Flexible linking of semantic, procedural and logic models for consistent multi-scale infrastructure design

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ABSTRACT: In recent years, a tendency toward the adoption of neutral product models has been observed in the Architecture Engineering and Construction (AEC) industry. Product models such as Industry Foundation Classes (IFC) allow engineers to exchange and integrate information in a flexible and reliable way. Thanks to the strict separation between geometry and semantics, a number of extensions have been developed, spanning from semantic definitions to procedural multi-scale geometric representations. However, the design knowledge underlying the design of infrastructure models cannot be completely encapsulated by the approaches proposed so far. This paper contributes to close this technological gap by introducing the concept of logic models, which enable engineers to describe, store and exchange the full design knowledge employed for specific design problems. Thus, logic models provide a bridge between abstract design rules and concrete geometrical representations. In addition, we propose an extension of the IFC model, which enables a flexible linking between logic and semantic-geometric models. As proof-of-concept we present three logic models for shield-tunnel infrastructure projects, which were coupled with a multi-scale geometric-semantic model.

1 INTRODUCTION

In the last decade, much research has been focused on moving the AEC industry from 2D modelling and planning into the 3D world. While 3D modelling is gaining increasing acceptance in building design and engineering, the infrastructure domain still heavily relies on 2D drawing-based processes, resulting in reduced efficiency due to manual data preparation, transfer and interpretation. However, recent research activities try to overcome these limitations by applying the 3D modelling paradigm onto the infrastructure domain (Ji et al. 2012, Borrmann et al. 2009).

Large infrastructure facilities present however, specific challenges that are not present in other AEC projects, most importantly the strongly diverging scales which need to be considered by engineers when designing the infrastructure object. One successful approach to a consistent handling of these different scales levels is the consequent application of a Level of Detail (LoD) approach, which mimics the different levels of abstraction engineers are accustomed to (Borrmann et. al. 2012a). The use of multi-scale models in the dynamic process of engineering design requires the preservation of the model's consistency between the different LoDs. To achieve this, we make use of a procedural geometry description, which creates explicit dependencies among geometric elements on the different LoDs and enables an automated update of the geometry in case of changes (Borrmann et. al. 2012b).

An additional challenge in the design of large infrastructure facilities is the exchange of information between partners. Architects and engineers use different software products to accomplish their contribution to the whole project. As the exchange of information based on proprietary formats is frequently constrained to the use of the same software, the development of a neutral exchange format has been pursued for a long time (Eastman 1999).

To achieve vendor-independent interoperability, neutral product models such as IFC, define a flexible structure based on a dual description comprising geometry and semantics. This clear separation fosters the creation of extensions on the semantic description and on the geometric representation. For example, Yabuki et al. (2009, 2013) presented a new semantic schema that describes the interaction between the shield tunnel and the soil conditions, in which the tunnel ought to be constructed. Differently, Hegemann et al. (2013) concentrate on the mechanized construction of shield tunnels, introducing a new semantic description that comprises shield tunnels and Tunnel Boring Machines (TMB) – nowadays the most widespread building method for shield tunnels. Finally, Borrmann and Jubierre (2013) presented a new IFC-based shield tunnel product model, which integrates the LoD concept with both the semantic and the geometric description, and which answers the consistency preservation question by applying a procedural geometric representation.

Hence, the combination of extended semantic schemas and the use of different geometry representations, allow product models to be one of the best methods to exchange and integrate AEC information. However, due to the complexity of large infrastructure facilities, engineers make use of field-dependent design knowledge that provides them with simple structures to easily create and modify the infrastructure model. These structures, which form part of the design rationale in infrastructure projects, are not yet integrated in product models. Consequently, this paper focuses on the flexible integration of construction knowledge and design rationale in product models.

2 RELATED WORK

2.1 *Multi-scale product models*

Multi-scale product models present two main benefits: (1) they allow engineers to work on different levels of abstraction appropriate to their design activity and (2) they allow geographic information systems (GIS) to be integrated in the design process (Steuer et al. 2013).

The main challenge of multi-scale product models – the preservation of model's consistency across the different LoDs – has been met by the use of parametric CAD systems and the incorporation of procedural models (Borrmann et al. 2012b). The main difference of procedural models in comparison with other geometrical representations relies on the geometric information stored. Instead of storing the resulting geometry produced through the design process, procedural models reproduce the construction steps (operations) needed to re-build the final geometry. In our approach, each individual operation is assigned to a specific level of detail, allowing us to execute the different operations up to the desired LoD (Borrmann & Jubierre 2013).

Another integral part of procedural models is the use of parametric sketches. Parametric sketches are flexible 2D representations defined by geometrical and dimensional constraints, which allow engineers to explicitly represent the design intent and enables a fast generation of valid design variations.

In conclusion, geometric representations defined using procedural models can be easily modified by the update of one parameter or the modification of a few number of construction operations. An example of the benefits of procedural representations in infrastructure models is found in the definition of the cross-section of a shield tunnel, where the tunnel diameter can be easily modified by just changing the value of the corresponding parameter.

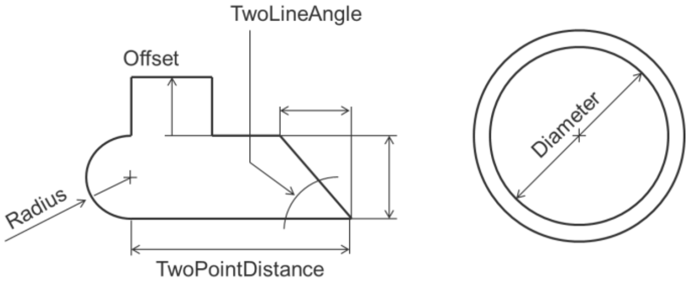


Figure 1.Typical dimensional constraints in a parametric sketch

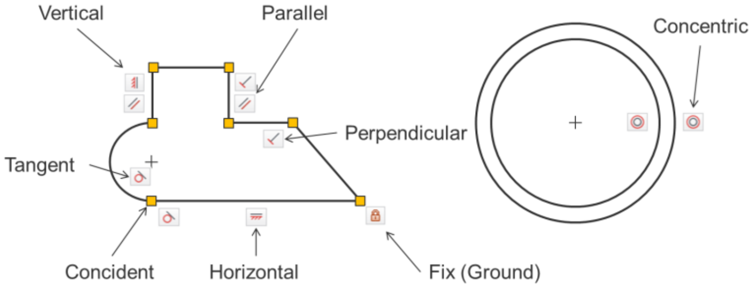


Figure 2.Typical geometrical constraints in a parametric sketch

2.2 *Product Models based on the IFC standard*

The Industry Foundation Classes (IFC) is an open standard dedicated to the digital description of construction and building information data, and is commonly used in Building Information Modelling (BIM) based projects. Although the standard is im-

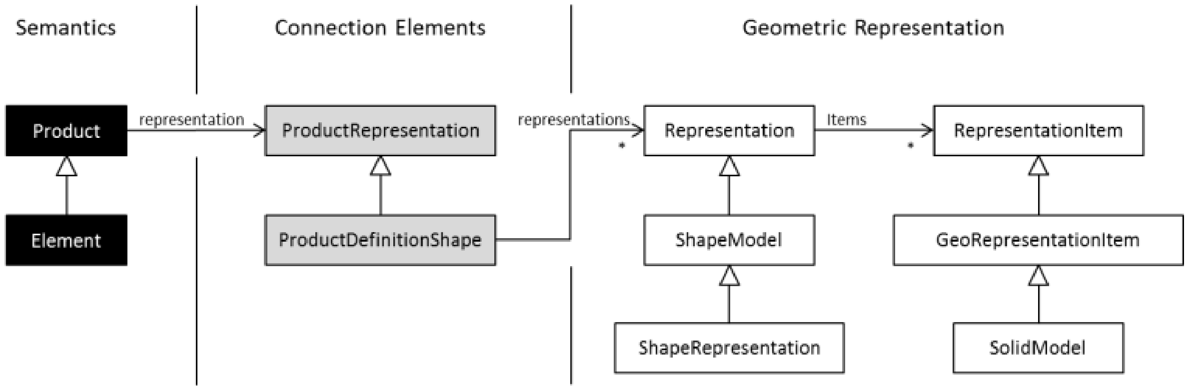


Figure 3. Connection between semantic and geometric representation in the IFC data model

plemented by a variety of vendors, its actual maintenance and development is controlled by the international, non-for-profit organization buildingSmart and registered at the International Organization for Standardization (ISO) 16739:2013 (buildingSmart Ltd., 2014).

The IFC standard defines a data model consisting of a large number of classes, denoted as entities, organized into an object-oriented inheritance hierarchy. An important principle of the IFC is its strict separation between the semantic description and the geometric representation. Therefore, some entities act as connection elements between these two separate models (Figure 3).

Connector elements such as *IfcProductDefinitionShape* are designed as one-to-many link entities, allowing the union of one semantic element with several geometrical representations. This paper concentrates on these elements and proposes an extension on the product model, which enables other models to be linked to the basic semantic-geometric description.

3 LOGIC MODELS

The use of procedural models and parametric sketches as geometric representation in product models significantly extends the means for representing design knowledge and design intent. Procedural operations can be defined in different levels of detail, allowing models to become multi-scaled, while parametric sketches enables the definition of parameters and constraints between geometric entities. When these two elements are applied in a comprehensive manner, engineers can focus on specific aspects of the design and then perform changes by updating only a few instances of information, while the CAD system manages the consistency of the complete model.

Despite the clear benefits that construction operations, parameters and constraints introduce, there is design knowledge which cannot be captured by these technologies. Construction operations – also known as features (Shah & Mäntylä, 1995) – create or modify a volumetric object in a pre-defined way, and parametric sketches – described by geometric elements and constraints – are restricted to 2D geometry. Moreover, parameters can only represent algebraic relations, leaving logical conditions (e.g. if-else conditions) uncovered.

Due to these restrictions, a significant portion of design knowledge cannot be captured. A good example of these shortcomings is found in the design of linear infrastructure facilities such as tunnels, bridges and roads. These buildings follow an alignment curve which defines the facilities' trajectory in 3D space, geometry that cannot be defined by the above mentioned methodology. Moreover, due to engineering regulations, the alignment itself is not directly defined as a 3D curve but through the combination of horizontal and vertical alignments following the specific rules of curvature and transition which apply in these views (Ministerio de Fomento Espanol 1999, Regelwerk Technik Eisenbahn 2007, State of Illinois 2010).

To fill this technological gap we propose the introduction of the novel concept of logic models, which extend product models by means of defining more abstract logical structures, thus drastically extending the knowledge representation capabilities. In order to be able to interpret these models and generate the respective geometry, specific interpreter modules are required to form part of the parametric CAD system importing the extended product model. In addition, interpreters of logic models can be linked to specific geometric elements or be fed with the result of other interpreters.

In opposition to traditional design process, the introduction of logic models allow engineers to easily define and modify basic structures of information, regardless of how their changes must be introduced in the final model.

To illustrate the proposed methodology, we developed three different logic models which are employed in the context of multi-scale modeling of large infrastructure facilities. The first logic model – the alignment model – responds to the difficulties concerning 3D alignment curves, by providing similar structures to what is required by track experts, namely the clear separation between horizontal and vertical alignments.

Then, for the specific case of shield tunnels, two more logic models are described; (1) the tunnel axis model, which is usually shifted from the alignment curve by two offset parameters, and (2) the ring configuration model, which determines the best arrangement of the rings in order to follow the axis of the tunnel. These two logic models are fed with the geometrical information contained in consequent procedural operations and updated without user intervention.

3.1 *Alignment model*

Almost all large infrastructure facilities are designed starting from its alignment. To allow the engineer to focus on the relevant aspects, such as curvature or gradient, the 3D alignment is designed by the superposition of 2D curves – the horizontal and vertical alignments. This approach is reflected by all major standards and exchange formats.

Despite the separation in horizontal and vertical components, the complexity in the description of both curves remains high. Even more, diverse exchange formats such as LandXML (Rebolj et al. 2008) or OKSTRA (Schultze & Buhmann, 2008) define different geometric elements and implement

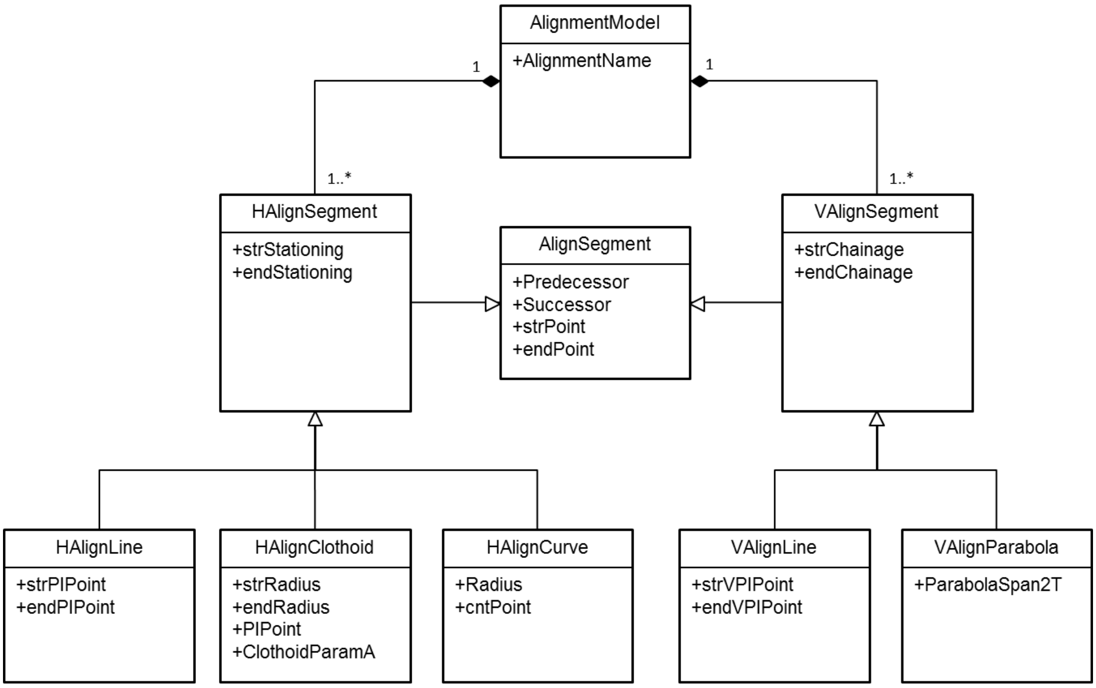


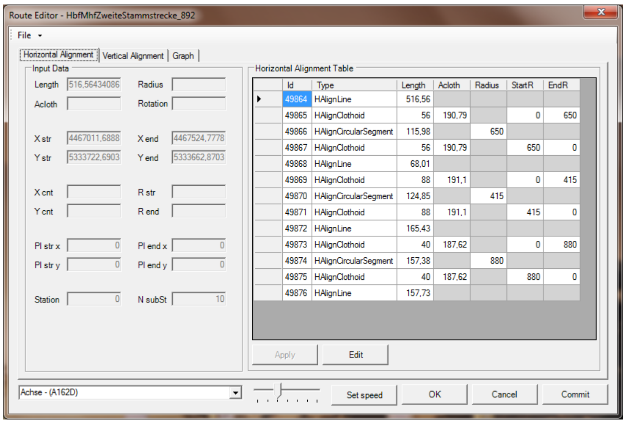
Figure 4. Alignment model which integrates the two curves – horizontal and vertical alignment – used to describe the 3D alignment path.

them in different ways (Amann et al. 2014a). In fact, the problem in the definition of the alignment is so crucial that for the future version of IFC a new distinguished work group has been created (buildingSMART Ltd. 2013).

In the scope of our research and in order to proof the proposed methodology of employing logic models, a basic alignment model was developed (Figure 4), which represents the native information underlying the design of a new infrastructure facility, i.e. the alignment elements, their attributes and relationships. A dedicated interpreter can use this information to create the resulting 3D curve representing the alignment in the parametric CAD system, which can subsequently be used to elaborate the tunnel model through the application of the available construction operations, such as offset, sweep or Boolean operation.

By definition, the interpreter of a logic model is responsible for the generation of the procedural geometry, disabling the direct manipulation of the geometry by the end user. Therefore, in the scope of our research, we developed a track editor (Figure 5), which acts as a common tool for the definition and modification of alignment models. The track editor was developed to fulfill two functionalities. First, the track editor is used to read the basic information of an alignment project – LandXML was chosen as input format – and second, the track editor enables the modification of parameters – e.g. the radius of a circle or the constant of a clothoid – which define the basic geometry of the horizontal alignment.

The workflow followed by the user – working on the alignment model – is as follows; first, the user loads a new alignment model based on a LandXML file using the track editor. Then, the track editor sends the information to the interpreter which finally creates the 3D curve – based on several construction operations – in the CAD system. In the same way, any modification introduced by the user in the track editor will be forwarded to the interpreter and later on to the geometry.



Length 516,56434086
Radius
Acloth
Rotation
X str 4467011,6888
X end 4467524,7778
Y str 5333722,6903
Y end 5333662,8703
X cnt
R str
Y cnt
R end
PI str x 0
PI end x 0
PI str y 0
PI end y 0
Station 0
N subSt 10

Id	Type	Length	Acloth	Radius	StartR	EndR
49864	HAlignLine	516,56				
49865	HAlignClothoid	56	190,79		0	650
49866	HAlignCircularSegment	115,98		650		
49867	HAlignClothoid	56	190,79		650	0
49868	HAlignLine	68,01				
49869	HAlignClothoid	88	191,1		0	415
49870	HAlignCircularSegment	124,85		415		
49871	HAlignClothoid	88	191,1		415	0
49872	HAlignLine	165,43				
49873	HAlignClothoid	40	187,62		0	880
49874	HAlignCircularSegment	157,38		880		
49875	HAlignClothoid	40	187,62		880	0
49876	HAlignLine	157,73				

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Figure 5. Track editor user interface developed to create and modify alignment models

3.2 *Tunnel axis model*

In railway infrastructure facilities, the alignment curve is defined by the middle point between the two rails. Therefore, in the specific case of single-track shield tunnels, the axis of the tunnel is shifted from the alignment by a vertical offset. Moreover, as the track bed is constructed with a superelevation on curved segments, tunnel engineers shift also the axis of the tunnel by a horizontal offset to avoid the clearance space crash with the lining space.

Similar to the value of the track's superelevation, the value of the horizontal offset increases gradually on clothoids and remains constant on curves. On straight segments the horizontal offset is neglected.

Once more, as the splines representing the axis of the tunnel are strongly coupled with the horizontal alignment and the transitory offset values, the definition of a new logic model match perfectly with the problem requirements.

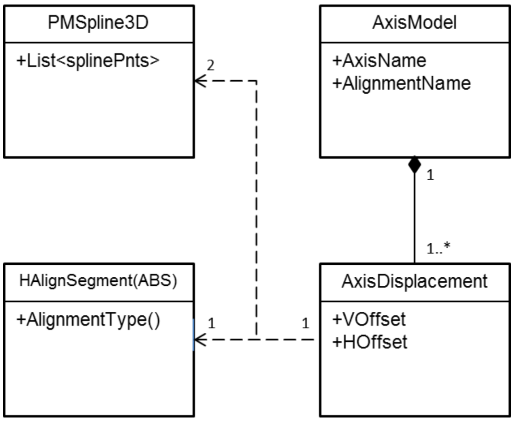

Figure 6. Tunnel axis model and its dependencies to the alignment model and construction operations

The proposed model (Figure 6) duplicates the list of *HAlignSegment* with a new list that contains the value of the horizontal and vertical offset parameters for each segment. Additionally, the interpreter of this model needs access to the alignment model and alignment operations to create or modify the axis curve. Thereby, any modification introduced in the alignment model will change the alignment curves (3D splines) first and the axis curves later on.

3.3 *Ring configuration model*

The lining of a shield tunnel is made up of ring segments that have one or two tapered sides. In order to make the resulting tunnel follow the defined axis, each ring is rotated in a way that the axis of the ring is consistent with the desired path. However, the lining with rings presents two main challenges: (1) the axis on the ring is straight, which force to approximate the axis' path with a polygonal curve, and (2) rings can only by assembled in a limited number of positions. Furthermore, at the beginning and at the end of the tunnel two special rings known as portals are built to complete the total length of the tunnel.

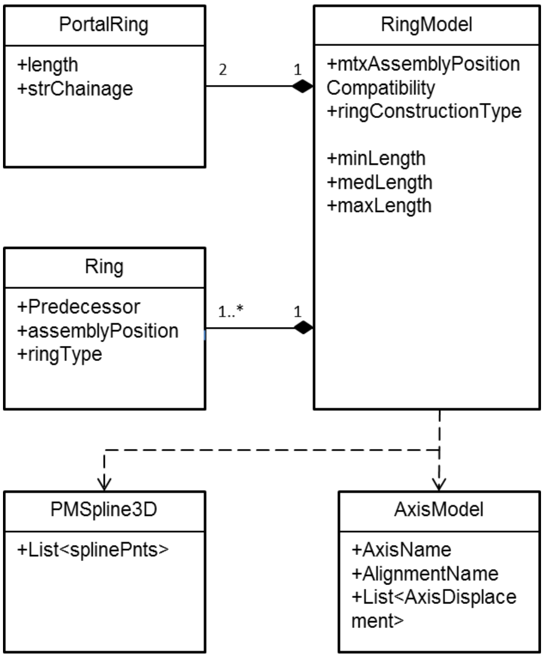

Figure 7. Ring configuration model and its dependencies to the tunnel axis model and construction operations

As the complexity of the problem exceeds the parametric capabilities of procedural models, a new logic model was developed (Figure 7). To address the challenges described above, two different methodologies have been employed. First, the feasible combination of rings is stored in a matrix of Boolean values, which must be specifically defined for the ring type used in the lining. Second, the approximation of the axis' path with a polygonal curve is left to the interpreter of the model, which is not explained here as it goes beyond the scope of this paper.

Similar to the tunnel axis model, the interpreter of the ring configuration model requires the infor-

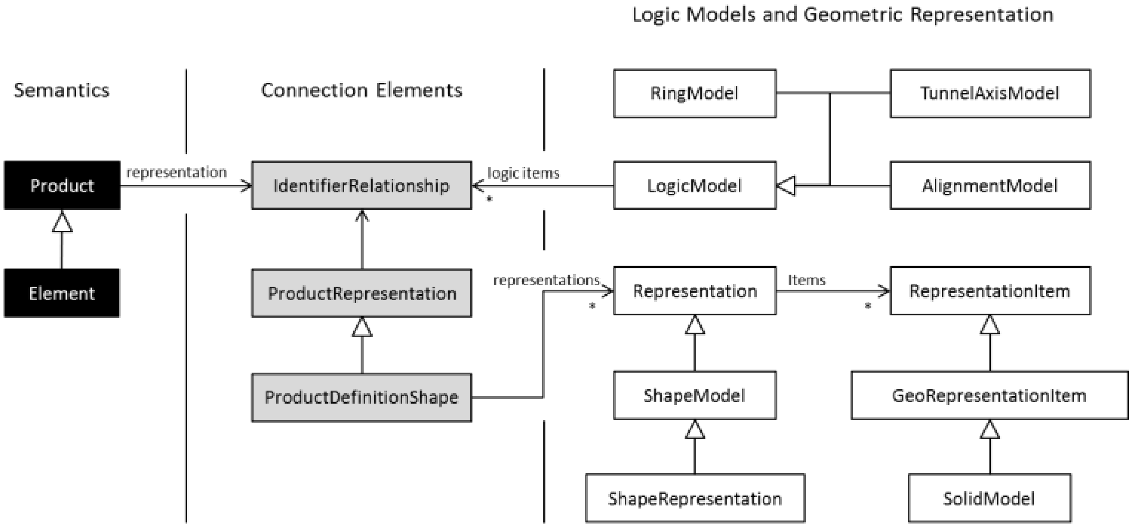

Figure 8. Extended IFC product model with three logic models and a new connector element

mation contained in both, the construction operations used to model the axis' curve and the logic model of the tunnel axis. As before, a modification of the alignment triggers the update of the axis and consequently, the ring configuration of the tunnel.

4 EXTENDING THE IFC PRODUCT MODEL BY LOGIC MODELS

The IFC product model enables the connection of one semantic element with a variety of geometrical representations. However, the aim of logic models is to extend the capabilities of design knowledge and design intent, and not to form a new geometric representation. Therefore, we present means for integrating logic model structures with the existing IFC standard.

The necessity of connecting several models is a well-studied topic in construction engineering. The first methodology studied in the scope of our research was the nD-modelling approach, which was developed to extend the 3D geometric representation with an unlimited number of additional models. In this approach, the complete information is transferred to a server and provided to the client as a service (Lee et al. 2007). The main drawback of this technology is that geometry and the additional models are loosely connected and therefore not suitable for the close connection between logic models and geometric representations.

Another approach investigated during our research and which provides firm connections between models is known as the multi-model approach. The multi-model approach creates a container for the involved models and then executes an analysis where exclusive connection structures among models are created and stored in a metadata assembly known as *link model* (Fuchs, 2013). The main drawback in this approach remains in the concept of container, which treat logic models as an independent structure of the product model.

Although the concept of container is not achieving the needs of logic models, the definition of connection elements in the IFC standard – *IfcRepresentation* and *IfcProductDefinitionShape* – is close enough to the multi-model's link model approach. Therefore, we developed a new IFC entity *IfcIdentifierRelationship*, which works as a central location where links to all models – semantic, geometric and logic – are stored (Figure 8).

With this minimal modification on the IFC standard, logic models can be integrated with procedural representations. Even more, the *IfcIdentifierRelationship* entity opens the door to connect a wider set of different models in an easy and reliable way.

5 CONCLUSIONS AND FUTURE WORK

This paper has introduced a new methodology to extend the capability of product models to include the design knowledge applied by engineers in the modeling process. The core concept is the definition of additional logic models to capture the rationale underlying specific tasks in the design process. As proof-of-concept, we developed and presented an alignment model, a tunnel axis model and a ring configuration model. In order to integrate logic models in neutral exchange standards, an extension of the IFC data model was presented, where a new *IfcIdentifierRelationship* entity is employed as central link location. In future, we want to extend the use of logic models to grammar structures and design rules which will allow us to connect knowledge-based engineering (KBE) with procedural geometry representations. In addition, we want to analyze how the interpreters of logic models can be integrated in the IFC standard. Promising first results have been achieved by current research activities in the field of procedural IFC programming language (Amann et al. 2014b).

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