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Exchange of Parametric Bridge Models using a Neutral Data Format

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Abstract:
Parametric modeling is a well-established methodology in the field of mechanical engineering. It allows the creation of flexible geometric models using parameters for dimensions and makes it possible to define numeric relationships between these parameters by means of mathematical formulas and define geometric-topological constraints between geometric entities. The result is a flexible geometric model which can be steered through the manipulation of its primary parameters. In contrast to explicit geometric models with fixed dimensions, a parametric model can capture the design intent and represent domain knowledge. The use of parametric modeling techniques is particularly beneficial for designing bridges. This is due to the fact that the geometric design of bridges is mainly determined by external constraints resulting from the size and the layout of both the overlying and the undercrossing carriageway. This reduces the effort required for reworking when changes are made, while simultaneously providing a high degree of reusability for the model in other, similar projects, resulting in significantly increased efficiency in the bridge design process. Due to the strong fragmentation of the AEC (Architecture, Engineering and Construction) industry, the data exchange between the different participants in a construction project is of crucial importance. The use of neutral, open data formats has proved to be the most suitable approach to realize this data exchange. However, currently existing neutral data formats do not allow for an exchange of parametric geometry. To overcome these technical limitations, this paper introduces an extension to the IFC-Bridge format, thus providing a means of interchanging parametric bridge models. This article describes in detail the necessary entities introduced to define parameters and capture dimensional and geometric constraints. The suitability of the developed extensions is proved by presenting the successful

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transfer of parametric bridge models between two parametric design systems as well as from a design system to a structural analysis system.

Introduction

Today's complex construction projects require in-depth expertise in various, widely differing domains. Accordingly, a large number of specialists are involved in the planning, execution and maintenance of buildings and constructions. These domain-specific experts usually employ software products which are highly specialized and often form so-called "Islands of Automation" (Hannus et al. 1987), i.e. they provide only very limited means of exchanging data with other software products. As a consequence, design data are regularly transferred using drawing-based methods or low-level digital formats. Both require tedious manual re-input into the receiving application, resulting in an inefficient overall workflow.

The concept of Building Information Modeling (Eastman et al. 2011), in short BIM, was developed to overcome this situation and it is now increasingly implemented in the construction industry. It is based on using a comprehensive digital representation of the building throughout its entire lifecycle in order to avoid the laborious and error-prone re-entering of data. This Building Information Model needs to be represented by an open, neutral data model in order to achieve the desired interoperability between different software products. The Industry Foundation Classes (IFC) form such a neutral data model for the field of building design and engineering, providing comprehensive means for the semantic and geometric description of a building and its components.

Chen and Shirolé (2006) introduced the concept of Bridge Information Modeling (BrIM) for the design and engineering of bridges. In analogy to BIM, the approach is based on the use of an interoperable digital representation of the bridge and all associated information. A number of different data models have been proposed for implementing this concept, among them TransXML (Ziering et al. 2007) and IFC-Bridge (Lebegue et al. 2007), the latter being an extension of standard IFC by bridge-specific elements. These two data formats differ widely with respect to the manner of representing the bridge's geometry. While TransXML uses pre-defined shapes and profiles, whose dimensions can be controlled by a fixed set of parameters, IFC-Bridge implements a more flexible approach using freely definable cross-sections and alignments. IFC-Bridge is consequently able to represent a wider range of bridge geometries.

There are severe limitations of the current IFC-Bridge proposal, however, when it comes to describing bridge superstructures with varying profiles along their main axis, as in the case of haunched superstructures or superstructures of varying width. As the data model does not provide any means of defining a varying cross-section, superstructures of this kind have to be subdivided into a large number of prismatic elements, each of which has to be defined by two different cross-sections. Demanding such an explicit geometry description means the underlying design intent is lost. In consequence, it is not possible to use IFC-Bridge for exchanging information in the early phases of bridge design, where the superstructure's shape is still subject to major modifications. In addition, such an approximated geometric model is only of limited use for the data exchange with structural analysis programs, as these require a precise shape description for the calculation of centrifugal forces or the effects of post-stressing tendons, for example (Katz, 2008).

To overcome these limitations, this paper presents an extension to the IFC-Bridge geometry description which makes it possible to exchange parametrically defined superstructures with varying profiles. The extension is based on modeling techniques implemented by parametric CAD systems for mechanical engineering, more precisely the notion of two-dimensional parametric sketches which are enhanced with geometric and dimensional constraints. This modeling technique not only allows defining dependencies between geometric entities, resulting in a model which is able to capture the design intent, but also provides a means for an automated update in the case of design modifications. The resulting data model accordingly introduces a novel concept for the efficient and flexible exchange of bridge design geometries.

The paper is structured as follows. Following a review of related work and the existing data model for bridges in the next section, the concept of applying parametric modeling techniques for the design of bridge superstructures is introduced. In the section following thereafter, the proposed extension of IFC-Bridge for capturing parametric geometry is presented and discussed in detail. At the end of the paper, the proposed extension is evaluated by means of two real-world application scenarios demonstrating the successful exchange of parametric bridge models.

Related Work

Parametric modeling in AEC

The application of parametric and constraint systems to capture engineering knowledge and design intent have already been taken into consideration in the early inception phases of CAD in the AEC sector, as well as in architectural design.

Most of the research efforts apply parametric concepts to building design. For infrastructure facilities in the field of civil engineering, such as roads, bridges and tunnels, only few activities have been reported. Sampaio (2003) proposed a parametric design system for box girder decks for bridges that makes it possible to create a series of predefined, cross-sectional profile diagrams with a fixed set of parameters. By parametrically positioning diverse configurations of the profiles along a curved and banked longitudinal axis, the proposed system enables the fast generation of a complete three-dimensional representation along with corresponding finite-element meshes for its structural analysis. Regarding the sketch-based parametric design

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approach, the work presented here applies similar strategies. However, Sampaio's work neither includes the user-defined definition of constraint interdependencies among the individual parameters and geometric sub-components, nor does it propose an interoperable, flexible and generic data structure as presented in this paper.

Data exchange in bridge design and engineering

Although a large number of different stakeholders typically using different software tools are usually involved in bridge projects, the data exchange in the bridge design and engineering domain is still poorly supported by open formats. As a result, data is regularly transferred using conventional, non-digital methods such as plotted plans, or low-level digital formats such as PDF documents. Both require tedious manual re-input into the receiving application, resulting in an inefficient overall workflow. In the best case, proprietary file formats such as Autodesk's DWG format are used. As the format is not openly documented, however, incompatibilities occur which again result in laborious manual reworking.

In analogy to the term Building Information Modeling (BIM), the term Bridge Information Modeling (BrIM) was coined to describe the concept of a semantically rich data exchange of bridge design and engineering information in order to provide seamless integration between different software solutions (Chen and Shirolé 2006; Chen et al. 2006; Shirolé et al. 2009). So far, software vendors have interpreted the term BrIM as an approach to enable data exchange between their own products, without considering the interoperability between products of different vendors (Bentley, 2008). In order to exploit the potential of Bridge Information Modeling to the full, a neutral format is called for (Chen et al. 2006).

This important issue has been addressed by a number of research initiatives. Within project 108 of the National Cooperative Highway Research Program (NCHRP) a data model for describing the main elements of bridges and their dimensions was developed (Chen et al. 2006).The data model, as developed, has been implemented as an XML (Extensible Markup Language) schema. In the course of the project, the CAD systems MicroStation/TriForma Bentley and Tekla Structure were employed to create a 3D model from the parameters stored in a corresponding XML file. In the presented approach, the geometric description provided is restricted to the use of predefined attributes of bridge elements such as the span length, the number of girders or the number of spans. However, this drastically limits its practical applicability in Europe, where bridges are much less standardized and a detailed geometry description for each individual design is necessary.

In another NCHRP project "TransXML: XML Schemas for Exchange of Transportation Data" a number of UML models and XML schemas have been designed for supporting data exchange in the highway design domain (Ziering et al. 2007). Apart from schemas for roadway survey and design, transportation construction and materials, as well as transportation safety, also a schema for highway bridge design was defined. This schema is based on the AASHTO Virtis/Opis bridge model and provides a comprehensive semantic description for a number of different bridge types, including multi-girder, pre-stressed concrete girder-line structures and reinforced concrete slab-line structures. Here again, however, the geometry definition is too restrictive, as it allows only the usage of pre-defined profiles, such as the “I” and “Box” profiles.

A sample application, the TransXML Bridge Input Converter, was developed to demonstrate the translation of a Bridge TransXML instance document produced by one piece of bridge analysis software to a format that could be interpreted by another bridge analysis software package.

At the same time, a number of alternative data exchange formats based on ISO 10303 (STEP) and the corresponding data modeling language EXPRESS (ISO 10303-11, 1994) have been implemented. This is mainly due to the success of the EXPRESS-based data exchange format Industry Foundation Classes (IFC) in the building sector and can be interpreted as an alternative approach to realizing the BrIM vision.

For example, Lee and Jeong (2006) proposed a model for steel bridges, which reuses and extends existing Application Protocols (AP) of the ISO 10303 for the creation of steel structures, such as geometric representations (AP 203) and structural analysis models (AP 209). The model is based on the concept of assemblies of steel beams and joins based on reconfigurable, yet predefined profiles. Although allowing detailed descriptions of the components such as abutments, footings, shoes and piers, the model lacks parametric genericity that is proposed here.

Parallel to the US efforts, Japanese and French researchers have proposed the IFC-Bridge data model for bridges as a domain extension to the Industry Foundation Classes (Yabuki et al. 2006; Lebegue et al. 2007). The scope includes various pre-defined types of bridges with different superstructures, materials and construction methods. The geometric representation of bridge elements, however, makes use of the explicit, non-parametric modeling resources of the IFC core model. Due to the limited number of implementations in commercial software applications, IFC-Bridge is not yet established in practice (Shim et al. 2012).

One of the most important use cases of IFC-Bridge is to transfer data between a bridge design tool and a structural analysis program. It is here that one of the major limitations of the current IFC-Bridge draft becomes apparent: In order to conduct structural analysis accurately, it is necessary to make use of the underlying design information behind the resulting 3D geometry, such as the mathematical description of the relationship between the haunch of a bridge and the bridge axis (Katz, 2008; Ji et al. 2011). As the current IFC-Bridge draft provides no means of transmitting dependencies of this kind, this information gets lost. Accordingly, it has to be reproduced manually for the structural analysis system, which is time-consuming and error-

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prone. The parametric extension to IFC-Bridge introduced in this paper overcomes these limitations.

Attribute-driven Geometry in IFC

The exchange of parametric models between different domain applications is required to facilitate design and planning processes in the building and construction industry. Although a range of building information modeling systems support parametric modeling approaches and the specification of design intentions, currently they can only be stored in the native formats of the proprietary authoring systems. The standardized exchange data model for the AEC sector, the Industry Foundation Classes (IFC), however, does not provide any functionality so far for capturing constrained, sketch-based parametric information (Hubers, 2010).

In the current version of the IFC, implicit and explicit geometric representations of objects which are based on profiles are limited to predefined parametric configurations. The geometry of the profile and the resulting shape of the extruded solid body are driven by the numeric value of its predefined attributes such as the *OverallWidth* or the *Radius* of predefined profiles. This kind of geometric representation is referred to as dimension-driven or attribute-driven geometry, which was introduced in the early stages of parametric modeling (Shah and Mäntylä, 1995). Compared with fully user-defined parametric descriptions that are capable of capturing design intent, such as the sketch-based approach described in this paper, the capabilities of the IFC model currently have the following limitations:

- Predefined profiles limit the expressiveness needed to communicate design intent to a fixed set of hard-coded choices. Users cannot create domain-specific profiles (e.g. a box-girder profile of a bridge) and freely define dimensional parameters.
- Users cannot impose algebraic relationships on different dimensional parameters (such as “the height of the box-girder is half of its length”).
- Users cannot specify geometric-topological relationships between parametric objects using general rules, for example appointing two lines to be *parallel* or *perpendicular* to each other.
- It is currently not possible to model a user-defined relation between object entity attributes on the semantic level and the geometric representations.

Due to these limitations, the IFC geometric model is not sufficiently advanced to capture the design intent underlying bridge geometries where flexible definitions of bridge profiles and dependencies between bridge components are required.

Parametric geometry approaches in STEP

From a historic perspective, the IFC model was developed as a fork of the Application Protocol (AP) 225 of the ISO 10303, the large framework of standards referred to as STEP (Standard for the Exchange of Product Model Data) (ISO 10303, 1995). Similar to other domain-specific APs, such as the ones for Process Plans for Machined Products (AP240) or Electrotechnical Design

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and Installation (AP212), geometric representations are captured in a common, domain-independent Integrated Resource (IR) model. This generic Part 10303-42 ”Geometric and topological representation”, however, shares the same limitations of expressiveness as the IFC, as described above. In order to address the demands for the exchange of constraint and parametric designs that dominate the manufacturing industry, a working group was established within the TC 184, whose aim was to create a parametric model schema (Pratt et al. 2005). As a result of this effort “Parameterization and constraints for explicit geometric product models” was standardized as ISO 10303 Part 108 in 2005 (ISO 10303-108, 2005). Subsequently, the ProSTEP Association launched an implementation project of Part 108 for the mechanical modeling systems CATIA, Pro/Engineer and Siemens NX (ProSTEP, 2006). However, due to the high complexity of mapping the 40 different geometric constraints among the individual CAD systems to the neutral standard (Pratt et al. 2005), STEP Part 108 import/export functionality has not gained acceptance in current commercial parametric CAD systems. In order to potentially overcome these interoperability issues stemming from the broad scope and the complexity of Part 108, we have decided to focus strictly on including the essential parametric and constraint constructs documented in the following section.

Parametric Modeling of Bridge Superstructures

Sketch-based Parametric Modeling

The concepts presented in this paper rely on a sketch-based approach to parametric design which is typically provided by mechanical engineering CAD systems. In the case of sketch-based parametric modeling, the designer first creates a 2D drawing, the so-called *sketch*. It does not follow precise dimensions but instead defines a rough layout consisting of basic geometric entities such as points, lines and arcs. The *sketch* is subsequently enhanced by the definition of dimensional as well as geometric constraints.

The dimensional constraints are used to control both distances and dimensions. There are four general types of dimensional constraints, restricting either the vertical dimension, the horizontal dimension, or the length of a line (called parallel dimension), and the angular dimension. They can be either defined by fixed values or by means of variables, which are also referred to as *parameters*. One of the main characteristics of parametric design is the possibility to define dependencies between these dimensional parameters by means of algebraic formulas. Each parametric formula consists of predefined arithmetic operators and operands. The operands refer to other defined dimensional parameters. This recursive definition ensures that if the value of a parameter changes, all related expressions are re-evaluated leading to an automatic update of the entire model.

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Besides dimensional constraints also geometric constraints can be defined, again pertaining to the basic geometric entities constituting the sketch. Depending on the type of the geometric entities involved, eight commonly used geometric constraints can be identified:

1. *Parallel Constraint:* Two lines must be parallel.
2. *Perpendicular Constraint:* Two lines are orthogonal to each other.
3. *Coincident Constraint:* Two geometric objects coincide at a common point: the starting point of a line or the end point of an arc, for instance.
4. *Fixed Constraint:* The position of any kind of geometric object is fixed.
5. *Horizontal Constraint:* A line object must be parallel to the horizontal axis of the local coordinate system.
6. *Vertical Constraint:* A line object must be parallel to the vertical axis of the local coordinate system.
7. *Tangential Constraint:* A line is tangent to a circle or an arc.
8. *EqualLength Constraint:* Two lines must have the same length.

Both dimensional and geometric constraints can be either unidirectional or bidirectional, depending on the capabilities of the constraint solving system.

The geometric and dimensional constraints defined for the parametric sketch are subsequently checked by the constraint solver component of the parametric modeling system. If no contradictions are detected, it applies a solution procedure resulting in an evaluated sketch where the position of the geometric elements and their relationships comply with the defined constraints.

On the resulting parameterized sketch, geometric operations such as extrusion, sweep and protrusion are applied in order to create volumetric objects (solid bodies). In most cases, these operations also provide parameters. Additional sketches can be created on individual faces of the 3D solid to further manipulate its shape. Boolean operations can be applied to combine different parametric 3D solids to form more complex shapes by means of Constructive Solid Geometry (CSG). The resulting volumetric model remains fully flexible. Its shape can be controlled by modifying the parameters of the sketches and the geometry operations as well as by adding and removing geometric constraints.

Application to superstructure bridge design

The sketch-based parametric modeling techniques introduced above form the foundation for the parametric design of superstructures. Figure 1 shows an example of a parametric sketch of a superstructure profile. In this example, several dimensional constraints are used to define the bridge design parameters, such as the total width of bridge (*total_width*), the width of carriageway (*carriageway_width*), the width of the bridge cap (*cap_width_right, cap_width_left*), and the angle between carriageway and bridge cap (*carriageway_cap_angle*). These parameters provide the basis for the flexibility and adaptability of the model. However, additional geometric constraints are required to ensure the validity of the resulting profile when the dimensional parameters are varied.

Include Figure 1 here.

In this example, all lines of the profile are set to be *coincident* with each other, so that the profile remains a closed polygon. Another example is the use of the *EqualLength* geometric constraint. It restricts the width of the right side of the carriageway to be equal to the left one. Changing the dimension of the left part automatically amends the right side to match. This is also an example of combining geometric and dimensional constraints in order to capture the underlying engineering knowledge.

After defining the parametric profile, the solid of the bridge's superstructure is created by extruding the sketch along the reference curves (Figure 2). If the superstructure consists of a haunch, the sketch-based sweep method has to be applied. With the help of this extrusion technique, it is possible to define a multitude of sketches positioned at different places on the reference curves. These sketches may vary in their dimensions. In the course of the superstructure the actual dimensions of the sketches may vary, as it is the case for haunched superstructures or superstructures with widening/narrowing profiles. In this case, the varying dimensions, e.g. height, width etc., are described by a functional expression relating the bridge's abscissa to the respective dimension of the sketch. By doing so, the exact geometric shape of the superstructure is described, while maintaining its flexibility.

The sketch-based extrusion process creates a solid which links the individual sketches and performs a geometric interpolation to configure the shape between these defined positions. This technique ensures that superstructures with non-constant profiles can be created and parameterized. In addition, the resulting superstructure will be automatically divided into sections according to the position and number of the profiles.

Include Figure 2 here.

Integration of Parametric Geometry into IFC-Bridge

The current IFC-Bridge draft

The IFC-Bridge data model is an extension of the IFC data model providing additional entities for the description of bridges. The data model is currently under development. Initial drafts have been proposed by French and Japanese researchers in 2006 (Yabuki et al. 2006). The current version is Version 2 Release 8, dating back to November 2007 (Lebegue et al. 2007). Most of the bridge-specific entities are derived from existing IFC entities.

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To fulfill the specific requirements of the geometric modeling of bridge superstructures, a number of specific entities have been introduced in IFC-Bridge (Lebegue et al. 2007). The superstructure of a bridge is described by an arbitrary number of "prismatic elements" (*IfcBridgePrismaticElement*). A reference curve can be associated to each prismatic element to make it possible to position and direct the element in the global reference frame (*IfcReferenceCurve*). A prismatic element is geometrically equal to a solid body created by a sweep operation between two cross-sections *IfcProfileDef* (Figure 4, B-1). Cross-sections are systematically positioned along the axis of the bridge by following the geometric reference system *IfcReferencePlacement* (Figure 4, B-2). This allows for modeling superstructures with variable cross-sections in the x-z-plane, for haunched bridges, for instance (Figure 3). The *IfcProfileDef* element can also be used to integrate cross-sections of varying width (x-y-plane), which allows the generation of ramps necessary to enter or exit the highways, for example.

Include Figure 3 here.

The local coordinate system of the cross section is defined with the help of two direction vectors (*IfcDirection*) and the abscissa (*IfcLengthMeasure*) marking the position of the cross-section on the reference curve, where the local coordinate system of the cross section is defined. The use of a geometric reference system is the main characteristic of the IFC-Bridge data model. The principle of this modeling concept is to place all geometric elements of the superstructure in reference to the bridge axis (*IfcReferenceCurve*).

The current IFC-Bridge draft provides two different ways of defining the reference axis: as an explicit 3D reference curve (*IfcReferenceCurve3D*) or by means of 2D alignment curves (*IfcReferenceCurveAlignment2D*) created in the course of the carriageway alignment design, i.e. vertical alignment and horizontal alignment (Figure 4, A-1). The latter option is more advanced, since the resulting bridge design axis is directly based on road alignment parameters. Accordingly, the roadway design intent is transferred to the bridge design process. To this end, specific elements of roadway design such as the track transition curve clothoids (*IfcClothoid*) have been included in the data model (Figure 4, A-2).

Include Figure 4 here.

By using the geometric reference system and the roadway-specific elements for describing the reference curve, it becomes possible to describe a bridge model depending on the course of the roadway. Thus the current draft of IFC-Bridge principally fulfills the demands on bridge model data exchange as mentioned above. However, it has a significant shortcoming which hampers its use and adoption by the industry: the individual profiles of the superstructure are defined independently of one another and represented by means of explicit geometry. In order to describe a complex geometric shape, e.g. the parabolic haunch form, a large number of cross-sections have to be used to get a good approximation (Figure 3). However, as the underlying

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mathematical description of the profile variation cannot be transferred (captured) by the IFC-Bridge data model, a number of serious limitations arise. This includes the loss of the flexibility of the model with respect to the modifications of the haunch form. If such modifications are to be carried out after the model has been transferred by means of IFC-Bridge, each profile has to be updated individually, resulting in an inefficient and error-prone process. Secondly, such models are only of limited use for structural analysis, as an exact mathematical description of the haunch form is required for the calculation of centrifugal forces or the effects of post-stressing tendons, for example.

In order to overcome these limitations, the authors propose to extend the current IFC-Bridge draft by the capability to capture parametric design including the definition of geometric and dimensional constraints.

Proposed extensions to capture parametric design

The proposed IFC-Bridge extensions make it possible to exchange the sketch-based parametric geometry descriptions of bridge components, allowing the transfer of flexible, adaptable bridge models capturing the main parts of the underlying engineering knowledge and design intent. The proposed data structure extends the bridge profile definition in IFC-Bridge with more than 40 entities for describing parametric dependencies. It introduces a new entity named *IfcParametricSketch* alongside the conventional explicit IFC profile definition *IfcProfileDef*. This entity contains elements for describing parametric sketches with geometric and dimensional constraints, as described above. The data structure is illustrated by means of an EXPRESS-G diagram provided in Figure 5. In the data structure, a parametric sketch consists of three types of objects, namely the geometric elements (*IfcSketchGeometry*), the geometric constraints (*IfcSketchGeometricConstraint*) and the dimensional constraints (*IfcSketchDimensionalConstraint*).

Include Figure 5 here.

The geometric elements of the parametric sketch can be of type *IfcSketchLine*, *IfcSketchPoint* and *IfcSketchArc*. These are basic geometric objects used for 2D sketching. Depending on the type of these objects, geometric constraints can be explicitly defined using the different subclasses of *IfcSketchGeometricConstraint* (Figure 6). The relations between design constraints and the geometry objects they are acting upon are clearly defined. Explicit specifications enhance the clarity of the data structure and reduce the possibility of misinterpretation in exporting and importing systems. For example, the geometric constraint *perpendicular* (*IfcSketchPerpendicularGeometricConstraint*) can be applied only to two line objects. By contrast, *IfcSketchFixedGeometricConstraint* sets any kind of geometric objects to have a fixed position while *IfcSketchTangentialGeometricConstraing* is used to specify the *tangential* relationship between one line and one arc object. The *coincidence* between

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geometric objects is defined by *IfcSketchCoincidentGeometricConstraint* where an additional specification of the type of association (*IfcSketchConstraintGeometryAssociationType*), e.g. *EndPoint*, *StartPoint*, or *CenterPoint*, is required.

Include Figure 6 here.

Besides geometric constraints, dimensional constraints (*IfcSketchDimensionalConstraint*) can be used to describe parametric profiles (Figure 7). Each dimensional constraint refers to a user-defined parameter (attribute *Parameter*) to which an explicit numeric value or an implicit mathematical formula is assigned. The subclasses of *IfcSketchDimensionalConstraint* define which kind of dimension the constraint applies to (distance, angle or radius) and how the distance is measured (horizontally, vertically or parallel to the line). For example, the entity *IfcSketchAngularDimensionalConstraint* defines the angle between two lines while *IfcSketchAngularDimensionalConstraint* is used to dimension the radius of an arc. Similar to the definition of *IfcSketchGeometricConstraint*, geometric entities associated with a dimensional constraint are explicitly defined.

Include Figure 7 here.

Each dimensional constraint is associated with a dimensional parameter which is of type *IfcParametricValueSelect*. This is an enumeration of two different entities defined in *IfcParametricFormula* and *IfcParametricConstant.* The composite design pattern established in software engineering (Gamma et al. 1995) is adopted here (Figure 8) in order to formulate mathematical dependencies between dimensional parameters. The purpose of using a composite is to recursively organize part-whole relationships in a hierarchical tree-like structure. Accordingly, the *IfcParametricFormula* consists of a set of operands (attribute *Operands*) and an algebraic operator (attribute *Operation*). Each operand can be an *IfcParametricFormula* object (comparable with “node” in the tree) which can be further decomposed, or an *IfcParametricConstaint* (comparable with a “leaf” of the tree)*. IfcParametricConstant* is the explicit definition of a dimensional parameter with a numeric value (*IfcParametricValue*).

Include Figure 8 here.

For example, to describe the algebraic expression “Height: = Width + Length / 2 + 5”, an object named “Height” of type *IfcParametricFormula* is created as a root element (Figure 9Figure). It is composed of two different types of objects defined in the enumeration type *IfcParametricValueSet*:

- numeric values (*IfcParametricConstant*) such as the number “5”,
- formula elements (*IfcParametricFormula*), in this case the parameters “Width” and “Length”.

In addition, a formula element is linked to a set of commonly used arithmetic operators (e.g. PLUS, MINUS, DIVISION, TIMES) enumerated in the type *IfcParametricOperatorEnum*. The range of predefined operators can be extended according to the demand in engineering practice. Finally, the numeric value of the parameter *Height* is evaluated according to the formula composition from the leaves back to the root of the tree (Figure 9).

Include Figure 9 here.

Proof of concept: Case studies

To prove the suitability of the proposed IFC-Bridge extension and the benefits of exchanging parametric bridge models in the design process, we have chosen two application scenarios that represent critical aspects in today's bridge engineering practice.

In the first scenario, the extended IFC-Bridge format is used to transfer a parametric model from one parametric CAD system to another to demonstrate the interoperability that can be achieved by sharing parametric bridge models between different design systems. To realize this, we have chosen the software products Siemens NX (Siemens, 2012) and Autodesk Inventor by way of representative programs, as (1) they provide the required powerful parametric modeling functionalities, (2) they are well-established programs with a large market share in the manufacturing industry, and (3) they are based on different geometry kernels, namely Parasolid (NX) and ShapeManager (Inventor), thus adding extra complexity to developing a neutral exchange format. Functionalities for importing and exporting parametric IFC-Bridge instances have been implemented as add-on modules for these systems.

In the second exchange scenario, the parametric bridge model created in a design system is subsequently transferred to a structural analysis program, where a structural analysis of the superstructure is performed. In this case, we chose the program SOFiSTiK Structural Desktop (SSD) as it provides an extensive range of bridge analysis features. This exchange scenario demonstrates the advantages of the possibility to describe mathematical dependencies between design parameters using the proposed IFC-Bridge extension.

Example of a parametric bridge model

A highway bridge in France with a haunched superstructure was chosen to demonstrate the parametric data exchange. This three-field bridge has a total length of 308m and is divided into three sections (82m, 144m and 82m). Due to the wide span a prestressed concrete box girder superstructure was chosen and has a total width of 20.5m in order to include four carriageways. Additional reasons for choosing this bridge example are: (1) The bridge type is widespread in Europe and typically used for highway construction projects when long spans are required. (2) Providing the possibility to describe the haunch geometry by means of parametric modeling technique which is one of the main motivations for the proposed IFC-Bridge extension.

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Using parametric bridge modeling techniques, the bridge superstructure has been parameterized in the following way (Figure 10Figure): the description of the bridge's main axis, which defines the course of the roadway, is used as the central control element of the parametric bridge model. As a general rule, the axis can be curved and sloped; in this example it is a straight line on an incline.

Include Figure 10 here.

In the first step, the haunch curve is described as a function of the abscissa. Since there are three different sections in the example, three different haunch curves are required. All three haunch curves are parabolic and the overall height of the superstructure can accordingly be expressed as a function $h = f(s) = as^2+bs+c$ with the coefficients a, b and c which have to be determined in advance. All other dimensions of the cross-section which vary along the axis are also expressed in relation to the position of the cross-section (abscissa) by means of a functional dependency $d_i = f(s)$. By parameterizing the cross-section in dependence on the abscissa, only one "master" cross-section is required for describing the superstructure shape precisely in one segment. Based on the parameterized cross-section, a parametric CAD system is able to create a number of intermediate profiles which then provide the basis for a subsequent *variational sweep* operation for creating the volumetric representation of the superstructure.

Include Figure 11 here.

Figure 11 depicts the parameterized cross-section for the example. The cross-section is positioned perpendicularly to the axis of the bridge. The height and width of the outer box-girder bridge profile are determined by a dimensional constraint expressed as a function of the position of the cross-section. In addition, geometric constraints are required for describing the geometric relationships between individual elements of the cross-section. For example, the right and left boundaries of the inner and outer profile lines are restricted to being parallel to each other. The bottom line of the box girder must be vertical and perpendicular to the bridge's axis. The resulting parametric bridge model, which was designed by means of Siemens NX, is depicted in Figure 12.

Include Figure 12 here.

Exchange of a parametric bridge model between two design systems

In the first exchange scenario, the extended IFC-Bridge format is used to transfer the parametric bridge model created by means of Siemens NX to a second design system, namely Autodesk Inventor, in order to demonstrate that the parametric relationships embedded in the model are transferred completely and correctly. The realized interoperability between different bridge

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design systems is necessary to aid collaboration between those participating in the design process who often use different design systems.
Since the original draft and the proposed extension of IFC-Bridge are not supported by any commercial parametric design or structure analysis systems, it is necessary to extend these programs with IFC-Bridge import and export functionalities. The most efficient way of implementing this is to use an Application Programming Interface (API) which forms part of most commercial CAD systems on the market. An API gives advanced users access to the objects and methods for creating, deleting and modifying geometric objects and their properties in a CAD system.

In the first step, the design of the haunched superstructure is realized by means of Siemens NX. The resulting model is stored as a STEP Part 21 file (ISO 10303-21, 1994). STEP Part 21 defines the encoding mechanism for representing data complying to a given EXPRESS schema, in this case, the extended IFC-Bridge schema for capturing parametric bridge geometry. A second engineer uses Autodesk Inventor to import the existing bridge model and make design changes (i.e., he modifies the curve of the haunch form). To realize this exchange scenario, functionalities for importing and exporting parametric IFC-Bridge instances have been implemented as add-on modules for both CAD systems.

Figure 13 shows a code fragment of the created STEP P21 file which implements the parabolic curve by using the recursive definition of the *IfcParametricFormula* concept explained in the section “Proposed extensions to capture parametric design”. First, four objects of type *IfcParametricConstant* are used to define the three coefficients of the parabolic curve namely *H0_coeff_a := 0.00097* (#149), *H0_coeff_b := 0.032* (#151) and *H0_coeff_c := -3* (#152) and the abscissa indicating the position of a cross-section on the bridge axis (*abscissa_0 := 83 of* #136). The parabolic function *Height* (#147) consists of three terms (*IfcParametricFormula*) connected by the arithmetic operator *ADD* (addition). In the receiving system, the expression *Height* := *H0_ax2 + H0_bx + H0_c* is recursively evaluated until the parabolic curve is completely reconstructed *Height : = H0_coeff_a * abscissa_0 * abscissa_0 + H0_coeff_b * abscissa_0 + H0_coeff_c.*

Subsequently, the height of the girder box profile (*IfcParametricSketch*) is defined as a dimensional constraint (*IfcSketchVerticalDimensionalConstraint*) at #243 relating to the formula definition of the haunch form *Height*.

Include Figure 13 here.

After importing the parametric bridge model into the receiving CAD system, the complete geometric shape of the bridge is automatically reconstructed including all geometric and dimensional constraints. This is essentially what distinguishes this method from the exchange of

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explicit geometry, where only the resulting shape is available but not the underlying parametric dependencies, which are able to encode design intent and engineering knowledge.

As depicted in Figure 14, the haunch form of the bridge's superstructure is modified in the receiving parametric system by altering the main design parameters, in this case the coefficients of the haunch curve. Bridge designers benefit significantly from being able to exchange parametric bridge models, preserving the flexibility and controllability of the original model. Major modifications to the bridge structure system, such as changing the bridge axis, can be performed easily.

Include Figure 14 here.

Exchange Parametric Model between Design and Structural Analysis Systems

Structural analysis forms an important aspect of the bridge engineering process, since it serves to prove the structural safety of the bridge. In addition, the computational results form the basis for optimizing the geometry of the bridge. In this context, geometric optimization means striving to save on material costs while simultaneously maintaining the safety of the structure. To achieve an ideal workflow, bridge designers and structural engineers should be able to share the bridge's geometry with the full range of design modification features.

Include Figure 15 here.

In this application scenario, we demonstrate the transfer of parametric geometry from a bridge design system to a structural analysis system using the extended IFC-Bridge format. The parametric bridge model stored as a STEP Part 21 file is imported into SOFiSTiK Structural Desktop (SSD). This avoids the need to manually reconstruct the geometric system for structural analysis and enables the bridge geometry to be created automatically in the structural analysis system. First, the axis of the bridge is created as a reference curve in the global coordinate system. The definition of the support system (Figure 15(a)) which is an essential prerequisite for structural analysis (such as the load test) is derived automatically from the dimensional parameter *span_width* which is explicitly available in the IFC-Bridge model. Subsequently, the exact formulation of the haunch shapes (Figure 15(b)) can be extracted from the parametric formula definition and directly used in the SOFiSTiK system.

The resulting parabolic curves define the height of all possible cross-sections of the bridge's superstructure. We distinguish between two types of cross-sections: master cross-sections which are defined by the designer and capture parametric dependencies (e.g. the height of cross-section in dependence of the form of the haunch) and intermediate cross-sections generated by the structural analysis system. Figure 15(c) shows one of the master cross-sections containing the parametric dimensions ("height" and "width"). The generated

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intermediate cross-sections are depicted in Figure 15(d). They are required to generate the finite element mesh shown in Figure 16(a), which forms the basis for the subsequent stress and displacement computations.

Include Figure 16 here.

Beyond transferring the geometry from the design system to the structural analysis system, a large amount of computation-specific parameters, such as the properties of the construction materials, the range of load forces, the load positions, as well as the applicable national or international building code (i.e., the German DIN Norm or Euro Code are required for performing the structural analysis).

After defining the geometric system and the specifying parameters for the structural analysis, various structural tests, such as the bridge load test, can be carried out to prove the structural stability. In the context of geometric optimization, design changes are suggested by the structural engineer and can be transferred back to the design system automatically by using the neutral data format IFC-Bridge with the proposed parametric extension. The result of a preliminary load test of the bridge example is illustrated in Figure 16(b).

Conclusion and Future Work

Parametric modeling provides a means of constructing geometric models by using parameters and defining dimensional and geometric constraints. This allows for the creation of inherently flexible models, which capture the underlying engineering knowledge and can be controlled by the variation in the primary parameters. On the one hand, this allows for a rapid adaptation of the design in the case of changing boundary conditions and, on the other hand, it facilitates the reusability of the models across multiple projects. Both aspects have a significant impact on the efficiency of design and engineering processes.

The application of parametric modeling techniques is particularly attractive for designing bridges, since fairly standardized approaches can be applied to form finding. The resulting geometry of the bridge and its components is mainly governed by external boundary conditions, such as the alignment of the overlying and the undercrossing carriageway. However, while the technology of parametric modeling is well established in the automotive and manufacturing industry, it is only gradually being adopted in the AEC sector. One of the main reasons is the substantial fragmentation of the design and engineering process which corresponds to a strong demand for data exchange between different participants and accordingly a need for interoperability between different software systems.

The IFC-Bridge data format aims at providing this interoperability for bridge models by extending the Industry Foundation Classes (IFC) by bridge-specific semantic and geometric

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elements. However, the current draft of the data model shows a number of shortcomings that prevent it being used in engineering practice. One of the main issues is the lack of support for a parametric description of a superstructure profile. In the case of a varying profile, the restriction to explicit geometry results in the need to store and exchange a large amount of mutually independent cross-sections. The underlying design intent, such as the mathematical description of the curve of the haunch, gets lost during the exchange process. Accordingly, the flexibility of the original model becomes inaccessible in the receiving system.

In this paper we propose a model for the interoperable, parametric description of bridge structures. The model is based on the notion of two-dimensional sketches enhanced with geometric and dimensional constraints to make it possible to capture the design intent. Extending the existing IFC-Bridge model to include the semantic description of bridges, the suggested data model introduces a novel way for the efficient and flexible exchange of bridge design geometries. This is achieved by harnessing the parametric capabilities of existing modeling applications in a vendor-independent data format.

The extended IFC-Bridge schema is evaluated in two real-world application scenarios: In cooperation with structural engineers, a bridge designer uses a parametric 3D modeling system to model the bridge. The parametric description includes the definition of the bridge's axis, the haunch form and the cross-section of the superstructure. The design model is subsequently exported into the extended IFC-Bridge data model which in turn is imported into a structural analysis system. This system automatically reconstructs the geometric form as well as the parametric description. This type of modeling for bridges gives structural engineers access to data which is available to the bridge designer by sharing design intentions and using them to optimize the bridge structure.

The proposed parametric IFC-Bridge schema makes it possible to transfer parametric models between design and structural analysis systems. The parametric description of bridge structures can be shared by both domain-specific systems. The data interoperability is improved significantly. While this paper has presented the successful integration of parametric concepts into a neutral data format for the exchange of bridge models, future work will focus on bringing this attractive and powerful means of describing geometry to the broad field of general building design by developing a suitable extension for the general IFC framework.

Acknowledgements

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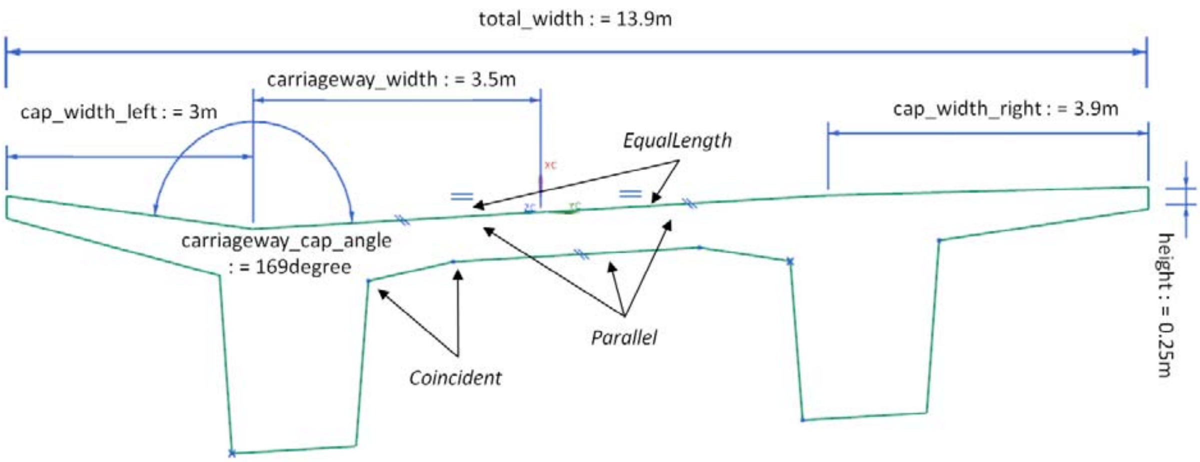

Figure 1: Example of parameterized cross-section of the slab-beam bridge with user-defined dimensional and geometric constraints

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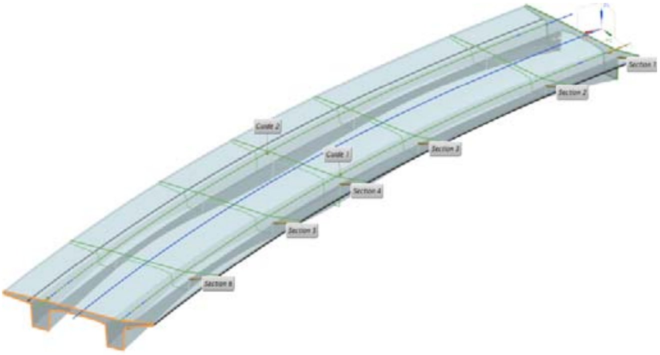

Figure 2: Example of a solid bridge superstructure created by variational extrusion along the reference curves involving seven cross-sections of the bridge's superstructure; the resulting solid body is divided accordingly into six sections

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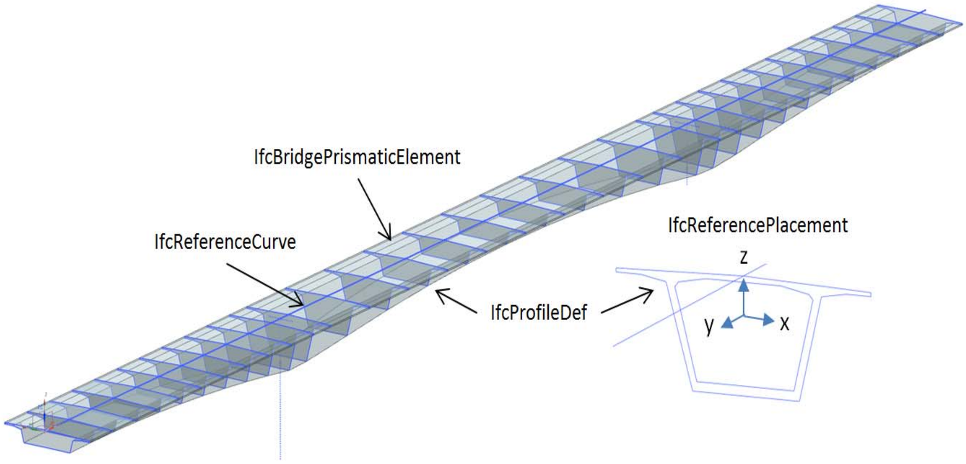

Figure 3: Principle of geometry representation in IFC-Bridge

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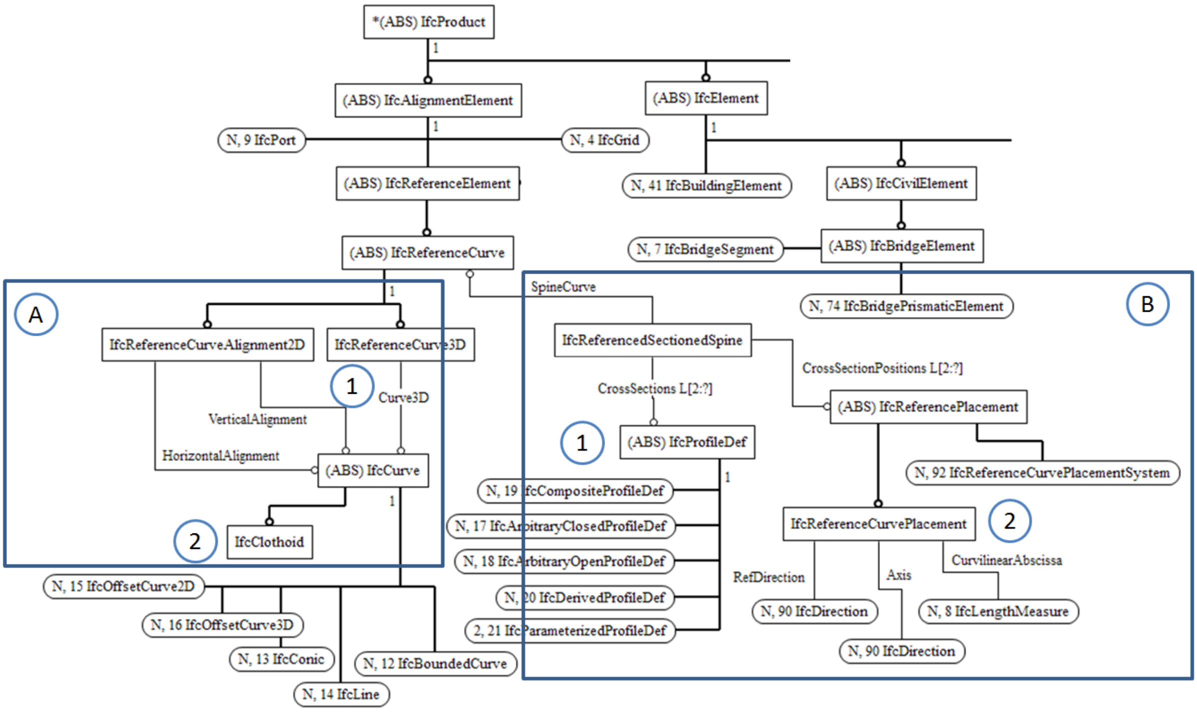

Figure 4: Entities for geometry representation in IFC-Bridge

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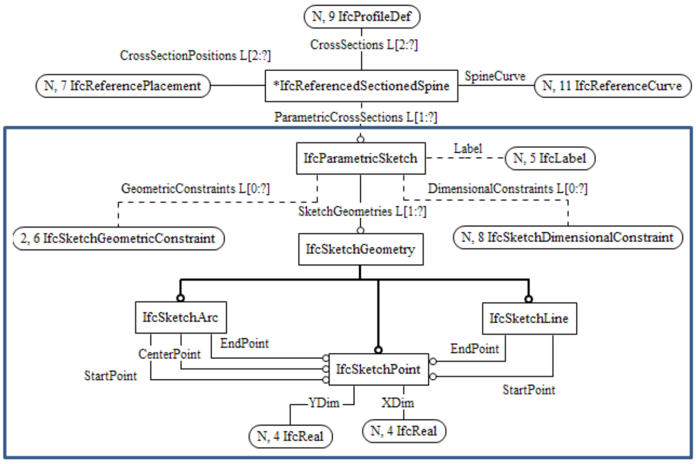

Figure 5: EXPRESS-G Diagram of the parametric IFC-Bridge extension depicting the entities *IfcParametricSketch, IfcSketchGeometricConstraint* and *IfcSketchDimensionalConstraint*

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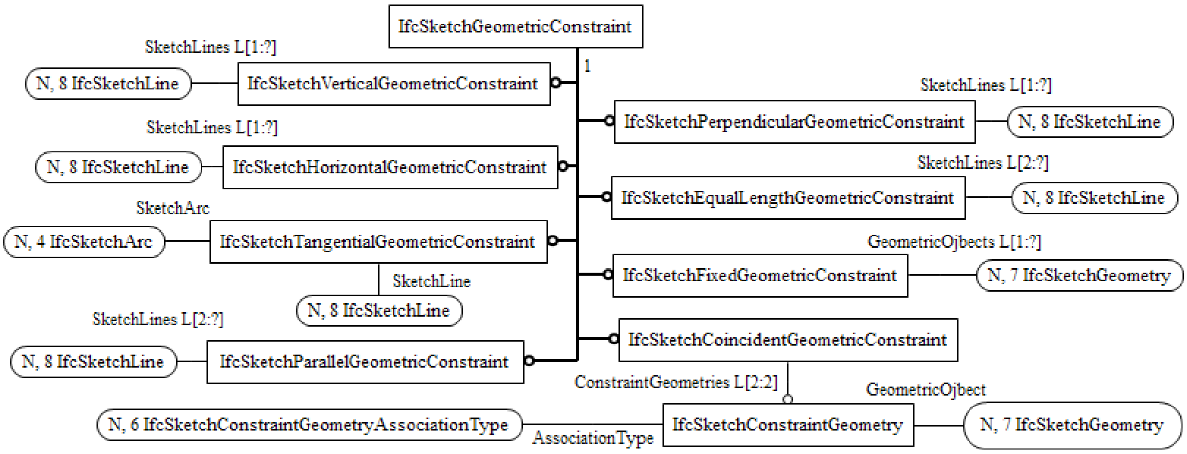

Figure 6: EXPRESS-G Diagram of the parametric IFC-Bridge extension depicting the entity *IfcSketchGeometricConstraint*

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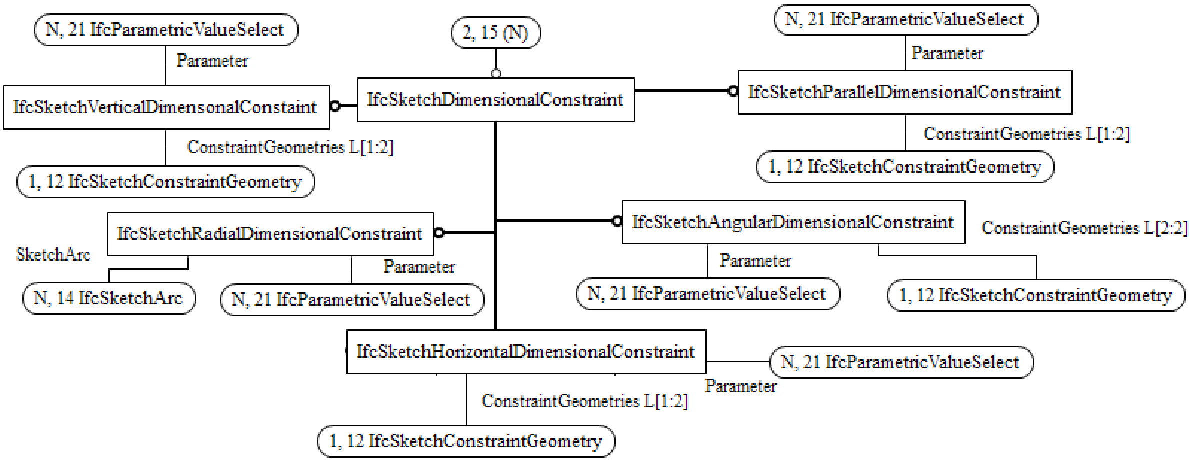

Figure 7: EXPRESS-G Diagram of the parametric IFC-Bridge extension depicting the entity *IfcSketchDimensionalConstraint*

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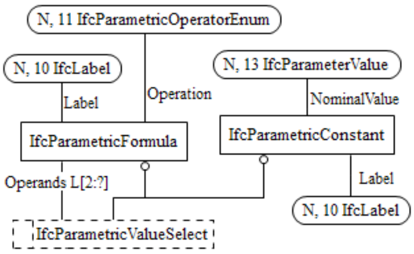

Figure 8: EXPRESS-G Diagram of the parametric IFC-Bridge extension depicting the entities *IfcParametricFormula* and *IfcParametricConstant*

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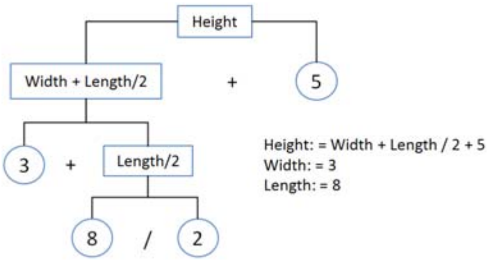

Figure 9: Example of recursively composed mathematical expression with *IfcParametricFormula* (rectangle) and *IfcParametricConstant* (circle) in a tree-like structure

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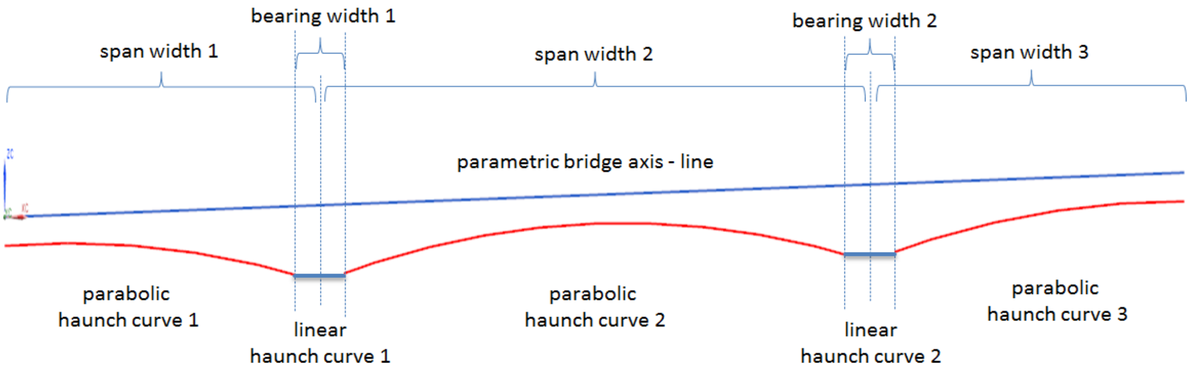

Figure 10: Schematic longitudinal view of bridge's superstructure with haunches together with the corresponding dimensional parameters (span width and bearing width)

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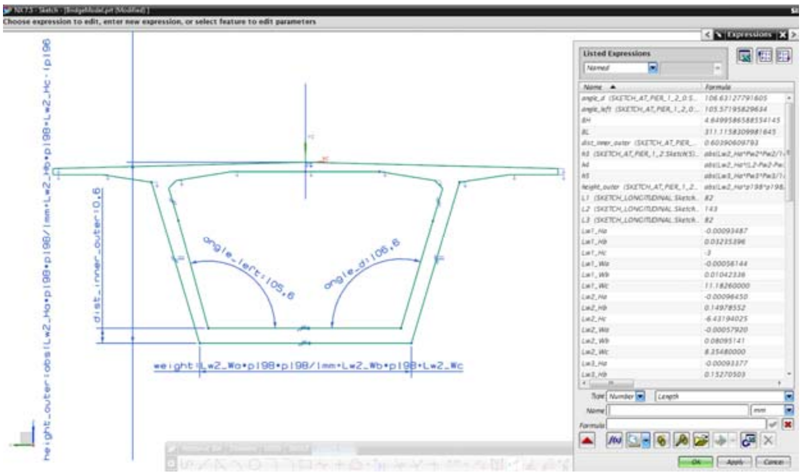

Figure 11: The parameterized cross-section of the master bridge in parametric dependence on the bridge axis with dimensional and geometric constraints; the coefficients of the parabolic haunch curves are listed on the right

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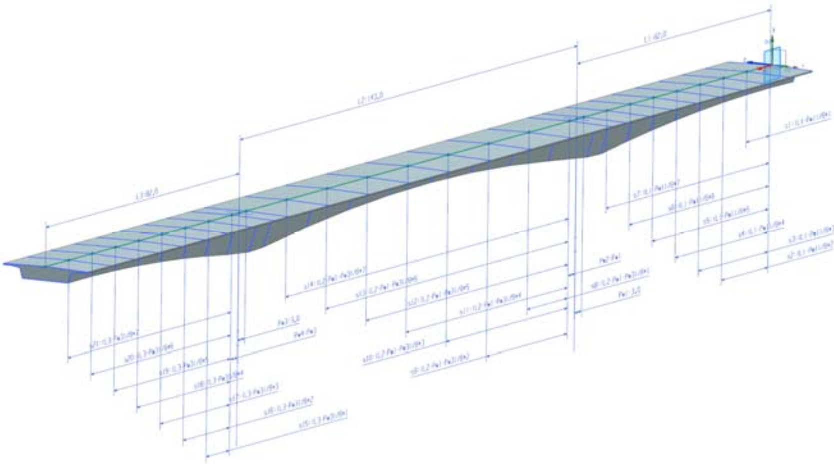

Figure 12: Resulting parametric bridge model in Siemens NX

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```
#136=IFCPARAMETRICCONSTANT('abscissa_0',83);
...
#147=IFCPARAMETRICFORMULA('Height',(#152,#150,#148),.ADD.);
#148=IFCPARAMETRICFORMULA(,H0_ax2',(#149,#136,#136),.MULTIPLY.);
#149=IFCPARAMETRICCONSTANT('H0_coeff_a',-9.3487E-4);
#150=IFCPARAMETRICFORMULA('H0_bx',(#151,#136),.MULTIPLY.);
#151=IFCPARAMETRICCONSTANT('H0_coeff_b',0.03235396);
#152=IFCPARAMETRICCONSTANT('H0_c',-3.0);
...
#166=IFCSKETCHPOINT('p2',$,0.0,0.0);
#172=IFCSKETCHPOINT('p8',$,5.5913,-3.0);
...
#243=IFCSKETCHVERTICALDIMENSONALCONSTAINT(#147,(#244,#245));
#244=IFCSKETCHCONSTRAINTGEOMETRY($,$,.NONE.,#166);
#245=IFCSKETCHCONSTRAINTGEOMETRY($,$,.NONE.,#172);
```

Definition of parabolic haunch form:

```
H0_coeff_a = -9.3487E-4
H0_coeff_b = 0.03235396
H0_c = -3.0

Heigth = H0_ax2 + H0_bx + H0_c
H0_ax2 = H0_coeff_a * abscissa_0 * abscissa_0
H0_bx = H0_coeff_b * abscissa_0
```

Definition of dimensional parameter *Height* of box-girder and reference to parametric formula

Figure 13: Example of a parametric formula definition in a STEP file (left) and code interpretation (right) respectively

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DOI: 10.1061/(ASCE)CP.1943-5487.0000286

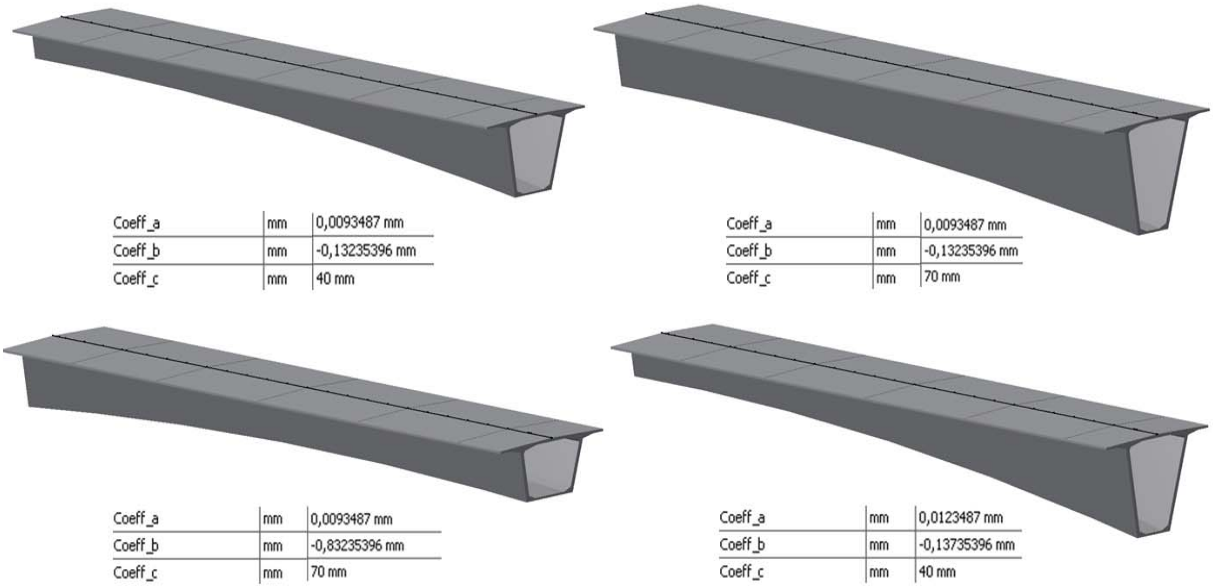

Figure 14: Exchange of design intent and modifications of bridge superstructure in receiving parametric CAD system Autodesk Inventor

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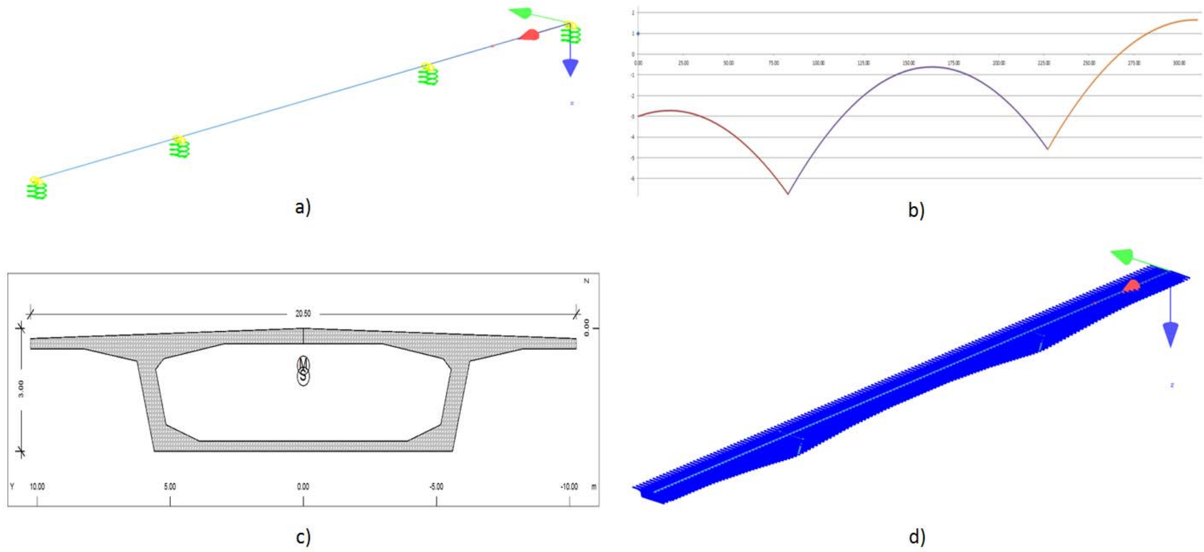

Figure 15: Reconstruction of the bridge's geometry in the structural analysis system using a parametric description; (a): Bridge axis with support system; (b): description of the haunch curve using the formulas transmitted via IFC-Bridge; (c): definition of the parametric cross-section; (d): generating intermediate cross-sections

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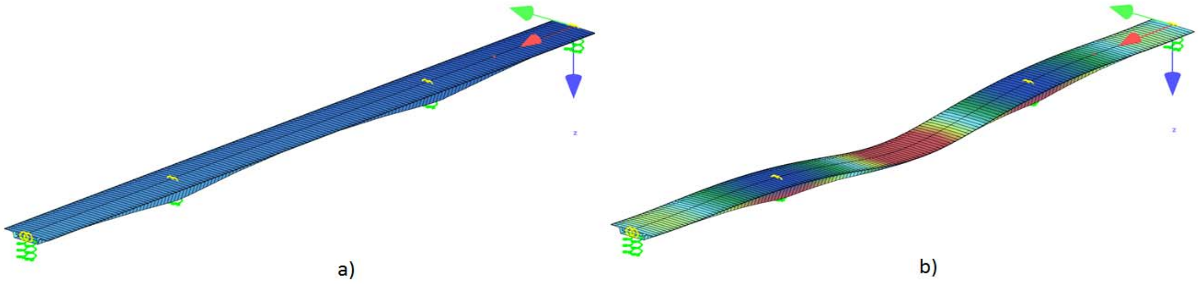

Figure 16: (a): Mesh of the bridge's superstructure; (b) Displacement results of the load test

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Figure 1: Example of parameterized cross-section of the slab-beam bridge with user-defined dimensional and geometric constraints

Figure 2: Example of a solid bridge superstructure created by variational extrusion along the reference curves involving seven cross-sections of the bridge's superstructure; the resulting solid body is divided accordingly into six sections

Figure 3: Principle of geometry representation in IFC-Bridge

Figure 4: Entities for geometry representation in IFC-Bridge

Figure 5: EXPRESS-G Diagram of the parametric IFC-Bridge extension depicting the entities *IfcParametricSketch, IfcSketchGeometricConstraint* and *IfcSketchDimensionalConstraint*

Figure 6: EXPRESS-G Diagram of the parametric IFC-Bridge extension depicting the entity *IfcSketchGeometricConstraint*

Figure 7: EXPRESS-G Diagram of the parametric IFC-Bridge extension depicting the entity *IfcSketchDimensionalConstraint*

Figure 8: EXPRESS-G Diagram of the parametric IFC-Bridge extension depicting the entities *IfcParametricFormula* and *IfcParametricConstant*

Figure 9: Example of recursively composed mathematical expression with *IfcParametricFormula* (rectangle) and *IfcParametricConstant* (circle) in a tree-like structure

Figure 10: Schematic longitudinal view of bridge's superstructure with haunches together with the corresponding dimensional parameters (span width and bearing width)

Figure 11: The parameterized cross-section of the master bridge in parametric dependence on the bridge axis with dimensional and geometric constraints; the coefficients of the parabolic haunch curves are listed on the right

Figure 12: Resulting parametric bridge model in Siemens NX

Figure 13: Example of a parametric formula definition in a STEP file (left) and

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Figure 16: (a): Mesh of the bridge's superstructure; (b) Displacement results of the load test