A multi-scale tunnel product model providing coherent geometry and semantics

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ABSTRACT

For the planning of large infrastructure projects, such as inner-city subways, widely differing scales have to be considered – ranging from the scale of several kilometers for the general routing of the subway down to centimeter scale for the detailed planning of subway stations and hubs. At the same time the strongly inter-disciplinary character of these projects necessitates an intensive exchange of data between the individual stakeholders. Data exchange on a high semantic level is supported by the technology of product models. However, currently available product models do not support the multi-scale aspects required to properly handle large infrastructure models. This paper contributes to closing this technological gap by proposing a general methodology for developing multi-scale product models which combine semantic and geometrical aspects in a consistent and coherent manner. The methodology is illustrated by the development of a multi-scale product model for shield tunnels. In addition, methods for the automated preservation of the consistency of geometric representations at different scales are discussed.

INTRODUCTION

For the planning of large infrastructure projects, such as inner-city subways, widely differing scales have to be considered – ranging from the kilometer scale for the general routing of the carriageway down to the centimeter scale for the detailed planning of subway stations and hubs. Despite the multi-scale characteristics inherent in the planning of carriageways, today's infrastructure planning software does not support multi-scale geometric modeling. The research unit "3DTracks", funded by the German Research Foundation, is tackling this issue by developing a methodological basis for introducing multi-scale geometry into civil engineering models.

The concept of multiple geometric representations at different scales is well known from both cartographic applications as well as 3D city modeling. For example CityGML (Kolbe 2008), an open standard for the storage of 3D city models based on the Geographic Markup Language (GML), provides five different Levels of Detail (LoD). The LoD concept in these application areas relies on the independent storage of individual geometric models at each level of detail. As the dependency between the individual levels is not explicitly represented, inconsistencies can easily arise. This is less problematic for geographic applications where data sets are rather static and only rarely subject to modifications. However, for the planning of large tunneling projects, a more robust approach is needed.

In (Bormann et al. 2012a) and (Borrmann et al. 2012b), the authors introduced the concept of multi-scale geometric modeling for tunnel design, which provides mechanisms for the automated preservation of consistency between the different LoDs. The concept relies on the explicit definition of dependencies between geometric elements and has been implemented using technologies provided by parametric CAD systems.

However, for comprehensive use throughout the entire design and engineering process, it is necessary to incorporate semantics into the model. Models that comprise both a semantic and geometric description are usually referred to as product models. Examples are the Industry Foundation Classes (IFC) for building design and the CIS/2 model for structural steel projects. These models are based on object-oriented principles and provide typing, inheritance, attributes and relationships, resulting in powerful mechanisms for describing semantics. Consequently, product models form a sound foundation for ensuring interoperability between different software products and between different stages of the construction project.

Based on preliminary work by (Yakubi et al. 2007) we are introducing a comprehensive product model for shield tunnels which fulfills the demands of the design and engineering of large infrastructure projects. The main emphasis of this paper is placed on integrating the semantic description with the multi-scale geometry approach discussed above. In the presented concept, the multi-scale approach also forms part of the semantic model, i.e. specific entities are only available at a particular LoD. The major challenge is then to achieve and maintain semantic-geometric coherence in the model (Stadler & Kolbe 2007; Clementini 2010), which means that geometric elements at a certain LoD are assigned to correct semantic elements on the same level.

POINT OF DEPARTURE: A SHIELD TUNNEL PRODUCT MODEL

The point of departure for our investigations is the development of a product model for shield tunnels. Although a first draft for a shield tunnel product model was provided in (Yakubi et al. 2007), it had to be adapted to the specific needs of our research, in particular with respect to the multi-scale modeling approach. Figure 1 shows an overview of the developed model. The semantic model presented is aligned with the Industry Foundation Classes[1] (IFC), a comprehensive, standardized product model for buildings. In particular, we make extensive use of the space structure concept. As explained in detail below, it significantly simplifies the integration of multi-scale concepts into the model. Like the IFC model, the proposed tunnel product model provides a clear separation between semantic objects and the associated geometry.

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[1] Please note that, for improved readability, we omit the prefix IFC in the class names throughout this paper.

The left-hand side of Figure 1 shows the semantic part of the model. Please note that, like in the IFC, we distinguish space objects (depicted in blue) from physical objects (depicted in green). The meaning of the individual entities is illustrated in Figure 2. Except for the ring space, all space objects represent longitudinal spaces along the entire *TunnelPart*. The *Ring* space, however, has the length of a segment only. The relations between the semantic objects rely on the space structure concept, modeling aggregation relationships between the site, the tunnel, the tunnel parts, the longitudinal spaces, and the rings.

The associated geometry representations are depicted on the right-hand side of Figure 1. The tunnel object is associated with a dedicated *Alignment* object. Since the alignment plays a key role in the design and engineering of tunnels, it is essential to provide the genuine alignment objects such as lines, arc segments and clothoids as part of the product model. Due the limited space available here, we have not depicted all these elements in detail here. For describing the geometry of the longitudinal objects (both the space objects and the physical objects), we rely on a profile geometry representation[2] to define volumetric geometry by means of cross-sections extruded along a given axis.

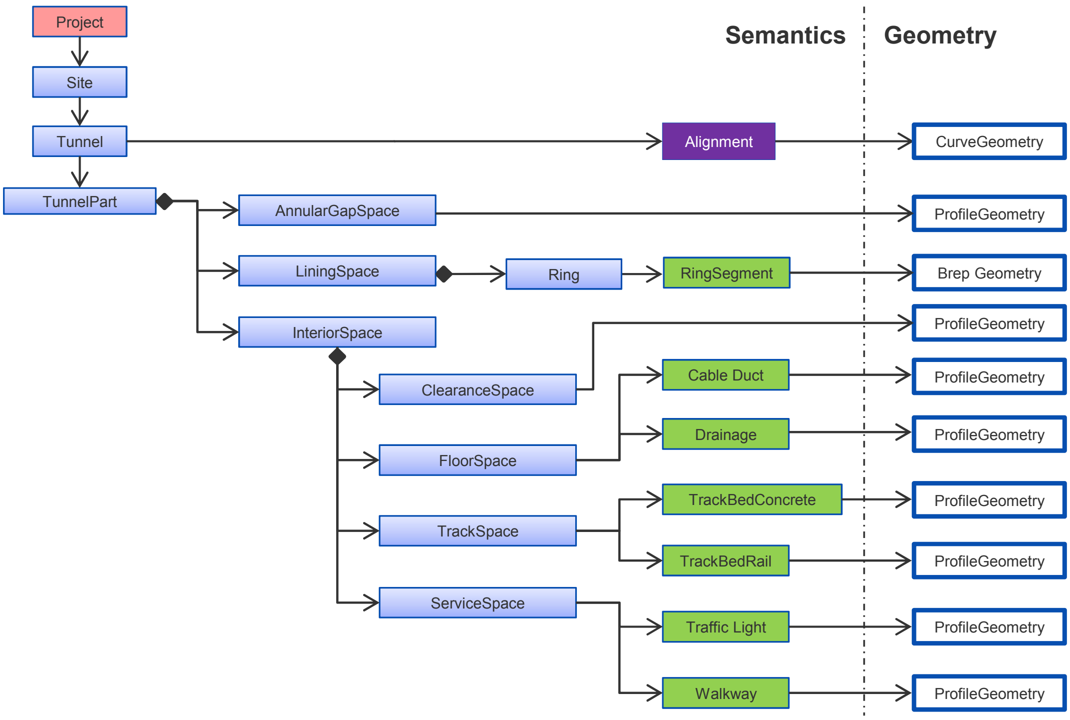

Figure 1: The proposed shield tunnel product model using conventional, non-multi-scale approaches[3]

[2] The IFC provide the entity IfcSurfaceCurveSweptAreaSolid to describe geometry by means of a closed profile and an extrusion along a reference curve.

[3] Please note that we use a simplified notation here. Relationships which are represented by dedicated objects in IFC are depicted here as direct associations. Aggregation relationships (IfcRelAgggregates) are marked with a rhombus. The containment relationships between Space Structure entities and physical objects (IfcRelContainedInSpatialStructure) are depicted as arrow lines.

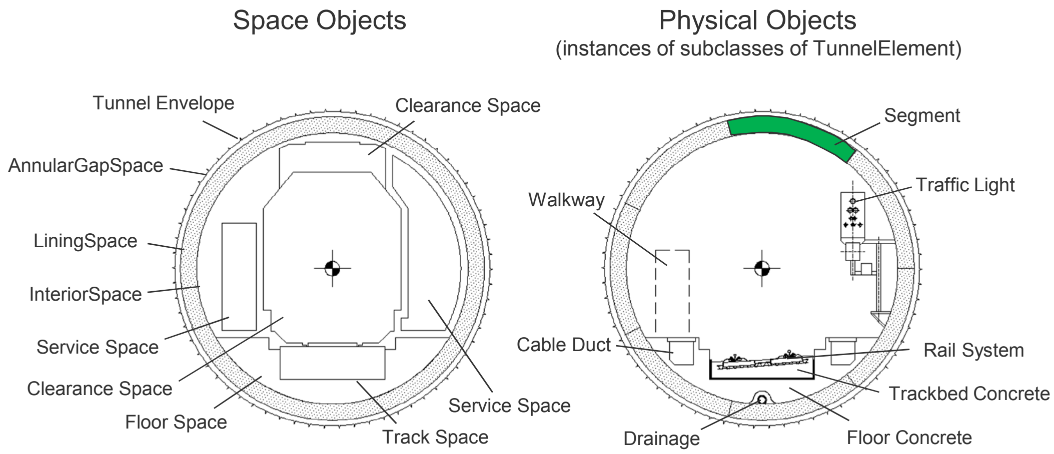

Figure 2: A tunnel cross-section showing the individual spaces (left) and elements (right) of the product model

INTEGRATING MULTIPLE SCALES INTO THE MODEL

A main shortcoming of existing product models is the lack of support for different levels of detail. As a consequence, they only poorly fulfill the demands of engineering practice, particularly in the early design phases, where 'coarse-grain' design information is successively enriched by more fine-grained information.

To better support the design and engineering of tunnels, we have developed concepts for integrating multi-scale approaches with tunnel product models. The main difference between our approach and the one followed by GIS standards, such as CityGML, is the scale-aware sub-division of the semantic part of the model. While the GIS standards allow the association of multiple geometric representations for the individual levels with one semantic object, but keep the semantic object structure fixed across the different LoDs, we propose to explicitly represent refinement relationships in the semantic part of the model, thus providing a much higher degree of semantic-geometrical coherence of the multi-scale model.

The resulting multi-scale product model is depicted in Figure 3. In order to group and provide access to all elements at a certain level of detail, we introduce dedicated LoD objects. These objects aggregate all spatial and physical objects at the corresponding level. At the same time, we maintain the aggregation relationships across the different LoDs in order to explicitly model a refinement hierarchy. One of the key aspects of our approach is that the refinement hierarchy is created with the help of space objects, while physical objects form part of the finest level only. This allows us to use spaces as placeholders on coarser levels, thus providing full compliance with standard IFC modeling approaches for space-element aggregation structures.

The geometry representation is basically identical to that of the model defined above. Figure 2 provides a 2D graphical illustration of the representations at the different LoDs, while Figure 4 provides a 3D illustration. Please note that on LoD1 the tunnel is represented by its axis only. On LoD2 the additional space object

TunnelEnvelope has been introduced to provide a semantic object representing the entirety of the tunnel. The *Ring* space objects belong to the finest level of detail, LoD5, since their definition happens at a more advanced stage of the planning process. Each *Ring* contains the *RingSegments* which belong to it.

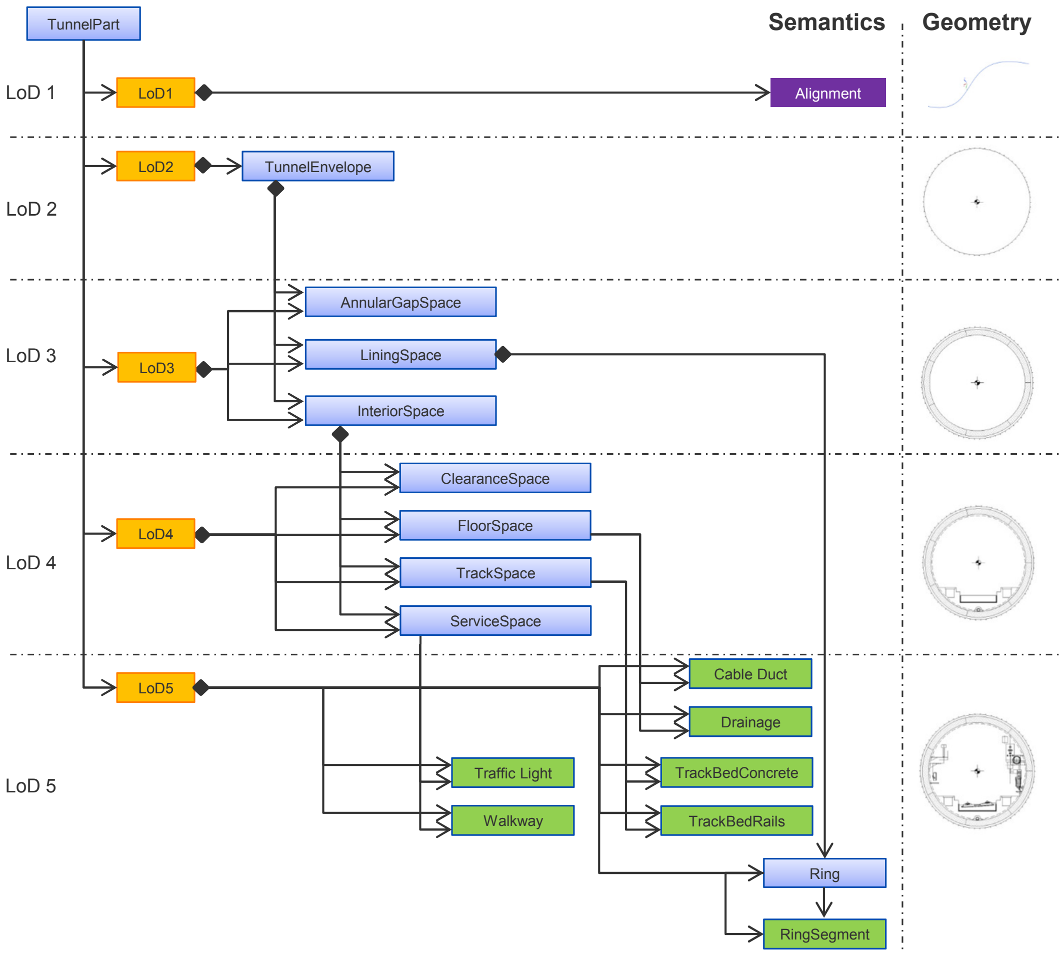

Figure 3: The proposed shield tunnel product model incorporating a coherent multi-scale representation of semantics and geometry

Although this model implements a multi-scale approach and provides a coherent representation of semantics and associated geometry, it does not yet provide a means of preserving the consistency between the different LoDs. This is caused by the fact that the geometry representations of the individual LoDs are independent of each other. Inconsistencies can arise, for example, when a modification is performed on one level, but not propagated to the other levels. To overcome this deficiency we propose to make use of procedural geometry descriptions, which allow us to explicitly define dependencies between individual geometric objects and thus provides a means for automatic consistency preservation. The resulting data model is described in the next section.

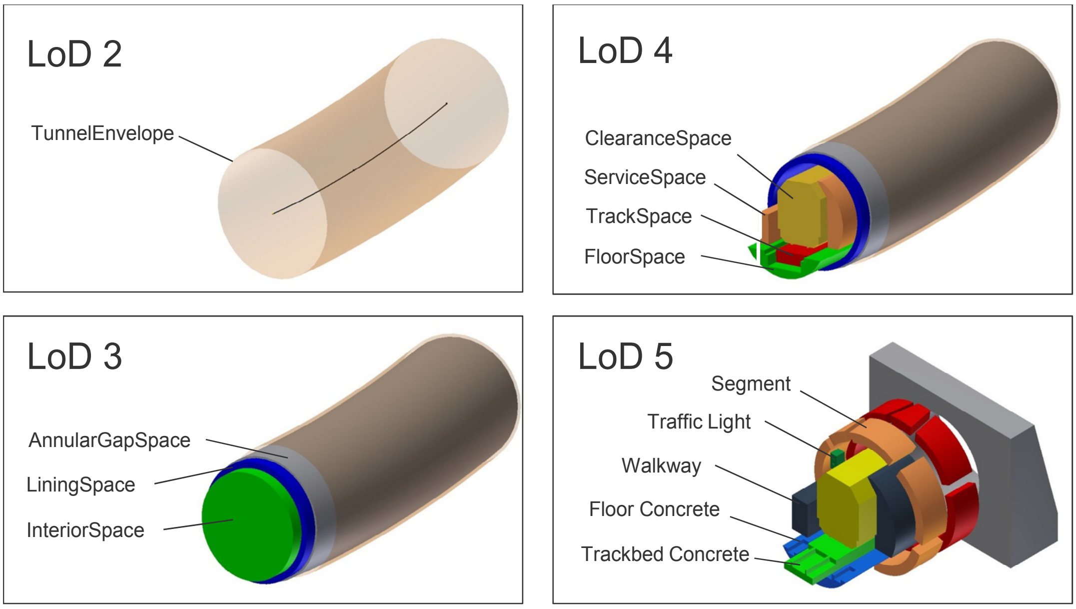

Figure 4: A 3D representation of the different LoDs of the multi-scale shield tunnel product model

PROCEDURAL GEOMETRY FOR AUTOMATED CONSISTENCY PRESERVATION

In the multi-scale product model introduced above, as well as in all multi-scale approaches known from the GIS domain, the geometry representations of the individual LoDs are stored independently of one another. In the case of modifications on one level, all other levels have to be updated manually in order to maintain the consistency of the entire multi-scale model. This is appropriate for geographic applications where we are faced with rather static models, which are rarely subject to modifications. However, for the highly dynamic processes of the design and engineering of tunnels, an automated means of preserving consistency is desirable.

This is realized by explicitly modeling dependencies between the geometric representations at the different LoDs using the concept of procedural geometry (Borrmann et al. 2012a, 2012b). The concept of procedural geometry is well known from parametric CAD systems, which usually provide parametric sketches allowing users to define constraints between individual geometric entities, and a construction history that relates individual construction operations to each other (Pratt 2010).

Figure 5 depicts how this form of geometry representation can be integrated into a multi-scale product model. The explicit geometry representation of individual elements of the model is replaced by a procedural one which can be linked to the geometric entities at lower LoDs. One example is the alignment curve which acts as the LoD1 representation and is subsequently used as the path for creating the extrusion geometry of all longitudinal objects on the finer LoDs. Another example is the sketch-based creation of profiles on finer levels from coarser ones using offset operations.

Applications that are capable of interpreting and processing procedural geometry are able to automatically preserve the consistency of the multi-scale model by propagating changes on geometric objects to all dependent representations and updating them accordingly.

To prove the suitability of the concept, we have developed import and export modules for the parametric CAD systems Autodesk Inventor and Siemens NX, respectively. Using these modules, we are able to exchange inherently consistent multi-scale models between these CAD systems by means of the neutral product model presented in this paper.

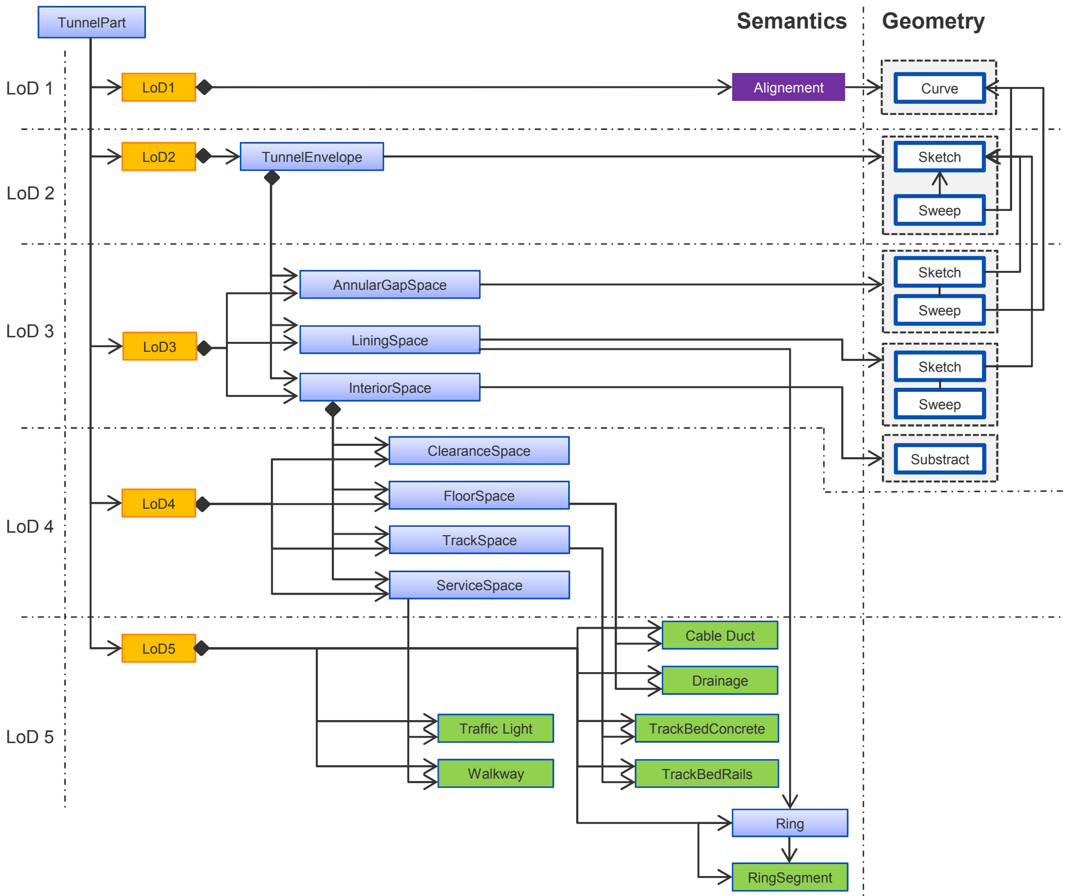

Figure 5: The shield tunnel product model incorporating a multi-scale semantic representation and a procedural geometry representation. It makes it possible to define dependencies between the geometric representations at the different LoDs, thus providing a means for preserving consistency across the levels.

CONCLUSION

This paper has introduced a novel approach for the design of multi-scale product models that provides inherent coherence between the semantic and the geometric entities. This approach was illustrated by describing the elaboration of a multi-scale product model for shield tunnels. The key aspect of the developed approach is the use of space aggregation hierarchies for representing refinement relationships on the semantic side. Physical objects which are located in these spaces are only included in the finest level of detail. Each of the spatial and physical objects is associated with a corresponding geometry representation. The resulting product model represents a complete and spatio-semantically coherent description of a multi-scale product model for data exchange purposes. However, since the geometry representations are stored independently of one another, their consistency cannot be automatically preserved. To rectify this, the product model has been extended in a second step through the inclusion of procedural geometry descriptions which establish explicit dependencies between the geometry representations at the different levels of detail. The extended product model makes it possible to exchange multi-scale models that incorporate rules for the automated preservation of the consistency of the geometry representations of the individual levels of details. The feasibility of the concept has been proven by the development of import and export modules for the exchange of multi-scale models between two different modeling systems.

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