Model-based quality assurance in railway infrastructure planning

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Abstract

A primary motive for adopting the methodology Building Information Modeling (BIM) in planning processes is to improve planning accuracy, cost security, and in turn quality. Up to now, however, a generally applicable, standardized means of validating design quality has been lacking. To address this shortcoming, this article presents 14 quality parameters in the domains of clash detection, semantics as well as quantities and costs, that apply to the field of infrastructure planning. The sets of rules outlined in the article are adaptable and extendable in order to respond flexibly to different model structures.

The investigation focuses on how important and recurring tests can be carried out automatically and how to make the results analyzable in a transparent and standardized manner. The proposed concept thoroughly extends well-known methods such as attribute testing and clash detection analysis of the 3D model. Doing so, the paper presents a set of novel methods for quality assurance, including 4D clash detection and checks for semantic-geometric coherence. The paper discusses in detail: the influence of modeling errors on clash detection, the difference of 3D and 4D clashes, formal methods for checking the correct linkage between 3D BIM and the bill of quantities, formal approaches for checking the semantic-geometric coherence of BIM objects.

The quality assurance concept presented in the article concludes with a standardized evaluation for the individual quality criteria using a school grading system, traffic light, and percentage scale. Finally, the concept is applied in a comprehensive case study on a large-scale infrastructure project and the results of the formal quality assessment are presented.

Keywords: BIM, Infrastructure, Quality, Consistency, Railway, Design, Clash Detection, nD Modeling Quality Assurance

1 Introduction

The construction industry promotes and develops modern and efficient technologies in an effort to respond to the increasing complexity of construction projects. Of these, the digitalization of the construction process using Building Information Modeling is one of the most well-known. The Reform Commission for Major Projects (Reformkommission Großprojekte) set up by the German Federal Ministry of Transport and Digital Infrastructure (Bundesministerium für Verkehr und digitale Infrastruktur) recommends that building owners should "*make greater use of digital methods such as Building Information Modeling (BIM) in all phases of the project process*" [1]. With the introduction of a staged implementation plan for digitally-mediated planning and construction (the "Stufenplan Digitales Planen und Bauen") the German Federal Ministry of Transport and Digital Infrastructure has committed itself to the digitalization of projects within its area of responsibility in three successive steps:

- Set-up phase (2015 – 2017)
- Extended pilot phase (2017 – 2020)
- Broad implementation for all new projects (starting in 2020)

According to [2], "*Design and coordination with 2D CAD systems is error-prone, labor intensive and relies on long cycle – times. BIM addresses these problems [...]. The benefits of BIM for subcontractors and fabricators include: ....] reduced cycle-times for detailed design and production; elimination of almost all design coordination errors; lower engineering and detailing costs [...].*" Bryde et al. [3] compares 35 projects and identifies various criteria that aim to demonstrate the influence of BIM on the course of the project. The study revealed that the use of BIM was of particular benefit for the criteria of project costs and positively influenced the criteria of time, communication, coordination, and quality. The influence of the BIM methodology on project costs and project duration is the focus of various studies [4–6]. Each compare different projects with one another and find that in all the examined projects, the BIM methodology has a positive influence on project costs and project duration. As they employ different methods, the results are not directly comparable. Berg [7] considers five Norwegian projects and identifies the reasons why the actual construction deviated from the original plans, and how this impacted on construction costs. The results showed that the rate of contract deviations due to incorrect or insufficient basic information ranged from 2 to 26% depending on the project. In 23 to 48% of the cases evaluated, planning errors were identified as the reason for contract deviations during construction. The projects that employed model-based planning tended to cause fewer necessary deviations from the contract: the impact of subsequent amendments on the construction costs lay between 4 and 10% of the original cost estimate for model-based planning compared with approx. 19% for conventional planning. While these values are of limited general validity due to the small number of projects compared, they do provide a good indication of the benefits of BIM for construction projects – a finding that is also borne out by other publications in the field.

One of the most important clients driving adoption of the BIM methodology for infrastructure projects in the German construction sector is currently Deutsche Bahn AG. "*No other client in Germany invests as much in infrastructure projects and their operation than Deutsche Bahn AG*" [8]. German railways has defined a comprehensive BIM implementation strategy covering both, stations as well as infrastructure network. In this context, a set of 13 pilot projects have been conducted and scientifically analyzed. In 2022, all construction projects of German Railways are supposed to be executed as BIM projects. This involves the implementation of the procedures defined in ISO 19650 [9].

2 Current best practice in quality assurance

ISO 19650 demands the implementation of quality checks when project data is transitioning from one status to the other, i.e. from Work in progress to Shared or from Shared to Published. As part of the current best practice of BIM project execution, basic model quality checking is implemented already today, mainly in the context of model coordination and data handover to the client. However, the tests applied are limited to basic clash detection and simple checks for the provision of the attributes demanded by the client. Executing only these basic checks does not exploit the full potential of automated quality assurance that becomes available when using comprehensive geometric-semantic models of infrastructure assets. For example, there is currently no best practice for implementing high-level consistency checks of 4D (geometry + time) and 5D (geometry + time + costs) models. The lack of quality checking can result in severe errors with significant impact on project costs and project duration. This paper addresses this issue by providing an in-depth analysis of quality analysis in railway BIM projects. It presents comprehensive methods with which 3D, 4D, and 5D models can be systematically examined for possible errors.

The quality assurance mechanisms currently used for BIM infrastructure projects are generally limited to attribute checks and clash-detection. During clash detection, the model is often checked against itself, which can lead to the detection of numerous but insignificant clashes that are not the product of planning errors but can be attributed to inaccuracies in the respective software for infrastructure planning on the German market, which sometimes fail to automatically output entirely clash-free objects.

The fact that the BIM model created is not computer-tested completely represents a break in the digital chain of infrastructure planning. Errors in 3D models inevitably lead to errors in scheduling (construction sequence) and in the calculation of quantities and costs. The overall objective of "*increasing planning accuracy and cost reliability*", as outlined in the staged implementation plan, implies a need to improve the quality of planning processes. "*High quality results and efficient workflow in the construction phase can only be achieved if the data basis is accurate*" [10]. To achieve this, a quality assurance system tailored to model-based working processes is necessary.
Various software products are already available on the market to carry out corresponding quality checks. Examples are Navisworks Manage, Solibri Model Checker and Desite MD Pro [11–13].

3 Current state of research

"*Project performance control can be defined as the identification of deviations between the desired and the actual performance of a project.*" [14] or model. Navon states that "*a comparison between the desired and the actual performances is the beginning of the control procedure*". The fact that an efficient, information-rich model-based working method requires standardized input data is, however, hard to reconcile with the often intuitive and rather unstructured planning process in early planning phases [15]. To exploit the potential of model-based working methods, it is therefore necessary to develop automated, standardized procedures for quality control.

Various approaches to digitally evaluating the quality of planning and models have been discussed in current research. Solihin and Eastman classify the possible quality criteria as follows [16]:

- *Checks for well-formedness of a building model, i.e. the syntactic properties of the digital model*
- *Building regulatory code checking*
- *Specific client requirements*
- *Constructability and other contractor requirements*
- *Safety and other rules with possible programmed corrective actions*
- *Warrantee approvals*
- *BIM data completeness for handover to the facilities management*

"The building industry uses numerous engineering standards, building codes, specifications, and regulations (henceforth, all are referred to as "regulations" for the purposes of brevity), and a diverse set of industry vocabularies to describe, assess, and deliver constructed facilities. These building regulations are available as hardcopy and searchable digital documents. Some building design software applications (e.g., building-energy analysis and fire-egress assessment) are available that include computer-interpretable representations of the logic and rules from relevant building regulations" [17]. A significant amount of research work has focused on verification of the 3D model with regard to compliance with standards and guidelines. Methods such as 'Automated Code Checking' or 'Code Compliance Checking' "*allow speedier, dematerialized and more transparent review processes*" [18]. An overview of work conducted in this area is outlined in [19,20]. Charles gives an overview of research dealing with code compliance checking and presents an approach on how to check for rule conformity using RDF [21]. The research presented by Getuli et al. uses code compliance checking in the context of health and safety on the construction site [22]. Preidel et al. [23] use a visual programming language to check for code compliance.

An important method for checking the constructability of objects is clash detection. "*The goal of collision detection (also known as interference detection or contact determination) is to automatically report a geometric contact when it is about to occur or has actually occurred*" [24]. "*Collision detection between rigid, and/or soft bodies is important for many fields of computer science, e.g. for physically-based simulations, medical applications [...]*" [25] and also for civil engineering. Schauer and Nüchter illustrate different clash detection procedures by means of two point clouds using the example of a railway wagon in a section of a tunnel [26]. Staub-French [27] describes the added value of 3D and 4D modeling and possible clash detection, but also points out that clashes cannot yet be detected automatically over the course of the construction project on site. Mawlana et al. [28] developed a method in conjunction with the planning of large motorway junctions with several flyovers for generating optimal construction sequences and avoiding clashes over the course of time.

The research conducted by Leite [29] and Zhang et al. [30] examines the model-based verification of safety risks on construction sites.

By integrating a so-called “POP quality model” and a 4D model, Chen and Huo [31] demonstrated that the processes and quality parameters of a construction site can be represented in an integrated model-based system. Alongside scheduling deadlines, the quality parameters also included the manufacturing tolerances of the respective structures.

The literature review shows that various approaches and systems for checking BIM models have been addressed in research, although in most cases they focus on individual aspects of building models. While they provide a basis from which to derive individual quality criteria, “*Quality criteria are difficult to use […], if they become too abstract. A typical approach to rectify this issue is to disaggregate the complex criteria into a series of more understandable criteria of lower conceptual difficulty. A problem arises when a compact list of abstract or dense criteria is replaced by a long list of simpler ones, which in many cases can make them impractical and time-consuming*“ [32]. Johansson et al. [33] recommend using model qualities with the help of the scoring system detailed in [32]. Here too, however, the research only pertains to the checking and evaluation of the CAD model structure.

In summary, a review of research shows that scant research work has been undertaken on model-based quality assurance in infrastructure planning. For the most part, current research activities have focused on individual rule classes and are not integrated into an overall quality assurance concept.

4 Quality assurance concept

While quality assurance mechanisms in the field of infrastructure planning are currently only applied on a random basis and several quality criteria are needed, which can be impractical and time-consuming compared to Company et al. [32], the model-based quality assurance concept proposed here is designed to be efficiently applicable and to use recurring rule types. Solihin and Eastman [16] categorize the rule types as follows:

(1) Rules that require a single or small number of explicit data
(2) Rules that require simple derived attribute values
(3) Rules that require extended data structure
(4) Rules that require a “proof of solution”

In this paper, rule types 1 and 2 are considered in more detail.

The individual work steps involved in model-based infrastructure planning are shown schematically in **Figure 1**.

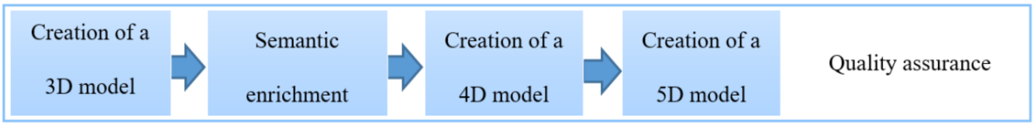


Figure 1: Procedure of model creation from 3D to 5D

The concept assumes that errors can occur in each of these steps. As such, it is necessary to have appropriate test routines in place in order to detect any errors that occur as part of quality assurance. Quality assurance checking can take place during the individual planning phases.

Eastman et al. [19] divide the inspection process into four phases, which have been adopted analogously in the present concept.

(1) Rule interpretation and its logical representation
(2) Building model preparation
(3) Rule execution
(4) Rule check reporting

Garrett et al. [17] define three steps for developing computable representation of regulations which are taken into account while creating the presented quality assurance concept. These principles are:

(1) Developing a simple understandable representation syntax for building-regulation writers and software developers
(2) Providing computerized support to enable regulation organizations to easily develop, test, and maintain these regulation representations
(3) Testing the sufficiency and implementability of the digital representations

"One of the key criteria […] is to be independent of any specific model-checker software used to check regulation compliance of building information models" [17]. Following these principles an independent model checker serves as the basis for model-based quality assurance. A database is linked to the program system, which contains both the test rules and the test results. The system design is shown in **Figure 2**.

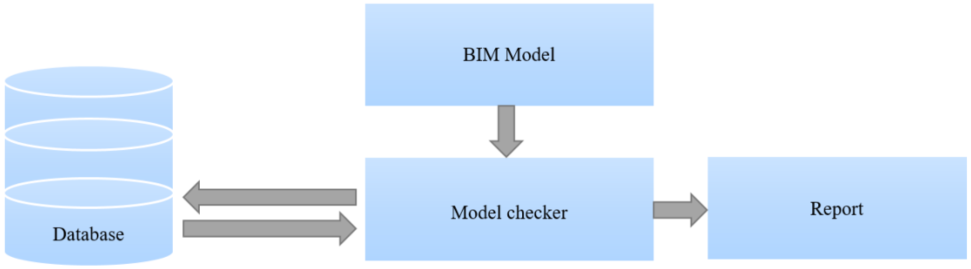


Figure 2: Software configuration, an independent model checker is linked to a database which includes both checking rules and checking results.

As part of literature research as shown in chapter 2 and 3, five domains have been identified for which various quality review mechanisms are assigned (see **Figure 3**). These are:

(1) Construction
(2) Clashes
(3) Semantics
(4) Construction sequence
(5) Quantities and costs

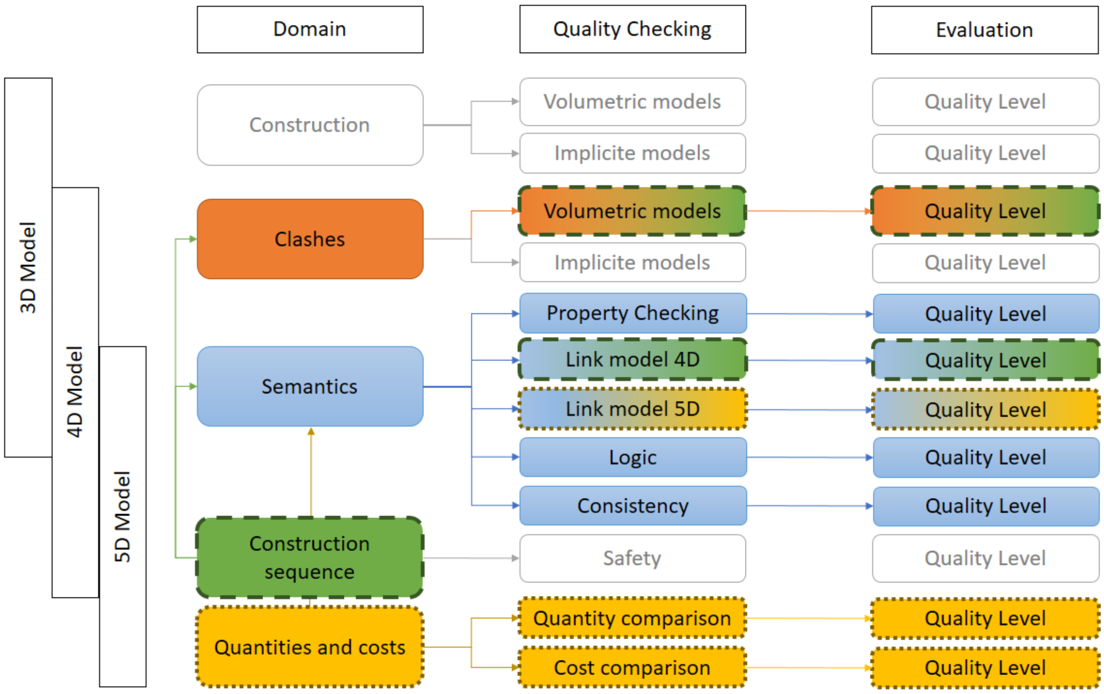


Figure 3: Quality assurance concept, the concept focuses on five domains. Each has their specifics aspects and needs for quality checks. To evaluate model quality, it is necessary to establish a generally applicable evaluation scheme.

Solihin et al. [34] is dealing with quality criteria of IFC exchanges and concludes that there is "*an urgent need to define robust and rigorous test criteria, processes and tools.*" This conclusion is not only valid for IFC exchanges but also for the quality for modeled infrastructure designs.

A 3D model must be considered in terms of its basic components of geometry and semantics. The geometry in turn comprises that of the construction itself and the resulting clashes when several objects are superimposed.

Most of the software products used for infrastructure planning offer a drawing-oriented view – split into site plan, cross-section and elevation – although these are stored internally as a three-dimensional model in the program. This type of model is referred to as implicit geometry description, since the parameters for creating the objects are saved, not the volume objects and their coordinates. The volumetric models are then generated from these parameters. As such, one should distinguish between volumetric 3D models that are the result of planning and the implicit models (2.5D models) used at the time of planning (see **Figure 4**). With implicit models, the governing design parameters become significantly more accessible than with explicit models. An example is the objects and parameters defining alignment. Accordingly, checking these parameters against codes and guidelines is more easily realizable with implicit models.

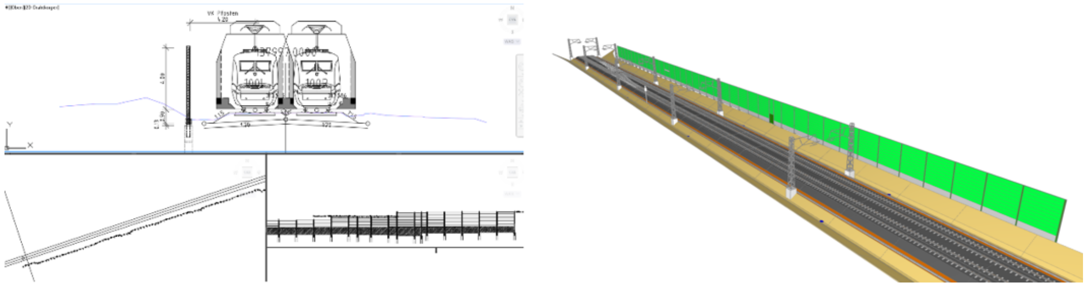


Figure 4: Comparison of implicit and volumetric 3D models, while implicit models (drawing-oriented view) are used at the time of planning, explicit models are used in the context of BIM-analysis

The quality of the 4D model, which comprises the 3D model, semantics and a schedule, is influenced by the “collisions” and “semantics” domains as well as by “construction process”. While the quality of the 5D model is largely informed by the domains “semantics” and “quantities and costs”.

The “construction” domain as well as the examination of a 4D model for “safety” will be dealt with in a subsequent step of the research project and will not be elaborated on in this paper. In the “semantics”, “construction sequence” and “quantities and costs” domains only volumetric models are considered.

To evaluate the model quality, it is necessary to establish a generally applicable evaluation scheme. This is referred to as Quality level.

The following sections explain the checking methods for the individual domains in more detail. In all the test methods, the aim is to minimize the work involved in preparing, carrying out and evaluating the results in order to achieve a time- and resource-efficient working method.

4.1 Model and database structure

Knowing the models’ structure is crucial for checking them. The concept presented here assumes that the model structure corresponds to a representation of built structures established in practice. In this example, it takes the form of the hierarchy shown for the “rail transport system” trade in **Figure 5** and is described in detail by [35,36]. The trade is divided into different groups, each of which consist of different objects. Each object can be identified by specification features. For example, there are various rail shapes (e.g. S49, S54, UIC 60) which have an effect on the geometry of the object. This component logic is represented relationally in the database used.

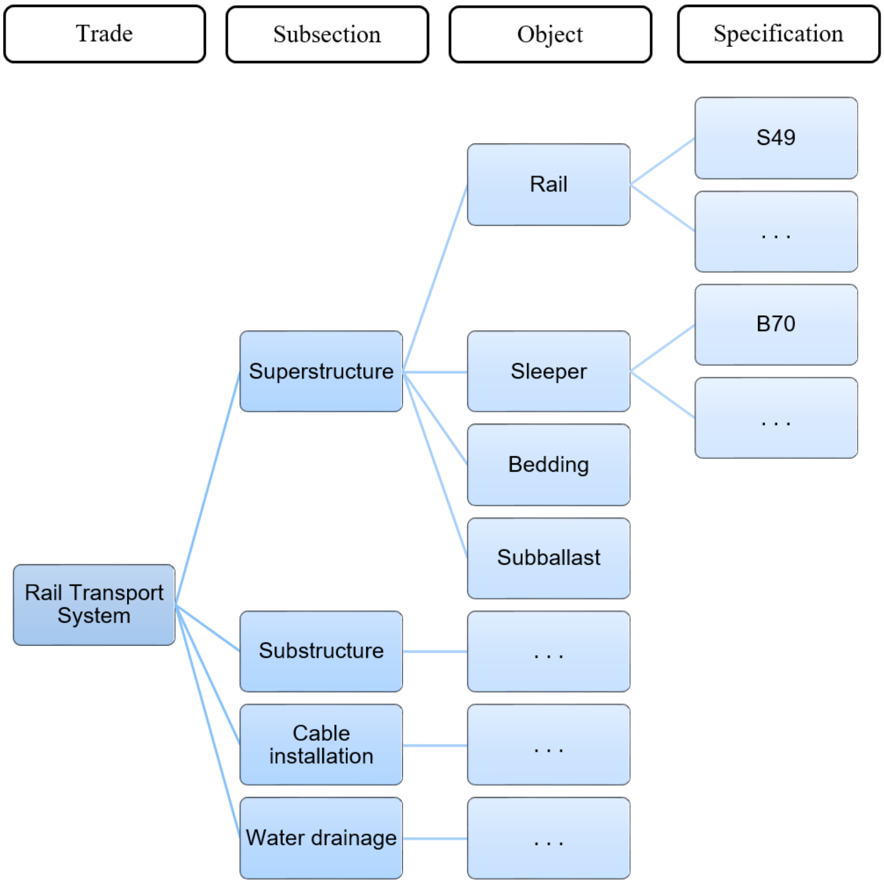


Figure 5: Building structure – the example of a rail transport system

4.2 Domain clashes

Clashes can occur in particular when merging different specialist models and thus plans from different specialist planners. There are several software products available, which offer good support for the automatic detection of such clashes. The BIM Center distinguishes between the following types of clashes [37], which are also considered in our concept.

- Hard Clash (HC) ≙ two or more objects overlap each other
- Soft Clash (SC) ≙ two or more objects come too close to each other, i.e. do not adhere to minimum distances between them
- 4D-Clash ≙ Clash during construction time

The software products for infrastructure planning currently available on the market have only limited ability to correlate different geometries with one another, producing clashes that do not exist in reality. These program-related clash detection errors are flagged up by the model checker but do not actually correspond to planning errors. The following irrelevant clashes (IC) are known examples of modeling errors:

- sleeper and ballast
- subgrade and manhole
- subgrade and mast of catenary or signal post

4.2.1 3D clash detection

Irrelevant clashes – produced by software and not by users – are often hard to avoid. But systematic clash detection errors can be avoided by explicitly specifying the objects that need to be checked for clashes. However, this entails both more preparatory work before undertaking the check and also introduces the risk of forgetting to include all the necessary checks. This approach is also not terribly efficient, since the process has to be repeated for each model.

The more common method of testing the model completely against itself for collisions is fairly quick, as no significant preparation is necessary, but requires a means of reducing the effort of evaluating the large number of clashes resulting from program-related modeling errors to a minimum. This can be partially automated with the help of a clash matrix that indicates the significance of collisions (see **Table 1**).

Table 1: Example of a clash matrix, HC – Hard Clash, IC – Irrelevant Clash

Object	Rail	Sleeper	Bedding
Rail	HC	HC	HC
Sleeper	HC	HC	IC
Bedding	HC	IC	

The clash matrix comes into play once clash detection has been undertaken using the model checker. Objects that clash are then checked against the matrix for permissible clashes and classified where appropriate as irrelevant. This therefore reduces the evaluation work necessary in the post-processing. An example is shown in Section 4.2.3.

The fact that the clash matrix can be updated and used across models also means this method is more efficient and sustainable. If necessary, it is also possible to define irrelevant clashes at group or specification level or across levels. The evaluation result is written to the results database, and the results can also be imported back into the model checker's clash detection.

4.2.2 4D clash detection

With 3D clash detection, a model can only be checked at a fixed point in time. However, it is also relevant to consider the construction sequence in clash detection. This is particularly important for objects that do not exist at the beginning or at the end of the project phase, for example temporary constructions such as supporting scaffolds or shoring systems. In the literature, there is little evidence of approaches to this aspect.

For this, it is necessary to identify the status of individual objects of the 3D model over the course of the construction process. The following categories are relevant here (see **Table 2**):

Table 2: Categories during construction process

Category	**Description**
Existing	Objects that already exist at the beginning of the process
Deconstruction	Existing objects that will be dismantled and removed over time
New Construction	Objects that will be constructed over time
Temporary Construction	Objects that are erected at a time x and dismantled at a time y

To detect potential clashes, the various processes of the schedule are mapped as static clash detection instances. For each of the above categories, the relevant test sets of the project (the so-called “left” and “right” test sets) must be determined. An example illustrating the principle is shown in Section 4.2.3.

Logic dictates that at the start of construction (t=0), all existing objects are available. These are assigned to the left test set. Time t=1 marks the point after which the first work measures take place: for example some existing objects may have been deconstructed and removed or alternatively some new objects have been erected. If existing objects are deconstructed and removed, they should be removed from the left test set, since they cannot cause a clash. If new objects are created, they should be added to the right test set. Clash detection analysis can then be performed after both test sets have been created. For the next clash detection analysis at time t=2 after the next work measures, the objects from the right test set (newly created) are assigned to the left test set and the right test set is changed according to the work done, and so on.

As the objects that exist temporarily during the construction period can only be sensibly assigned to one category, they should be represented as “new during construction” and “removed during construction” and the point at which the change takes place recorded in the schedule. The assumption is that time objects in the schedule also contain details about the changes made to an object, so that these can be evaluated during clash detection. Where objects belong to “new during construction” at a defined point in the schedule, they are assigned to the right test set while those belonging to “removed during construction” removed from the left test set.

The clash detection analysis, its evaluation and the recording of the results in the database is carried out as described in Section 4.2.1.

Since with this method, the dynamic process of the construction site is reduced to individual points in time, the situation can arise where two processes take place simultaneously but are checked one after the other. This can lead to problems, in particular when an object that is deconstructed and removed in one of the two processes clashes with the objects from the second process. In certain circumstances, these clashes may not be recognized correctly. In such cases, the granularity of the 3D objects, processes and schedule times has a key impact on the result.

4.2.3 Case examples – Clash detection

The 3D models shown in the case studies were created with ProVI [38], and the 4D and 5D models as well as the test mechanisms were realized with Desite MD Pro [13].

The case of 3D clashes is demonstrated on the example of sleepers that have been bedded in ballast for better track stability (see **Figure 6**).

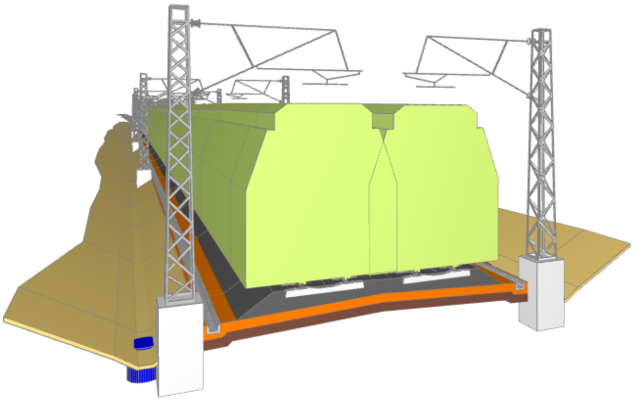


Figure 6: Irrelevant clash of sleeper and bedding caused by superimposition, clash due to missing recess in bedding

The planning software used generates the volume object for the bedding independently of the sleepers. As a result, clash detection analysis flags clashes at every point where the bedding and sleeper objects overlap. These are merely irrelevant clash detection errors and not actual project clashes. If one assumes a normed sleeper spacing of 0.6 m, this results in at least 1,667 clashes per kilometer of track that will require manual evaluation.

Figure 7 shows an example of how a hard clash and 4D clash can differ for a situation in which a road bridge is to be built over a railway line at a point where a mast for overhead lines stands. A time-independent clash detection analysis of the 3D model flags a clash. However, once the temporal development of the construction schedule is considered, a clash situation (4D clash) will only occur if the mast still stands at that position at the moment in time when the road bridge is built.

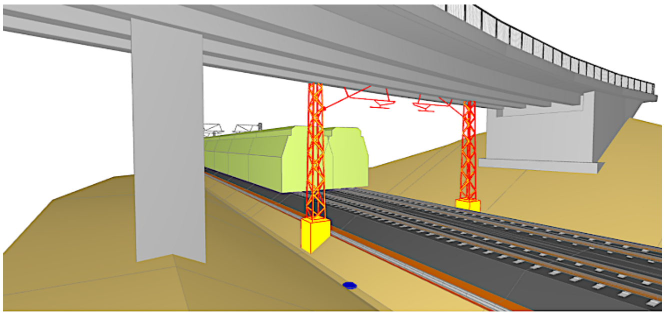


Figure 7: An existing mast structure and a new road bridge: a hard clash or a 4D clash?

4.3 Domain semantics

The following checks outline means of verifying the coherence and correctness of the semantic model. Various test routines are required which examine the semantics from different perspectives.

4.3.1 Attribute testing as per project specifications

The definition of attributes that a model may contain is a vital part of working successfully with models. They can range from relevant project information to the geometric properties of the objects, the materials used or operation-relevant data. Alongside the collision-free 3D and 4D models, these coordinated results represent a further quality parameter. In the field of building construction, standardized specifications already exist in the form of OmniClass [39], UniClass [40] or the buildingSMART Data Dictionary [41]. Corresponding software extensions for modeling software make it relatively easy to employ this data. Böger et al. [42] demonstrate how the buildingSMART Data Dictionary can be accessed right from the model creation phase with the help of a specially developed plug-in for the modeling software Autodesk Revit [43]. Although this method is not in itself a quality checking system, it contributes to limiting possible sources of error already at the model creation stage. The existing classification instruments are, however, at present of little applicability for infrastructure planning. In Germany, several industry representatives have meanwhile joined forces to develop a similar standard within the framework of buildingSMART for the infrastructure construction sector in Germany. Up to now, each contractor in the Deutsche Bahn AG's pilot projects has drawn up its own definition. And, as mentioned earlier, the verification of the models is rarely automated.

Although the various quality assurance tools offer corresponding test routines, they are not easily integrated into the concept described here. For this reason, an independent algorithm was developed that checks the attribute definition in the 3D model. The use of an open data schema such as mvdXML is also conceivable but has not been implemented here.

All objects are checked against the specifications according to the project specifications. During the check, the following status messages are returned with details of the object and attribute:

0 The object exists with the required attribute (value)
1 The 3D object found is not present in the project specifications
2 The required attribute is not defined in the 3D object
3 The attribute value of the 3D object does not correspond to the specified value range

In order to check value lists, a corresponding check rule must be formulated for each object. The functionality is explained in Section 4.3.2.

4.3.2 Checking link models

Technical project management encompasses construction design, scheduling, and cost planning. In conventional project management, these aspects are stored in independent documents (e.g. 2D plan and schedule) and require manual, cognitive input by the project manager to link them. The model-based working method presents a major advantage in that this information is linked digitally and logically through the 3D model via properties to the corresponding information in the time schedule (4D) and the quantity and cost calculation (5D). The linking of different information sources or specialist models is also referred to as a multi-model. "*The basic idea of the multi-model is to combine selected specialist* *models from planning and project management in a single information resource and to map their dependencies through additional explicit link models*" [44]. Studies at Stanford University "*have shown that more project stakeholders can understand a construction schedule more quickly and completely with 4D visualizations than with the traditional construction management tools*" [45]. The uses and benefits of 4D and 5D models are discussed by Fischer et al. [45,46].

The method of linking different sources of information is also called nD modeling and "*is not limited to the domains represented in the building model. It concerns instead a concept for the integrated use of technical and building data. The aim is to create a multidimensional computer model to support the entire planning and construction process*" [47]. These digital relationships are created with the help of link models. The 3D objects are filtered via their properties and linked to the processes of the 4D model or cost positions of the 5D model. "*When filtering, a subset of the data is formed that corresponds to a predefined criterion, e.g. all processes in the month of May, all walls higher than 3 m or all specified services for concrete work. The criterion can be as complex as required, the only proviso being that they are calculable so that they can be executed automatically*" [47]. **Figure 8** shows the linking logic of the models and the necessary checks.

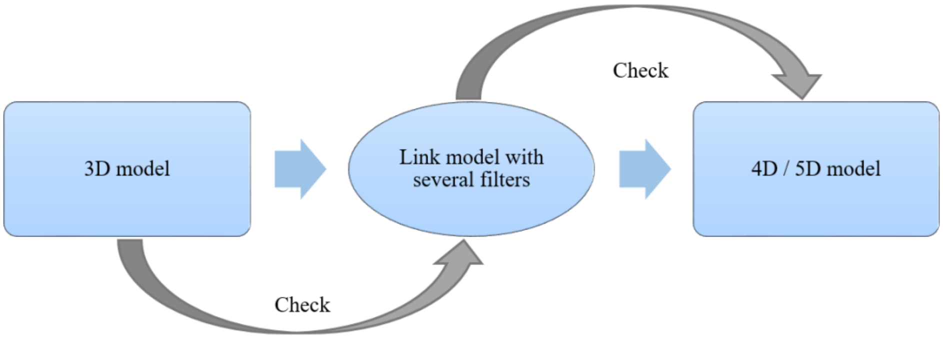


Figure 8: Linking logic of models. The correctness and completeness of these links should be considered as quality parameters. A model will only be of a high quality when the filters in a link model are correct and complete.

Since the interlinking of the various model objects is elementary for the BIM methodology, the correctness and completeness of these links should be considered as quality parameters. A model will only be of a high quality when the filters in a link model are correct and complete.

In the following, the procedure in principle is explained, although the process is identical for 4D and 5D models. In principle, the following situations must be distinguished in the evaluation and assessment (see also **Figure 9**):

(1) The filter of the link model is used several times with identical attribute values
(2) The filter of the link model is used several times with different attribute values
(3) There are several filters with identical attribute values
(4) There are several filters with different attribute values

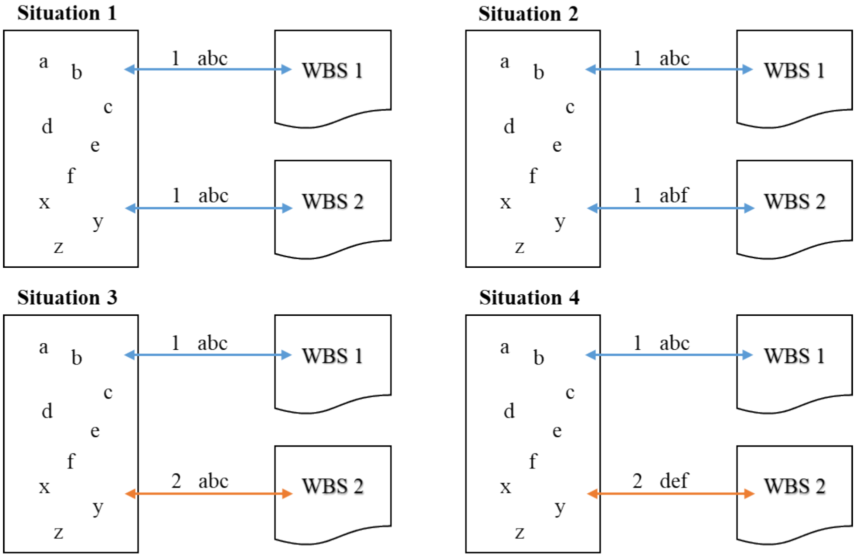


Figure 9: The different distinct filtering situations: the blue line describes link rule 1, orange line describes link rule 2 and letters a-z describe attribute values. A link rule can be used several times with the same or different values (situation 1 and 2). It is also possible to use different rules with same values or different values (situation 3 and 4).

In situation 1, the check rule is created only once, avoiding the need for multiple and identical check runs. In situations 2 to 4, several check rules must be created, since these are formally several filters that differ in at least one criterion. Corresponding case examples are presented in Section 4.3.3.

As with attribute checking, all objects are checked according to the project specifications (Section 4.3.1) against the same status messages. To filter the objects to be checked, all suitable checking rules that match a given criterion, e.g. object type, are determined and the check is carried out. In situation 2, this can mean that some objects within a filter may evaluate both positively and negatively. To correct this, a post-processing routine is necessary that checks whether objects in the negative check results also evaluated positively with the same filter number in the same attribute, and in such cases removes the object from the negative result set to ensure that the check results are evaluated correctly.

In addition, it can also be useful to create the same formal filter with the same properties but different filter numbers (situation 3), even if the same object types are queried. In this situation, the post-processing routine described above is not sufficient as it only searches for positive results with the same filter number. A second post-processing routine therefore queries the model structure described in Section 4.1 and checks whether the attribute value is a valid alternative value at the various levels. If it is found to be a valid alternative, the apparent error check is corrected.

After the above checks, what remains is the set of negative results. From these those objects that are not addressed by a filter in the link model can be identified. In addition to recognizing non-functioning links, it can also be an important indicator of missing processes in the scheduling plan or missing service items in the bill of quantities. An overview of the possible results situations is shown in **Figure 10**. On the left, the service items are shown with the link criteria (prop 1 to 4) and the corresponding property values (a to d). The right-hand side shows the objects of the 3D model with the respective attributes and their values.

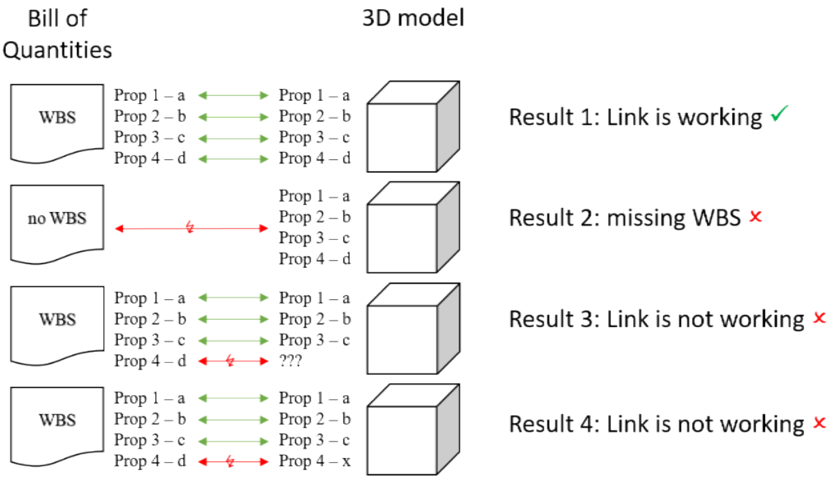


Figure 10: Overview of the results situations. On the left, the service items are shown with the link criteria (prop 1 to 4) and the corresponding property values (a to d). The right-hand side shows the objects of the 3D model with the respective attributes and their values. The green line (without flash) describes working links, red line (with flash) describes non-working links or links without a service item.

By the same token, in addition to checking the correctness of the link model against the 3D model, it also makes sense to check the filters against the process descriptions or service items. If, for example, object A (e.g. rail) is filtered from a 3D model, but object B (e.g. overhead line mast) is described in the respective linked position of the 4D or 5D model, a technical error occurs because the 3D object and the process or service position do not correspond. Although the filter finds the corresponding 3D objects, their content does not pertain to the linked position. The system checks per item or process whether the attribute values of the linking rules appear in the long texts or process descriptions. Because the system undertakes an exact string match of the attribute values against the descriptions, the terms contained in the descriptions must be written identically. If synonyms are used or the term itself is not used at all in the text, the check will flag an error. Synonyms can be identified with the help of a post-processing routine to reduce the degree of subsequent manual evaluation. For this, a corresponding synonym dictionary was created in the connected database that can be extended as required.

4.3.3 Case examples – Link models

The procedure explained below uses the example of a bill of quantity, but the process is identical for filter to the construction schedule.

To check the several filters in a link model, the linking criteria are first read and stored in a table. In certain cases, the same filter can be used for several service items (situation 2), usually when similar object types are specified in different service items. One example might be the posts of a noise barrier: depending on the structural calculations, different post profiles may be used for a noise barrier, e.g. HE-B 180 and HE-B 200 wide flange profiles. While these must be listed separately in the bill of quantities, their semantic logic follows the same structure with the exception of the property value for the profile series.

An example for situation 3 might apply when the posts of the noise barrier have different foundation forms: for example, deep foundations could be driven or bored piles. To clearly delimit the service items, each is given its own independent filter. However, when searching for suitable objects only one criterion (here object type) is used for comparison in the course of property checking. Since both bored and driven-pipe piles match the "Foundation" object type, a driven-pipe pile will also be selected for checking when comparing against the rules for bored piles.

A case example for checking a filter to the 5D model can be illustrated by the following: The Deutsche Bahn AG provides model bill of quantities and prescribes their use when submitting tenders. For the practical tests carried out as part of the project, the model bill of quantities for noise barriers are examined. Based on the model structure shown in Figure 5, the various levels of connection logic were taken into account. Each filter begins with the object group (here "noise barrier"), followed by the object type and then a list of various specifications. While the Deutsche Bahn AG stipulates the use of their model service specifications as the standard for invitations to tender, checking the terminology used reveals non-standard inconsistencies in the wording of the service descriptions. Noise protection barriers are also referred to as sound insulation barriers and some long texts also explicitly state that these are descriptions of noise barriers, while others do not. When synonyms are used or even when terms are not used at all, the check will flag these up as errors, which increases the effort required for subsequent manual evaluation of the test results.

4.3.4 Logic checks for geometric properties

In addition to evaluating the coherence and consistency of semantics in the form of text values, it is also necessary to check the geometric properties of the 3D objects and derive corresponding quality parameters. To this end, various logic checks for geometric properties have been developed, which are stored in the database and can be extended or changed.

In some circumstances, it can happen that the export or import of 3D models via exchange format interfaces does not function perfectly. Typical problems are gaps between objects, surfaces that are not closed or vectors with incorrect orientations. This usually becomes evident when trying to evaluate the objects in the analysis software and often results in the geometric properties, especially the volume, being set to zero. With the help of the first logic check, all objects can be automatically checked for properties equal to zero. This quality check makes it possible to identify faulty objects and avoid incorrect evaluations.

The various authoring programs often also store the object's geometric properties, such as volume, length, width, height, etc., as an attribute of the object. Analysis and evaluation software can independently determine these properties using their own calculation methods to verify the details and compare authoring and evaluation software. The second logic check therefore compares the individual geometric properties of both calculation sources with globally valid rules for each 3D object and saves the results in an object-specific manner. When comparing values such as height, length and width, the oriented bounding box is used because it describes the limits of the 3D object. The result is output as one of three possible statuses:

0 The comparison values agree

1 The comparison values differ from each other

– There is no comparison value from the authoring software

The effect that the bounding box has on the comparison result is explained in a case example in Section 4.3.5.

In addition to the two logic checks mentioned above, one must also verify that the dimensions given for a 3D object are also correctly modeled. In research, this principle is described as semantic-geometric coherence and is sometimes used in 3D city models in combination with CityGML. "*In the context of geodata, spatial-semantic consistency [...] describes the consistent relationship between spatial and semantic information*" [48]. Daum and Borrmann extend the method to IFC models using the query language QL4BIM [10]. In the concept presented here, it is possible to link the rules database with the model structure and to store specific geometric properties at object or specification level. The value of these checks lies in detecting differences in the data in the geometric and semantic models. "*High quality results and efficient workflow in the construction phase can only be achieved if the data basis is accurate*" [10]. Correcting inconsistencies at this stage avoids errors further down the line, for example in the 5D modelling.

In the logic tests presented, a tolerance value in percent can also be specified in order to allow minor deviations between the comparison values. This tolerance value can also be used to map the different accuracy requirements within the individual work phases.

4.3.5 Case examples – Logic checks

To test for semantic-geometric coherence, it is possible to store specific geometric properties at an object or specification level linked to the model structure described in chapter 4.1. The oriented bounding box is used to compare geometric data against the respective checking rules. This can be determined by the model checker to differing degrees of accuracy and indicates the maximum dimensions of a 3D object (see **Figure 11**). The resulting degree of accuracy has implications for both the measurement results as well as the quality inspection. In Desite MD, for example, calculation accuracy is specified as a numerical precision with a standard value of 0.01. This means that the bounding box in all three coordinate directions is determined precisely to the second decimal place.

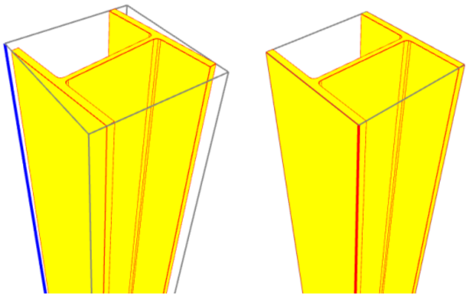


Figure 11: Bounding box (grey) with different degrees of accuracy: the left side is imprecise, the right side is precise.

To counteract any resulting inaccuracy, a tolerance value in percent can be stored in the database for the comparison test. For the tests performed on the wall and base elements of the aforementioned noise barrier, a permissible tolerance of 1.00% was set. The geometric property of the wall element and base thickness (d_req =0.12 m), which is defined by the bounding box as “cpOOBBWidth”, did not test positively to a numerical accuracy of 0.01 (bounding box calculation) and a permissible tolerance of 1.00% (n=1699). The deviations determined ranged from 1.0 to 19.5%. The measurement results of these objects are shown in **Diagram 1**.

In this case, the numerical accuracy for calculating the bounding box must be set to at least 0.001 in order to pass the control test with a tolerance of 1.00 %. Otherwise, the measurement results cannot be used as a quality criterion because system inaccuracies impact negatively on the apparent quality of the model.

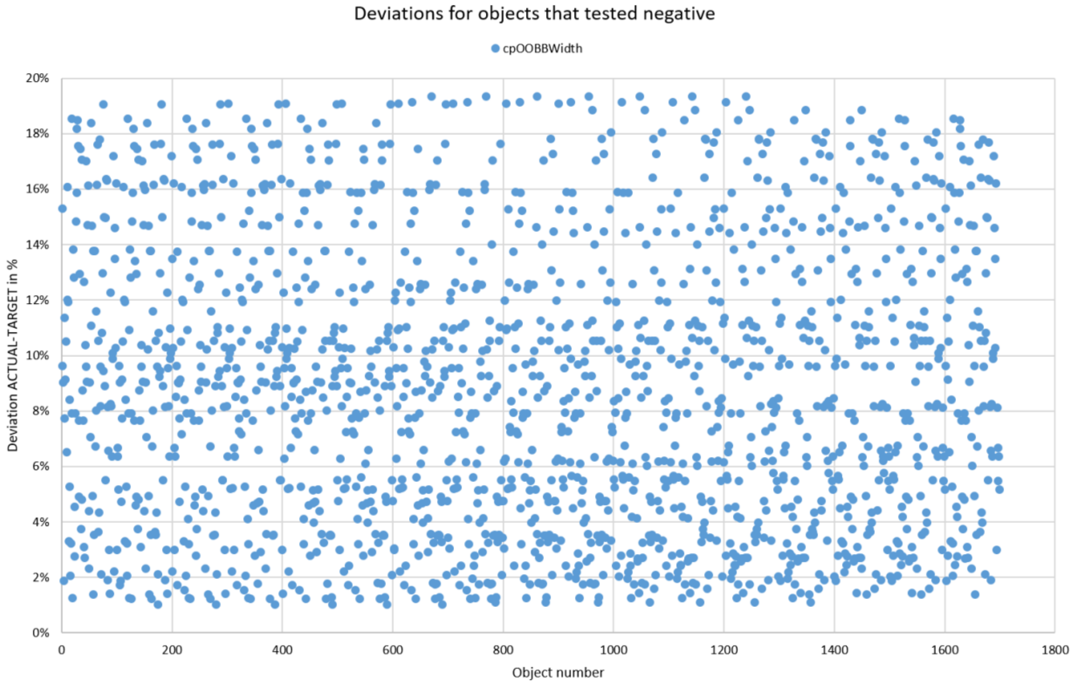


Diagram 1: Percentage deviation of the “thickness” of wall and base elements that tested negative. The geometric property of the wall element and base thickness (d_req =0.12 m), which is defined by the bounding box as “cpOOBBWidth”, did not test positively to a numerical accuracy of 0.01 (bounding box calculation) and a permissible tolerance of 1.00% (n=1699). The deviations determined ranged from 1.0 to 19.5%.

It is also possible to carry out the corresponding tests at the specification level. Using the example once more of the noise barrier posts, the different profile series are characterized by different dimensions. For example, a post with a HE-A 160 profile has the dimensions h × w = 0.160 × 0.152 m, whereas a HE-A 180 profile has the dimensions h × w = 0.180 × 0.171 m. These rules can also be checked automatically.

Diagram 2 shows the results for the geometric property “post width” (w = 0.152 m), which were determined by the analysis software using a bounding box (numerical accuracy 0.01). Only standard posts were evaluated, since corner posts have irregular dimensions and cannot be tested by the logic. The deviation of the target from the actual dimensions (bounding box) lies between 0.0 and 0.5% for all the evaluated objects (n=188).

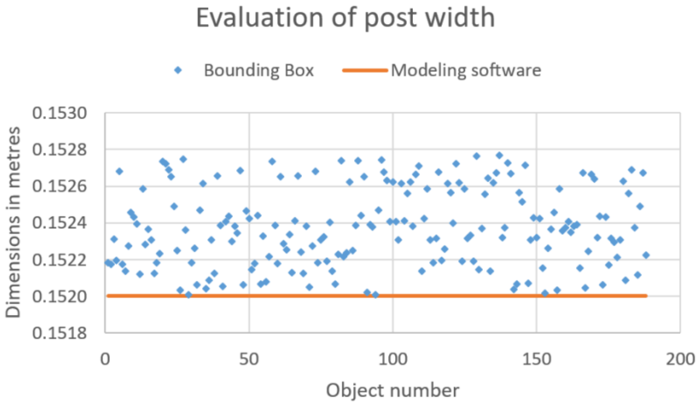


Diagram 2: Evaluation of the attribute “post width” for standard posts, shows the results for the geometric property “post width” (w = 0.152 m), which were determined by the analysis software using a bounding box (numerical accuracy 0.01).

The properties for post height and width therefore tested positive with a permissible tolerance of 1.00% and a numerical accuracy of the bounding box of 0.01.

A key problem of this approach is the difference between global and object-oriented coordinate systems. While in the model checker, the three coordinate planes x, y, and z describe the geometrical properties length, width and height in global terms, the coordinate system in the infrastructure software is object-oriented. When the geometric information in the 3D model is object-oriented (**Figure 12**, right) but the coordinate system used in the evaluation software is global (**Figure 12**, left), it is necessary to formulate several rules. For example, the condition height (global) ≙ length (object-specific) applies to the post, whereas length (global) ≙ length (object-specific) applies to the wall element. For the check, it is therefore advisable to formulate independent rules for the necessary combinations. This inevitably produces false checks, which can, however, be determined and filtered out with a post-processing routine.

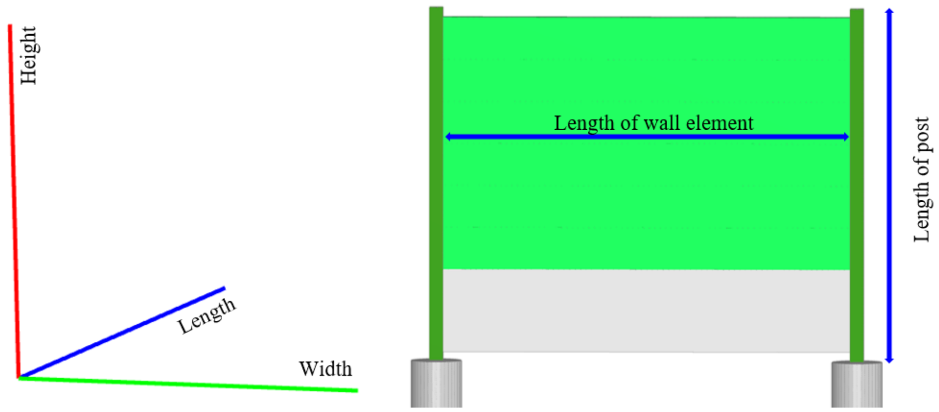


Figure 12: Difference between global and object-specific coordinate systems

Alongside orthogonal objects, as shown here using the example of a noise barrier, infrastructure constructions frequently have objects arranged along a three-dimensional curved path and that are rotated around their coordinate axes, as is the case with railway tracks. To test the influence of alignment parameters on three-dimensional object formation, test models were developed under standardized boundary conditions and tested using the same mechanisms. The curved path is essentially the product of the superimposition of axis and gradient. The axis is constructed as straight lines, circular arcs, and transitional segments. The axis also defines the cant of the rails, which in the transitional segment leads to a twisting of the objects around the longitudinal axis. The gradient in turn consist of straight pieces and rounding arcs. The latter results in a bending of the objects around their transverse axis, but this was not considered to simplify plausibility checking of the results. For the test models, a fictitious route was designed. For its design, discretionary limits were used as discussed in [49] that in real-life layouts are not permissible in such combinations but here make it possible to generate objects that are as twisted as possible in order to verify the measurement method. The parameters of the alignment for the test case are given in **Table 3**.

Table 3: Test case parameters for testing the influence of alignment parameters on three-dimensional object formation

Axis parameter	Length of straight section	100	m
	Cant of straight section	0	mm
	Length of Bloss transition arc	105	m
	Length of circular arc	100	m
	Radius of circular arc	300	m
	Cant of circular arc	160	mm

Gradient parameter	Longitudinal gradient 1	0	‰
	Longitudinal gradient 2	5	‰
	Longitudinal gradient 3	10	‰
	Longitudinal gradient 4	12,5	‰

Calculation interval	Calculation interval 1	1	m
	Calculation interval 2	5	m
	Calculation interval 3	10	m
	Calculation interval 4	20	m

Object formation in infrastructure planning frequently involves the extrusion of a cross section, with new cross sections calculated at regular intervals and connected linearly with each other. This step of model creation therefore also influences the accuracy of the objects created. The effect of different calculation intervals on the resulting 3D objects is shown in **Figure 13**. The figure shows the calculation results for tracks with the same underlying alignment (axis and gradient with longitudinal gradient 1) at different calculation intervals. While the rail tracks on the left side (calculation interval 1) follow the real situation well (continuous course), also in the curved section, the rail tracks on the right side (calculation interval 4) clearly deviate from the real situation.

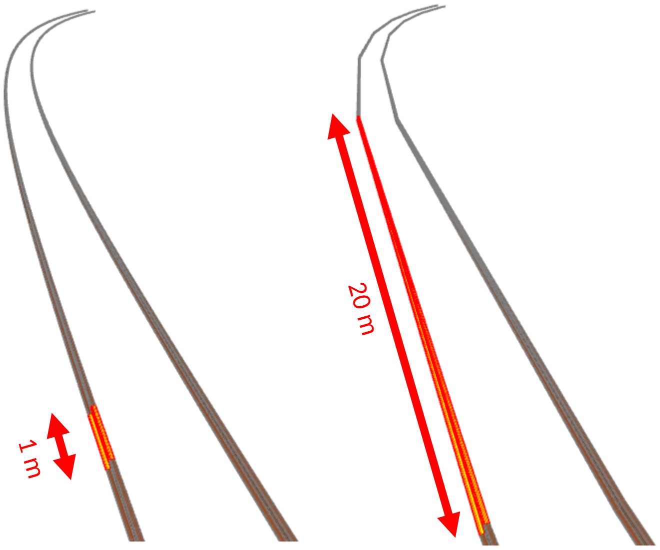


Figure 13: Calculation results of 3D objects at different intervals. The calculation results for tracks with the same underlying alignment (axis and gradient with longitudinal gradient 1) at different calculation intervals (1m and 20m) are shown. While the rail tracks on the left follow the real situation well (continuous course), also in the curved section, the rail tracks on the right clearly deviate from the real situation.

The interaction between the calculation interval and the cant influences the calculation of the bounding box. To illustrate this, **Figure 14** shows an example of a superelevated rail. While the rail has no cant at the beginning of the section of track (left) and the bounding box perfectly matches the base of the rail, the rail at the end (right) tilts due to its cant. The bounding box, however, follows the maximum expansion of the 3D object and does not exactly fit the base of the rail profile. The situation is reversed at the top of the rail. The bounding box is therefore higher than the rail profile itself for the section where the rail is elevated.

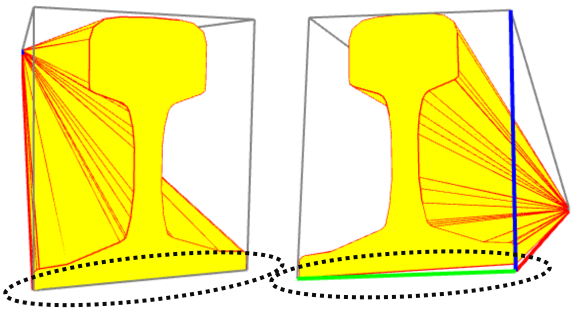


Figure 14: Effect of the elevation on the bounding box. The bounding box follows the maximum expansion of the 3D object and does not exactly fit the base of the rail profile in segments with an elevation greater than 0.

Taking into account the axis, the four gradients and four calculation intervals, 16 test cases result. The rail height of a S54 rail (h = 0.154 m) and the rail foot width (w = 0.125 m) are evaluated. As per description the accuracy of the bounding box has a decisive effect on the test, the numerical accuracy was set to 0.0001 so that the fourth decimal place of the bounding box adapts exactly to the 3D object. The two geometric properties were then evaluated and compared with the target values. The mean deviation of the objects that flagged as negative in testing is shown in **Diagram 3** and ranges from 0.02% to 1.20%.

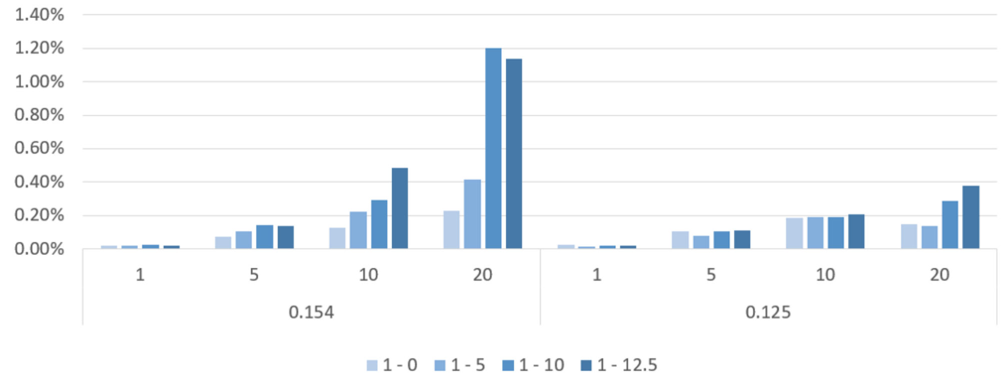
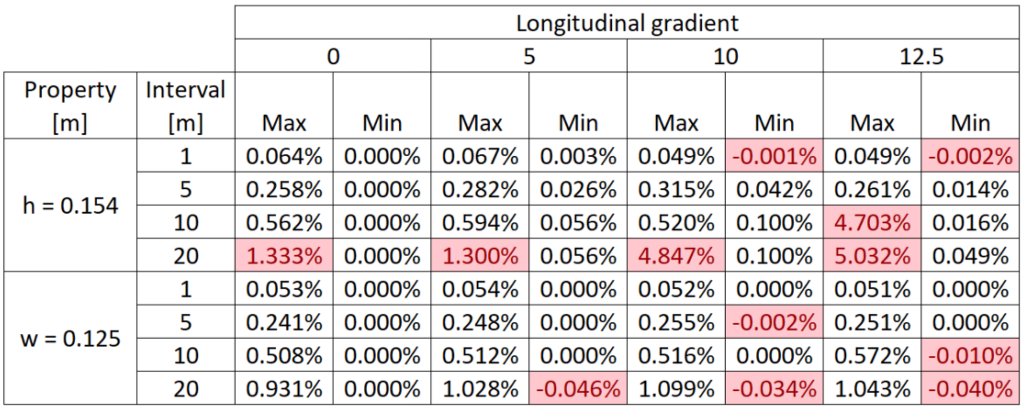


Diagram 3: Average deviation of objects inspected with errors. The rail height of a S54 rail (h = 0.154 m) and the rail foot width (w = 0.125 m) are evaluated. The mean deviation of the objects that flagged as negative in testing ranges from 0.02% to 1.20% depend on the four gradients (0 – 12.5 ‰) and four calculation intervals (1 – 20 m).

The minimum and maximum deviations of the negatively tested objects per test case are shown in **Table 4**. As expected, the greatest deviations occur at a calculation interval of 20 m: in combination with a high longitudinal inclination, the maximum deviation increases to 5.0%. This applies particularly to the objects in the transition curve, where the twist is greatest.

Table 4: Maximum and minimum deviation per test case. The greatest deviations occur at a calculation interval of 20 m: in combination with a high longitudinal inclination, the maximum deviation increases to 5.0%.



		Longitudinal gradient							
		0		5		10		12.5	
Property [m]	Interval [m]	Max	Min	Max	Min	Max	Min	Max	Min
h = 0.154	1	0.064%	0.000%	0.067%	0.003%	0.049%	-0.001%	0.049%	-0.002%
	5	0.258%	0.000%	0.282%	0.026%	0.315%	0.042%	0.261%	0.014%
	10	0.562%	0.000%	0.594%	0.056%	0.520%	0.100%	4.703%	0.016%
	20	1.333%	0.000%	1.300%	0.056%	4.847%	0.100%	5.032%	0.049%
w = 0.125	1	0.053%	0.000%	0.054%	0.000%	0.052%	0.000%	0.051%	0.000%
	5	0.241%	0.000%	0.248%	0.000%	0.255%	-0.002%	0.251%	0.000%
	10	0.508%	0.000%	0.512%	0.000%	0.516%	0.000%	0.572%	-0.010%
	20	0.931%	0.000%	1.028%	-0.046%	1.099%	-0.034%	1.043%	-0.040%

In addition, it is noticeable that the minimum values lie in the range of -0.04 to 0.1%. The minimum values shown at 0.00% only deviate in the third decimal place. A total of 3,304 objects were checked.

With a tolerance value of 1.20%, 100% of the objects passed the test in terms of rail foot width and 99.3% of the objects with respect to rail height.

4.3.6 Consistency check: component semantics

Since constructions follow a structure established in practice (see Section 4.1), one must also check that the model corresponds to the expected structure. To this end, the 3D objects or their semantics are compared with the expected model structure (see Figure 5 for an example).

Deviations or erroneous results indicate either that the digital model structure in the database is incomplete or that the expected value has actually been violated. This makes it possible to detect inconsistencies in the semantic model and in turn to avoid evaluation errors.

4.4 The domain “quantities and costs”

In addition to checking the various aspects of the geometric and semantic models, the results of the 5D modelling likewise need checking. For the most part, this concerns quantities and cost evaluations, and corresponding test methods were devised and incorporated into the overall concept as described below.

4.4.1 5D model – Quantity checking

In the context of ensuring a continuous digital chain for model-based construction planning, it is necessary to develop a checking mechanism for validating the quantities determined. A 5D model is created from the building blocks “3D model”, “link model”, “quantity formula”, and “unit” and these must therefore also be considered in any verification procedure. In a first step, those service items in the specification that have a link to 3D objects are determined. The quantity recorded and the unit of measure is likewise retrieved for each item. The connected database contains rules for the individual units of measure, which reference the independently determined properties of the evaluation software. A tolerance value in percent can be specified in the rule definition, which is taken into account during the check.

Where evaluation programs allow the flexible input of mathematical functions using factors/quotients or similar when creating 5D models, these too must be validated and taken into account when checking the quantities.

In cases where the same unit is used – for example the square meter is universally used to denote areas – it is currently not possible to automatically recognize which area is concerned. It could be the footprint, the elevation surface or the entire surface of the tested object, each of which has a different absolute value. In the database, all surface attributes are defined as rules, which entails several test runs and therefore produces more erroneous results. A post-processing routine can, however, determine whether a service item unit that was flagged as incorrect was identified as being correct for another attribute or area value. The error code of the “wrong” area value is then automatically adjusted.

4.4.2 5D model – Cost checking

In addition to checking the model-based quantity determination, it is necessary to validate the unit prices for each service item. An object can, however, have multiple different unit prices depending on the unit. It must therefore be possible to define separate cost calculation rules specific to the object and to the unit. This is possible in the rule database.

It is also necessary to be able to define unit prices according to model´s level of detail. While the model and object structure may still be quite rough in early work phases and detailed only as far as the object level shown in Figure 5, the objects must nevertheless be costed at specification level as part of the preliminary planning and tendering.

This requirement is likewise supported by the relational database. For better user-friendliness, the permissible upper and lower limits of the unit prices can be defined as absolute values.

The method was developed conceptually and tested on a theoretical example. While the determination of the lower and upper cost limits at object level was not carried out on the basis of real projects, this data can be determined, for example, according to Sajadfar and Ma [50], where the historical data was evaluated using both regression analysis and data mining methods. These can, however, also be determined for a specific project using a unit price catalog.

5 Quality metrics and evaluation

The aim of the evaluations is to compare the elaborated quality criteria according to a standardized scale and in turn to identify those criteria which meet the project requirements and those which still need improvement. There are various ways of conducting this assessment. The following systems have been implemented in the concept presented here:

- Percentage scale
- Grades
- Traffic light scale

To define the correctness of a BIM model in a qualitative manner, the concept of “Quality Level” is used. A quality level describes the ratio of false results to checks conducted and so the quality of the BIM model for each quality parameter can be determined on a percentage scale. The concept considers six “Quality Levels”, as outlined in **Table 5**. The ratios used for each level are freely definable but should at least be defined consistently across a project. For cross-project comparisons, it is advisable to determine the ratio ranges once and apply them consistently to the different projects. A possible approach for a cross-project comparison method is outlined by Choi and Leite [51] although in that case the comparison parameters do not describe the digital correctness of the model components – as implemented here – but compare the results of different planning projects (costs, time, equipment, etc.).

The verbal description of the individual levels is based on the school grading system. Each “Quality level” is also given a corresponding color that follows the pattern of a traffic light scale. Green corresponds to levels A and B, with a slight color shift from green to yellow-green. Level C is assigned the color yellow, followed by orange for D, red-orange for E and red for F. This same concept for data quality visualization was used by Lee et al. [52] to verify the data integrity of IFC models.

Table 5: Evaluation metrics based on the ratio of false results to checks conducted and determined on a percentage scale. The ratios used for each level are freely definable. The verbal description of the individual levels is based on the school grading system.

Quality level	Ratio of false results to checks conducted [%]	Description	Corresponding color
A	0	very good model quality	A
B	$0 < x < 5$	good model quality	B
C	$5 \leq x < 10$	satisfactory model quality	C
D	$10 \leq x < 25$	sufficient model quality	D
E	$25 \leq x < 50$	poor model quality	E
F	$50 \leq x$	insufficient model quality	F

6 Validation

The concept presented in this paper was applied to a large-scale German project and tested for feasibility. Due to the degree of progress of the project, it was only possible to conduct tests that apply to the 3D and 4D model. Likewise link models could not be tests as the project does not employ them. The linear transport infrastructure project has an overall length of approximately 16.0 km and comprises 108,976 3D objects in the model. The results of the validation are presented below.

At the beginning of the project, a catalog of attribute definitions was agreed with the client and the project was then initially tested for compliance. 42 different attributes were defined, to which the model objects must adhere in different combinations, and a total of 1,511,279 checks were carried out. The check revealed that the agreed definitions had not been implemented consistently throughout the model as errors were identified in the semantic model in 32% (absolute 483,445) of the check runs. In this test, the model only reached quality level E.

In a second step, various logic tests were performed to check the semantic correctness of the model. To begin with, the geometric properties supplied by the authoring software in the attributes were compared against the evaluations of the model checker. Here, 762,832 checks were performed, and errors were detected in 15.36 % of the checks (absolute 117,190). In this test, the model achieved quality level D.

When checking the geometric properties determined by the model checker, 2,870 erroneous results were found (435,904 tests in total), indicating that some objects are not evaluable. This corresponds to an error ratio of 0.66% and a quality level of B.

In the object database as described in chapter 4.1, the standardized geometric dimensions of the elements of a noise barrier as well as of rails and sleepers were stored and checked for consistency in the model. According to the building logic, a distinction must be made between testing at object level and testing at object specification level. The test yielded a total of 33 false results for 7,634 inspections at object level (0.43% and quality level B). The test at object specification level yielded 2,105 incorrect results in 19,916 tests, which corresponds to an error rate of 10.57% and a quality level of D.

As described in chapter 4.3.6, the consistency of the model was also checked against the expected building logic described in the comparison database. 108,976 3D objects and their semantic logic were tested. In 15.81% of the tests, the expected value was not met, which is sufficient for a quality level of D.

The 3D model was also subjected to a collision check. First, the static model was examined: 103,528 collisions were detected. In order to filter out irrelevant collisions, the collision matrix described in Chapter 4.2.1 was extended and the results of the collision check re-verified. 64,997 of the collisions could be classified as irrelevant, so that the remaining error rate was 37.22%. The model therefore achieved quality level E in the "3D collision" check. In addition, the time schedule was also included in the collision check, taking the time dependencies into account. A total of 31,501 collisions were detected in the 4D collision check. After evaluating and discounting the irrelevant collisions, 92 % (absolute 28,935) remained, corresponding to a quality level of F. In total 28,633 clashes were identified between rails and sleepers, which follows from sleepers modeled in wrong height.

The validation process made it possible to evaluate and identify inconsistencies within the BIM model. The results helped to improve the subsequent processing of the model and have had a lasting positive influence on the quality of the model.

7 Conclusion

The application of the BIM method aims to make the entire process of a construction project more efficient. Initial studies have confirmed that BIM has a positive influence on the course of a project in terms of costs, time, communication, coordination, and quality. With the help of the BIM method, errors and their sources can be detected better and earlier. However, new error sources can arise in the process, which can have an impact on the model quality and in turn on all subsequent processes. This paper has presented a method with which 3D, 4D, and 5D models can be systematically examined for possible errors. This method was explored in the context of model-based rail infrastructure planning.

An overall quality assurance concept has been developed drawing on current best practice. A total of 14 quality parameters were developed for the three domains of "clash detection", "semantics", and "quantities and costs", each of which were examined in more detail. Infrastructure planning, and model creation in infrastructure planning in particular, exhibit some special characteristics – as shown by the example of rail objects that are dynamically defined by route alignment – which were considered in the investigation. Finally, an evaluation metric was presented which allows model quality to be measured based on previously defined threshold values for the individual criteria. The quality assurance concept was applied on a large-scale infrastructure project. Depending on the selected quality parameter the quality of a model can vary considerably.

While the investigations described here were limited to explicit volumetric models, implicit models (2.5D models) will also be considered in future research, since these are an important pillar of digital project design for infrastructure planning. Further research is also needed in the domain of "construction". Considerable research work has already been conducted in the field of building construction and it will be necessary to examine their applicability and feasibility for use in the field of infrastructure planning. A further benefit of model-based design is the possibility to carry out simulations. In practice, the focus here is usually on simulating the construction sequence. The aspects of safety checks and simulations will therefore also be a focus of future research activities.

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