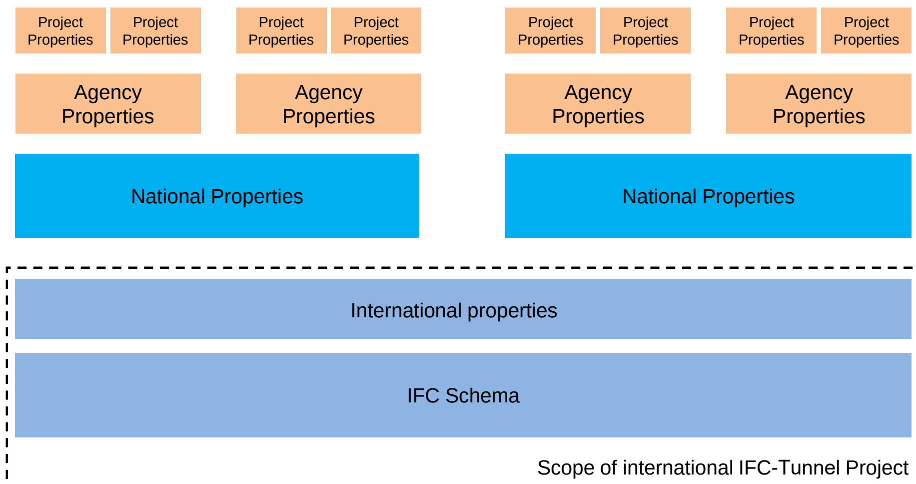

Fig. 21. The extension mechanisms of IFC allow the definition of properties on different levels.

semantics required for tunnel-specific concepts. In most cases, an extension of the predefined type enumerations was sufficient. This approach helps to keep the effort low for software vendors that already implemented previous versions of IFC when integrating the extensions.

With respect to properties, only a limited number were defined and became part of the official international specification.

13 Conclusion

The project has proven that the creation of a well-defined extension of IFC in limited time frame is possible. The formalized processes of buildingSMART International help to deliver a high quality product, ensuring both its technical validity and its applicability in the target domain.

Acknowledgements

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