IFC 4.3 Implementation & Validation Report

Appendix D – Alignment Rework Report

Motivation for extending and changing IfcAligment – overview of core Rail Domain requirements and their implementation in IFC 4.3

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Contents

1 Introduction

This document describes the rework of the alignment topic in IFC 4.3. It is part of the official deliverables of the report for implementation and validation of IFC 4.3, and also a part of the final deliverables of IFC Rail Phase 2, as shown in Figure 1**Error! Reference source not found.** below. Please refer to the *IFC Rail Phase 2 Final Report – Executive Summary* for further details.

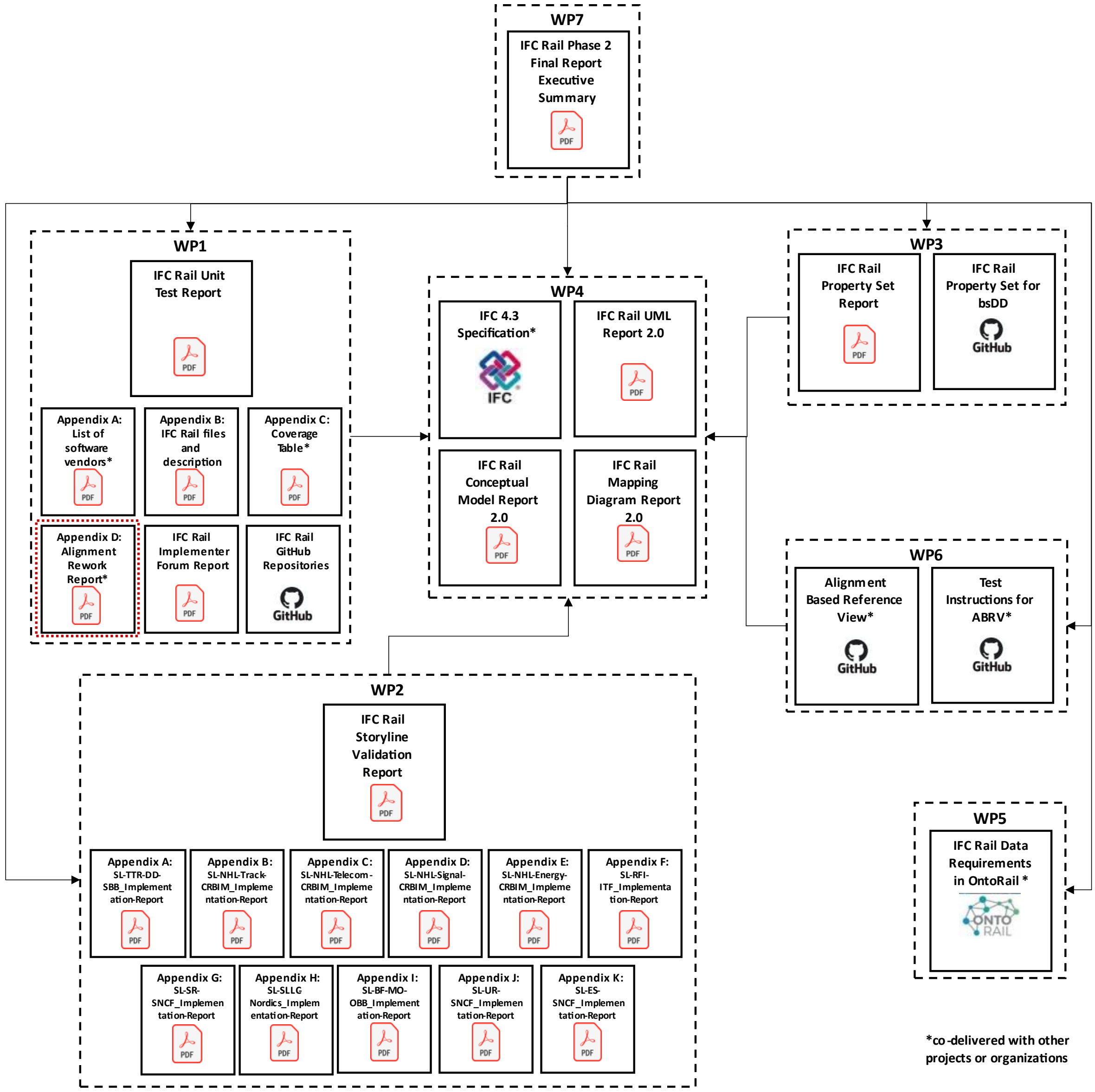

Figure 1 The position of this document in the structure of deliverables

This document reports central aspects of modelling alignment in the IFC 4.3 specification. Alignment has been introduced in IFC 4.1. From the onset of the IFC Rail Project it was clear that extensions to the existing schema were required.

After availability of IFC 4.3 RC1 the unit test phase started. At the same time IFC Rail storylines were initiated to check the fitness of purpose of the upcoming IFC 4.3 specification and to develop a first set of best practices for usage of IFC in the rail domain. Additional insights gained both, in unit test execution and in storyline preparation caused additional changes to the core IFC 4.3 schema.

Given the substantial number of alignment related changes between IFC 4.3 and previous versions it seems appropriate to document the main reasons for the rework.

1.1 Scope

This report focuses on the motives behind the new IFC 4.3 schema for alignment modelling of linear infrastructure especially in the rail domain. The following aspects shall be addressed. If appropriate the resulting changes to the IFC schema are described.

- *Rail perspectives on alignment*
- *Business semantics versus geometry*
- *Cant as a railway specificity*
- *High performance transition bends and kinematics*
- *Regulations and legacy documentation*
- *Example for conversion from semantics to geometry*

1.2 Acknowledgments

The extension to IFC alignment and the content of this report is based on a huge number of conversations with many persons. The IFC Rail project would like to thank all of them for their contributions and the insights they provided.

1.3 Resources

Some of the issues described in the document are related to developments in the field of track engineering which are not known to the average reader. In this document it is out of scope to cover all these aspects in all relevant details. Therefore, the interested reader finds here pointers to additional helpful resources as a starting point.

- Robert Wojtczak, (Basics of) Railway Curve Kinematics, 2018
- Brustadt/Dalmo, Railway Transition Curves: A Review of the State-of-the-Art and Future Research, 2020
- Björn Kufver, Optimisation of horizontal alignments for railways, 2000
- Constantin Ciobanu, Bloss transition - a short design guide, 2015

- Constantin Ciobanu also runs a well understandable blog with a strong focus on track engineering and track geometry: https://pwayblog.com/

- European norm EN 13803: Railway applications - Track - Track alignment design parameters - Track gauges 1 435 mm and wider; English version EN 13803:2017

2 Rail perspectives on alignment

In the context of the rail domain the English term "alignment" defines three essentially separate but closely interconnected concepts.

1. Definition of a reference system for linear positioning
2. Safeguarding and optimization of the movement of vehicles
3. Geometric construction of railway tracks or other linear infrastructure

2.1 Reference system for linear positioning

An alignment is used to define a reference system to position elements mainly for linear construction works, such as roads, rails, bridges, and others. The relative positioning along the alignment is defined by the linear referencing methodology. For linear infrastructure projects the establishment of first alignment is an important milestone in the design process. Almost all lineside assets are referenced to a base alignment.

2.2 Kinematic perspective

In the kinematic perspective focus is on the safe and optimized movement of a vehicle under the constraints induced by changes in the direction of the horizontal and the vertical layout.

2.3 Geometric perspective

In the geometric perspective the focus is on the proper placement of horizontal and vertical segments to connect certain points along a proposed path. A huge body of knowledge has been developed for this task over a long period of time, in many aspects predating the availability of modern computers and their software.

2.4 State of the art in contemporary engineering

- In contemporary engineering at first a horizontal layout is established in a properly projected plane.
- In a second step the vertical profile (i.e., sequence of segments with constant gradients) is added.
- In the rail domain in most cases a cant layout is added to the horizontal layout to compensate a part of the unwanted lateral acceleration.

- In a final step the proposed layout is checked against a defined set rules, formulas and thresholds to guarantee the conformance with safety requirements stated in the relevant regulation.

The sequence of the steps might change from case to case and might be repeated one or more times to achieve the economic objectives and fulfil regulatory safety requirements. Contemporary alignment design itself implements almost always a 2.5-dimension approach. The final documented geometry might be very precise or just good enough to meet safety thresholds. This depends on factors like priorities of the management, date of the design - existing alignments might have been completedmore then 50 years ago - or software tools used. Working with legacy data in a high precision BIM model requires a good understanding of these factors.

3 Business semantics versus geometry

In the rail domain alignment segments carry different properties which possess a very direct functional dependency from the geometric properties of the segment itself.

Static variables which can be re- measured directly in the track:

- longitudinal slope (ascending, descending)
- curvature and radius (longitudinal section)
- curvature and radius (horizontal section)
- cant (cross slope)
- twisting section (cant change)

dynamic variables, which are a function of the geometry but cannot be re-measured directly in the track:

- vertical acceleration
- unbalanced lateral acceleration
- (cant deficiency / cant excess)
- real vertical shock
- real horizontal shock
- roll angel velocity
- roll angel acceleration
- real roll angel shock

The following diagram in Figure 2 was taken from Bjoern Kuver 2000. It gives a basic insight into the interaction between static variables and dynamic variables for segments.

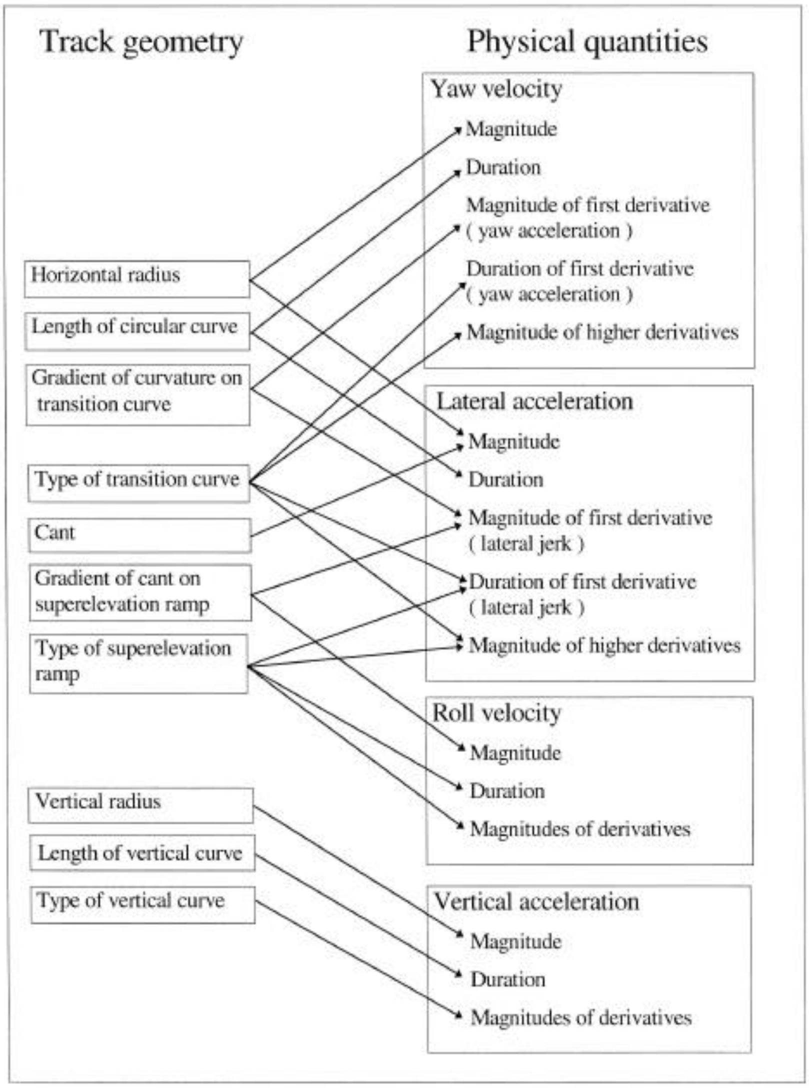

Figure 2 some relations between charateristics in the track geometry and certain physical quantities of vehicle motions

From the perspective of rail domain experts the static variables items define the geometry of the track segments. The dynamic or physical variables are in turn to a large extent part of fully depending on track geometry with variables like design speed or vehicle characteristics being the other part. The together are recorded on a segment level and input for checking of the kinematic safety properties of each individual segments and for a sequence of segments.

From the perspective of IFC geometry principles the dynamic / physical properties above do not define a 3-D representation of a specific segment and therefore **must not** be directly attached to the geometry representation.

To accommodate both groups of requirements and to avoid misunderstandings in communication, alignment inside the IFC vocabulary is now split into two areas (see Figure 3):

- Business semantic
- IFC geometry core

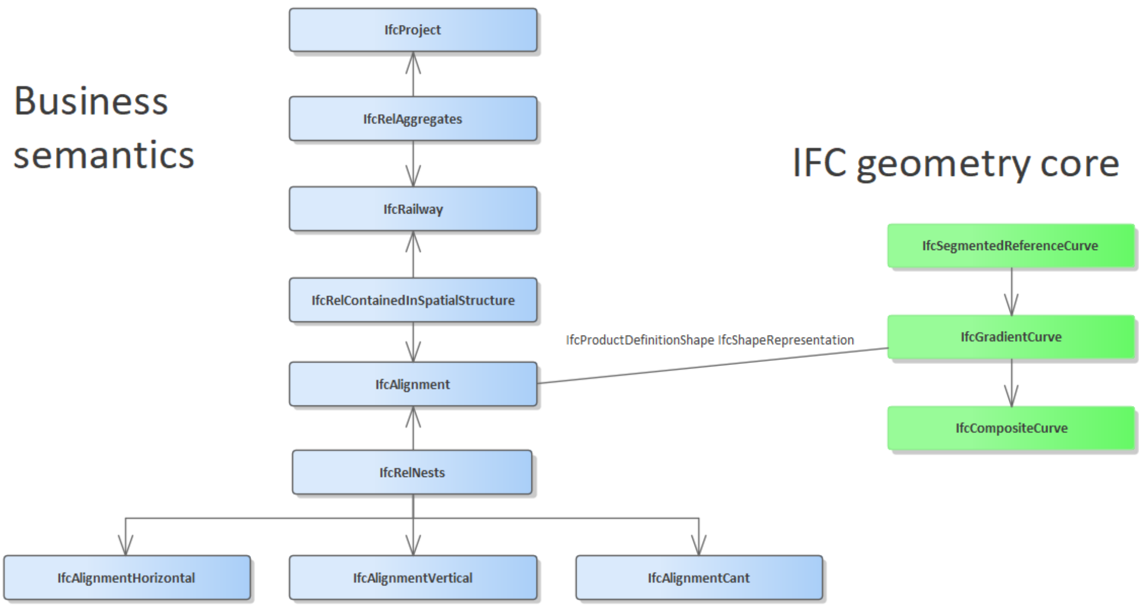

Figure 3 Business semantics – IFC geometry core

It should be noted that the notion of geometry exists in the business semantic area too. The domain specific geometry concepts have been part of the railway business from the very beginning. Many business processes, applications and subsystems in the rail domain use the well-established rail geometry vocabulary. For rail domain experts the introduction of an additional geometry layer might indeed seem to be a strange decision.

But in numerous discussions based on analysis of IFC 4.3 RC1 with contributions from many experts both from the rail domain and established BIM SW-vendors it became evident that a clear separation of concerns is the best way to solve the identified problems.

3.1 Business aspects of alignment in IFC

The business semantic modeling of alignment reflects the separation of the three layouts which are currently produced in rail engineering. The IfcAlignment is assembled by the three entities IfcAlignmentHorizontal, IfcAlignmentVertical, IfcAlignmentCant. Each of these three layouts is assembled by segments. The segments are separated into the generic IfcAlignmentSegment and entities specific to the respective layout. Those are IfcAlignmentHorizontalSegment, IfcAlignmentVerticalSegment and IfcAlignmentCantSegment (see Figure 4).

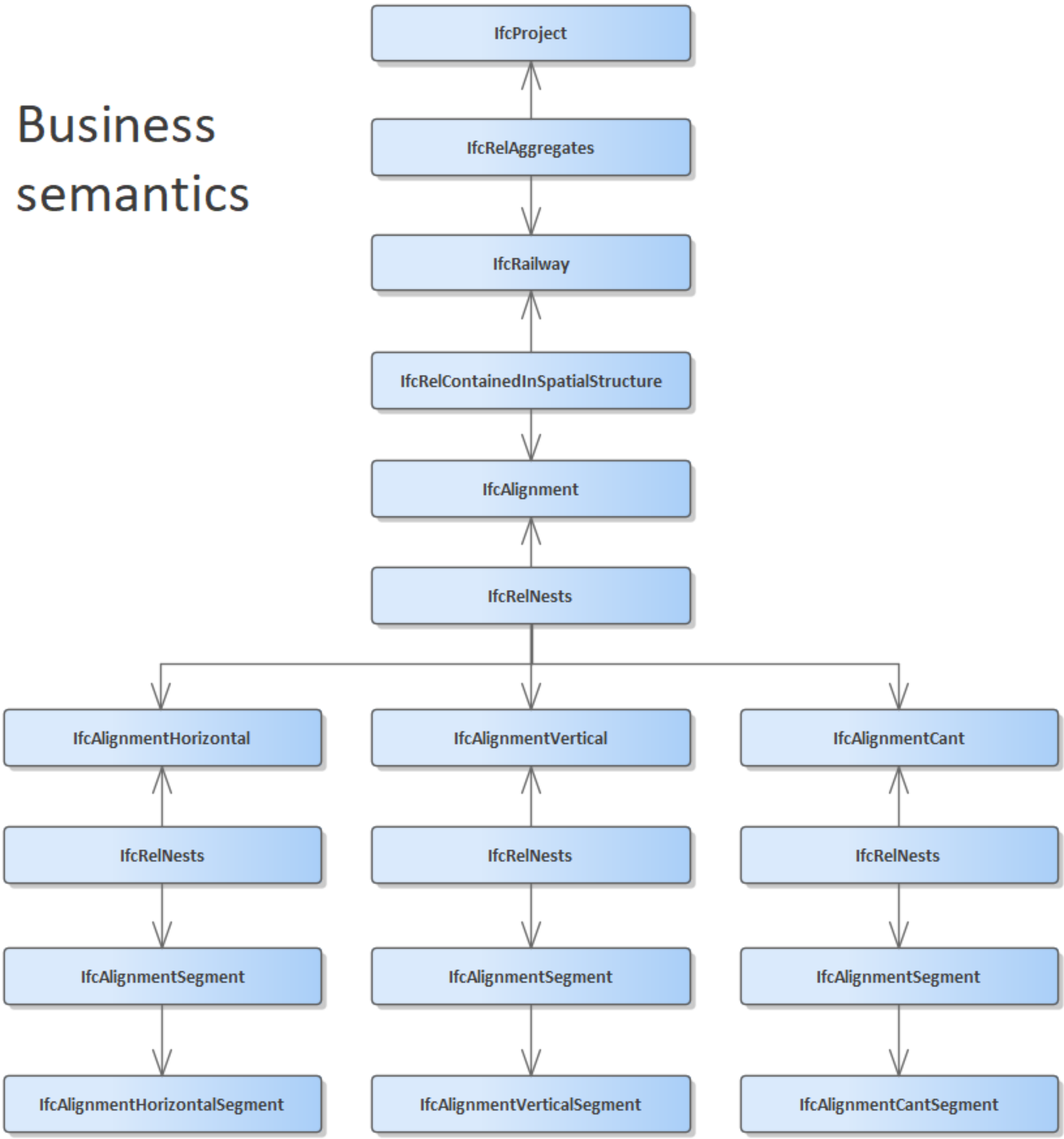

Figure 4 Business semantics details

3.2 IFC – geometry aspects of alignment

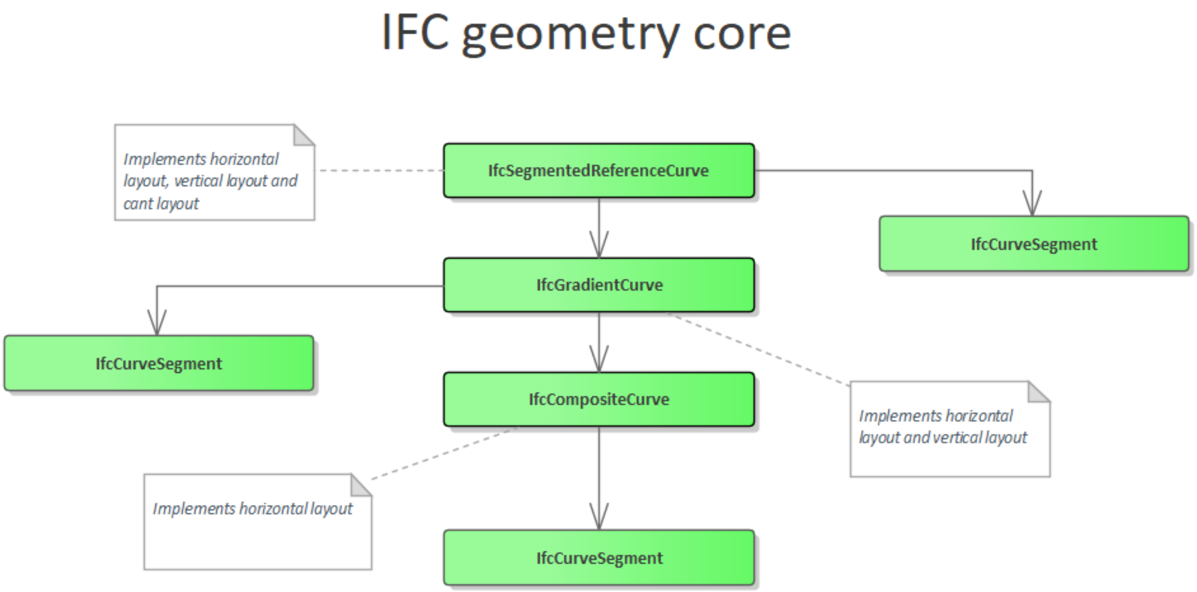

Figure 5 IFC geometry core details

The IFC geometry core modeling for alignment allows very flexible modeling of alignment according to available information in the business semantic layer. The geometry core modeling is based on IfcCurveSegment definitions which are specialized according to the segmenttype defined in the business semantics (as shown in Figure 5 and Figure 6).

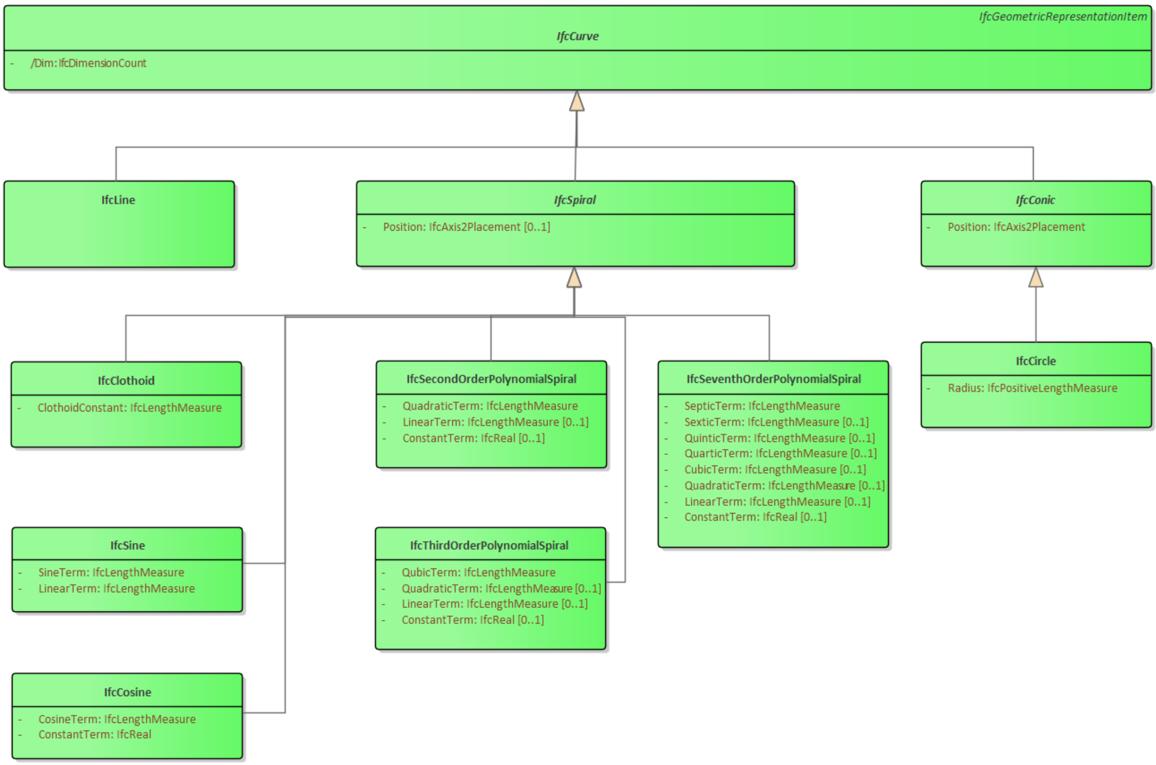

Figure 6 IfcCurve specialisations for alignment

The flexible application of IfcCompositeCurve for horizontal layout, IfcGradientCurve for horizontal and vertical layout and of IfcSegmentedReferenceCurve for horizontal, vertical and cant is visualized in a screenshot provided by RDF. This is an artificial sample alignment with exaggerated, extrem testdata(as shown in Figure 7).

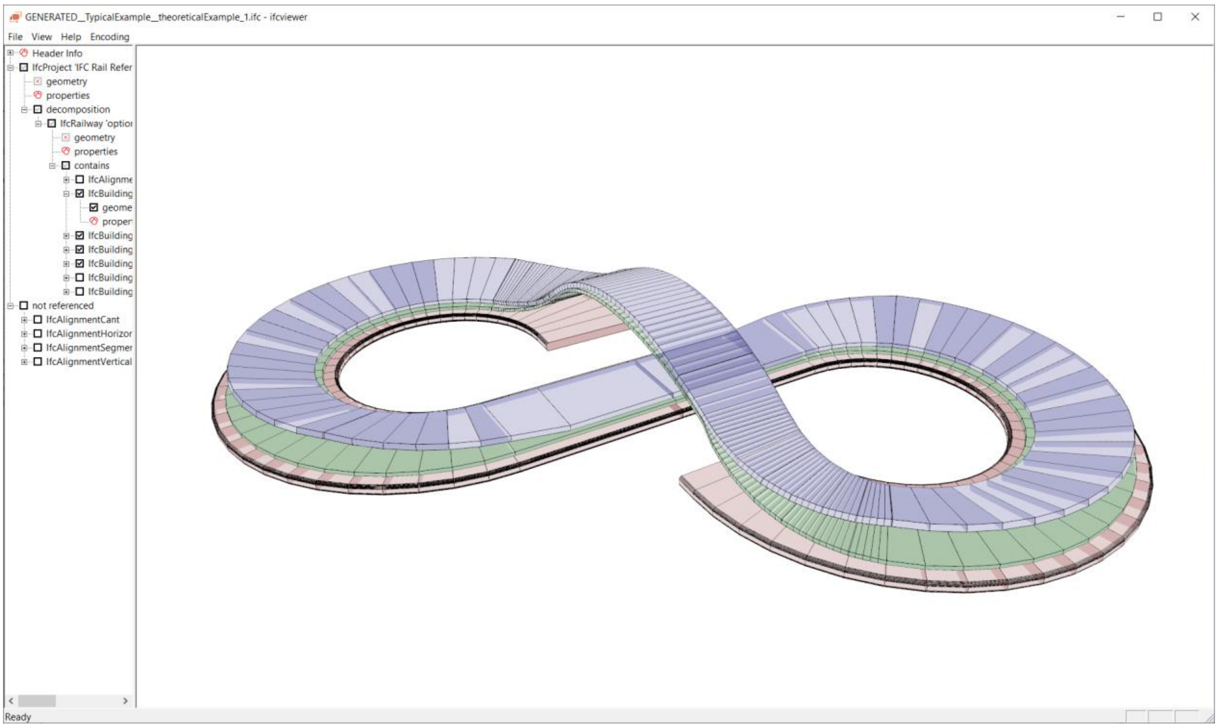

Figure 7 IfcCompositeCurve, IfcGradientCurve and IfcSegmentedReferenceCurve to show implementation of horizontal, vertical and cant layout

The feedback of the participating and contributing Software Vendors was very positive. The final solution for alignment in IFC 4.3 is considered to be a very flexible and clean solution.

4 Cant as a railway specificity

In IFC 4.1 the question of proper modeling of cant was left to a future rail extension.

Inclusion of cant is a major extension coming with IFC 4.3. So it might be good to start with a short introduction.

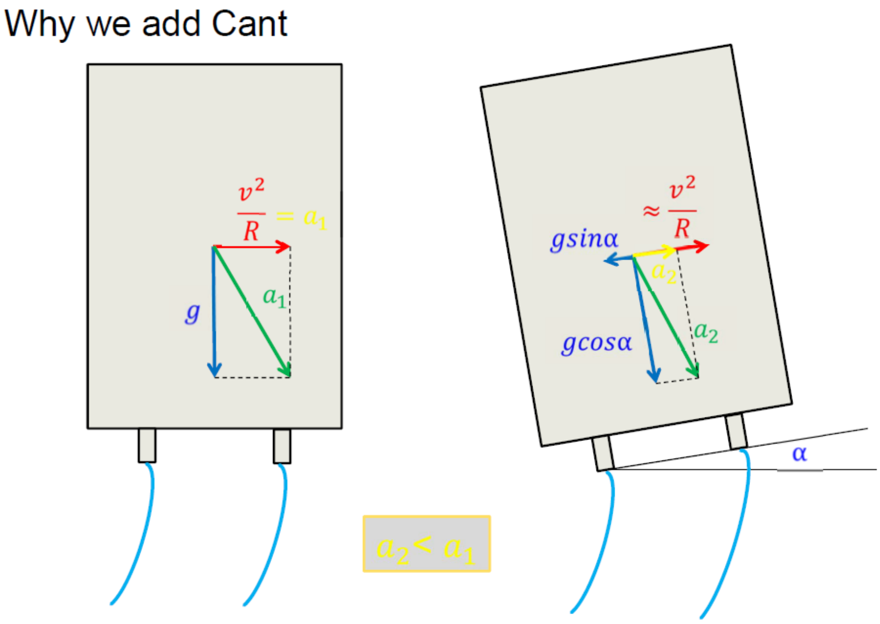

Figure 8 Cant in track geometry design (Wojtczak 2018)

The diagram in Figure 8 shows the principle of compensating part of the lateral acceleration by elevating the outer rail relative to the inner rail of a track.

Almost always the following principles for the placement of horizontal segments and cant segments are implemented:

- Straight horizontal line: no applied cant
- Horizontal circular arc: constant applied cant
- Horizontal transition bend: variation of applied cant according to a defined formula

In specific difficult topographic environments like mountain lines the extension of a cant transition may differ from the horizontal transition. So far this has only been found for clothoids and is either a so called shortened ramp (can transition is shorter than the corresponding horizontal curvature transition) or a so called “scissor” ramp (overlapping variations of cant on both rails with opposite direction). Application of high-performance horizontal transition bends is always combined with a cant transition with identical start and end location.

In real world designs, such as slow speed sections in railway stations, exceptions to the above principles can be found. It might even happen that the inner rail is elevated relative to the outer rail.

Cant modeling in IFC 4.3 accomodates for all of these possibilities (see Figure 9 and Figure 10).

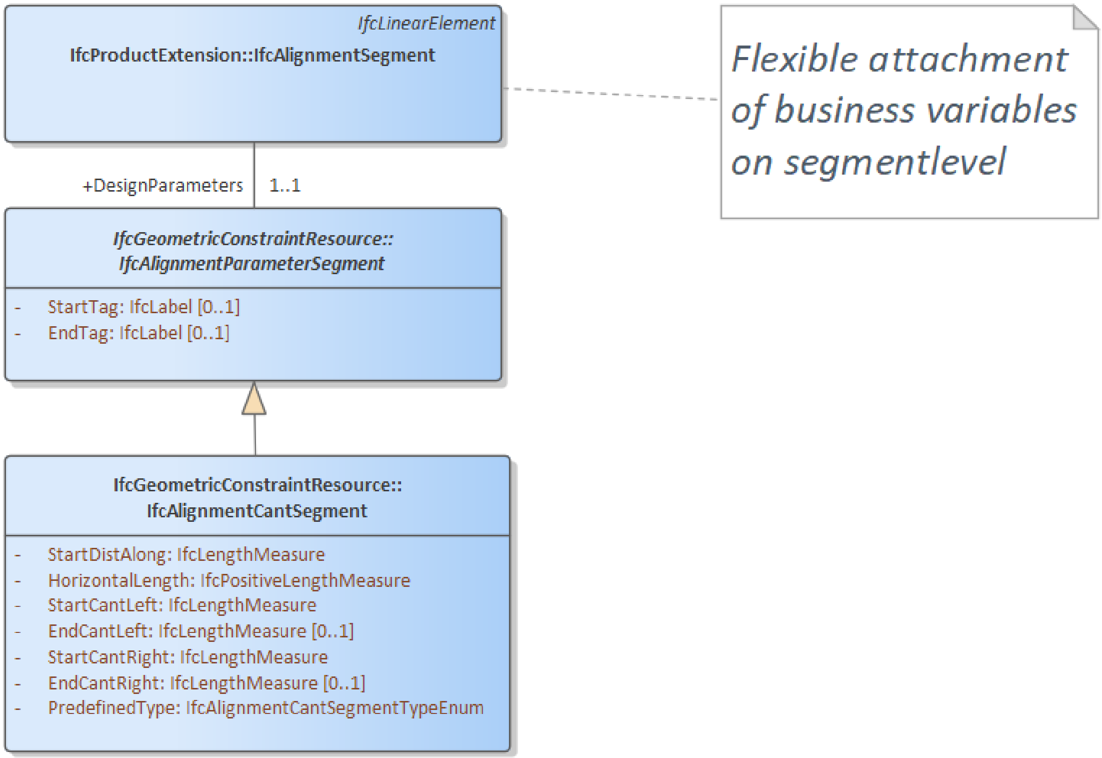

Figure 9 UML CLASS for Cant segment

Detailed geometric modelling of the superelevation has a low priority in the existing processes in most rail companies. This will very probably change with the introduction of 3D modelling in rail design. The following list shows some use cases.

- Correct 3D placement of certain assets (e.g. sleepers)
- Relevant input for calculation of structural gauge space
- Correct calculation of horizontal coordinate values for the Viennese Bend® (high performance transition bend)

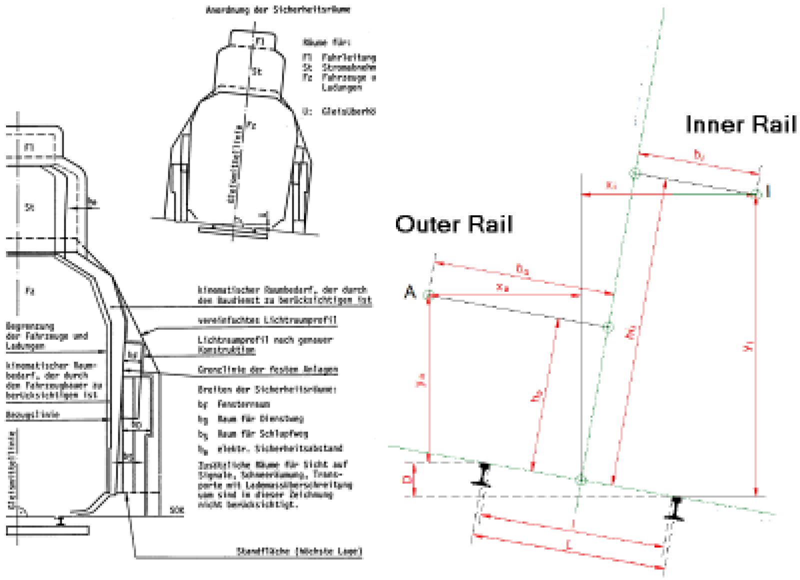

Figure 10 Structural Gauge and Cant

5 High performance transition bends and kinematics

The big majority of existing transitions in track alignments are designed as clothoids. The easy to manage geometric properties of the clothoid-curve made it a natural choice when transition bends were introduced in railway design.

It was especially the increase of design speed over time which made the kinematic limitations of linear curvature variation visible and resulted in curve geometries with improved kinematic properties. The central idea is to guarantee a smooth transition not only in the base parameter but also in the first derivative (curvature gradient) and higher derivatives (see Figure 11).

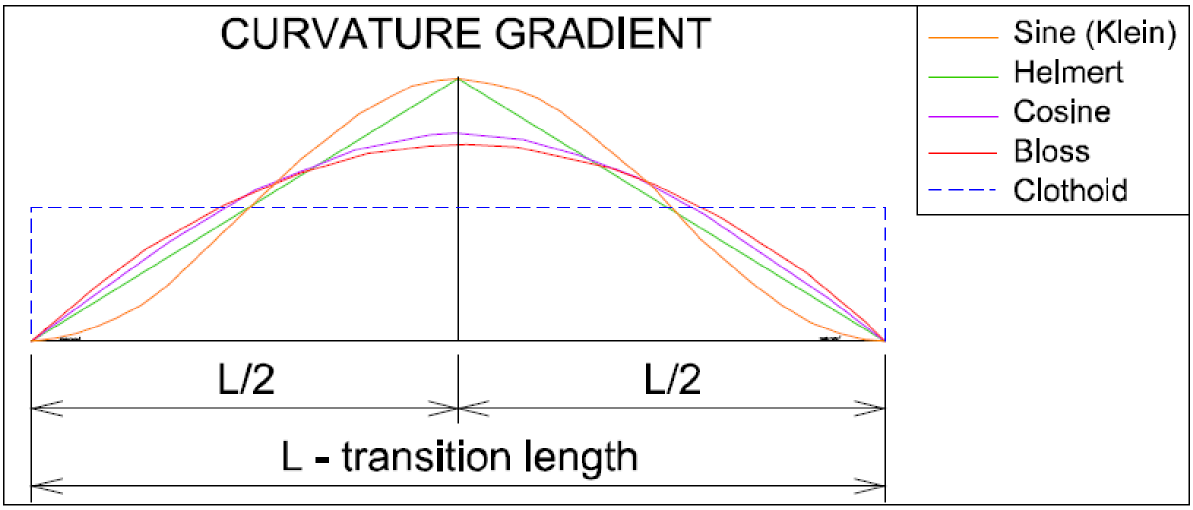

Figure 11 Comparison of curvature gradients for common transition bends. – Ciobanu, 2015

There is still ongoing research, and it is quite possible that new geometries may become relevant in the future. A very recent and comprehensive introduction in these aspects of rail geometry design can be found in Brustad/Dalmo 2020.

Current research has established that the clothoid shows significant disadvantages starting with design speeds higher than 120 km/h.

This was and sometimes still is contested by academics in the field, but there is an increasing number of track design regulations, which require transition segments other than the clothoid in demanding design conditions.

Examples are regulations for the Japanese Shinkansen lines, German lines or the Californian High Speed line. One of the IFC Rail stakeholder put very recently a new highspeed line regulation into effect. Here sine transition bends are used in the horizontal layout. Very notable is also that in this new regulation the traditional vertical circular arc segment transition of the gradient (slope) is supplemented by vertical clothoid elements. This is due to the very high design speeds (up to 500 km/h).

In IFC 4x3 the supported high transition bend types are:

- Helmert (aka Schramm)
- Bloss
- Cosine
- Sine
- Viennese bend ®

Except for the Viennese bend® these transition bend types are mentioned in Annex C of EN 13803/2017.

In French TGV designs there is a methodically different approach using clothoids also in the highspeed part of the network. Both the curvature and the cant variation is smoothened 40 m left and right from the start point and the end point of the base clothoid. This smoothing affects not only the clothoid but also the neighbouring straight line and circular arc segment.

The doucine was discussed as a potential shortcoming of IFC 4.3 RC1 by two participating software vendors in the unit test phase. The affected IC Rail stakeholder confirmed to the project team that there is no current requirement to include the doucine into the IFC standard. Currently the doucine is implemented as a hint to the tamping machines (high precision track construction machines), which implement this geometry automatically. In the first phase of BIM introduction, it is not planned to model details of the doucine. This situation might change in the future and might result in a modification of a future IFC release.

6 Regulations and legacy documentation

IFC Rail project stakeholders provided a rich set of real-world data for unit tests and storylines. During unit tests it became apparent that in some cases the original endpoint coordinates of alignment segments and the parameter values on the business semantic layer did not fit together according to formulas stated by stakeholders and verified in contemporary literature.

In the following analysis it became clear that alignment data obtained from legacy documentation has to be handled with special care. In both cases the endpoint and the start point of two consecutive segments did not meet within a reasonable threshold.

6.1 Case 1

In a long sample alignment of almost 100 horizontal segments 10 transition bends were off by up to 100 millimetres. Originally this was considered not acceptable by the stakeholder. Two independent implementations by a participating software vendor and by IFC Rail technical services came to sufficiently close, almost identical solutions, whereas the provided real world data was off by 100 millimetres. Fortunately, the source code of the current production software was still available. It was established that more than 40 years ago an approximation algorithm was implemented which indeed produced this large gap. At the time this was accepted to be sufficiently safe against the limits defined in the regulation and to be, from a practical engineering point of view, **"good enough".**

6.2 Case 2

In another sample dataset the horizontal alignment contained so called "cubic parabolas". Again, one of the sample transitions segments were off a few centimetres. In this case there was no source code to be checked. Although the network of this stakeholder contains many "cubic parabolas" for none of them a digitally produced dataset could be found. It is assumed that all of the cubic parabolas have been designed before the introduction of computer software. Both the Cartesian x,y coordinates and the kinematic parameters (length, curvature values) had been manually checked against the regulation at the time and passed as sufficiently safe. Again, at the time these specific designs have been considered to be **"good enough".**

6.3 Lessons learned

Legacy documentation might be too imprecise to be included immediately into high precision 3D modelling. In case 1 this was caused by a software implementation decision 40 years ago, in case 2 there was probably "only" manual calculation used and no software involved at all.

The important takeaway for future BIM modelling is that this data is absolutely valid according to current or previously valid regulations. But it cannot be expected that valid legacy data will always produce sufficiently precise and sufficiently consistent coordinates.

6.4 Recommendation

"Good enough" traditional designs have to be carefully checked before being included into a high precision 3D model. Intermediate corrections might be necessary. Fortunately, the clothoid works very well with comparable documentation quality both in the classic geometric perspective and in the more recent kinematic perspective. Fortunately, the huge majority of horizontal transition bends are designed and implemented as clothoids.

Check the relevant regulations for the network in question. Alignment designs as such are very stable over the lifetime of a road or a track. Especially for old designs quality and precision of available documentation has to be checked very carefully. A clear understanding of limitations should be established before implementing automated data flows between high precision BIM environments and legacy documentation systems. This applies both to legacy central databases and to individual legacy documents.

7 Example for conversion from semantics to geometry

With the separation of track geometry business semantics from the IFC geometry core the translation from business semantics into geometry entities becomes a necessity. To support software vendors sample implementations are provided by RDF for transition bends. The implementation for Bloss curve is shown as an example below.

```
    IfcCurveSegment.Transition = CONTSAMEGRADIENTSAMECURVATURE;  // (in case it is the last segment: DISCONTINUOUS)
    IfcCurveSegment.Placement = IfcAxis2Placement2D;
    IfcCurveSegment.ParentCurve = IfcThirdOrderPolynomialSpiral;

    IfcAxis2Placement2D.Location = IfcCartesianPoint;
    IfcAxis2Placement2D.RefDirection = IfcDirection;

    IfcCartesianPoint.Coordinates[0] = IfcAlignmentHorizontalSegment.StartPoint.IfcCartesianPoint.Coordinates(0);
    IfcCartesianPoint.Coordinates[1] = IfcAlignmentHorizontalSegment.StartPoint.IfcCartesianPoint.Coordinates(1);

    IfcDirection.DirectionRatios[0]           =           cos(IfcAlignmentHorizontalSegment.StartDirection           *
planeAngleUnitConversionFactor);
    IfcDirection.DirectionRatios[1]           =           sin(IfcAlignmentHorizontalSegment.StartDirection           *
planeAngleUnitConversionFactor);

    double    a = -2., b = 3., d = 0.;
    if (startRadiusOfCurvature == 0.) {
        a /= endRadiusOfCurvature;
        b /= endRadiusOfCurvature;
        IfcCurveSegment.SegmentStart = 0.;
        IfcCurveSegment.SegmentLength = IfcAlignmentHorizontalSegment.SegmentLength;
    }
    else if (endRadiusOfCurvature == 0.) {
        a /= startRadiusOfCurvature;
        b /= startRadiusOfCurvature;
        IfcCurveSegment.SegmentStart = IfcAlignmentHorizontalSegment.SegmentLength;
        IfcCurveSegment.SegmentLength = -IfcAlignmentHorizontalSegment.SegmentLength;
    }
    else {
        double  factor = (1. / IfcAlignmentHorizontalSegment.endRadiusOfCurvature) -
                         (1. / IfcAlignmentHorizontalSegment.startRadiusOfCurvature);
        a *= factor;
        b *= factor;
        d = 1. / startRadiusOfCurvature;
        IfcCurveSegment.SegmentStart = 0.;
        IfcCurveSegment.SegmentLength = IfcAlignmentHorizontalSegment.SegmentLength;
    }
```

```
//    IfcThirdOrderPolynomialSpiral.Position => can have any value, will be completely ignored
if (a != 0.) {
    IfcThirdOrderPolynomialSpiral.CubicTerm =
        IfcCurveSegment.segmentLength * std::pow(std::abs(a), -1. / 3.) * a / std::abs(a);
}
else {
    IfcThirdOrderPolynomialSpiral.CubicTerm = 0.;
}

IfcThirdOrderPolynomialSpiral.QuadraticTerm =
    b ? IfcCurveSegment.segmentLength * std::pow(std::abs(b), -1. / 2.) * b / std::abs(b) : 0.;
IfcThirdOrderPolynomialSpiral.LinearTerm = 0.;        //    (or can be left empty)
IfcThirdOrderPolynomialSpiral.ConstantTerm = d;
```

This example was provided by rdf.bg

8 Conclusion

In the IFC Rail project, rail domain experts and participating Software Vendors tested the alignment modelling in IFC 4.3 in a very complete and detailed procedure based on unit test execution and storyline execution.

IFC 4.3 contains a substantially extended and a substantially reworked alignment model.

All parties agree that the general architecture of the new schema is capable of fulfilling the business requirements and also fits good into existing IFC enabled software solutions.

During unit test execution a few issues, like the doucine, have been discovered which will not be addressed in IFC 4.3, but observed in the future as soon as operational experience is available.

A major challenge in the future implementation of BIM methodology will be the integration of legacy data which has been considered "good enough" in the past but are too imprecise for state-of-the-art BIM models. Here Software Vendors and Service Providers need to be aware of the problem and implement acceptable solutions together with the client companies. It can be expected that very often the acceptable solution will be an organizational procedure.