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Development of an Autodesk Revit Add-in for the Parametric Modeling of Bridge Abutments for BIM in Infrastructure

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Master Thesis

for the Master of Science degree in Civil Engineering

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Abstract

Development of an Autodesk Revit Add-in for the Parametric Modeling of Bridge Abutments for BIM in Infrastructure.

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In the scope of BIM in infrastructure, aim of this thesis was to develop a plug-in tool for Autodesk Revit, for the modeling of a parametric bridge abutment, in cooperation with SSF Ingenieure AG. After research, it was concluded that, various state of the art BIM modeling applications for bridges compatible with the Revit environment do not provide any options for the complete parametric modeling of bridge abutments with the required geometric accuracy. The developed Abutment-Tool enables Revit users to model abutments based on the “cross-sectional” concept. As a result, the created abutments correspond not only to straight, but also curved road alignments and therefore match the geometry of curved bridge superstructures. The achieved geometric accuracy of the Abutment-Tool proves to be very satisfying and is evaluated in various test cases presented in this thesis.

Zusammenfassung

Entwicklung eines Autodesk Revit Add-ins für die parametrische Modellierung von Brückenwiderlager für BIM in der Infrastruktur.

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Im Rahmen von BIM in der Infrastruktur ist Ziel dieser Arbeit, in Zusammenarbeit mit der SSF Ingenieure AG, ein Plug-in Tool für Autodesk Revit zur Modellierung eines parametrischen Widerlagers zu entwickeln. Nach Recherche wurde festgestellt, dass verschiedene aktuelle BIM-Modellierungsanwendungen für Brücken, die mit der Revit-Umgebung kompatibel sind, keine Option für die vollständige parametrische Modellierung von Brückenwiderlagern mit der erforderlichen geometrischen Genauigkeit bieten. Das entwickelte Widerlager-Tool ermöglicht es Revit-Anwendern, Widerlager nach dem Konzept des "Querschnitts" zu modellieren. Dadurch entsprechen die erzeugten Widerlager nicht nur geraden, sondern auch gekrümmten Straßenausrichtungen und passen sich somit der Geometrie von gekrümmten Brückenaufbauten an. Die erzielte geometrische Genauigkeit des Widerlager-Tools erweist sich als sehr zufriedenstellend und wird in verschiedenen in dieser Arbeit vorgestellten Testfällen bewertet.

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Glossary

AEC	Architecture, Engineering and Construction
API	Application Programming Interface
BIM	Building Information Modeling
BMVI	Bundesministerium für Verkehr und Infrastruktur
BrIM	Bridge Information Modeling
CAD	Computer Aided Design
CIM	Civil Information Modeling
GML3	Geography Markup Language Version 3.1.1
GUID	Global Unique Identifier
HOAI	Honorarordnung für Architekten und Ingenieure
IAI	International Alliance for Interoperability
IFC	Industry Foundation Classes
IFCPL	Industry Foundation Classes Programming Language
LOD	Level of Detail
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
MVD	Model View Definition
NCHRP	National Cooperative Highway research Program
OGC	Open Geospatial Consortium
ParamML	Parametric Markup Language
PSET	Property Set
ROI	Reduction of Investment
STEP	Standard for the Exchange of Product model data
UI	User Interface
UML	Unified Modeling Language
VDI	Verein Deutscher Ingenieure
VPI	Vertical Point of Intersection
W3C	World Wide Web Consortium
XML	eXtensible Markup Language
XSD	XML (Extensible Markup Language) Schema Documentation

Chapter 1

Introduction

1.1 Initial situation and problem stating: BIM in Infrastructure

In the last decade Building Information Modeling (BIM) has attracted a lot of attention in the architectural, engineering and construction (AEC) industries. BIM processes have already been applied for actual design and construction of several building projects worldwide. Almost a decade ago, BIM for the civil infrastructure domain had not advanced as much as for the building industry (Yabuki, 2010). The Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) first introduced the term Construction Information Modeling (CIM) in 2012, which is interpreted as “BIM for Infrastructure” (Yabuki, 2012).

There are various reasons that caused this delay. It is a fact that, in most cases the public sector handles the construction of infrastructure projects. In the building sector the cost of design varies from 7 to 10% of the total construction cost, whereas it is only between 3 and 4% in the public infrastructure domain (Yabuki, 2010). As a consequence, the actual reduction of the design costs and the so called “return on investment” (ROI) may be not very significant in the civil infrastructure domain, when compared to the building domain, by introducing BIM process. In addition, many civil engineers of the infrastructure domain are not concerned about the effectiveness of the processes that are currently used for the design and construction of infrastructural measures. Under these circumstances both public sector and individual engineering companies do not dare to engage and take risks by introducing new technologies, such as BIM (Yabuki, 2010). Another major obstacle for the development of BIM in infrastructure is the lack of various effective BIM software tools specialized in the infrastructure domain, as well as the lack of suitable information exchange data formats.

However, various studies have proven that BIM can have major merits in the civil infrastructure domain, as summarized in Jones & Bernstein (2012). The most significant advantage is

that [CIM](#) models are expected to improve the efficiency and the quality of the construction with clash detection, 4D and 5D CAD capabilities. As a result, the number and scale of design changes can be dramatically decreased. Furthermore, another important aspect is achieving lower project risks by better planing of multiple project variants (Jones & Bernstein, 2012).

In order to promote [CIM](#), it is necessary to develop interoperable product models for sharing and exchanging data, as well as suitable modeling tools for their creation. For the development of such product data models and tools much research is required, not only at universities and institutes, but also at companies.

Germany has become one of the major European countries to mandate the implementation of BIM, closely following United Kingdom's lead. Germany's Federal Ministry of Transport and Digital Infrastructure (Bundesministerium für Verkehr und Infrastruktur, [BMVI](#)) founded the "Construction of Major Projects Reform Commission" in April 2013. BIM has been acknowledged as a major step towards utilising the opportunities and the benefits that are offered by the digitalization in the construction industry. In December 2015 the Federal Minister of Transport and Digital Infrastructure, Alexander Dobrindt, officially announced that, the use of BIM will become mandatory for all transportation projects by the end of year 2020 (BMVI, 2015).

1.2 Scope and Outline of Thesis

The scope of this thesis is to investigate the current state of infrastructure planning processes, the current state of data modelling in infrastructure with focus on road bridges, as well as the available bridge modeling software tools. In addition, in the context of this thesis, a plug-in tool for Revit is developed with which a parametric bridge abutment is modelled within the Revit environment. This tool is meant to be part of a Bridge-Module that creates a complete parametric bridge model in Revit.

In the second chapter of this thesis, the current state of planning processes in infrastructural projects is presented, with a greater focus on German specifications and guidelines concerning roads and highways. The project phases are presented and the road alignment design process is explained in detail. In the end of the chapter, a modeling concept for the creation of 3D parametric bridges is briefly presented and explained.

In the third chapter, after a brief background on standardization efforts regarding the infrastructure domain, various BIM data schemas for bridges are presented. For better understanding the data schemas are divided in two categories: data schemas based on Extensible Markup Language ([XML](#)) and data schemas based on EXPRESS. The last section of the chapter includes a small evaluation of the data formats.

The next chapter contains an overview of currently existing software tools, that can be used for the modeling of bridges. Focus is given in tools that operate in the Revit environment. The workflow of each application, its characteristics and its limitations are briefly explained.

The sixth chapter presents the Abutment-Tool that was developed in the context of this thesis. Initially, general information about bridge abutments, their geometry and functions is provided. Next, the user interface ([UI](#)) of the plug-in is presented and the workflow for the parametric modeling of the abutment is stepwise exhibited. Finally, various results of created abutments are shown. A further important aspect is then the export of the abutment as a neutral data format.

In the last chapter considerations for future improvements for the Abutment-Tool are briefly presented and the outlook of this thesis is summarized.

Chapter 2

Current State of Infrastructure Planning Processes

2.1 Overview

Since thousands of years, roads and bridges have been part of human civilisations around the globe. Nowadays, infrastructure has become a very important aspect of the modern society with the increasing mobility in our world, that is needed in order to connect people and move goods to their destinations. In the past few years, the German government funded a considerable amount, not only for the maintenance and upgrades of existing roads, railways and waterways, but also the construction of new infrastructure measures (BMVI, 2015).

Generally, an infrastructure project consists of two phases, the planning and the construction phases. In Germany the “Schedule of Services and Fees for Architects and Engineers” (“Honorarordnung für Architekten und Ingenieure”, [HOAI](#)) regulates each project phase, the responsibilities of the involved parties and the requirements for the execution of the infrastructural project. The whole planning process consists of the following four phases: Establishing the basis of the project (Grundlagenermittlung), preliminary design (Vorplanung und Kostenschätzung), final design (Entwurfsplanung und Kostenberechnung) and building permission application (Genehmigungsplanung) ([HOAI](#), 2013).

Nowadays, the design of roads and bridges in most cases across the world is realised with the use of 2D drafts and drawings. These 2D drawings describe implicitly the 3D geometry of the road or bridge and contain the legally binding information for the execution. The main advantage of these 2D design drawings is, that they can be directly used as construction drawings in the execution phase (FGSV, 1996). On the other hand, the disadvantage of 2D drawings lies in the process of data and information exchange. During every design process the drawings need to be transferred and exchanged between various engineers, updated and again

exchanged many times and between a lot of participants. Furthermore, the 2D drawings, either in paper form or in the digital form of .DWG or .PDF formats, are very limited in the information they contain. This means that, in order to include the necessary information, a larger number of drawings is required to be created and exchanged. As a consequence, a larger number of drawings needs to be updated after each exchange too. It is thereby obvious that, the larger the number of documents exchanged, the higher the possibility for errors (Borrmann *et al.*, 2018).

2.2 Road Design with Location Plan, Longitudinal Section and Cross Section

Firstly, the 2D road axis is designed on the site plan (e.g. the global x-y plane) with the use of various geometric routing elements, such as straight lines, circular arcs and transitioning lines in order to form a continuous axis. Subsequently, the gradients of the 2D axis are planned in the global Z axis direction in the elevation plan. Straight lines are connected to each other with the help of parabolic curves in order to form crests and sags. Therefore, the superimposition of the various geometric elements in the site and elevation plan results in the 3D road course, as illustrated in Fig.2.1 (Ji, 2014). The exact process for creating the alignments is given in the following subsections. The same processes are used for the creation of the alignment used in the Abutment-Tool and is presented in detail in chapter 5

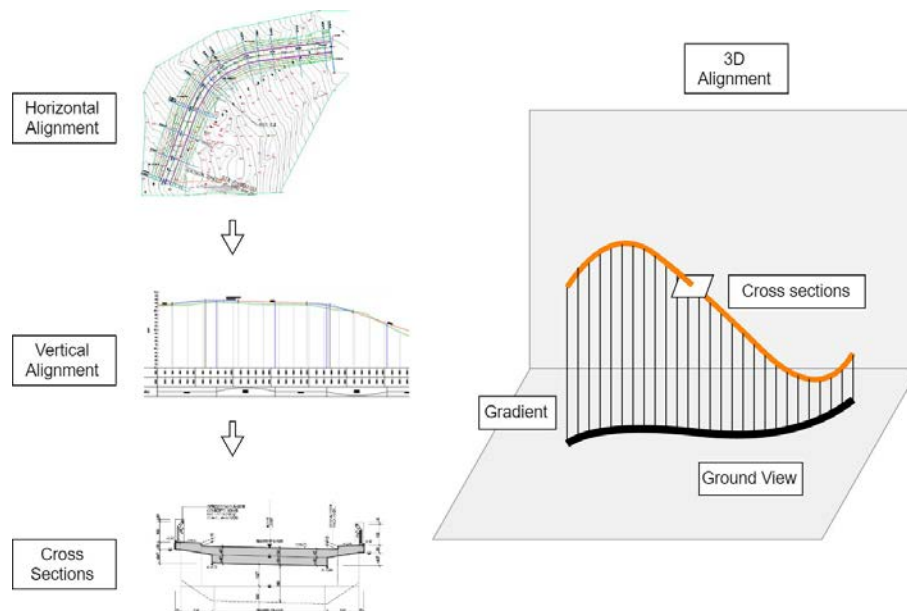


Figure 2.1: Implicit description of the 3D alignment axis, based on Ji (2014)

The alignment of a bridge is similarly defined as (MainDOT, 2004):

“The baseline for construction of a bridge and its approach roadway, described horizontally by a series of tangents and circular arcs, and vertically by a series of tangents and parabolic curves.”

The basic layouts are briefly presented in section 2.3.

2.2.1 Types and Properties of the Horizontal Alignment

As mentioned previously, the purpose of the site plan is the design of the 2D horizontal axis. The horizontal alignment for linear transportation facilities, such as highways and railways, consists of horizontal tangents, circular curves and transition curves. Fig. 2.2 illustrates an example of the components of a horizontal alignment (FGSV, 1995).

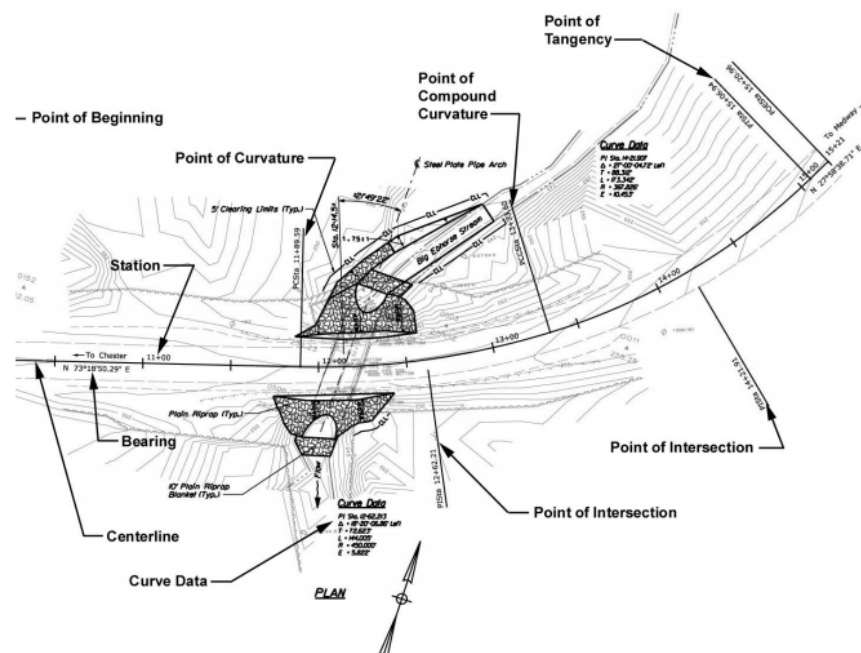


Figure 2.2: Example components of a horizontal alignment, from Ray *et al.* (2014)

Circular Curves

Horizontal curves are usually circular arcs. Fig. 2.3, left illustrates several of their important features. The main points that describe a circular arc are the following (Wunderlich, 2013):

- the arc starting point A
- the arc end point B
- the arc center M
- the tangent intersection point D (intersection point of the two tangents of the circular arc that pass through points A and B)

- the zenith point S as an intersection point of the straight line DM with the arc. S divides the bow b in half.

Secondary points are:

- the middle point S' of the cord AB
- points E , F and G

Further in Wunderlich (2013), various methods for constructing circular arcs with specific constraints and boundary conditions are described.

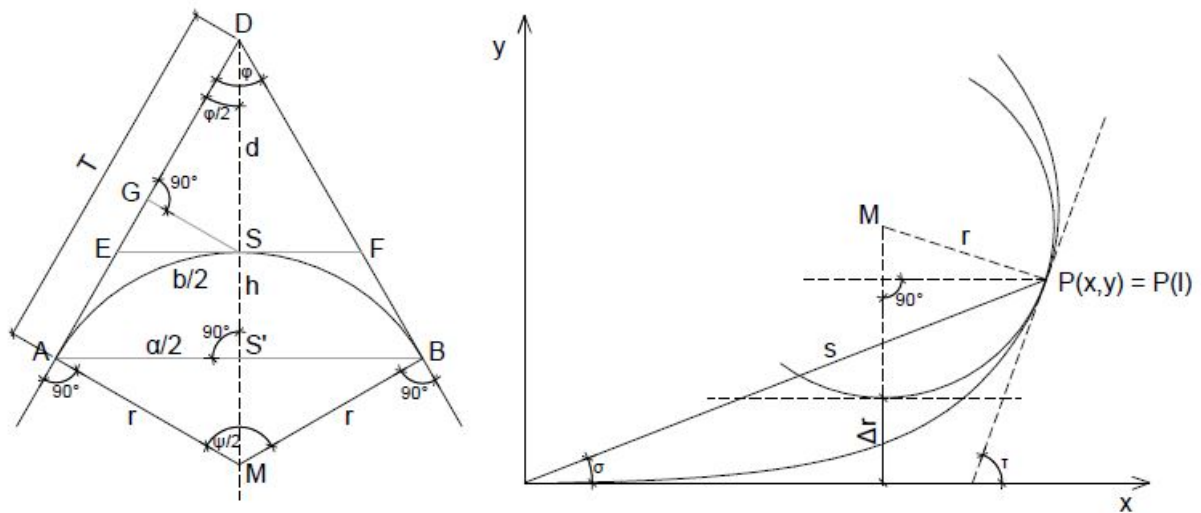


Figure 2.3: A circular curve and its properties (left), a clothoid (right), based on Wunderlich (2013)

Transition Curves

In the creation of the horizontal alignment, transition curves are used, either to connect the straight lines to the circular curves or to connect circular curves with each other. Several kinds of curves can be used for this purpose. The only one discussed further in this thesis is the clothoid spiral, also called Euler spiral, for which the radius of curvature varies as the inverse of the distance along the curve from its beginning. Other transitional curves are sinusoidal curves, cubic parabola, BLOSS curves and many more.

Euler spirals are used both for aesthetic reasons and because they provide a “rational” superelevation transition (see also Fig.2.5, right). In the case of highways, spirals are most appropriate for roadways with relatively high design standards, where curves with large radii are used. Under these circumstances drivers are often able to see a considerably long way ahead on the roadway (FGSV, 1995).

The constant parameter A is called “flatness” or “homothetic parameter” of the clothoid and it defines the size of a clothoid. The clothoid equations can be defined starting from the

condition of linear relation between the radius r and the arc length l , which is (Wunderlich, 2013):

$$k = \frac{1}{r} = c \cdot l \Rightarrow A^2 = r \cdot l \quad (2.1)$$

with k being the curvature and specifically

$$A^2 = r_E \cdot l_E \quad (2.2)$$

with r_E and l_E being the radius and length at the end of the clothoid curve. For $A = 1$ we get the normalised clothoid curve with:

$$\frac{1}{r} = k = l \quad (2.3)$$

All clothoids are similar to the normalised clothoid. Fig. 2.3, right illustrates the most important properties of a clothoid. The easiest way to describe a clothoid is by parametrisation of its length with the use of the linear relationship $A^2 = r \cdot l$. However, for practical reasons it makes more sense to derive and calculate Cartesian points (Wunderlich, 2013). The term dl denotes a differential arc length element and the direction of the tangent τ is measured in radians. With the help of the differential geometry then following applies:

$$dl = r d\tau = \frac{1}{k} d\tau \quad (2.4)$$

$$d\tau = k dl = \frac{1}{A^2} l dl \quad (2.5)$$

After integration following relation is derived:

$$\tau = \frac{l^2}{2A^2} + C \quad (2.6)$$

and in case of a horizontal tangent at the starting point of the clothoid ($\tau = 0 \Rightarrow l = 0$) we get $C = 0$. Therefore one can derive the Cartesian coordinates for a clothoid with the formulation of the following integrals:

$$dx = \cos \tau dl = \cos \frac{l^2}{2A^2} dl \Rightarrow x = \int_0^l \cos \frac{l^2}{2A^2} dl \quad (2.7)$$

$$dy = \sin \tau dl = \sin \frac{l^2}{2A^2} dl \Rightarrow y = \int_0^l \sin \frac{l^2}{2A^2} dl \quad (2.8)$$

These integrals are called Fresnel integrals. Since there is no closed solution for these integrals it is necessary to use the series of sinus and cosinus (Runge-Kutta Method). With $\bar{l} = \frac{l}{A}$ being the length of the normalised clothoid so that following equations applies (Wunderlich, 2013):

$$\tau = \frac{\bar{l}^2}{2} \quad (2.9)$$

and

$$dl = A d\bar{l} \quad (2.10)$$

After developing the sinus and cosinus series (up to the third term) one derives following equations:

$$\cos \frac{\bar{l}^2}{2} = 1 - \frac{\left(\frac{\bar{l}^2}{2}\right)^2}{2!} + \frac{\left(\frac{\bar{l}^2}{2}\right)^4}{4!} \mp \dots \quad (2.11)$$

$$\sin \frac{\bar{l}^2}{2} = \frac{\bar{l}^2}{2} - \frac{\left(\frac{\bar{l}^2}{2}\right)^3}{3!} + \frac{\left(\frac{\bar{l}^2}{2}\right)^5}{5!} \mp \dots \quad (2.12)$$

These equations can now be integrated and one derives the solution:

$$x = A \sum_{n=1}^{\infty} (-1)^{n+1} \frac{\bar{l}^{4n-3}}{(4n-3)(2n-2)!2^{2n-2}} = A\bar{l} \left(1 - \frac{\bar{l}^4}{40} + \frac{\bar{l}^8}{3456} - \frac{\bar{l}^{12}}{599040} + \frac{\bar{l}^{17}}{17547264} - \dots \right) \quad (2.13)$$

$$y = A \sum_{n=1}^{\infty} (-1)^{n+1} \frac{\bar{l}^{4n-1}}{(4n-1)(2n-1)!2^{2n-1}} = A\frac{\bar{l}^3}{6} \left(1 - \frac{\bar{l}^4}{56} + \frac{\bar{l}^8}{7040} - \frac{\bar{l}^{12}}{1612600} + \frac{\bar{l}^{17}}{588493440} - \dots \right) \quad (2.14)$$

The explicit formulation $f(x) = y$ is then (Wunderlich, 2013):

$$\frac{y}{A} = \frac{1}{6} \left(\frac{x}{A}\right)^3 + \frac{1}{105} \left(\frac{x}{A}\right)^7 + \frac{293}{237600} \left(\frac{x}{A}\right)^{11} + 0,0002053995 \left(\frac{x}{A}\right)^{15} + 0,0000387463 \left(\frac{x}{A}\right)^{19} + \dots \quad (2.15)$$

and the derivative:

$$y' = \tan \tau = \frac{1}{2} \left(\frac{x}{A}\right)^2 + \frac{1}{15} \left(\frac{x}{A}\right)^6 + \frac{293}{21600} \left(\frac{x}{A}\right)^{10} + 0,0030809925 \left(\frac{x}{A}\right)^{14} + 0,0007361797 \left(\frac{x}{A}\right)^{18} + \dots \quad (2.16)$$

2.2.2 Types and Properties of the Vertical Alignment

The aim of the elevation designing is the planning of the vertical alignment. The elevations plan is depicted in a longitudinal section of the road axis, forming a cutting section with the terrain. The vertical alignment is subsequently described with the stationing of the road axis through specific routing elements in the elevation plan. Such routing elements are tangents, resulting in constant grades, or parabolic curves, resulting in crests and sags (Freudenstein, 2015).

The longitudinal inclination, also called tangent grade, describes the slope of the road and is given in percentage. In Germany, the limits for the inclinations are specified in the technical regulations RAS (FGSV, 1995). The underlying decision criteria for the selection of the slopes are the design speed and the road category, which have already been determined prior to the road design. The slope S is defined according to the height difference of the stations as following:

$$S = \frac{h_2 - h_1}{s_2 - s_1} \cdot 100\% \quad (2.17)$$

where s_1 and s_2 are the inclinations of the straight lines through the two adjacent tangent intersections.

As shown in Fig. 2.4, the abscissa of the coordinate system of the longitudinal section represents the stationing. The vertical tangents with different grades are joined by vertical parabolic curves (Freudenstein, 2015).

The parabolic, rounding curve of a crest or sag is defined by the tangent length T and the radius H . T is the horizontal distance between the start and end points of the rounding curve. The radius H is the radius of curvature of the rounding curve and results from the longitudinal inclinations and the tangent length with the following equation (Freudenstein,

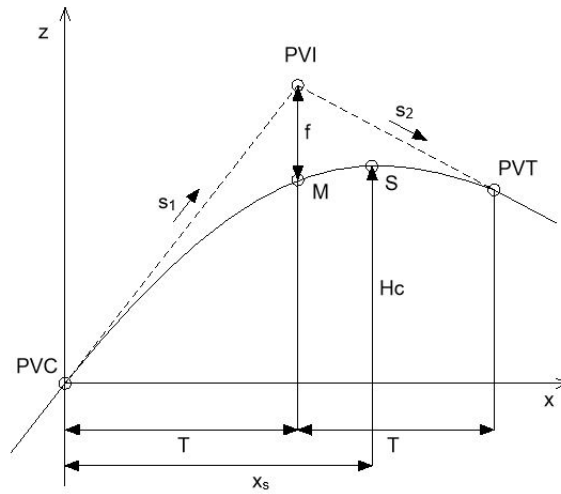


Figure 2.4: A symmetrical vertical curve and its properties, based on Freudenstein (2015)

2015):

$$H = \frac{100}{s_2 - s_1} \cdot (2 \cdot T) \quad (2.18)$$

The height z results from the longitudinal inclinations S_1 and S_2 and the radius H , depending on the stationing x along the rounding curve as following:

$$z = \frac{s_1}{100} \cdot x + \frac{x^2}{2 \cdot H} \quad (2.19)$$

One more important value is the distance f which can be calculated with the following formulation:

$$f = \frac{T^2}{2 \cdot H} = \frac{H}{8} \cdot \left(\frac{s_2 - s_1}{100} \right)^2 \quad (2.20)$$

A further useful value is the horizontal distance of the curve highest/lowest point, which can be calculated as:

$$x_s = -\frac{s_1}{100} \cdot H \quad (2.21)$$

One can calculate the value of the slope at any point along the curve with the following equation:

$$s(x) = s_1 + \frac{x}{H} \cdot 100 \quad (2.22)$$

2.2.3 Cross Slope and Superelevation

The cross slope is a geometric feature of the road surface and therefore, a feature of the road cross section. It is defined as the transverse slope with respect to the horizontal axis. The cross slope is a very important safety factor, as it is necessary in order provide a drainage gradient so that water will run off the surface to a drainage system, such as a street gutter or ditch (Freudenstein, 2015).

There are various forms of cross slopes, as presented in Fig.2.5, left. In cases of straight sections of regular two-lane roads, the road cross section is usually highest in the center and drains to both sides (crown section). The cross slope in this case needs to be at least 2.5% (FGSV, 1996). In case the horizontal alignment is a curve, the cross slope is banked into superelevation in order to reduce steering effort required to go around the curve. As a result, all water drains to the inside of the curve (Wolf *et al.*, 2013). In this case the minimal cross slope is again 2.5%, whereas the maximum cross slope is 6.0% for highways. However, it is important to note that, according to the German guidelines, the cross slope on bridges must not exceed 5.0% (FGSV, 1996).

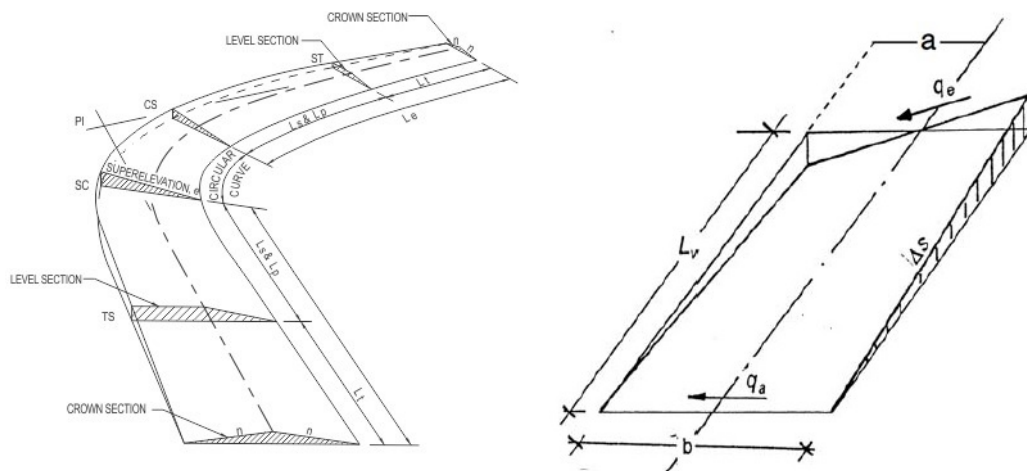


Figure 2.5: Left: Example of cross slopes and superelevation from Deutsch (2019), Right: Superelevation of a clothoid, from Freudenstein (2015)

When a vehicle travels along a horizontal curve, centrifugal forces act on the vehicle, pulling it in an outwards direction. In case of relatively low travelling speed or in case of curves with larger radii, the effects of centrifugal forces are minor. However, when travelling at higher speeds or around curves with smaller radii, the effects of centrifugal forces are considerably higher. Excessive centrifugal force could lead to increased lateral movement of the vehicle and it may become impossible for the vehicle to remain inside the driving lane. There are two possible counter measures to deal with the un-stabilizing centrifugal forces: the side friction of the tires and the superelevation (Wydot, 2019).

The side friction that is developed between the tires of a moving vehicle and the road surface also acts in favour of counter-balancing the outward pull of the vehicle. However the side friction can be drastically reduced when water, ice or snow is present on the road or when tires become excessively worn (Wydol, 2019).

Superelevation is defined as “the banking of the roadway cross sections, such that the outside edge of pavement is higher than the inside edge” as illustrated in Fig.2.5. As a result the use of superelevation in roads allows the vehicles to move along the horizontal curve with greater safety. Superelevation also allows the vehicles to travel with a higher speed, making transportations faster (Wydol, 2019). Therefore, the superelevation depends on the radius of the horizontal curve. According to the German design guidelines the superelevation for highways can be calculated with the use the diagrams of Fig.2.6

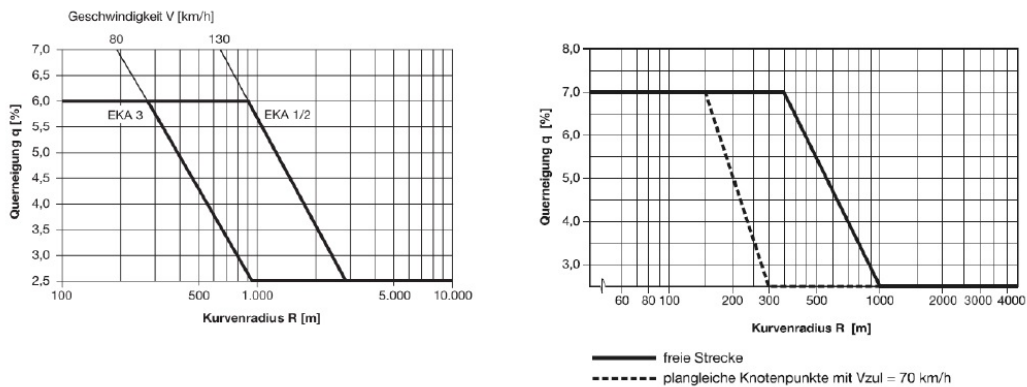


Figure 2.6: Diagrams for the calculation of the superelevation according to the curvature, from FGSV (1996)

The diagrams can be used in case of a circular curve in the horizontal alignment. However, a clothoid requires more attention when designing the superelevation, as it is a curve with a curvature that changes linearly with its curve length. In this case, the superelevation rollover Δs ‰ is calculated with the following formulation, as illustrated in Fig.2.5, right (Freudenstein, 2015):

$$\Delta s = \frac{q_e - q_a}{L_v} \cdot a \quad (2.23)$$

2.3 Bridge Layouts

In infrastructure planning the layout of a bridge depends highly on the road alignment. Bridges can be geometrically very complex structures, especially when they are located on a curved horizontal alignment or when they are located on a crest or a sag. In such cases,

the resulting geometry of the bridge superstructure is curved spatially in all three space directions (Ji, 2014). Besides the superstructure dependence on the alignment, the form and the location of the bridge substructure elements, such as the pillars and the abutments, depend on the geometry of the superstructure. The geometry of the entire bridge structure can be therefore extremely complex and with a large number of dependencies.

Generally there are no templates for the layout of bridges, as each project has unique geometrical characteristics. In the next subsections three different possible cases of a bridge layout are briefly presented.

Tangent Alignment

In case the geometry of the horizontal alignment is a straight line as shown in Fig.2.7, the layout of the bridge is not complicated. The layout is simply created from the intersections of the center-lines of bearing of each substructure unit (such as abutments and piers) with the axis of construction. The stations are thereafter given for each intersection along the axis. These intersections are then used as the basis for further detailing of the structure.

The skew angle of each substructure of the bridge is defined as “the angle between the center-line of bearing of the substructure unit and a line perpendicular to the center-line of construction at the intersection point”. If a skew is required, each substructure element should be skewed by the same angle relative to the axis of construction. Furthermore, with the term “Heavy skew” skew angles greater than 30 degrees are noted. Although such cases should be avoided, in case of a heavy skews special considerations need to be made for the structural detailing of the bridge (Chipman *et al.*, 2016).

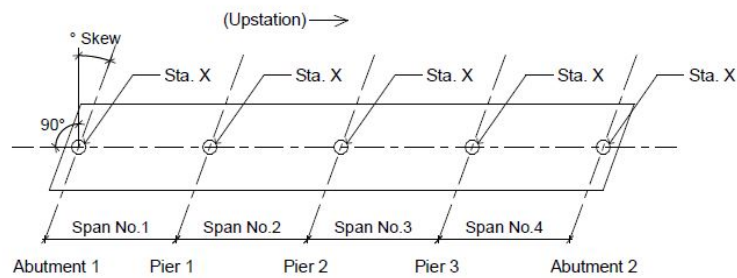


Figure 2.7: Layout of a bridge on a straight axis element, based on Chipman *et al.* (2016)

Curved Alignment

The layout of a bridge along a curved alignment is not so simple. Firstly, the working line needs to be established, which is a straight line starting from one bridge abutment to another. This working line intersects both the axis of construction and the center-lines of bearing of each abutment, as illustrated in Fig.2.8. The stations are thereafter derived according to the intersections of the center-line of bearing of each substructure unit with the axis of construction. In addition, a “working point” needs to be established at the intersections of the bearing center-lines of each substructure unit with the working line. These working

points can be later used in the creation of further structural details. Moreover, according to Chipman *et al.* (2016), the skew angle of a curved bridge is defined as “the angle between the center-line of bearing of the substructure unit and a line perpendicular to the working line at the intersection point” (Fig.2.8). Furthermore, in case the bearing center-lines are positioned at 90 degrees to the working line, then the curved bridge is not skewed.

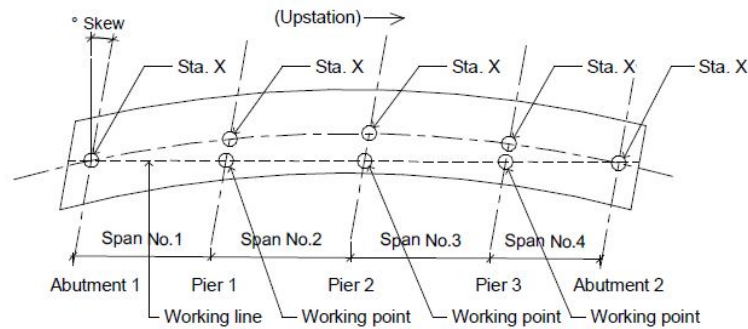


Figure 2.8: Layout of a bridge on a curved axis element based on Chipman *et al.* (2016)

Partially Curved Alignment

The layout of a bridge that is located on a partial curve is not very different from the layout of a bridge on a straight line and is established by extending the tangent through the center-line of bearing of the abutment. This extended tangent then becomes the working line for the curved part of the structure. The stations are created for each intersection of the bearing center-lines of the substructure units with the working line. Next, these intersections become the working points that are used in the further detailing of the curved part of the structure. In addition, the skew angle of a partially curved bridge is referenced to the straight working line. Therefore, the skew angle can be measured in the same way as in the case of a completely straight bridge (Chipman *et al.*, 2016).

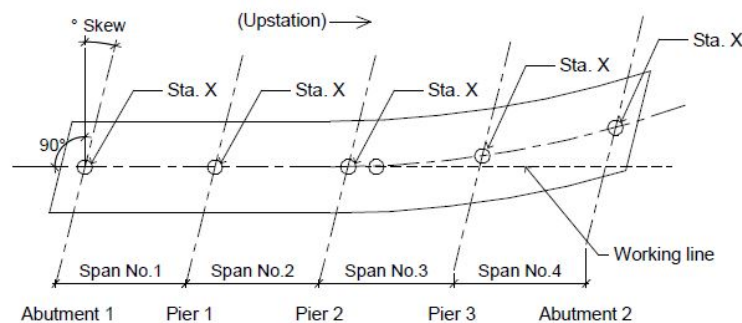


Figure 2.9: Layout of a bridge on a partially curved axis element, based on Chipman *et al.* (2016)

These layouts can not be used as templates for each bridge, but only as guidelines. Each bridge project needs to be designed from scratch according to the various environmental conditions. Furthermore, the effort needed in bridge design with the conventional 2D plans is enormous, due to the geometric complexity. Even more critical is the handling of the unavoidable

planning changes during the entire bridge design process. The statical calculations often demand further modifications of the road and bridge geometry. As a result, changes of each affected design data with manual update of the 2D drawings mean huge workloads that are costly, time and energy consuming and error prone (Günthner & Borrmann, 2011).

Section 5.1 of this thesis presents in more detail the way the alignment of the bridge influences the location and geometry of the abutments.

2.4 Modeling Concept of a Parametric Bridge Superstructure

In Obergrießer (2017) a modeling concept for creating a complete bridge model is presented. This concept is based on previous research since the 2000s, such as Ji *et al.* (2011), and has thereby been broadly accepted by the academic community. There is also a certain affinity of this concept to the traditional 2D planning process, which leads to greater acceptance from the engineering sector. In the following paragraphs this concept is briefly presented and explained.

The bridge superstructure is composed by the two components, deck and parapets. Each of these components can be modeled in the following four steps:

1. Creation of the tree space curves

It is obvious that the bridge deck should follow the alignment of the road. Therefore, the space curve that represents the 3D alignment of the route is initially required. Furthermore, two more space curves are necessary, placed with an offset on the right and on the left side of the first space axis. These further two curves are needed in order to place the profiles of the bridge deck with a specific angle. As a result, the extra two space curves are essential for the creation of the superelevations.

2. Geometric and parametric definition of the 2D profile

The 3D bridge superstructure is modeled based on the 2D cross sections, allowing to construct the complex bridge deck geometry with parametrization. Firstly, one needs to define the planes on the space curve of the alignment. These planes must remain parallel to the global Z axis along the alignment. On these planes the 2D profiles are thereafter placed or sketched. The bridge deck can be modeled based on a constant cross section. However, from a structural as well as an aesthetic point of view, various cross-sectional heights along the bridge axis may be required. The modeling of these continuously variable cross-sectional geometry is achieved with the use of a larger number of cross sections. With the same modeling technique one can create bridge decks that have variable widths.

3. Sweep of the 2D profiles into a 3D solid.

The creation of the solid is performed in the third step. Firstly, a series of cross sections

is generated along the three space curves. Secondly, sweeping one or more cross sections along the curves results in an interpolated loft form. This form corresponds to the required geometric conditions of the bridge cross sections. In other words, the 2D profile sketches are aligned parallel to the global Z axis, which is an essential characteristic for a correct image of the planar cross sections of the superstructure.

4. Boolean modification of the solid to determine the final geometry.

Adjustments of the superstructure total length can be implemented by shortening the created form with a trimming operation.

The modeling of the bridge superstructure usually is sufficient with the sweep of the cross-sections along the axis curve. This makes it much simpler than the modeling of the sub-structures, especially the abutments, which require an increased number of modeling steps (Obergrießer, 2017). In section 5.2 two modeling concepts for bridge abutments are further explained.

Chapter 3

Current State of Data Modelling in Infrastructure

International standards bring a lot of benefits, not only technological, but also economic and societal. They contribute to the harmonisation of technical specifications of products and services and they make global industries more efficient by breaking down the barriers of the international trade (ISO, 2019).

3.1 BIM Standards in Infrastructure Industry

The differences between BIM for building construction and infrastructure are more than evident. Among other things, there are distinct differences in the availability of certain BIM software tools, as well as differences in the development of open standards for data formats, data content and feature definitions. As mentioned in section 1.1, considering all these aspects, the international development of BIM in the building sector is much more advanced. In the building sector following formats are already developed (Borrmann *et al.*, 2016)

- IFC (ISO 16739) as a leading, openBIM Format
- for specialised applications also
 - gbXML for models aimed for thermal energy analysis
 - CIS/2 for steel constructions and
 - CityGML for city models

So far, infrastructural projects in Germany have been carried out mainly at a national level. Therefore, the various standards, regulations and permits have been created and defined in the German national context. Nowadays large infrastructural projects are tendered in

Europe and carried out by European consortia. As a result, it is important that the general BIM standards for the infrastructure are also developed on a European or even better on an international basis. This basis can thereafter be supplemented nationally with regard to specifications of each country (Borrmann *et al.*, 2016).

Currently in Germany, the official standardization activities have been based on two organisations, the “Association of German Engineers” (Verein Deutscher Ingenieure, [VDI](#)) and the German Institute for Standardization – DIN. The VDI is authorised to produce legally binding standards such as the VDI2552 series, which is currently being drafted and will become the German national BIM standard in the near future (VDI, 2019).

The most important consideration for the development of a data schema is that, it should be accessible from any software package and retain an exact definition the structure and of the connections between the components. Regarding these requirements, representative examples of data model description languages include the EXPRESS language from Standard for the Exchange of Product model data ([STEP](#)), and the Extensible Markup Language ([XML](#)), which is an internationally standardized modeling language of the World Wide Web Consortium ([W3C](#)). As a result, the development of bridge data schemas has been based on EXPRESS or [XML](#).

In the following sections the most important current data exchange formats for bridges are presented and explained.

3.2 Bridge Data Schemas Using XML

3.2.1 The TransXML Data Format

TransXML is an open data schema developed by the National Cooperative Highway Research Program ([NCHRP](#)) project of the US National Research Council for the exchange of transportation data of the public sector. As stated in Spy Pond Partners (2011):

“Project 20-64 was initiated to develop a unified, broad-based approach to facilitating data exchange across transportation applications used within and across different phases of the facility life cycle. The goal was to create a set of agreed-upon, open, vendor-neutral sets of data formats for storing, exchanging and archiving data.”

TransXML specifies and focuses on four business areas, Survey/Roadway Design, Transportation Construction/Materials, Highway Bridge Structures and Transportation Safety. The part of LandXML that refers to the geometric design of the roadway is adopted by the TransXML schema. This part of LandXML is adopted, because it provides good coverage of the important information for routing elements and already has an established base of user

and vendor support. Furthermore, according to Ziering (2007), the Bridge Design and Analysis schema enables the transfer of bridge description information across bridge structural analysis packages. The major advantage of this is, that it allows comparative analyses with the use of a variety of structural analysis tools.

3.2.2 The CityGML Data Format

CityGML is an open data model and XML-based format for the storage and exchange of virtual 3D city models. It is an application schema for the Geography Markup Language version 3.1.1 (GML3), the extendible international standard for spatial data exchange issued by the Open Geospatial Consortium (OGC) and the ISO TC211. The aim of CityGML is to reach a common definition of the basic entities, attributes, and relations of a 3D city model (OGC, 2019). CityGML established the schema by adopting separate modules for each of the facilities that form a city. The initial version of CityGML did not include bridges but version 2.0, released in 2012, includes a bridge module, namely a data schema for bridge structures (Kolbe, 2009).

CityGML supports different Levels of Detail (LOD). LODs are required in order to reflect the various independent data collection formats (Gröger *et al.*, 2012). Furthermore, LODs facilitate efficient visualisation and data analysis. One major advantage of the CityGML data format is, that it distinguishes between spatial and physical objects (Gröger *et al.*, 2012). Moreover, with the use of the *BridgeConstructionElement* or *BridgeInstallation*, functional information can be attached to a physical object. Generally, a bridge is represented by an object of the class *Bridge*. This class inherits its attributes and relations from the abstract base class *AbstractBridge*, as one can see in the UML diagram of Fig.3.1. The semantic attributes of an *AbstractBridge* are *class*, *function*, *usage* and *ismovable*. The attribute “class” is used to classify bridges, e.g. to distinguish the various construction types. The attribute “function” allows the representation of the utilization of the bridge independently of the construction type. For instance, possible values may be “railway bridge”, “roadway bridge”, “pedestrian bridge”, etc. Like the subclass *Bridge*, *BridgePart* is also a subclass of *AbstractBridge* and has the same attributes and relations. The relation *consistOfBridgePart* represents the aggregation hierarchy between a *Bridge* and its *BridgeParts* (Gröger *et al.*, 2012).

While there is no explicit description of the spatial in CityGML, spatial information can be represented using the *BridgePart* element. The spatial properties are defined by a solid for each of the four LODs (relations *lod1Solid* to *lod4Solid*). In addition, while the representation of horizontal alignment is not included in CityGML as an explicit item, it can be implemented using the *lod0Network*, which is included in the transportation modules, and the *CompositeCurve* elements. In addition to the solid representation of a bridge, linear

characteristics like cables or antennas can be specified geometrically by the *lod1MultiCurve* to *lod4MultiCurve* relations. For the semantic representation of those characteristics the features *BridgeInstallation* or *BridgeConstructionElement* can be used (Gröger *et al.*, 2012).

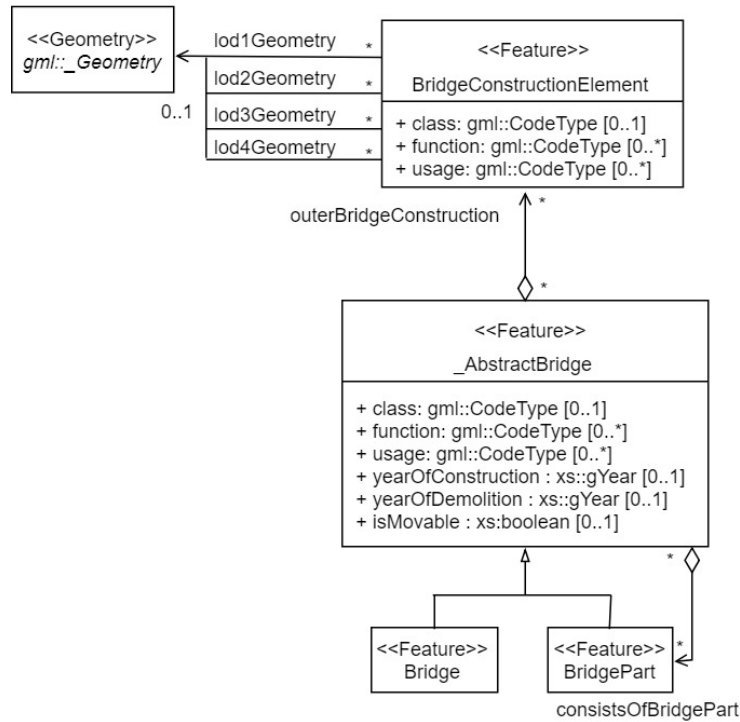


Figure 3.1: UML Diagram of the CityGML for bridges, based on Gröger *et al.* (2012)

However, it is quite obvious that the bridge module of CityGML does not include the items required for the identification of the spatial arrangement of the various bridge components, which poses a major disadvantage. Another significant disadvantage of CityGML is that its application is difficult to use due to the current lack of modeling software packages that directly support CityGML.

3.3 OpenBrIM 2.0

OpenBrIM is defined as “a bridge industry consensus standard for engineering data description, modeling and interoperability for integrated structural design, construction, and lifecycle management of bridges” (FHWA, 2019). Generally, OpenBrIM has following characteristics:

- OpenBrIM is a fully open standard for the digital description of bridge information. It can be exchanged between various stakeholders (engineer, fabricator, contractor, owner, etc.) in project development and it can be used to define a digital record for the bridge life-cycle.

- OpenBrIM includes the geometries, materials, various parameters, etc. that are commonly used for the description of bridge elements and components.
- OpenBrIM covers the formatting, syntax, schema and workflows that are necessary for a standardized digital description.
- OpenBrIM is not software.
- OpenBrIM is completely software independent.
- OpenBrIM is a community driven, free, open, on-cloud information modeling system
- OpenBrIM is expandable, adaptable and customizable according to the specific needs of each party.

In other words, OpenBrIM is an alternative method for exchanging bridge information modeling data between different application platforms, organizations and users in the infrastructure sector. With OpenBrIM there is no file exchange. Instead, there is one central data repository which can be operated by all participants. This also means that, the various participants are allowed to access information from the repository and also contribute information into the repository. The resulting advantages are obvious: the OpenBrIM community contributes in managing the data, contributes in assuring integrity and promotes effective collaboration (Bartholomew *et al.*, 2015).

OpenBrIM uses a subset of XML called Parametric Markup Language(ParamML). A thorough description of ParamML is given in (ParamML, 2019). A detailed XSD data schema is also available on the OpenBrIM website. To be more specific, OpenBrIM allows users to describe a bridge with hierarchical *Obj* element sets. An *Obj* may compose of child(ren) elements and can define its type *ObjTypes* as a template to describe frequently used child *Objs* (Jeong *et al.*, 2015).

As mentioned previously, one of the fundamental principles of the OpenBrIM concept is the use of an open bridge object data repository for BrIM models. This repository is currently organized as a central database on cloud. In other words, it is designed as a distributed system, where the involved organizations can host and manage their own open bridge libraries. These libraries and their objects can be exchanged and used by the community just by sharing a simple URL. Optionally, users can access the information directly online via an application, found on the site openbrim.appspot.com. This application allows the users to interact with OpenBrIM data through simple web requests. Instead of file exchange, the data can be accessed directly from the hosting server. It is also possible to use OpenBrIM Connect, a free library developed and maintained by the OpenBrIM community. Using this library, the various software providers and the bridge industry community can create plug-ins to integrate OpenBrIM into software applications utilized in professional workplaces. (Bartholomew *et al.*, 2015)

Fig.3.2 illustrates an example of a complete bridge model on the BrIM Cloud. It is also important to note that the user is enabled to manipulate various parameters of the bridge model, which is thereafter automatically updated to the new changes.

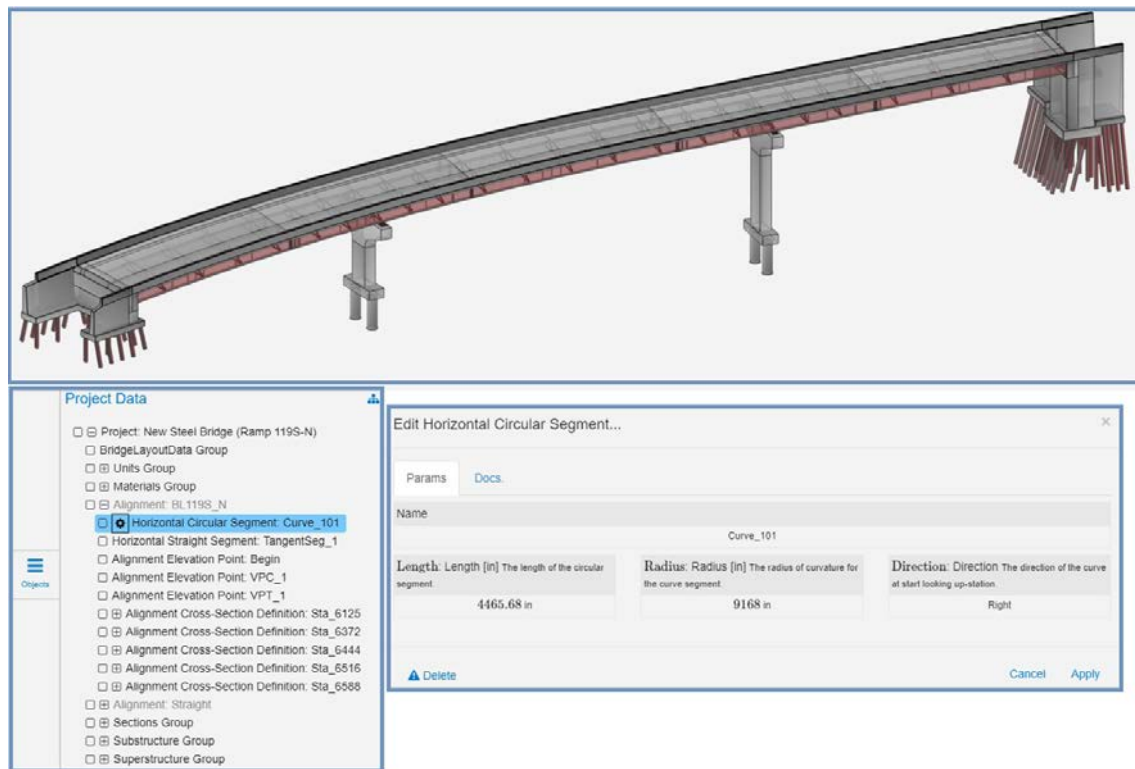


Figure 3.2: Bridge Model Example on the BrIM Cloud, screenshots from the online application under openbrim.appspot.com

The approach of OpenBrIM is quite different than the IFC approach. It is very possible, that the bridge engineering industry may have need of both suitably-defined exchange format, such as IFC, and the flexible approach of OpenBrIM (Bartholomew *et al.*, 2015).

3.4 Data Schemas Using EXPRESS

3.4.1 IFC Overview

Industry Foundation Class (IFC) is a standardized data model for the construction industry and was developed by the International Alliance for Interoperability (IAI). Up to the current version (4.0), IFC only supports structural engineering for buildings and ignores civil engineering for infrastructure. But due to the rapidly increasing importance of BIM for infrastructure around the globe, the next big release, IFC 5, is planned to include a comprehensive civil engineering infrastructure extension. This extension will make it possible to describe

elements such as roads, railways, bridges, and tunnels (BuildingSmart, 2019b). Some of the parts of IFC5 are presented in more detail in the following subsections.

The separation of semantics and geometry is a major advantage of the IFC data model when compared to the conventional, geometry-oriented exchange formats. As presented in the Fig.3.3, an IFC building model includes both semantic structuring and geometric representation (Borrmann *et al.*, 2013). The IFC building model (*Product*) can be broken down to individual parts (*Elements*). These Elements further consist of more construction-specific parts (*BuildingElement*). For example, these components include object types such as Windows, Doors, Walls, Columns etc. In other words, with this semantic structure a building can be described entirely semantically with no need of any geometric representations. It is important to note that, this semantic description is decoupled from geometry (Borrmann *et al.*, 2013). In addition, the non-geometric information of a building (such as material properties) represent a necessary data basis for most calculations (statical, thermal, etc).

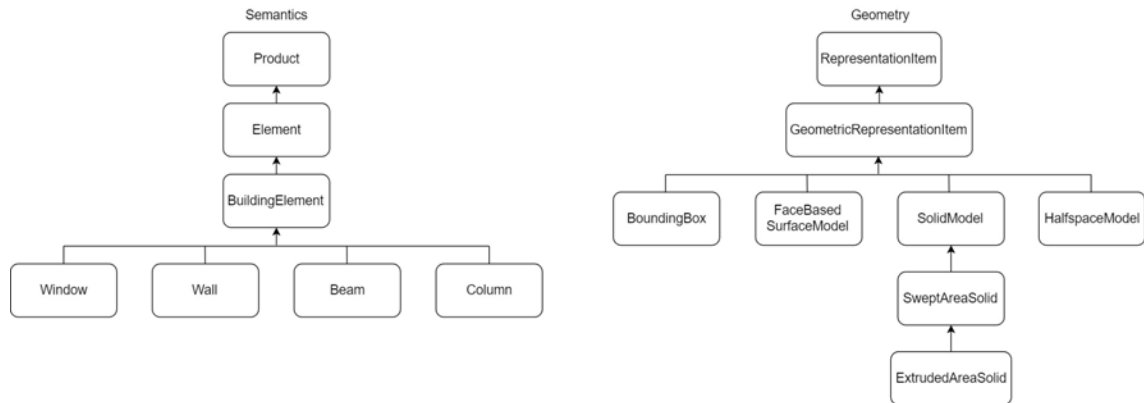


Figure 3.3: Semantics vs Geometry of the IFC data schema, based on Borrmann *et al.* (2013)

3.4.2 IFC Alignment Schema

As the name suggests, the main scope of the IFC Alignment project is the extension of the IFC4 schema to capture semantically rich alignment information (BuildingSmart, 2019b). The alignment definition will be used by other infrastructure extensions for IFC5, such as IFC Road and IFC Bridge, as illustrated in Fig.3.4.

Some of the principles which have governed the development of the conceptual schema are following (BuildingSmart, 2019b):

- Alignment is seen as a “reference system associated to linear constructions, such as roads, railways and bridges and is used to position such elements”.
- A single alignment is defined as a “non-branching, continuous, single alternative, single location alignment”.

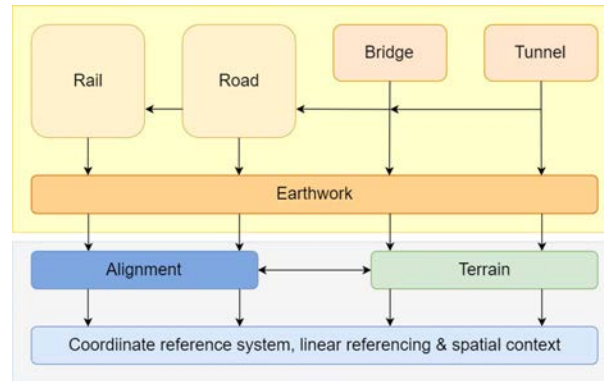


Figure 3.4: Overview of different Infrastructure components and their dependencies in IFC5, based on BuildingSmart (2019b)

- A single alignment can be represented as:
 - A horizontal, a vertical and a resulting 3D alignment
 - A horizontal and a vertical alignment
 - Only a horizontal alignment
 - Only a 3D alignment
- Multiple vertical alignments can be defined using the same horizontal alignment.
- Alignment segment geometry includes curve types used for road constructions and a generic template for additional spirals for alignment segments used in rail constructions.
- Tangential continuity between alignment segments can be enforced by a Boolean setting. This allows to use the alignment definition also for other infrastructure works, such as power lines.

Horizontal Alignment

The horizontal alignment currently consists of straight lines (*IfcLineSegment2D*), arcs (*IfcCircularArcSegment2D*) and clothoids (*IfcClothoidalArcSegment2D*). In the paper Amann *et al.* (2014), a novel approach for the description of transition curves is introduced, which is based on the so-called Industry Foundation Classes Programming Language (IFCPL), as well as its integration into an IFC alignment model.

As presented in the UML diagram in Fig.3.5, one can note that all horizontal alignment elements have the following common properties: *m_StartPoint*, *m_StartDirection* and *m_SegmentLength*, which are inherited from *IfcCurveSegment2D*. Furthermore, the *IfcCircularArcSegment2D* has a radius (*m_Radius*) and an orientation of the circular arc (*m_IsCcw*). Furthermore, the *IfcClothoidalArcSegment2D* also provides a start radius (*m_StartRadius*), which represents the radius of the clothoidal arc at the start point of the clothoid. If there is no value defined for this radius, i.e. the value is “NIL”, it is interpreted as being infinite, which means that the curvature at the start point of the clothoid is zero (this is the case

where a clothoid connects a straight line with an arc). Moreover, the *m_IsCcw* attribute denotes the orientation of the clothoidal arc, with “true” being counter-clockwise and “false” being the clockwise direction. The attribute *m_isEntry* also defines whether the curvature is increasing (“true”) or decreasing (“false”) towards the end point. Finally, the clothoid parameter A is stored as the attribute *m_Clothoid* (Amann *et al.*, 2015).

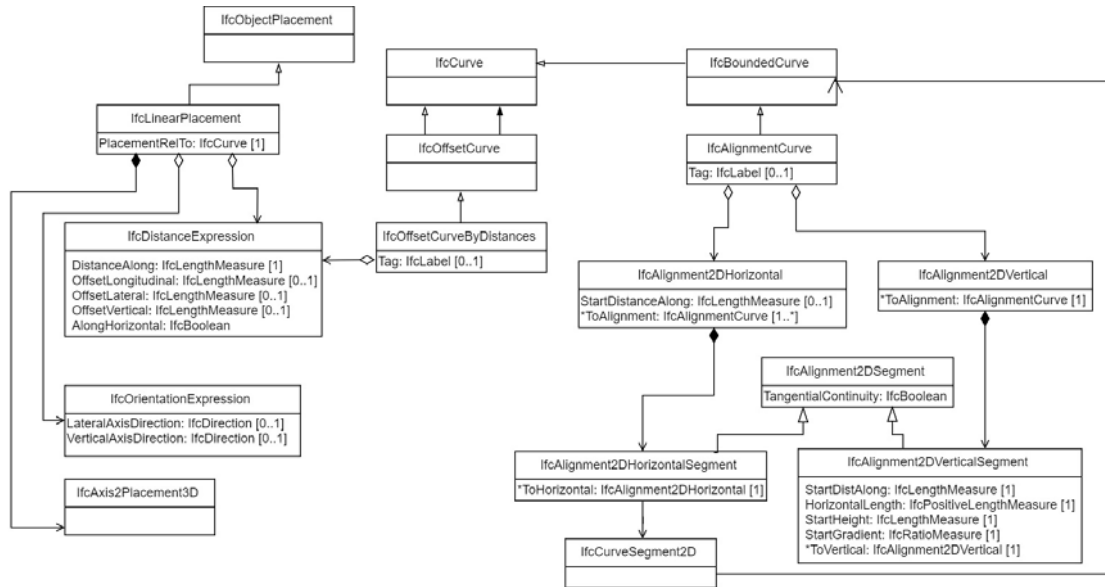


Figure 3.5: UML Diagram of the IFC Alignment Schema, from BuildingSmart (2019b)

Vertical Alignment

The IFC-Alignment describes the vertical alignment using the segment-based approach. This approach is quite different than the vertical point of intersection approach (VPI approach), as illustrated in Fig.3.6. The segment-based approach stores data about the individual vertical segments, e.g. the start and end point of each segment is stored for each line and every parabola (Amann *et al.*, 2015). On the other hand, the VPI approach stores only the points of vertical intersection and the radius of curves, meaning that the start and end points of the individual segments have to be computed explicitly. Both approaches are equally efficient, however the VPI approach is closer to the traditional concept of the vertical alignment creation (described in Section 2.2.2). As a result, the VPI approach is generally considered to be more understandable and trustworthy from the point of view of civil engineers. It is therefore also adopted by the Abutment-Tool that is presented later in this thesis, in section 5.3.3.

3.4.3 IFC Bridge Schema

Unlike with road and railway planning, there are currently no open standards for the exchange of bridge planning data, which are mature enough for practical and industrial application.

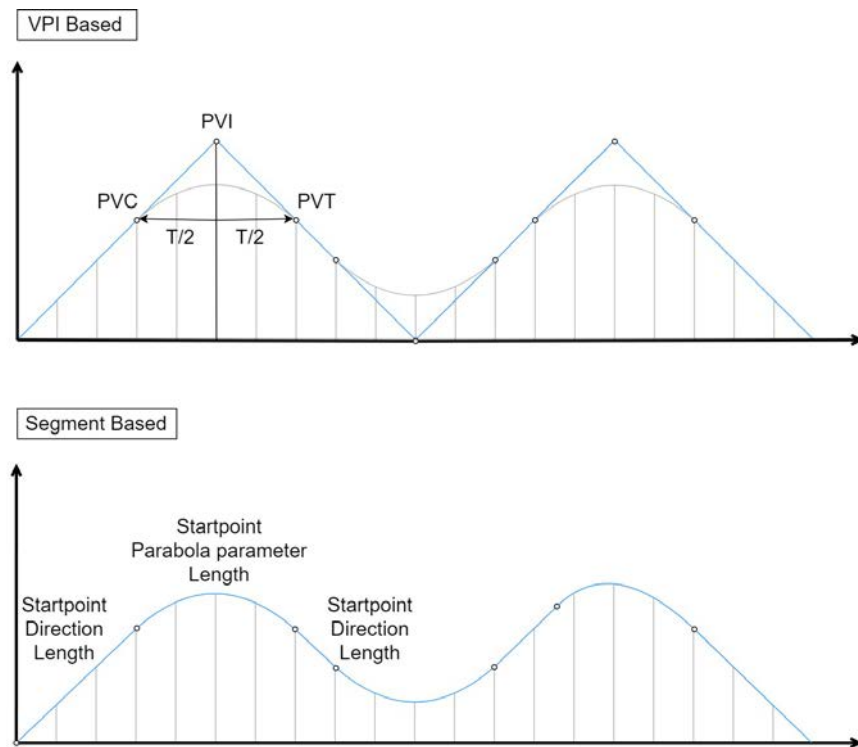


Figure 3.6: The VPI approach compared to the segment-based approach, based on Amann *et al.* (2015)

The goal of IFC-Bridge is to expand the current IFC data format in order to include specific elements for bridge construction. Certainly, among all infrastructure works, bridges can have many structural elements with a lot of considerable common characteristics to building elements. Therefore, the extension of the existing IFC data schema to the inclusion of bridges would be a natural evolution. The IFC-Bridge project began on the basis of the IFC2x3 platform as a French initiative MINnD. It was based on an earlier national standard, called OA-Express (MINnD, 2019).

In the following paragraphs the current structure of IFC Bridge data format is presented. The information is derived from the latest work package report of the IFC Bridge Fast Track Project (Castaing *et al.*, 2018) and new concepts are marked in blue.

Geometric Representation and Placement: Spatial Elements

The first aspect of the IFC Bridge schema that needs to be considered, is the way that the IFC Alignment schema will be used as the basis, in order to position the bridge structure properly in space. For this reason, following types of the class *ObjectPlacement* have been added, marked in blue:

ObjectPlacement

As defined in BuildingSmart (2019b), *ObjectPlacement* is “an abstract supertype for the

special types defining the object coordinate system”. This means that the *ObjectPlacement* must be provided for each product with a shape representation. Consequently, the object placement can be given as (Castaing *et al.*, 2018):

- Absolute, meaning by an *axis2placement* according to the global coordinate system
- Relative: meaning by an *axis2placement* according to the object placement of another product
- By grid reference: by two intersecting grid axes with reference directions.
- Linear placement: by a predefined distance along a curve. Offsets from this curve are possible too. As a result, the placement and axis direction of the coordinate system of the object is defined by a reference to a curve, which could be an *AlignmentCurve*, for instance.
- Span placement: In this case the object is placed as an extension or repetition relative to other object placements.
- Interval placement: This placement defines the relative position and repetition of an element along a span.

One alternative proposed in Castaing *et al.* (2018) for the use of the IFC-Alignment, is that it plays a central role in the project structure and organizes the referenced products. In this case, the positioning is achieved by means of stationing Referents along the Alignment. This concept is based on existing relationships, such as *RelNests* for Referents assigned to Alignment. A new relationship similar to *RelContainedInSpatialStructure*, which is derived from *RelConnects*, serves to specify the relationship between the Referent and the Product, namely the proposed *RelPositions*. In other words, the relationship *RelPositions* may be used to relate Objects for which placement or geometry is defined relative to alignments (or grids) (Castaing *et al.*, 2018). The concept is illustrated in Fig.3.7.

Element

The *Element* is already included in the IFC4 schema. Its subtypes not only represent all physical components, but also their aggregations and, in case of tangible components, they can have an associated material definition. Currently the attribute “Category” is used in order to distinguish general categories of materials, for instance steel or concrete. However, this attribute is still not standardised. To enable such standardization, but also preserve compatibility with existing usage of this attribute, it is proposed in the IFC Bridge schema that an additional attribute to material, called “PredefinedType” is added. This should be an enumeration so that at least the types “concrete”, “steel” and “timber” are included for the purposes of bridge construction, along with the types “notdefined” and “userdefined”

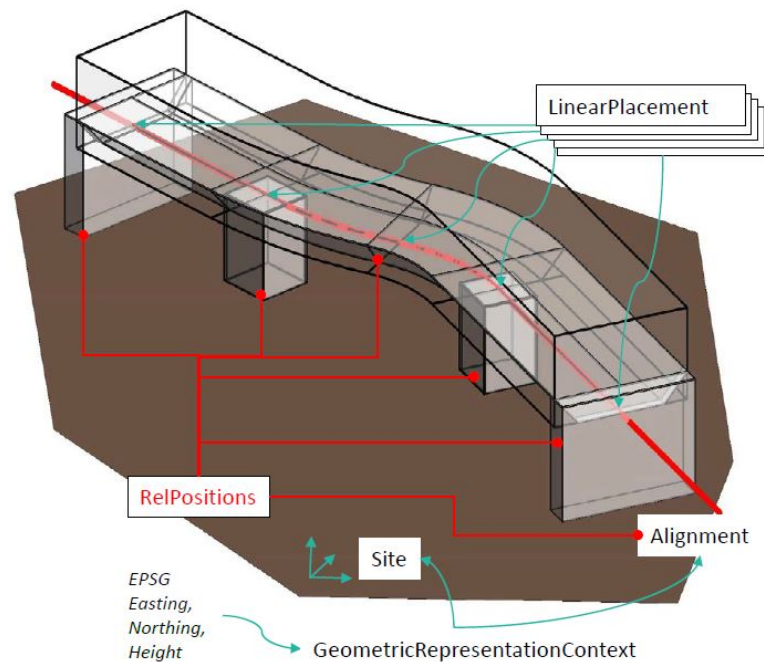


Figure 3.7: Definition of the placement of the bridge elements according to the Alignment, from Hyvärinen (2018)

(Castaing *et al.*, 2018). Moreover, it is possible that more general types could also be included, such as those defined at “ConstructionMaterialResourceTypeEnum”. The general characteristics of the *IfcElement* are following (BuildingSmart, 2019b):

- Elements are physically existent objects. Holes and openings can also be defined as void elements.
- Material and quantity information can be assigned to an Element with the use of the relationships “*AssociatesMaterial*” and “*RelDefinesByProperties*”.
- Elements can be either permanent parts of a facility or only temporary, such as formwork.
- Elements can be either pre-manufactured or built on site.
- The elements can be contained by a spatial structure element in a logical manner. This spatial structure element constitutes a certain level within the project structure hierarchy (e.g site, bridge, facility part or space). This is done by using the “*ContainedInSpatialStructure*” relationship.
- With the use of the relationship “*RelConnects*”, Elements can also be attached to each other and therefore express a physical connection.

In addition, as stated in BuildingSmart (2019b) “an element can be declared to be a specific occurrence of an element type (and thereby be defined by the element type properties) us-

ing the *RelDefinesByType* relationship”. It is also important to note that, an element can be defined as an element assembly. An element assembly is defined as “an aggregation of semantically and topologically related elements that form a complex product or part of a facility”. Those element assemblies are connected with the use of the relationship the *RelAggregates*. An example of an element that could be an assembly is a bridge abutment, composed of retaining walls, a footing, footing piers etc.

SpatialElement

Spatial elements are intangible, but they can have a shape and a location in space. They can also have physical (tangible) elements contained in them. They are used for creating the main breakdown structure for the project model (by the subtype “*SpatialStructureElement*” and its subtypes) or to define a spatial zone (by the subtype “*SpatialZone*”)(BuildingSmart, 2019b). A *SpatialStructureElement* is the “generalization of all spatial elements that might be used to define a spatial structure”. With the use of such spatial structures a hierarchical project structure is often provided. As a result, this hierarchy defines the overall organization of the project information, as depicted in the UML diagram of Fig.3.8. Elements within the spatial project structure, proposed in Castaing *et al.* (2018) are:

- Site (where facility/facilities is/are built)
- Facility, specifically as:
 - Building
 - [Bridge](#)
- Decomposition of a facility using “*FacilityPart*”, specifically as:
 - *BuildingStorey* in Building
 - [BridgePart](#) in [Bridge](#)
- Space

A **Site** is defined as an “area of land, possibly covered with water, on which the project construction is to be completed” (BuildingSmart, 2019b). It is important to note that, the site is not only the container for the future developed objects, but also contains objects existing before the project starts. These can be for instance the terrain, the surrounding buildings and infrastructures, the utility networks and bodies of water.

A **Facility** is derived from the class *SpatialStructureElement*) and may be either a Building or a Bridge (in the future also Road, Railway and Tunnel). According to ISO 6707-1:2014, a **Bridge** is “civil engineering works that affords passage to pedestrians, animals, vehicles, and services above obstacles or between two points at a height above ground”. The **FacilityPart** is utilized for the spatial breakdown of the facilities. Therefore, it may be further

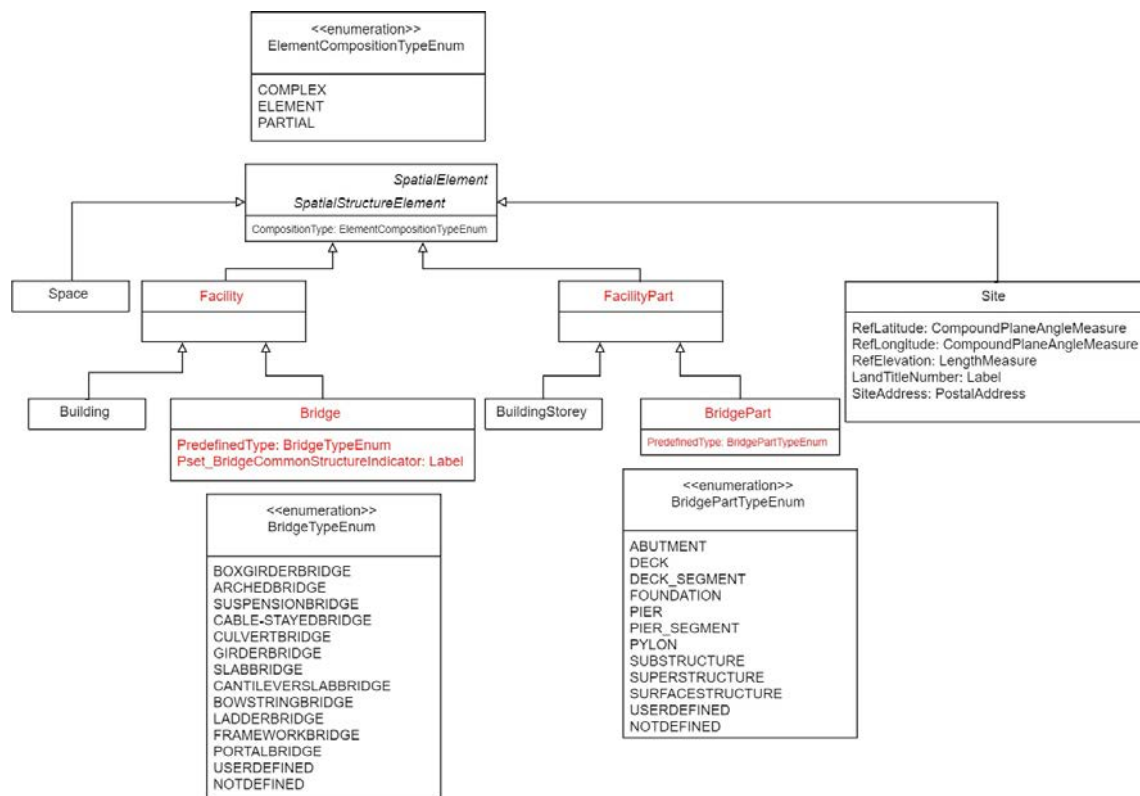


Figure 3.8: New concepts of IfcBridge as existing classes with new Predefined Types (red): Spatial Elements, from Castaing *et al.* (2018)

specialised according to the type of facility, e.g. BuildingStorey for Building or BridgePart for Bridge. In a bridge, **BridgePart** as subtype of FacilityPart represents parts such as Superstructure, Substructure, Foundation which can also be broken down further. For example, the bridge substructure as a whole can be “complex”, while each abutment and pier would be “element”. A bridge pier can also be composed of separate towers, which would then be “partial” (Castaing *et al.*, 2018).

Geometric Representation and Placement: Physical Elements

BuildingElement

According to the definition given by BuildingSmart (2019b), the *BuildingElement* “comprises all elements that are primarily parts of the construction of a built facility, i.e. its structural and space separating system. Building elements are all physically existent and tangible things”. Fig.fig:IfcBridge objects (red) depicts the UML diagram for the concept of the existing building elements with new Predefined Types for the IFC-Bridge.

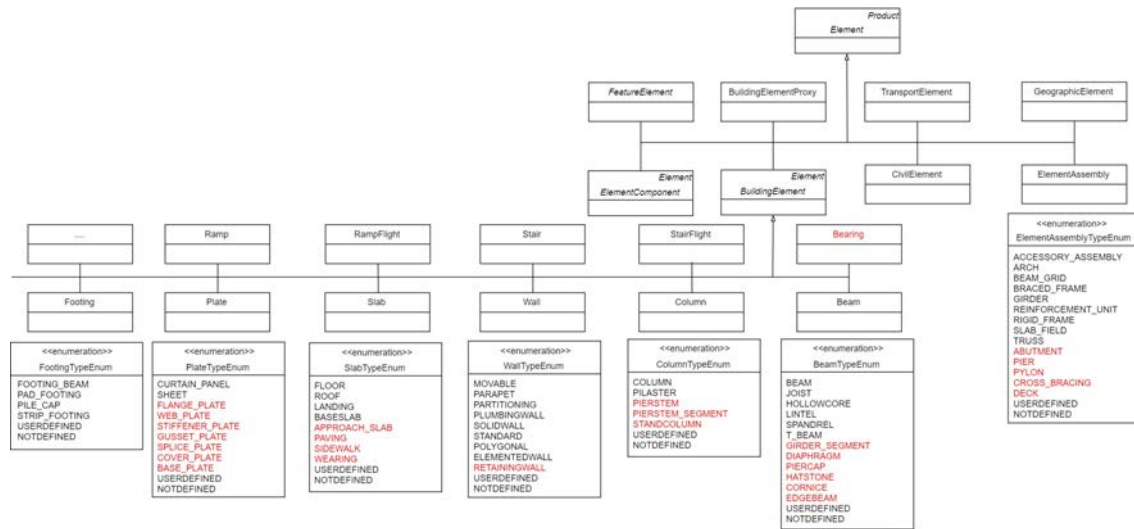


Figure 3.9: New concepts of IFC-Bridge as existing classes with new Predefined Types (red): Physical Elements, from Castaing *et al.* (2018)

3.5 Semantic Enrichment of Bridge Models

The international development of BIM standards for the building domain has already started since before the 2000s (BuildingSmart, 2019a). However, it was not only until a decade after, that the construction industry had started to adopt BIM processes. But the need for BIM in infrastructure is direct and the suitable tools and data formats are still not available or fully efficient. This means that, in order to confront the current needs for CIM, alternate methods need to be developed. These methods exploit the current existing BIM tools and data formats of the building sector and adapt them for CIM processes with suitable semantic enrichment. As defined in Belsky *et al.* (2016):

“Semantic enrichment of building models refers to the automatic or semi-automatic addition of meaningful information to a digital model of a building or other structure by software that can deduce new information by processing rules or by applying machine-learning”

As described in the previous sections, IFC contains various entities for the exchange of information about a building during its lifecycle. However, it cannot fulfil all the requirements that exist in less standardised structures, such as bridges, yet. One of the most significant reasons of this inability to utilize IFC properly as a data format for bridges, is the difficulty in representing the functional meaning of the bridge elements (Lee & Kim, 2011). While this can be resolved by establishing a new data schema through the extension of entities with the IFC Bridge as mentioned above, IFC also internally supports extension through property sets (PSETs). Unlike the addition of entities, IFC PSETs are created as references to external data and therefore do not modify the IFC schema in any way. The user-defined PSETs of IFC can be represented using a container class, *IfcPropertySet*. For the IFC export of the

abutments that are modeled with the use of the developed Abutment-Tool, the PSETs are explained in more detail in subsection 5.5.1.

In the article Ismail *et al.* (2016) a tool is presented that can be used for the semantic enrichment of the bridge models, called “BIM-Annotator”. The BIM Annotator is not meant to be a modelling tool for bridges, but as an annotation and online collaboration tool in order to improve the semantic quality of bridge models. More specifically, the aim of this tool is to annotate the bridge model with additional parameters for structural analysis and FEM mesh generation. Furthermore, in the article Park *et al.* (2018), a method is proposed in order to enable the information modeling of steel box girder bridges based on the current IFC schema. According to Park *et al.* (2018), following two steps need to be performed:

- Geometric modeling of the bridge structure with current BIM software, meaning that the components of the bridge are modeled through the currently available IFC entities of building structure, e.g. the subtypes of *IfcBuildingElement*.
- Reassignment of the semantic information. This can be done with two methods:
 - Utilize BIM authoring software, which builds a geometric model. The IFC of the bridge model can be created by the IFC exporter.
 - Input the reassigned functional meanings of bridge components directly into the generated text file of the IFC.

Moreover, the aim of the user-defined property sets proposed in the study of Park *et al.* (2018) is to generate functional semantic information of the various bridge components. These components need to be considered not only with respect to their location, but also their functional meaning. Consequently, the items necessary for the generation of the semantic information need to be classified in regard with their spatial ,as well as physical aspects.

Another project that developed an engine for the semantic enrichment of bridge models is the SeeBIM 2.0. In the article Sacks *et al.* (2017) the workflow of the engine is presented. The tool parses an IFC file to extract shapes, relationships and other attributes of the various objects. It then ”applies forward chaining to infer additional facts about the model, using sets of rules compiled in advance by experts in the domain of interest, e.g. bridge engineers”. Finally, the engine records the results in an enriched IFC file. Fig.3.10 illustrates the process.

3.6 Summary

In this chapter current data formats used for the exchange of infrastructural projects, as well as formats under development were presented. These schemas can be divided in two categories: schemas using XML and schemas using EXPRESS. The various data formats, their basic features and limitations are summarized in Tab. 3.1:

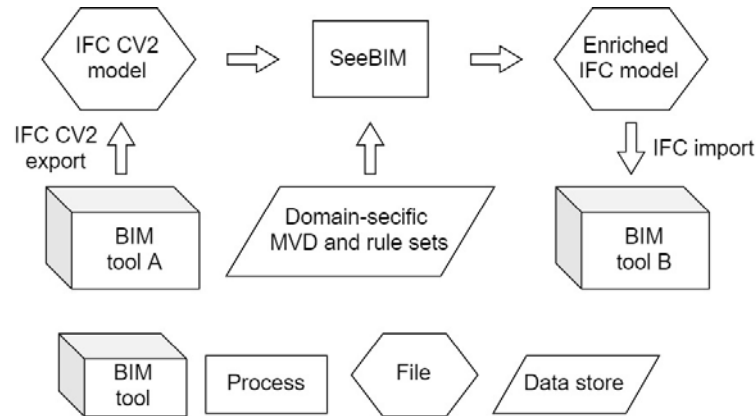


Figure 3.10: Visualisation of the semantic enrichment workflow with SeeBIM, based on Sacks *et al.* (2017)

Bridge Data Model	Description	Limitations
TransXML	Bridges included as a highway structure in the data model for transportation data exchange	Specialized only in the highway bridges Insufficiently detailed elements from a functional point of view.
CityGML	Bridges included as facilities of the city information model	Insufficient elements for the detailed bridge components. Insufficiently elements for the accurate spatial positioning of bridge components. Few commercial authoring software packages.
IFC4 (without user defined PSETs)	The standard data schema of BIM. Available for various BIM software packages	Infrastructural domain not considered.
IFC4 with semantic enrichment		An indirect and limited method for the representation of bridge structures
IFC Bridge	Based on current IFC resources, it adds new entities for the bridge structure.	No authoring software that supports IFC Bridge currently available
IFC5	Includes the infrastructure domains. Currently under planning.	

Table 3.1: Bridge data formats, their basic features and limitations, based on Park *et al.* (2018)

Chapter 4

Available Bridge Modeling Software Overview

4.1 Introduction

In section 2.4 the theoretical background for the parametric modeling of a bridge superstructure was briefly presented. At this point, it is of great interest, how this concept has been adopted by various software applications. In this chapter some of the current software solutions for CIM are presented and briefly evaluated.

Until the 2000s the available building software tools provided limited bridge modeling capabilities. Consequently various software products from the sector of mechanical engineering and vehicle construction industries were intensively investigated for their potential for the modeling of civil engineering projects (Obergrießer *et al.*, 2008). The result of those investigations was that the CAD programs used in those industries are actually very well suited for the parametric 3D modeling of bridge structures. However, these are purely geometric 3D models that do not provide the additional semantic information needed for a true BIM model on the types and properties of the components. Furthermore, there are obvious limitations in terms of overall civil-oriented planning processes. For instance, there is a lack of connections with structural analysis software. Further restrictions are the importing or exporting of routing data with the use of neutral data formats.

Currently, there are several software products available worldwide for the BIM-based planning of bridges. Some of them are:

- DynaBridge, Dynamo
- NX, Siemens
- LEAP Bridge, RM Bridge und LARS Bridge, Bentley

- Advance Bridge, Graitec
- VisualARQ (Spain, IFC)
- Allplan Bridge, Nemetschek
- Tekla Structures, Tekla
- VESTRA Infravision, AKG Software
- FIDES Infrastructure Toolkit, FIDES
- SOFiSTiK Bridge Modeler, SOFiSTiK AG

Studies on the use of some of these BIM tools for the design and construction of bridges can be found in the following works: (Johansen, 2013) Revit, (Nöldgen, 2016) Siemens NX, (Wang & Eng, 2012) Siemens NX.

Since SSF Ingenieure AG is oriented mostly on Autodesk products, more focus is given on programs that operate in the Revit environment in this thesis. Furthermore, the developed Abutment-Tool is compatible with Revit. Subsequently, only solutions provided for Revit were examined and are presented in the following sections.

4.2 Bridge Modeling with Dynamo

One of the first tools used to create bridge superstructures in Revit is Dynamo. Dynamo is an open source software that can be downloaded and run in either stand-alone “Sandbox” mode or as a plug-in for other software like Revit or Maya. It is described as (dynamobim.org, 2019):

“A visual programming tool that aims to be accessible to both non-programmers and programmers alike. It gives users the ability to visually script behavior, define custom pieces of logic, and script using various textual programming languages.”

Dynamo enables the user to work within a Visual Programming process. Various elements are connected together, not only to define the relationships, but also the sequences of actions, in order to compose algorithms. These algorithms can be used for a wide variety of applications. The principle of coding with Dynamo implies the replacement of “methods” in classic object-oriented programming languages by “nodes”, which already contain both methods and objects. This means that no deep programming knowledge from the user is required (dynamobim.org, 2019).

In the blog “Revit beyond BIM” Vermeulen (2019) a workflow for creating a bridge model in Revit is presented. The general workflow, also illustrated in Fig.4.1, is summarized in the following three steps:

- The conceptual road and bridge design are planned externally, for example using Infra-works 360.
- The Infracworks model is then imported in AutoCAD Civil 3D for further detailing of the road design.
- The data is then inserted in Revit and Dynamo to get the detailed bridge design.

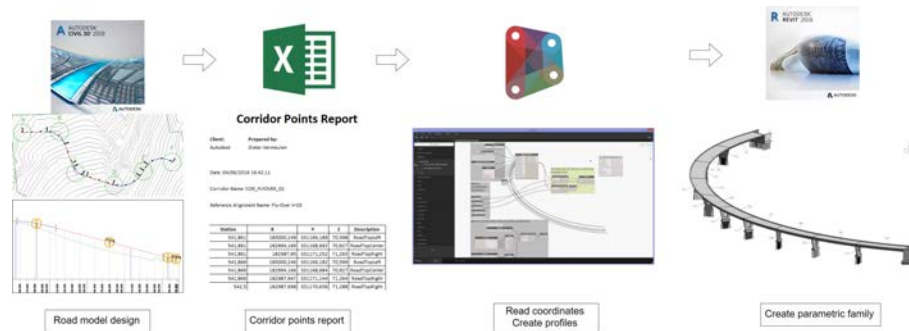


Figure 4.1: Conceptual design workflow for Dynamo, based on Vermeulen (2019)

Firstly, following conditions that the bridge deck should meet are defined:

- The superelevation, the width and the cross slope for each lane of the deck cross section are calculated from the Civil 3D data.
- The profile family for the cross section should be flexible and modifiable in the Revit project.
- The Dynamo script used for the creation should be generic, in order to be used for several bridge cross sections or even tunnel cross sections.
- The deck family needs to be able to host rebar.
- The Dynamo script needs to be able to handle any orientation of a bridge.

Step 1 – Extract Civil 3D Corridor Points

Firstly the solid geometry of the road should be designed with the use of an external program, for instance Civil 3D. The geometry of the bridge deck is then based on the geometry of the road. Since the cross-sectional slopes of each lane of the road can vary along the road axis, it is important to also extract this information from Civil 3D. This is done with the use of “Corridor Points Report” and the data is then exported and stored in an Excel file. For the presented method points for the “Top Left”, “Top Right” and “Top Center” edges of the road cross section are needed. In other words, the Top Center points represent the 3D alignment, whereas the Top Left and Top Right points are used for the superelevation and cross slopes (Vermeulen, 2019).

Step 2 – Create the parametric bridge deck profile

In the next step one also needs to create a family representing the section profile of the deck.

This is based on a “Metric Mass” Revit family template. In this family the user is required to create parameters for the superelevation, lane width and cross slope at the right and left of the road. After saving this family, the user must load it into a new family based on the “Metric Generic Model Adaptive.rft” template. From there on Dynamo is used to create the bridge deck geometry (Vermeulen, 2019).

Step 3 – Reading road data into Dynamo

In the third step the information from steps 1 and 2 are combined. The information about the road geometry is read into Dynamo as a starter, e.g. the Corridor Points Report is imported in Dynamo. For this process it is necessary to indicate the proper column indexes and Point Code descriptions (i.e. “RoadTopLeft”). The result of this operation are four 3D Polycurves representing the road top edges (left, right and center) and also the projection of the centerline at level of 0 m, which represents the horizontal alignment (Vermeulen, 2019).

Step 4 – Setting the bridge deck parameters in Dynamo

Before proceeding to the creation of the bridge geometry the following bridge parameters should be setup, illustrated in Fig.4.2:

- Bridge Alignment Variables: This group allows to add an offset and skew angle to the first and last profile of the bridge deck.
- Bridge Superstructure Section Definition: The configuration of this group depends on the way the “Concrete Deck Profile” Revit family is created. The user should set the type parameters of the nested family, before it is placed.

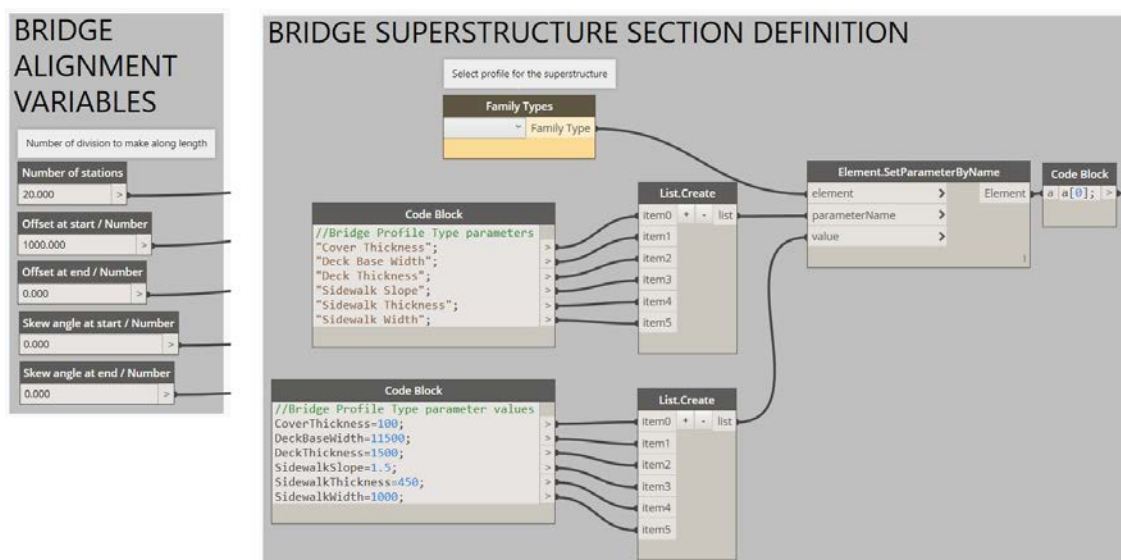


Figure 4.2: Screenshot of the Dynamo Script

Step 5 – Generating the bridge deck geometry with Dynamo

In the fifth step a second custom node is brought into the Dynamo script. The node “Bridge

Section Profile Placement” places the initially created “Concrete Deck Profile” Revit family at the right positions and orientation along the alignment. This node uses the three polycurves from the road as inputs. The “ProfilePositionParameters” port of this node needs a list with values between 0 and 1, which indicate the positions of the profiles. It is obvious that, the more elements in the list, the more accurate the geometry of the solid will be (Vermeulen, 2019).

The output of this node returns the “Profile Instances” placed in the Revit family of the bridge deck, as well as the generated points on each road edge. The Profile instances are used at a later point, when we need to integrate the calculated values from Step 6 into the Revit family. It is important to note that, in this step only the position and orientation of the section profiles are handled. The results of the generated points are further used in Step 6 to define the individual section dimensions (Vermeulen, 2019).

Step 6 – Calculate dimensions of each section profile

After the profile placements, the coordinates and orientation of each point on the road edges in Dynamo can be derived. As a result, the values of the superelevation and thus also the width and slope of each road lane are calculated.

Step 7 – Modify profile instances and create geometry

The results of the parameter calculations in Step 6 are connected with the “Element.SetParameterByName” node, which makes the proper adaptations to each individual profile. The geometry of the section profile instances is send back to Dynamo (as “Element.Curves”) and used to create the solid deck geometry with the help of the “Form.ByLoftCrossSections” node (Vermeulen, 2019).

Dynamo provides unlimited options with the user-created nodes. The workflow presented above includes just the basic steps for creating the bridge deck. The proposed workflow can be extended to included more complicated and complete structures. In addition, more detailed elements, such as railings or tendons can also be created with the use of Dynamo. After getting familiar with the Dynamo modeling concept, it is relatively easy to create any kind of geometry of bridge substructures controlled by Dynamo too. For example parametric piers and abutments as illustrated in Fig.4.3. A quite recent extension package is the Dynabridge, which can be freely downloaded from dynamopackages.com. Instructions for the use of Dynabridge are given in the blog Zakrzewski (2019).

Dynamo is a user-friendly tool when compared to Revit Macros in the [API](#) that require coding knowledge of C#. However, Dynamo still poses difficulties for a lot of engineers to understand its workflow and modeling concept, as it uses a very different way of modeling structures than the conventional [CAD](#) software. Instead of the common ribbons and buttons for modeling functions, Dynamo uses the previously presented graphs with nodes (see Fig.4.2). A further disadvantage of the workflow with Dynamo is that the alignment data is imported in the

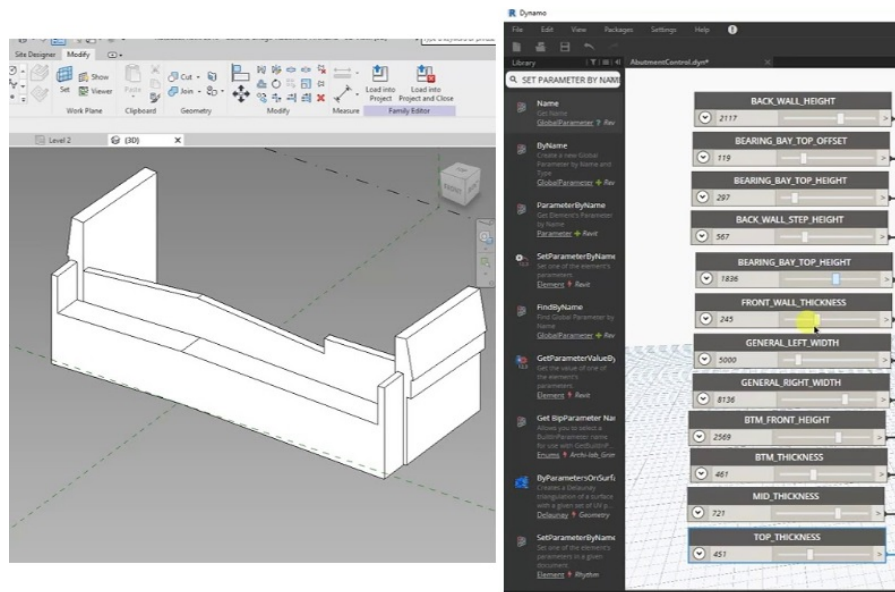


Figure 4.3: Modeling a parametric abutment with dynamo, from Zakrzewski (2019)

form of points, coordinates and elevations. As a result the user does not have a “clear” view on the true geometry of the alignment, e.g. is it a curvy horizontal alignment, a crest or a sag.

However, the Dynamo workflow has proven to be very practical and efficient in praxis. The recently developed extension package DynaBridge is a very complex script that enables the modeling of complete bridges. In order to adapt the bridge deck geometry to changes in the alignment, it is only required that the modified Excel file with the alignment data is imported in Dynamo. The process is highly automated and this enables the creation of several alternatives of bridges fast and effectively. Various companies including SSF Ingenieure AG, have adapted to this workflow and used it for the modeling of bridges in infrastructural projects.

4.3 AKG Vestra Infravision

Vestra Infravision is provided by the German company AKG and was firstly released in year 2017. It is a software that includes a great variety of designing functions in infrastructural projects, such as digital terrain models, roads, railways, channels, bridges and tunnels. In this section the Infravision plug-in in Revit and its workflow are briefly presented. With this plug-in it is possible to create bridge decks and tunnels in the Revit environment.

Step 1 - Create/Import the bridge alignment

Before creating anything in Revit the user is required to create the alignment in the Vestra Infravision environment. Alternatively the alignment can also be imported from Civil 3d.

Infravision provides its own toolbox for creating elements of the horizontal alignment in the site plan and defining gradients for the vertical alignment. In addition, the user is enabled to create the data for the road cross section. In other words, in case of a highway project the number of lanes are defined and so on. The advantage that comes with such an option is, that the user is not required to use a lot of programs for the bridge model creation, compared to the case with Dynamo. However the toolbox of the alignment creation in the Vestra Infravision includes certain complex procedures, with which the user should first become familiar. This may pose certain difficulties for unspecialised CAD engineers.

The alignment is then exported as an .XML file in order to be later used in Revit. This file includes all of the produced stations of the alignment. Each station contains the information for the number of lanes and for each lane its position, width and slope are provided too. The form of this file is much more understandable than the chaotic Excel list “Corridor Points Report” that is used in Dynamo. Still, the user has no clear understanding of the routing elements that form the exported alignment.

Step 2 - Create the parametric bridge deck profile

Similar to the workflow presented in the previous section, the user is required to create the bridge deck profile as a “Metric Mass” Revit family. Parameters should also be created in the same way as for the profile used in Dynamo.

Step 3 - Create the bridge deck geometry

In the next step the bridge superstructure is created as a “Generic Adaptive” Family in Revit. By initiating the Infravision plugin, the axis and cross section data are imported. The result of the import is the creation of the axis and the creation of the profiles, as shown in Fig.4.4. The deck profiles are automatically placed at the right position and with the right orientation along the axis. The user then is required to manually select all profiles and create the form of the superstructure. This process has to be repeated for the creation of the parapets. The bridge superstructure, including deck and parapets is now modeled as a Generic Adaptive Family and needs only to be inserted in the Revit project.

This process seems extremely simple, effortless and automated. However, after conducting various tests with Vestra Infravision multiple problems were raised, which prevented the proper creation of the bridge deck geometry. In most cases unpredictable errors prevented the correct creation of the bridge deck. Even after investigation, the reasons for these problems remain unclear. In addition, the software documentation does not actually provide further help on such topics and there were also no specific warnings or indications, that could help the user solve those obstacles. As a result, it is fair to deduce, that certain improvements need to be made so that design engineers can trust and use this tool in the professional workplace.

Moreover, regarding the bridge substructures, Infravision provides some predefined families for the modeling of the bridge abutments and piers. These families may be used for the

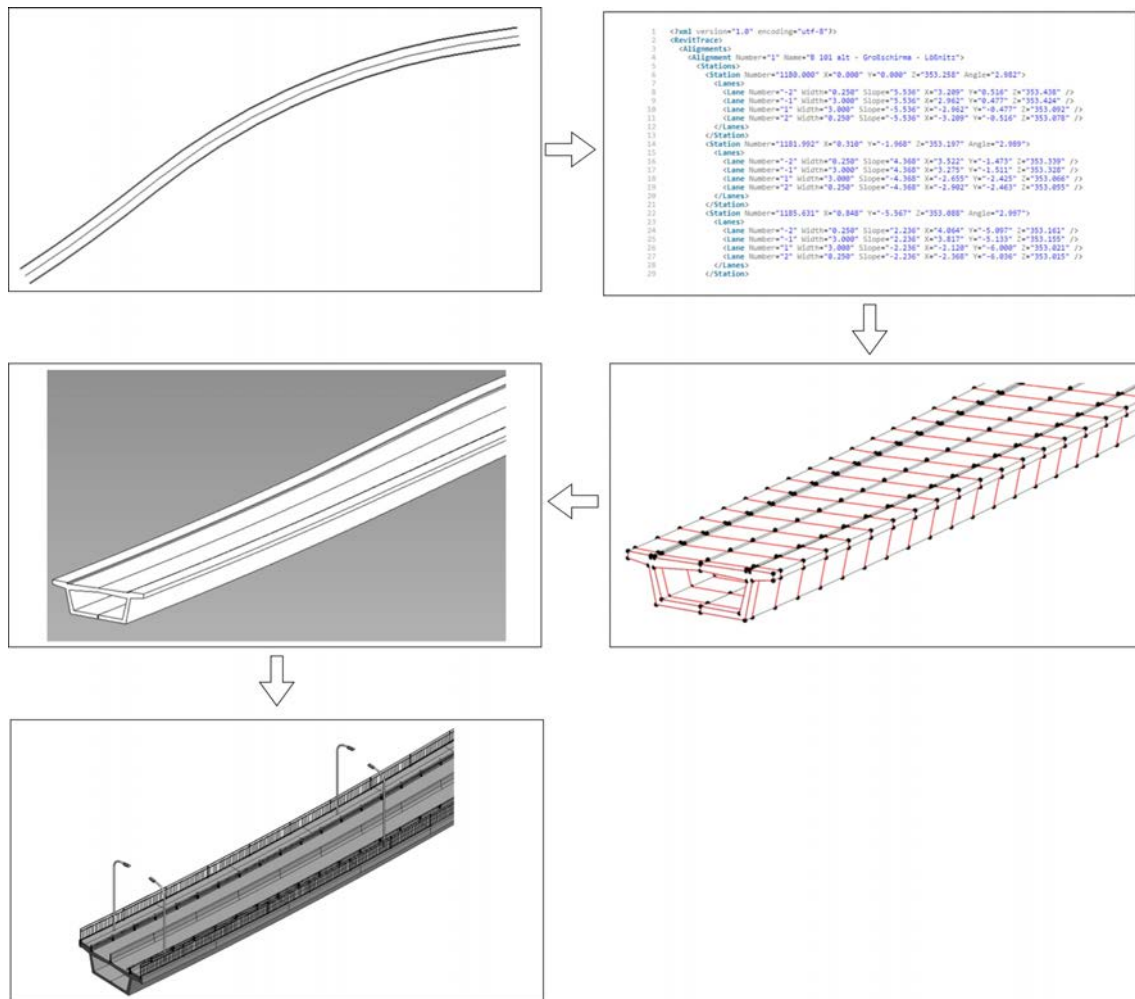


Figure 4.4: Vestra Infravision workflow for the modeling of a bridge superstructure in Revit

fast modeling of the complete bridge, however they are not parametric families and are quite limited.

4.4 FIDES Infrastructure Toolkit

FIT is a Revit plug-in that was released by FIDES. The conceptual workflow of the FIT is in general quite similar to the workflow described in the previous sections.

Step 1 - Create the parametric bridge deck profile

Before initiating the FIT add-in in Revit, the user is required to create the cross section of the bridge as a Generic Adaptive family. The user has also the possibility to use various cross sections that are already provided in the FIT. It is also important to define the parameters of the cross section, such as the cross sectional inclination and many more, as shown in Fig.4.5.

With this approach it is clear that the FIT is also suitable for the creation of other structures than bridges, by using different cross sections, for example retaining walls.

Step 2 - Reading road data from Excel file

In the next step the user needs to open a “Generic Adaptive” Family in Revit in order to create the bridge superstructure family. By initiating the FIT plugin, the axis and cross section data is imported from the selected Excel file as presented in Fig.4.5. This file includes the stationing and the global coordinates of the stations, as well as the elevations of each station. In addition it includes the type of the cross section profile family that was created in the previous step.

This again poses a disadvantage in this approach, as the alignment data have to be created with the help of another software, possibly Civil 3d and then exported to an Excel file, which has to be formatted in this specific way in order to be imported by FIT.

Step 3 - Creation of the bridge superstructure

The result of the import is the creation of the axis and the creation of the profiles, as shown in Fig.4.5. The deck profiles are automatically placed at the right position and with the right orientation along the axis. The user then is required to manually select all profiles and create the form of the superstructure. This process has to be repeated for parapets and also for the creation of void forms. The bridge superstructure, including deck and parapets is now modeled as a Generic Adaptive Family and needs only to be inserted in the Revit project.

Step 4 - Creation of drawings

In the third step, a “virtual” 3D model is derived from the real model which is then used for the creation of the drawings, as illustrated in Fig.4.5.

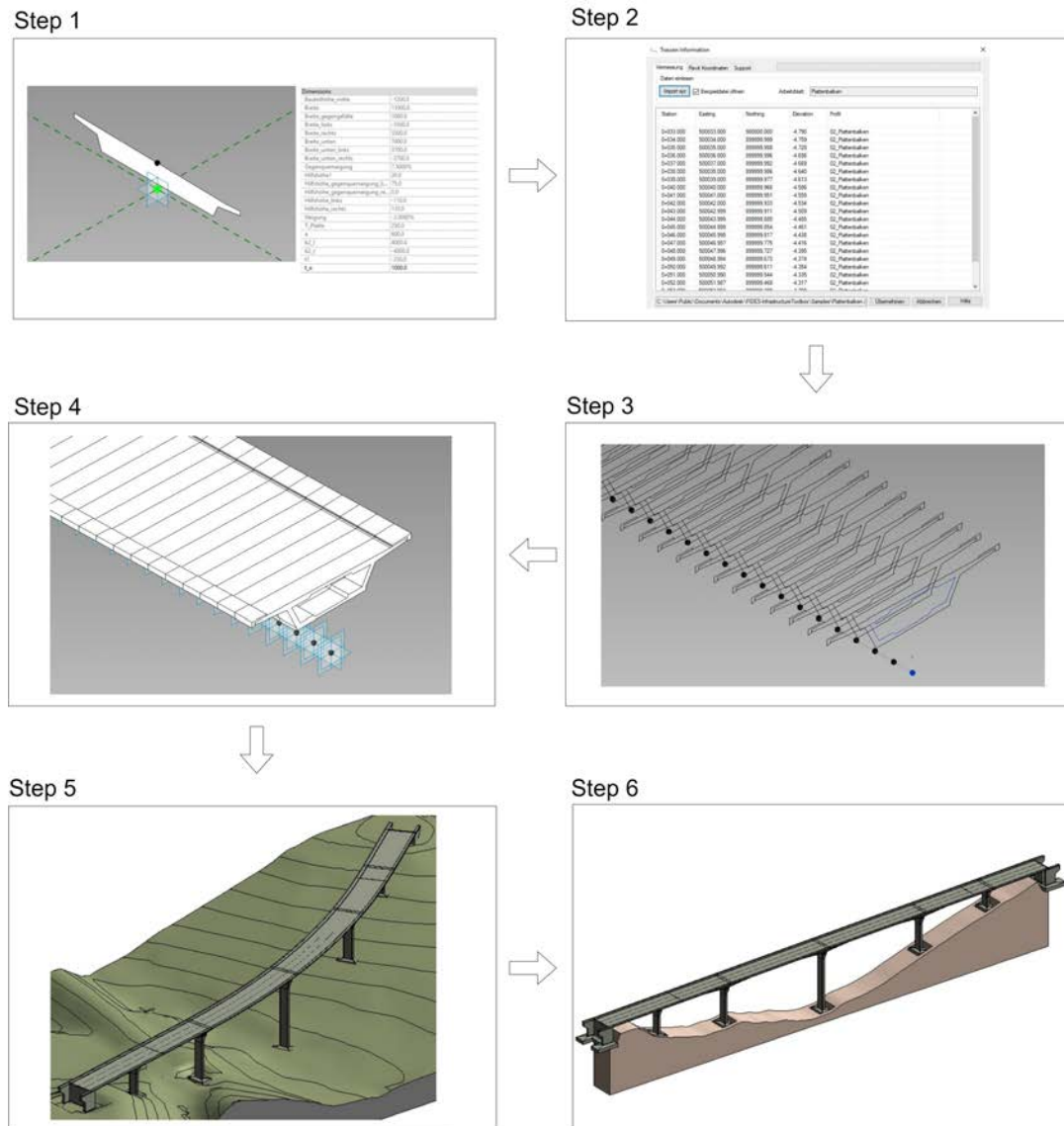


Figure 4.5: FIT workflow for the modeling of a bridge superstructure in Revit

It is important to notice that by selecting the profiles in the Revit Generic Adaptive Family, a so called “sweep form” is created. This means, that in order to have a certain accuracy, a large number of profiles is required, e.g. the more profiles used, the better the accuracy of the model. Instead a “swept blend form” in a Revit Generic Adaptive Family would require fewer profiles and a path for the entire bridge superstructure. This approach results in a much better accuracy than the “sweep form”.

After several tests with FIT it is concluded, that FIT is not yet mature enough in order to be used on a professional level. Similarly to AKG Vestra Infravision, the creation of the bridge deck was in many cases not possible. Again, the exact reasons for these unsuccessful results

remain unknown. It is very likely, that with the use of external input data for the creation of the alignment axis multiple unpredictable problems could arise. In addition, FIT does not yet provide the user of any options for the creation of abutments and piers of a bridge. Furthermore, more detailed elements, such as railings or tendons can not be created with the use of FIT.

4.5 SOFiSTiK Bridge Modeler

The SOFiSTiK Bridge Modeler integrates with Revit and is an easy-to-understand, BIM tool for bridge modeling. SOFiSTiK AG launched the Bridge Modeler in November 2018. Benefits of the software include advanced modelling capabilities and parametrisation of the entire structure. In Fig.4.6 the basic workflow of the SOFiSTiK Bridge Modeler is presented and will be explained with more details next.

In contrast to the previously described workflows the SOFiSTiK Bridge Modeler functions independently from any other software applications. In other words the whole modeling process, meaning from the creation of the alignment until the modeling of the complete bridge structure, takes place in the Revit environment with the Bridge Modeler UI. This not only reduces the complexity of the whole process, but also makes it more understandable for the user and ensures a better design quality, since there are absolutely no interfaces or interactions with other external applications. This poses a major advantage of the Bridge Modeler, since exactly such interfaces are considered to be problematic for Vestra Infravision and FIT.

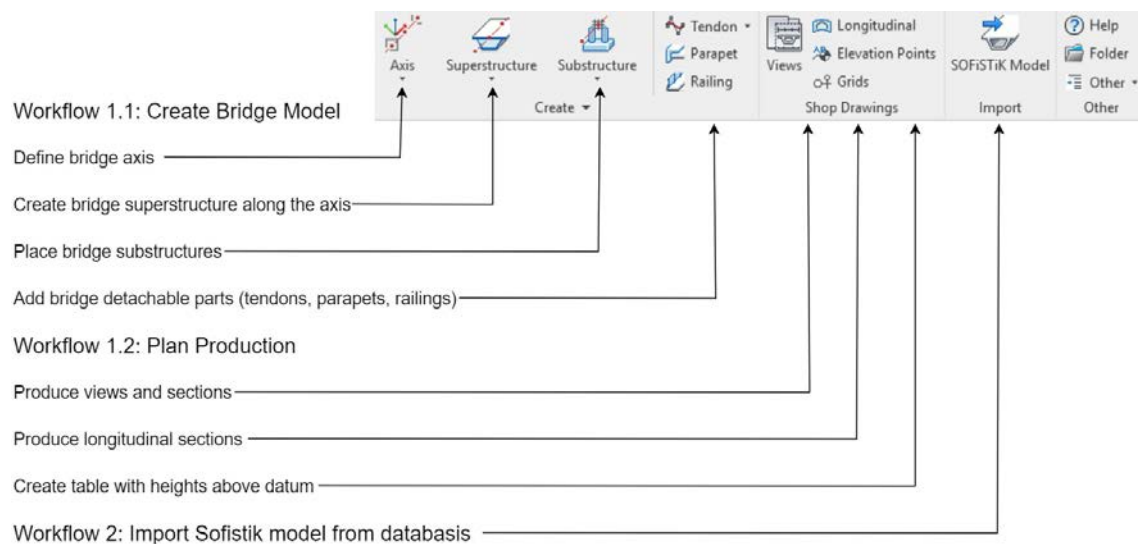


Figure 4.6: SOFiSTiK Bridge Modeler general Workflow

Step 1 - Alignment definition and creation

In the first step, the user defines the alignment data of the bridge with the use of a windows

form (“Alignment” tab), depicted in Fig.4.7, left). The user inserts the horizontal axis data, selecting between straight line, arc, clothoid, blossom, sinus or cosinus curve. As expected, for a straight line the length is required, for an arc the user must insert both arc length and radius, whereas for a clothoid length, start and end radius are needed. While the user inserts the input data for the axis, the horizontal alignment is displayed on a window graph, which is very practical for the user, as it is easy to understand the exact geometry of the horizontal alignment.

Next in the “Vertical” tab (Fig.4.7, right), the user defines the vertical alignment. The vertical alignment is defined by the heights at each station. In case of a vertical curve, crest or sag, the user is required to insert a radius. Again the alignment is displayed and automatically updated with the elevations and as a result, a 3D curve is created. In the “Placements” tab the user has the option to create various placement stations which will be later used for piers and abutments. It is possible to choose whether the reference planes of the placement points will remain vertical along the axis, or will be placed orthogonal to the axis. With the “Variables” tab it is possible to define variables for parameters, such as the height of the bridge along the axis. For example, this option enables the creation of bridges with variable heights of cross sections. The cross slopes and superelevations have to be also defined as variables in this stage.

With the button “Accuracy” it is possible to adjust the geometric accuracy of the bridge deck. The user has the option to define the number of the profiles used to create the bridge deck. In case of a straight alignment only two profiles would be needed, whereas in case of a curved alignment a larger number of profiles is required. In addition the user has the option to regulate the accuracy of the curve interpolation.

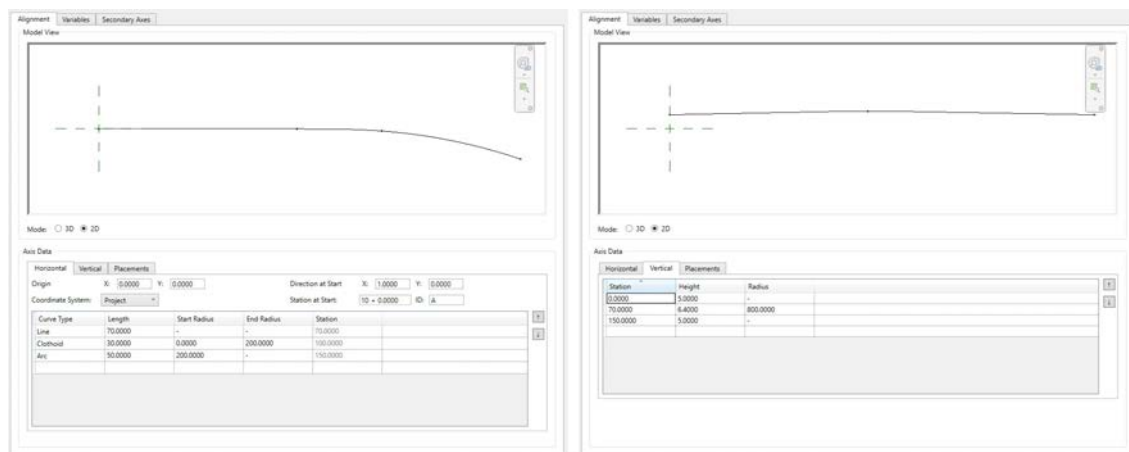


Figure 4.7: Input dialog windows for the creation of the horizontal alignment (left) and the vertical alignment(right) with the SOFiSTiK Bridge Modeler

Step 2 - Creation of the bridge superstructure

In the second step, the user creates the bridge deck. In the windows form presented in Fig.4.8,

left, the user can select the type of the cross section, which is a Revit Generic Adaptive family and arrange the various built-in parameters accordingly. It is also possible for the user to create his own cross section family and insert it in the bridge superstructure creation, thus allowing more flexibility. The available window display allows the user to control the values of the parameters, as the 2D cross section is automatically updated. At this point the user is able to couple the previously defined variables with the cross section, e.g. define the variable height for the bridge deck.

Step 3 - Creation of the bridge substructures

The third step involves the substructures creation, namely abutments and piers, as depicted in Fig.4.8, right. Similarly to the previous step, the user can selected the appropriate family from the available list and again arrange the parameters to create the desired geometry. The user selects the stations on which the substructures should be placed as well as the proper positioning, for example in case of a skewed bridge. The SOFiSTiK Bridge Modeler also includes content of generic families for substructure creation. These families can be easily modified or created from scratch to meet company standards.

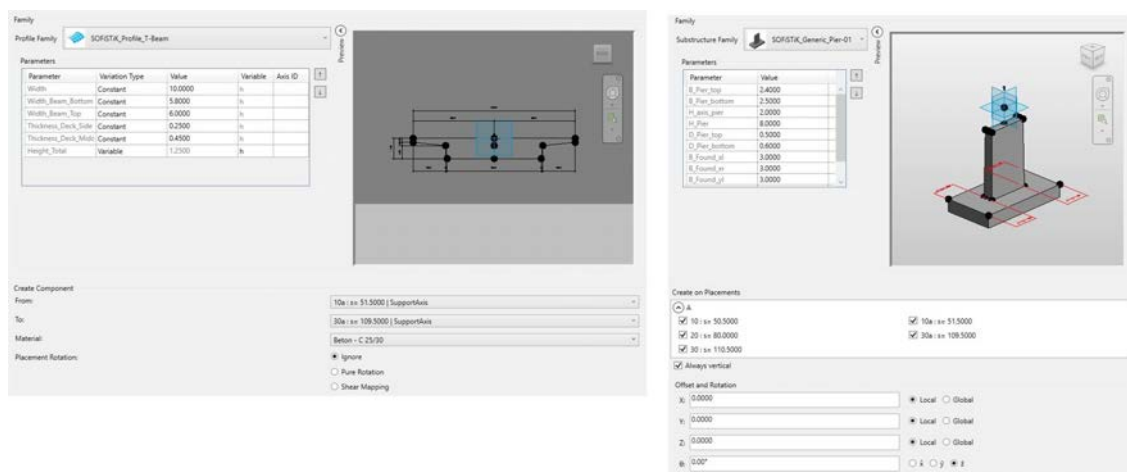


Figure 4.8: Input dialog windows for the creation of the parametric bridge deck profile (left) and the bridge substructures (right) with the SOFiSTiK Bridge Modeler

This function makes it very simple to model various forms and types of substructures in no time. However the families provided are quite limited and it is very possible that the user needs to manually model the bridge substructures from scratch.

Step 4 - Complete modeling of the bridge superstructure, parapets and railings

In the fourth and last step the user has the option to create additional elements for the bridge, such as parapets, railings and bridge tendons. For instance the creation of the bridge parapets is simply done by clicking on the edges of the bridge deck. The parapets automatically follow the curvy edges of the deck. Similarly, the railings are placed on the parapets and follow the curved geometry.

Step 5 - Production of plan sheets

The SOFiSTiK Bridge Modeler enables the user to produce plan sheets for the various stations, site plans, longitudinal views and cross-sections in a quick way. Cross sections and longitudinal views are automatically produced for each station of the bridge.

The advantages of SOFiSTiK Bridge Modeler are quite obvious; it is a tool that requires no other programs for the creation of the complete bridge from scratch. As a result the user has full control over the creation of the alignment, axis geometry and axis precision. The Bridge Modeler enables engineers to create and examine various design alternatives with little effort. In addition, with the modification of either the horizontal or vertical alignment, the bridge deck is automatically updated in order to follow the axis. Changes in the parameters of the deck profile automatically update the geometry of the whole deck too. However, in case of modified alignment data or deck profile, the positioning of the parapets and railings is not updated. As a result, they need to be placed again after the deck geometry has changed.

In addition, in case the position of a “Placement” is changed along the axis, the piers of this placement are repositioned automatically. However the height of the piers needs to be readjusted. These issues of the current version of the SOFiSTiK Bridge Modeler (January 2019) are expected, considering that the first version was released just in November 2018. Such problems do not pose great difficulties for the modeling of a large number of bridge variants.

Another disadvantage is that, in the family of the deck profile the cross-sectional slopes are parametric defined and have to be coupled to the axis alignment with the use of specific functions. This poses a certain difficulty for the design engineers, since this method is not similar to the traditional method for creating superelevations and could lead to confusion. Furthermore, it is important to notice that the geometric modeling of the abutments is not sufficient in case the ends of the bridge are located on an arc axis. In other words, even in such a case the abutment wing walls are modeled straight and do not follow the curved geometry of the bridge superstructure, resulting in problems with the modeling of parapets and railings.

4.6 Summary

Every program has its own advantages and disadvantages. There is no ultimate tool that could fit all the needs of the project and the engineers. In conclusion choosing the appropriate automation method and the appropriate tools depends on many factors.

- The kind of the modeling task.
- The number of people that will use the resulting tool.

- The skill level and the types of skills of the people using the tool.
- The different methods and work processes.
- Practical issues, such as expenses for the modeling software.

In the following table an overview of the tools presented in the previous sections is summarized.

Bridge Modeling Software	Description	External programs required	User-friendly, characteristics, improvements needed	Creation o bridge substructures, e.g.abutments
Dynamo	Revit plug-in, textual programming language with nodes	Infraworks, Civil 3D	Presents difficulties in using and understanding due to different modeling concept	Can be realised
Vestra Infravision	Revit plug-in	Vestra Road (alternatively Civil 3D)	Difficulties in defining cross slope and changes in cross sectional height. Improvements needed.	Not provided
Fides Infrastructure Toolkit	Revit plug-in	Infraworks, Civil 3D	Suitable for the fast creation of many variants of bridge decks. Improvements needed by errors when creating geometry.	Not provided
SOFiSTiK Bridge Modeler	Revit plug-in	None	Easy and fast to use. Parametric adaptation in case of modifications. Difficulties in defining cross slope.	Partially provided

Table 4.1: Summary of the currently available software tools for the modeling of bridges in Revit

Chapter 5

Abutment Tool

5.1 Overview of Abutment Geometry and Function

Abutments are special structures placed at both ends of bridges, in order to retain the earth and carry the vertical and horizontal loads from the bridge superstructure to the ground. They could be designed either as piers or as retaining walls and they should be able to withstand against the overturning and sliding forces. The footings should also be designed to counteract differential settlement and excessive displacements (Mehlhorn, 2010). Fig.5.1 illustrates the primary components of an abutment.

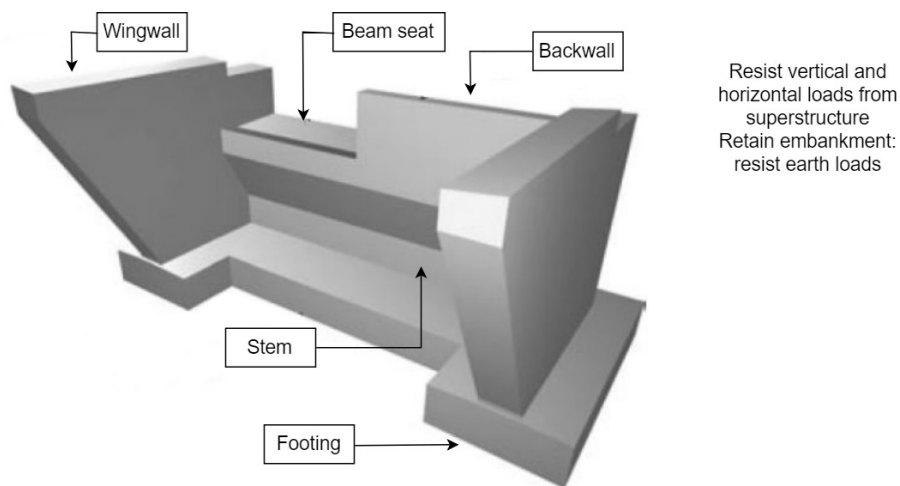


Figure 5.1: Overview of the components of an abutment, based on Mehlhorn (2010)

5.1.1 Geometry of Wingwalls

Structures forming an extension of the abutments to retain the earth of the approach bank are called wingwalls. In other words, these are retaining walls adjacent to the abutment

backwall and can be constructed either integrally or independent with the abutment wall. There are various methods for the constructive connection of the abutment wingwalls to the backwall, as extensively explained in Kordina & Westphal (1984). The rear side of the abutment wall, as well as the wing walls must withstand the following loads (besides the own weight) (Mehlhorn, 2010):

- The pressure from the earth backfill.
- The weight of the bridge superstructure.
- The surcharge from the live loads from the superstructure, both horizontal and vertical.
- The hydraulic loads from the saturated soil conditions.
- The loads resulting from the deformations.

The exact procedures for the statical calculations of various types of bridge abutments are presented in detail in Mehlhorn (2010). Moreover, there are generally three common arrangements of wing walls in bridge abutments:

1. Wing walls perpendicular to abutments or “return wings”

Return wings follow the direction of the bridge superstructure, as shown in Fig.5.2, top left and top middle. It is important to note, that in this case the bridge parapet and railing system continues along the top edges of the return wings. In addition, return wings generally result in the greatest concrete quantities when compared to a different orientation of the wings. However, due to the reduced volume of fill required, they have the least impact on the site. Furthermore, return wings are particularly suitable in cases of bridge decks with high cross-sections (MainDOT, 2004).

2. Wing walls at an angle to abutments or “flared wings”

According to MainDOT (2004), “the ideal flared wing bisects the angle between the centerline of bearing and the roadway berm”, as presented in Fig.5.2, middle. Flared wings actually result in the best balance between the embankment fill requirements and the cost of the structure. As a result, this configuration is used in many cases.

3. Wing walls parallel to abutments or “extension wings”

Extension wings are extended straight out from the abutment. They are built parallel to the centerline of bearing, as illustrated in Fig.5.2, bottom right. One disadvantage of this type of wingwalls is that they could result in huge volumes of fill, that is required around the abutment. Consequently, this configuration is well suited only for cases of relatively shallow superstructures (MainDOT, 2004).

Combinations of the types of wing walls that are mentioned above are also considered in many cases, as illustrated in Fig.5.2, . In addition, the length of the wing walls could define the type of the abutment. In other words, when the abutment wall is located close to the

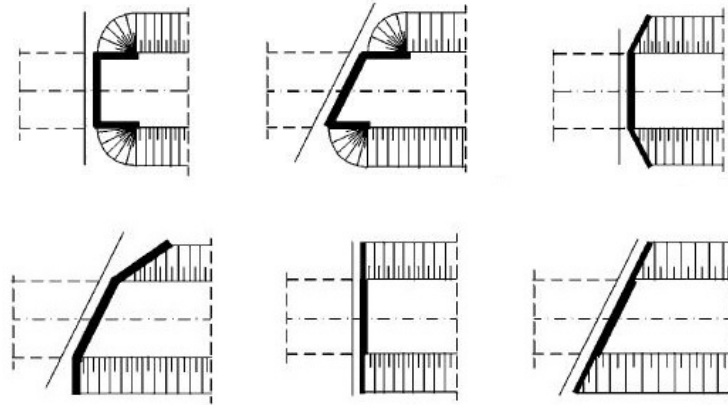


Figure 5.2: Various orientations of wingwalls of abutments, from Mehlhorn (2010)

foot of the slope, the wing walls have to be longer. As a result, they are constructed with a footing and therefore the whole abutment forms a rectangle, as illustrated in Fig.5.3, left (Mehlhorn, 2010). Otherwise, the wing wall is designed as a cantilevered wall, as shown in Fig.5.3, right.

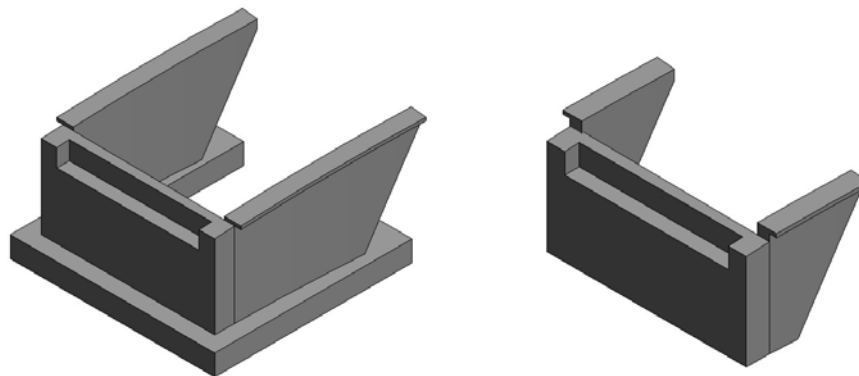


Figure 5.3: Wingwalls with and without foundation

Furthermore, one of the most important parameters that define the geometry of the wingwalls is the slope of the earth bank. In Germany, the inclination of the bank is regulated in RAS-Q96 and in most cases is $1/n = 1/1,5$ (FGSV, 1996). The length of the abutment wingwall can then be calculated with the following formula (Fig.5.4):

$$L > (a + b) + H_b \cdot n \quad (5.1)$$

All in all, the configuration of the wing walls depends on various parameters, such as:

- The horizontal alignment of the roadway
- Whether underneath the bridge there is a river, road or railway etc.
- Skewed bridge or not.

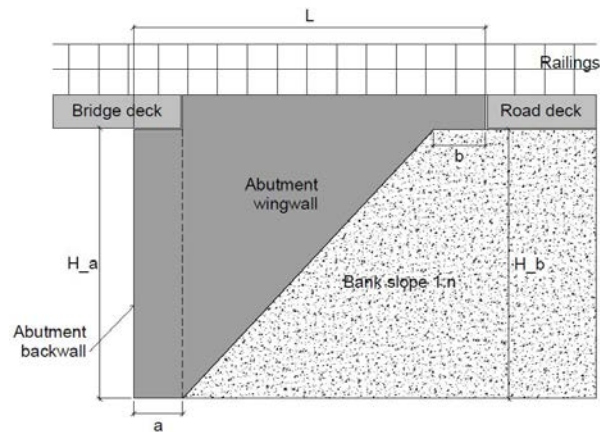


Figure 5.4: Dependence of the wingwall length on the distances and slope of the earth bank, based on Römer & Hochmuth (2013)

- The height of the upper structure of the bridge.
- The height of the slope.
- The stiffness of the ground.

However, as stated in White *et al.* (2010), there are no established maximum lengths for the abutment wingwalls. In Germany, the constructive specifications are defined in the guidelines (BVDI, 2017). According to the guidelines, two variants for the wingwall form can be used, depending on the wing height and on the cap width. Both variants are shown in Fig.5.5. These variants can of course be modified in order to adapt to the specific needs of each project.

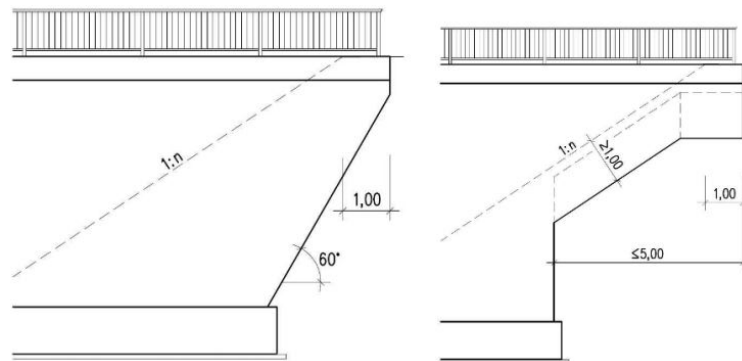


Figure 5.5: Variants for the abutment wings according to the RiZ-ING, from BVDI (2017)

It is very important to note that, as mentioned before, in case of an abutment with parallel wing walls (U-Abutment), the deck construction including the parapets and railing, is extended on the wing walls, as illustrated in Fig.5.4 .

5.2 Modeling Concepts of Bridge Abutments

As mentioned in section 2.4 , the modeling of the bridge superstructure can be achieved relatively simply with a sweep of the 2D cross-sections along the bridge axis. The bridge abutments however, being a more complex geometric shape, require more modeling steps.

Firstly, one needs to analyse the individual components of the abutment, namely the backwall, the wingwalls and the footing. The top surface of the abutment backwall and wingwall must follow the geometry of the superstructure, whereas the footing remains planar on the x-y plane. In Obergrießer (2017) two modeling concepts for a bridge abutment are introduced: the “cross-section related” and the “ground plan related” concepts. The ground plan concept is also met in other publications, such as Ji (2014).

Cross-sectional concept

In the first step of this concept, the profiles of the backwall and the wingwalls are created. Their exact geometry is derived from the profile of the bridge deck, as illustrated in Fig.5.6. In the second step both wingwall and backwall profiles are placed on the trasversal planes, that are derived from the alignment. The third step of this approach includes the creation of the wingwalls and backwall geometry with a sweep of the profiles along the alignment axis. In the fourth step the created solids are trimmed in order to derive the exact length of the solids. Finally, in the fifth step both solids are modified with proper boolean operations and then connected to each other (Obergrießer, 2017).

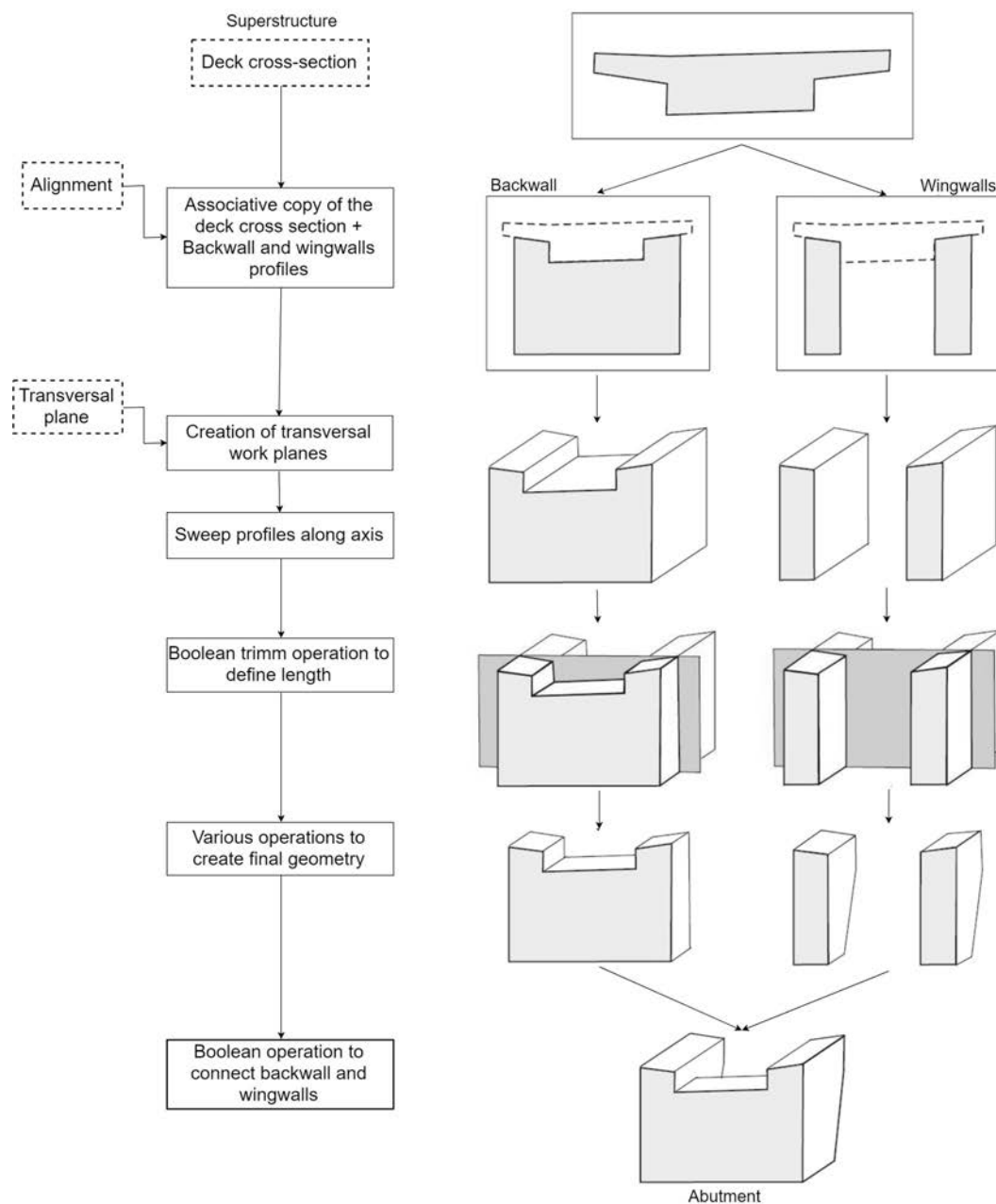


Figure 5.6: Cross-sectional Modeling Concept of a bridge abutment, based on Obergrießer (2017)

Ground-plan concept

The first step of this concept includes the creation of the profile of the abutment on the global X-Y plane as a complete structure, meaning wingwalls and backwall together (Fig.5.7). In the second step the horizontal profile is extruded along the global z axis, creating a U-form solid. In the next step, with the use of the deck profile and the bridge axis, a sweep form is created, which represents the upper edge of the deck profile. The U-form solid of the abutment is then trimmed with the sweep form, in order to define the height of the abutment, as well as

the geometry of the upper edges of the abutment. Finally, with the proper boolean operation the final geometry can be created (Obergrießer, 2017).

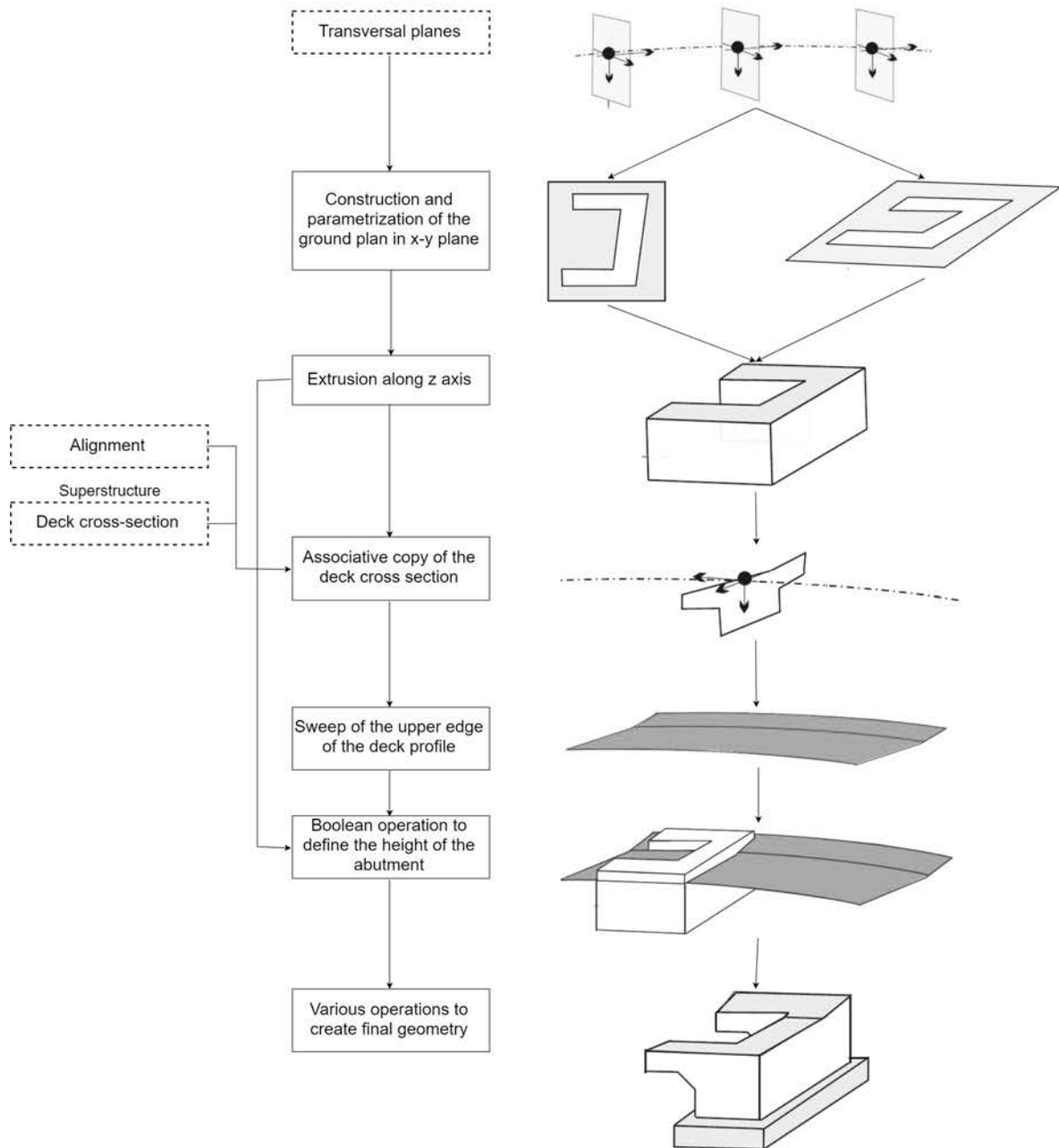


Figure 5.7: Ground plan Modeling Concept of a bridge abutment, based on Obergrießer (2017)

The main difference between the two methods is the accuracy of the geometry outline of the abutment. For instance, if the bridge axis is strongly curved, meaning with an $R \leq 1000$ m, the abutment should correspond to this curve. In such cases, the cross-sectional modeling concept should be applied (Fig.5.6). In case the geometric course of the bridge on the horizontal plane is either straight or very slightly curved, namely with a radius $R > 1000$

m, the modeling of the abutment can be implemented with the second concept (Fig. 5.7) (Obergrießer, 2017). However, it is essential to note that, the cross-sectional modeling concept can also be used with straight horizontal alignments or radii $R > 1000$ m and would result in exactly the same accuracy as the ground plan concept.

5.3 Description of the Abutment Tool

As presented in chapter 4, the various current bridge modeling tools for Revit do not yet provide a solution for a fully parametric bridge abutment. Revit provides the option to model complex and non-standardized structural components as “In-place” masses or families. Although a bridge abutment may seem simple to model in Revit, as it basically consists of three walls and a footing, it actually requires a lot of effort to be manually modeled in case of wingwalls perpendicular to the backwall. As mentioned before, in such a case the wingwalls need to follow the geometry of the bridge deck, as the parapets and railings of the bridge deck are extended on the wingwalls. This means that the wingwalls are now non-planar solids, that could be curved in three directions: a curved horizontal alignment in the X-Y plane, a curved vertical alignment in the X-Z plane, plus the rotation in the Y-Z plane because of the cross slopes and superelevation. The manual modeling process in Revit is therefore extremely complex. Furthermore, in case of a clothoid axis element, the manual modeling is even impossible, since Revit does not provide an option for creating clothoidal model lines.

As a result, part of the present Master thesis was to develop a plug-in for Revit in order to create a fully parametric bridge abutment. The Abutment-Tool is thought to be part of a Bridge-Module, that is being developed in the IT department of SSF Ingenieure. This tool is briefly presented in Sundmacher & Meyer (2017). However, the Abutment-Tool was developed separately and is meant to be integrated to the program in the near future. The programming language used for the Revit API is C# and the program is written in Microsoft Visual Studio 2017. Moreover, the plugin is compatible with Revit 2019.

Another aim of the Abutment-Tool is to also evaluate in praxis the applicability of the theoretical modeling concept based on cross-sections introduced by Obergrießer (2017). In the following section the Abutment-Tool and its concept are stepwise presented.

5.3.1 Abutment-Tool Overview

Generally, with the Abutment-Tool the user is able to create a bridge abutment as a Generic Adaptive family called “Abutment”. This family is a host family for three further nested family instances, a “Backwall”, a “Wingwall” and a “Footing” family, as illustrated in Fig. 5.8. One advantage of this approach is that it makes it possible for the nested families to appear on different material lists, since they may have different material parameters. A further

advantage is the better and easier manipulation of the separate families in the Revit project. For example, the user is able to replace just one nested family instance, e.g. the footing and keep the backwall and wingwall family instances unmodified inside the complete Abutment instance. A further important advantage considering the manipulation of the created families is presented in subsection 5.6.2.

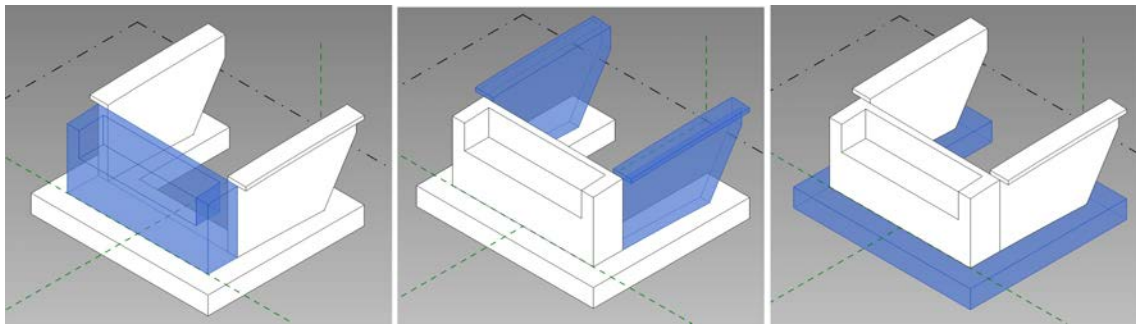


Figure 5.8: Nested families (backwall, wingwalls and footing) in the host abutment family

In addition, the user creates the alignment on which the abutment is placed from scratch in Revit. The main advantage of this approach is, that there is no need for use of any external programs for the alignment creation. Thus, the user has full control and understanding of the alignment geometry creation and precision.

The modeling concept that is implemented by the Abutment-Tool is similar to the first concept presented in section 5.2. More specifically, the abutment is created with the cross-sectional approach. Both components, the wingwalls and the backwall are modeled based on the same alignment axis in order to provide consistency. On the contrary, the footing component is not created based on the alignment, but is geometrically connected to the backwall and wingwalls of the abutment.

Unfortunately Revit is not the easiest tool to create multiple curved forms. In Revit, it is not possible to create 3D solids by lofting along 3D sweeping paths, as stated in the Online Documentation for Revit API (RevitApiDocs, 2019):

“The path of the swept blend form should be 2D, where all input curves lie in one plane. If there’s more than one profile, the path should be a single curve.”

It is therefore required to use a planar path and place the profiles at the proper elevations in order to create a solid that is curved in space. This approach already poses a significant difference to the cross-sectional approach of section 5.2.

5.3.2 Horizontal Alignment Creation

The first window dialog of the Tool (Fig.5.9, left) enables the user to insert the input data of the horizontal alignment, namely the axis data on which the abutment is created. First of all, the user defines the station on which the abutment is placed. Secondly, the user can select one of three axis elements, straight line, arc or clothoid. For a straight axis element only the length is required, for an arc the user is required to insert the arc length as well as its radius, whereas for a clothoid axis element, starting radius and end radius are required.

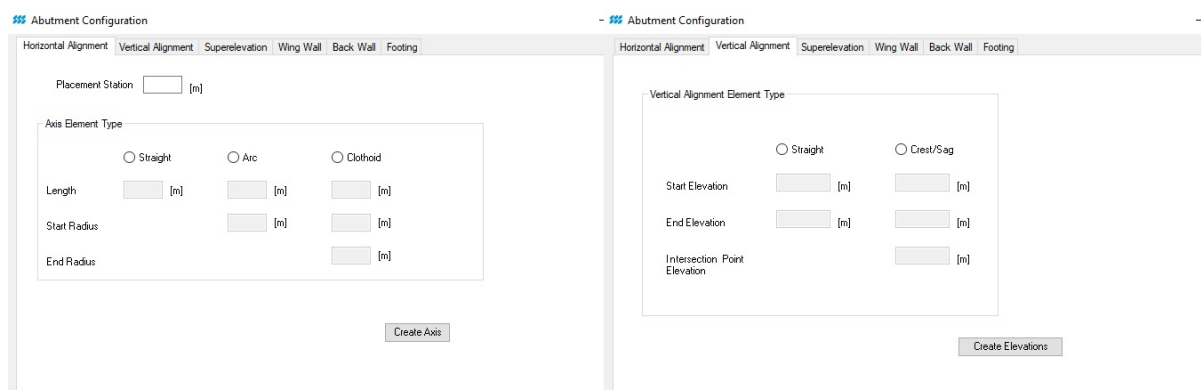


Figure 5.9: Input Dialog for the horizontal alignment (left) and the vertical alignment (right)

As a result the axis element is created on the global X-Y plane, as a Revit “ModelCurve” (Top of Fig.5.14). In case of a straight axis, the model line is created by connecting two points, whereas in case of an arc axis element, the model line is created through three points. The clothoid spiral requires more attention as to how to approximate a clothoid curve with a CAD program in comparison to an arc curve.

Various methods and algorithms for this approximation have been developed by researchers, creating the so called discrete clothoid. For example, in the article Meek & Walton (2004) a method is presented, with which a clothoid is approximated by a special arc spline, meaning by a collection of circular arcs joined with continuous tangent vectors. The same authors also present a different method for a clothoid approximation in their article Walton & Meek (2005), where they examine a control polyline approach to guiding a clothoid spline. Furthermore, the paper Habib & Sakai (2008) describes a method for joining two circles with an S-shaped or with a broken back C-shaped transition curve (Fig.5.10), composed of at most two spiral segments and have extended the method presented in Walton & Meek (1999).

In the case of the tool presented here, the coordinates of the clothoid are calculated with the mathematical formulas introduced in subsection 2.2.1. However the formula is given for a clothoid that connects a tangent with an arc element, meaning that the starting curvature is infinite. For the creation of a clothoid with starting curvature, that will be used as transition curve between two circular arcs, the same formula is used with a different approach. For

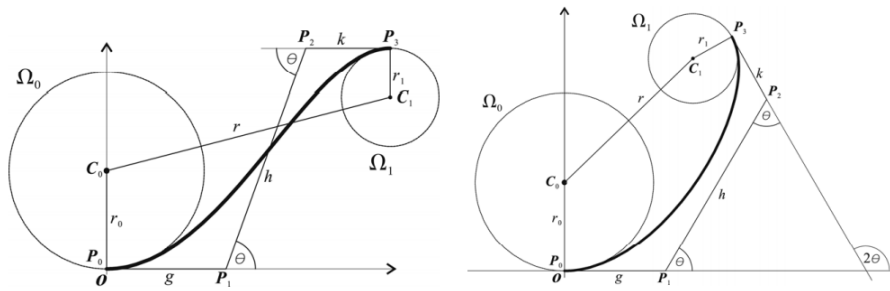


Figure 5.10: S-shaped and C-shaped cubic Bezier transition curves, from Habib & Sakai (2008)

example, to calculate a clothoid with start radius 500m and end radius 200m, following steps are implemented:

- 1. Calculate a clothoid with infinite starting curvature and end radius 500m.
- 2. Derive the total arc length of the first calculated clothoid l_1 .
- 3. Calculate a clothoid with infinite starting curvature and end radius 200m.
- 4. Derive the total arc length of the second calculated clothoid l_2 .
- 5. Calculate a clothoid with the same parameter A starting from l_1 until reaching l_2 .

For an infinite starting radius the user needs to insert 0m. In this case a clothoid that connects a straight line with an arc is created.

For the current version of the Abutment-Tool only one type of transition curve is available, namely the clothoid with a starting curvature bigger than the end curvature. In the future updates more types of clothoids will be implemented, as illustrated in Fig.5.11.

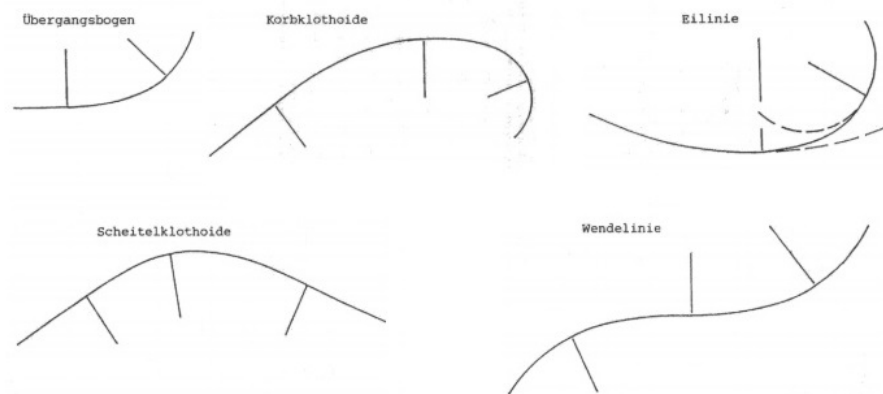


Figure 5.11: Various types of clothoids, from Wunderlich (2013)

The clothoid is thereafter created as a *CurveByPoints*, namely a spline that connects the Cartesian points. The Online Documentation for Revit API states that (RevitApiDocs, 2019):

“In terms of appearance and graphics control, CurveByPoints behaves similarly to ModelCurve. The main difference being that a ModelCurve refers to a SketchPlane, while a CurveByPoints does not.”

This poses a certain difficulty for the implementation of the Abutment-Tool, since clothoids need to be treated slightly different than straight or arc lines. After the creation of the axis line, reference points are then created on the model line, which functions as a host (Fig.5.14). The reference points are placed equidistantly along the line and each reference point has three reference planes which are automatically oriented on the host line. Since the axis lies on the X-Y plane, the Z plane of each reference point always remains vertical along the axis.

5.3.3 Vertical Alignment Creation

In the second window dialog (Fig.5.9, right) the data for the vertical alignment are requested. The Abutment-Tool implements the “VPI based” concept for the creation of the vertical alignment, that is presented in detail in section 3.4.2 (see also Fig.3.6). As a result, in case of a constant inclination the user needs to insert only the heights in meters at the start and end stations. Thereafter, the inclination is calculated from the height difference and the length of the axis element with an accuracy of .000. This option was deliberately planned so, since conventional inclinations have an accuracy of only .00. In case of a crest or a sag, the user has to additionally insert the VPI level location. Again, the incoming and outgoing inclinations are calculated from the height differences and the length of the axis element.

The Abutment-Tool does not exactly create the vertical alignment in the sense of the concept presented in section 2.2.2. The difference is that the elevations along the axis reference points are calculated according to the input data and stored in a list as doubles. In other words, these doubles represent the elevations on which the upper edge of the profiles need to be placed and there is no actual creation of a vertical alignment axis.

5.3.4 Cross Slope and Superelevation

Although the cross slope and superelevation are geometrical features of the bridge deck profile, they have to be taken into consideration also for the modeling of the bridge abutment too, although it is part of the substructures of the bridge. The wingwalls of the abutment are placed at the edges under the roadway, meaning that they need to be placed at different heights, according to the cross slope of the roadway above them.

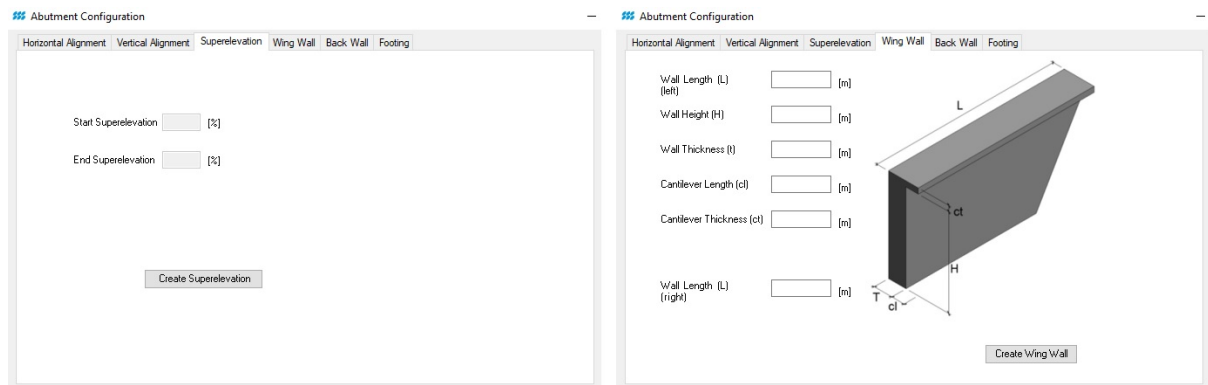


Figure 5.12: Input Dialog for the superelevations (left) and the wingwall profile dimensions (right)

Since there is no specific formula to calculate the superlevation given in the German guidelines, but only the diagrams depicted in Fig.2.6, the user is required to insert the value of superlevation manually. In the third dialog form the user inserts the cross slopes of the superlevation in percentage (see Fig.5.12). In case of a straight horizontal axis element, the input text-boxes are not enabled, as there is no superlevation. In case of an arc axis element only the “Start Superlevation” is enable, which is the superlevation according to the radius of the arc element. Finally, in case of a clothoidal axis element, both text-boxes “Start Superlevation” and “End Superlevation” are enabled. The “Start Superlevation” corresponds to the curvature of the clothoid at the start point, whereas the “End Superlevation” corresponds to the curvature of the clothoid at the end point (see also Fig.2.5, right).

The superelevations are also calculated as elevations and again stored in a list as doubles, similarly to the concept of the creation of the vertical alignment.

5.3.5 Modeling of the Wingwalls

In the theoretical concept presented in section 5.2, the profiles of wingwalls and backwall are derived according to the geometry and the position of the bridge deck. In its current version, the Abutment-Tool operates entirely independently from the modeling tool of the bridge deck. As a result, the user is required to insert the necessary dimensions of the wingwall and backwall profiles.

In the third window dialog (Fig.5.12) the user defines the various geometrical input data of the wing walls of the abutment. Various dimensions of the wingwall and the smaller cantilever are inserted, namely the wingwall thickness and height, as well as the cantilever length and thickness. The profiles of the wingwall are then “sketched” on each vertical reference plane of the reference points on the axis line that were created in the first step. Since the upper edge of the wingwall needs to follow both horizontal and vertical alignments, the upper line of the profile is placed at the proper elevations, as calculated in subsection 5.3.3.

The wingwall is thereafter created by sweeping the profiles along the axis. According to the Revit SDK, the created geometry is called a “swept blend” form. It is important to note that, not only the profiles are used but also the axis is used as the path, resulting in the fact that fewer profiles are needed to achieve a good geometric accuracy. This leads to a quicker process, since the form creation of a “sweep” in Revit with a large number of profiles can be very time consuming.

After the solid is created, it is suitably trimmed with two void elements in order to derive the final geometry of the wingwall. The rear side of the wingwall is cut by a diagonally slanted (60 degrees) void form. This form is a sweep that is attached to the last profile of the wingwall, as depicted in Fig.5.14.

The second void form is attached at the front of the wingwall solid. This void form regulates the exact length of the wingwall. In other words, it is a void form that represents the position and the geometry of the backwall. The initial thoughts of the Abutment-Tool did not include the creation of this void form, because the wingwalls were connected with a boolean operation with the backwall. This would result in a correct final geometry of the complete abutment, however upon opening of the wingwall family, the wingwalls are of course displayed with the “uncut” solids, namely with wrong length. Another disadvantage was that the concrete quantities were also not calculated correctly.

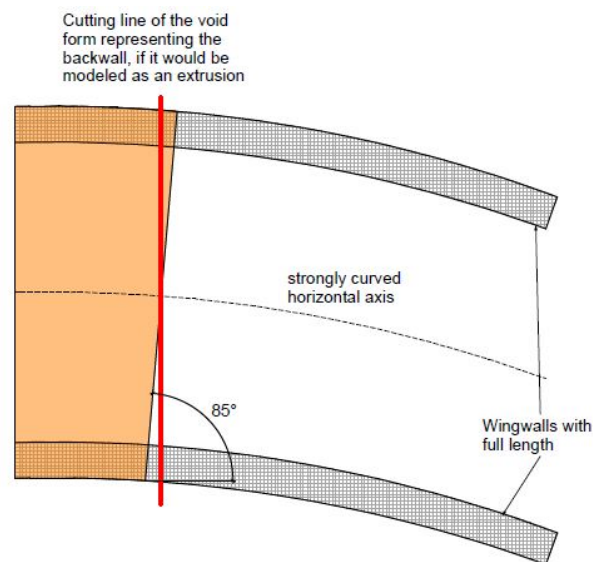


Figure 5.13: Creating the void form in order to regulate the exact length of the wingwalls

It is important to note that this void form is not a simple extrusion, because of resulting geometrical inaccuracy. Since it represents exactly the geometry of the backwall, it is also modeled as a swept blend based on the alignment data. Fig.5.13 illustrates an exaggerated situation of a strongly curved abutment for better understanding.

With the same approach the second wingwall is also created, with the only difference that the profile is now “mirrored” on the X-axis. The second wingwall is placed at the right distance to the first wingwall. The creation of the entire wingwall family is therefore completed. The wingwall family is automatically placed in the host abutment family and we proceed with the creation of the backwall family.

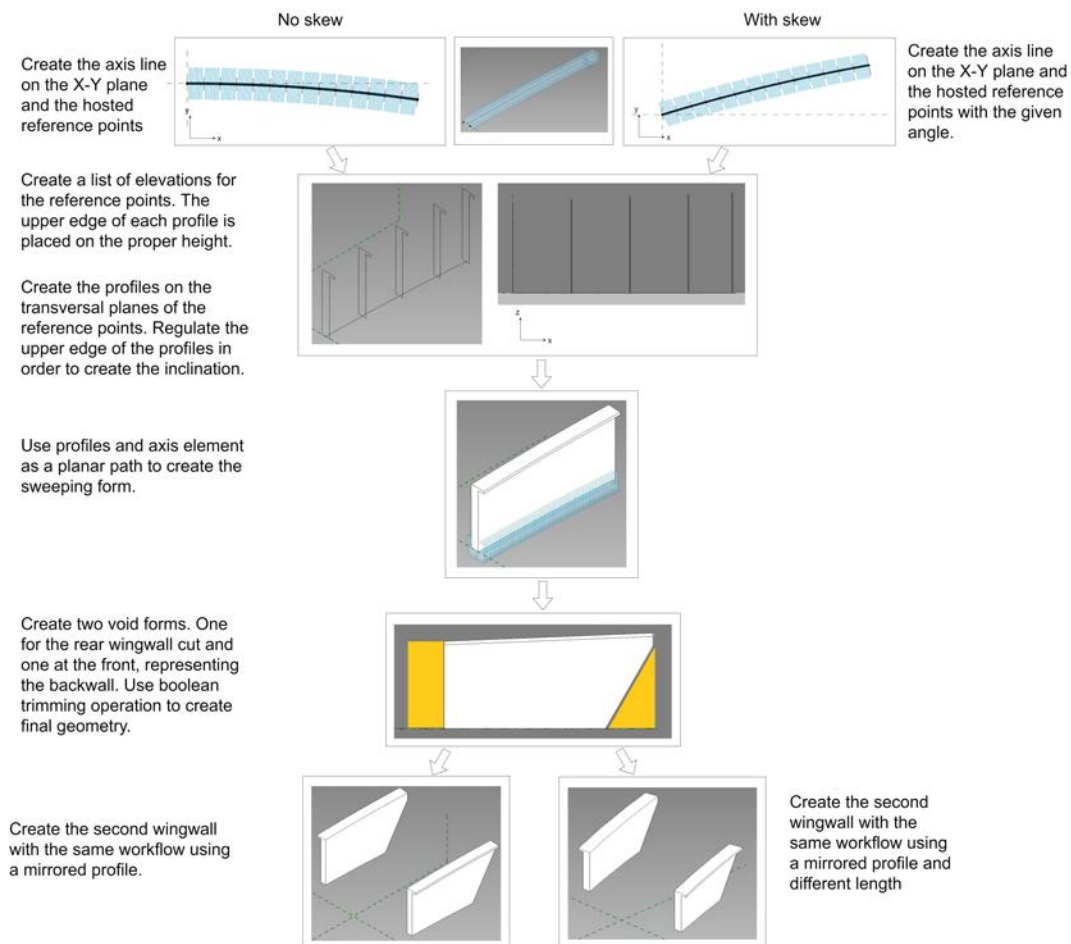


Figure 5.14: Modeling workflow of the wingwalls

5.3.6 Modeling of the Backwall

In the fourth window dialog (Fig.5.15) the user defines the geometrical data of the back wall of the abutment. As mentioned before, the backwall is also created along the horizontal alignment as a sweep form. The modeling concept is identical to the one presented for the wingwalls, with the use of different profiles. The gap for the embankment is created as a “void” form which is then trimmed with a boolean operation with the backwall.

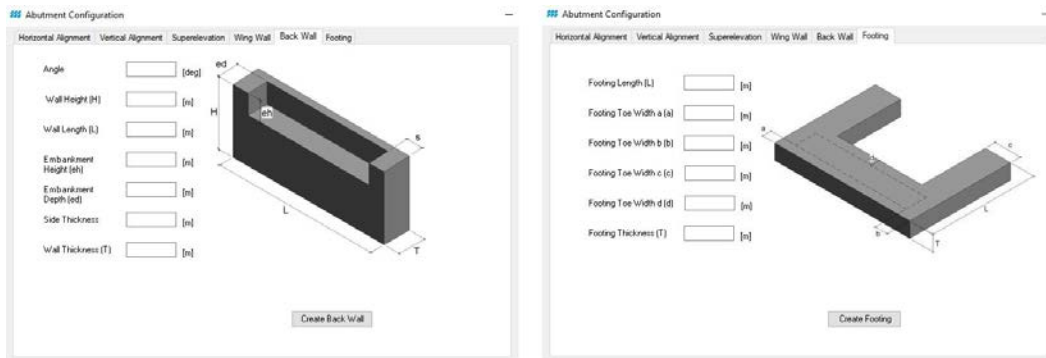


Figure 5.15: Input Dialog for the backwall profile dimensions (left) and the dimensions of the footing (right)

In case of a skewed abutment, the modeling process is slightly altered for the backwall, as illustrated in Fig.5.16. The horizontal axis is not rotated with the given angle, as seen in the case of wingwalls (Fig.5.14). Instead, the axis remains without any rotation and the backwall profiles are then placed with the specific angle. The rest steps are identical to the ones with no skew.

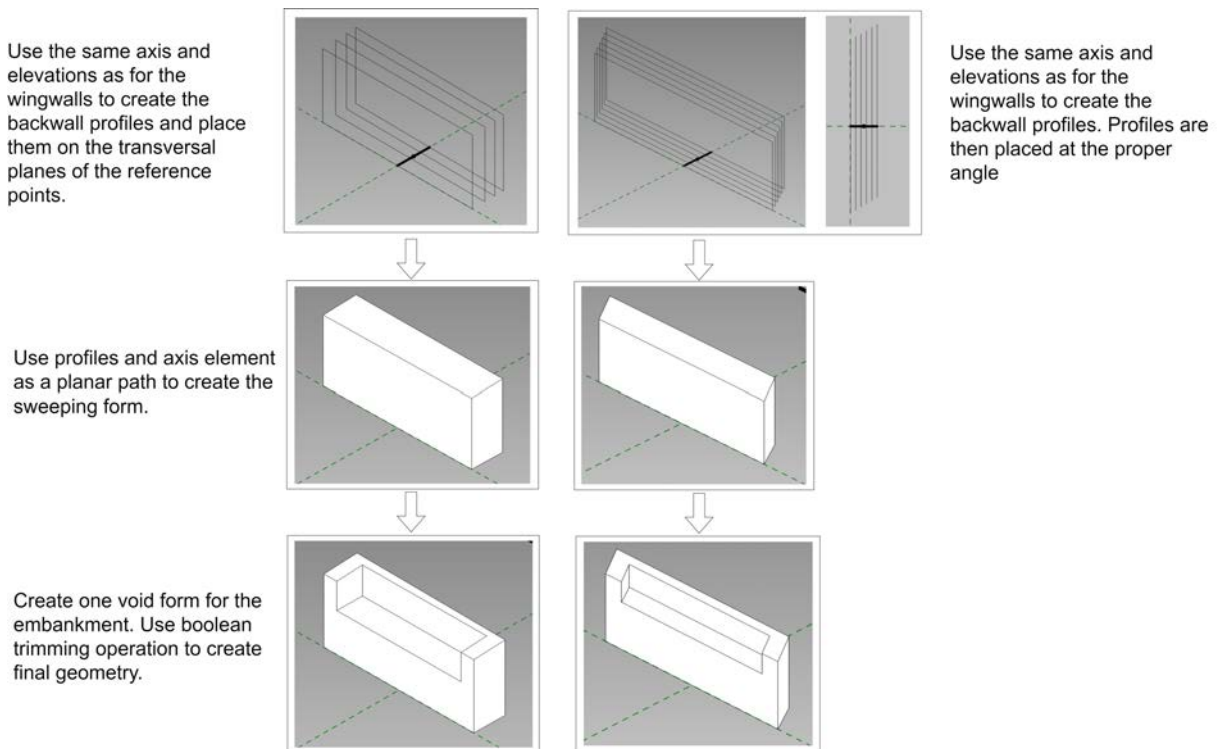


Figure 5.16: Modeling workflow of the backwall

5.3.7 Modeling of the Footing

In the fifth window dialog the dimensions for the geometry of the footing are inserted. The footing, in contrast to the wingwalls and the backwall, is not modeled based on the alignment. However, the geometry of the footing is dependent on whether the abutment is skewed or not. The footing is modeled as an extrusion, meaning that the outline of the footing is firstly sketched on the x-y plane and then extruded along the z axis, with the given thickness being the height of the extrusion, as illustrated in Fig.5.17

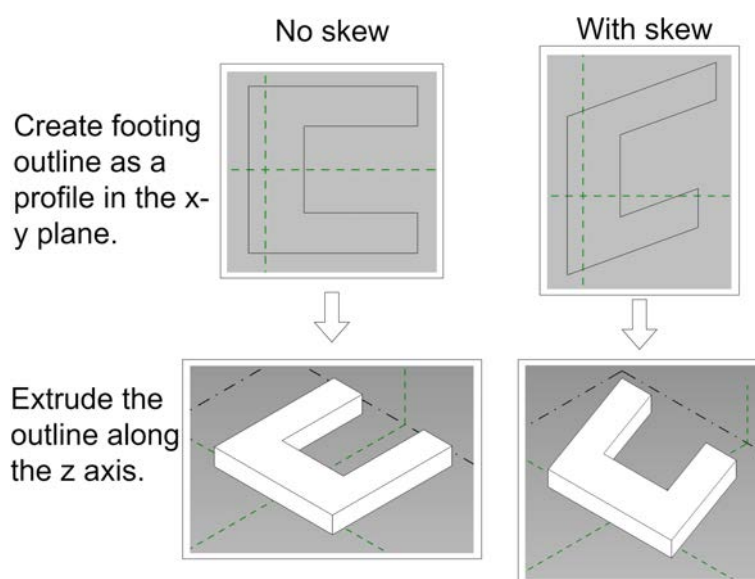


Figure 5.17: Modeling workflow of the footing

5.4 Results

In the following figures various results of created abutments are illustrated. It is clear that, the geometry of the abutments is created with a very high accuracy in all cases. The created parameters for each family are summarized in Tab. 5.1.

On the left side of Fig.5.18 the resulting abutment of the first test case is presented. The input data for the horizontal alignment was a circular arc with a length of 70m and a radius of 200m. The resulting curvy form of the wingwalls can be easily seen on the floor plan. For the vertical alignment a constant gradient of +5% is chosen. Furthermore, the upward direction of the upper edges of both wingwalls and backwall is depicted on the side view of the abutment. In addition, with such a small radius for the horizontal arc the resulting necessary superelevation is 5%. This cross slope is seen on the front view of the abutment. The first example is a bridge abutment with no skew.

Parameters of the Abutment family (host)	Parameters of the Wingwall family (nested)	Parameters of the BackWall family (nested)	Parameters of the Footing family (nested)
Placement_Station	WingWall_Height	BackWall_Height	Footing_Length_Left
Horiz_Alignment_Element_Type	WingWall_Length_Left	BackWall_Length	Footing_Length_Right
Axis_Element_Length	WingWall_Length_Right	BackWall_Thickness	Footing_Thickness
Axis_Start_Radius	WingWall_Thickness	BackWall_Sides_Thickness	Footing_Width_a
Axis_End_Radius	WingWall_Cantilever_Length	BackWall_Unique_ID	Footing_Width_b
Vert_Alignment_Element_Type	WingWall_Cantilever_Thickness		Footing_Width_c
Incoming_Grade	WingWall_Unique_ID		Footing_Width_d
Outgoing_Grade			Footing_Unique_ID
Start_Superelevation			
End_Superelevation			
Abutment_Unique_ID			

Table 5.1: Parameters of the nested families Wingwall, Backwall and Footing and the host family Abutment

On the right side of Fig.5.18 a second test case is illustrated. In this case the horizontal element type is a straight line with a length of 60m. The vertical alignment is a parabolic curve, namely a crest, with an incoming gradient of +10‰ and an outgoing gradient of -3.33%. The resulting curve of the upper edges of the wingwalls is seen on the side view of the abutment. Moreover, as depicted in the floor plan, the abutment is skewed with an angle of 25 degrees. Because of the straight horizontal alignment there is no superelevation.

At the bottom of Fig.5.18 both abutments are modeled with parapets and railings on the wingwalls, as well as with the earth bank. Both parapets and railings were simply created by clicking on the edge of the wingwalls, with the use of the function provided in SOFiSTiK Bridge Modeler (see Fig.4.6).

Axis Element: Arc
 Axis Element Length: 70m
 Radius: 200m
 Gradient: +5%
 Superelevation: 5%
 No skew

Axis Element: Straight
 Axis Element Length: 60m
 Incoming Gradient: +10%
 Outgoing Gradient: -3.33%
 Angle: 25 degrees

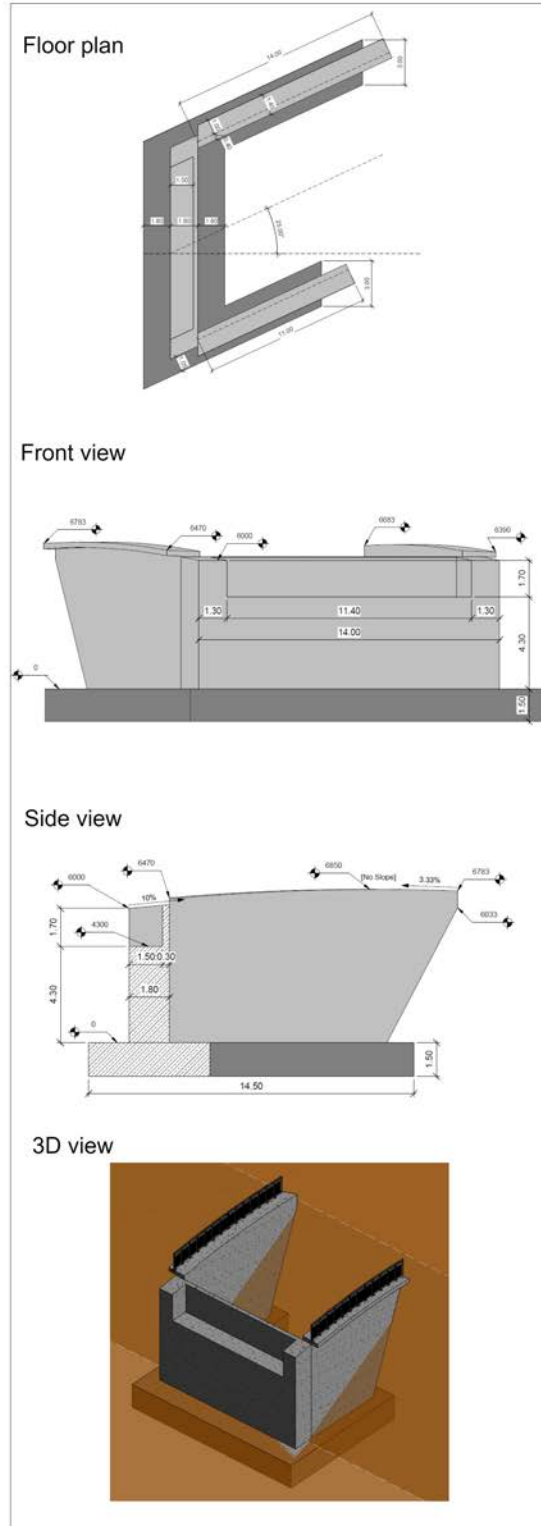
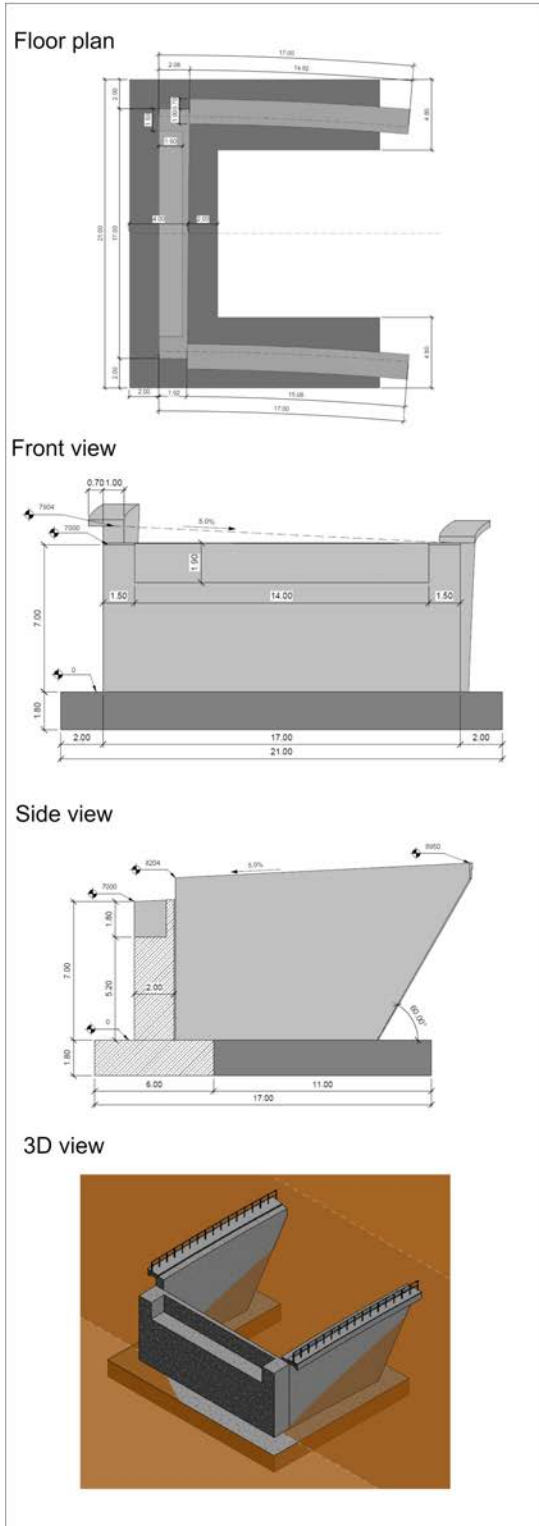


Figure 5.18: Left: Abutment with curved wingwalls in the x-y plane. Right: Abutment with curved wingwalls in the x-z plane

In Fig.5.19 another test case is presented. The element for the horizontal axis is a clothoid with a length of 15m, an infinite starting radius and end radius of 200m. In other words a clothoid used as a transition curve to connect a straight line with an arc of radius 200m. In addition the superelevation at the start point of the clothoid is zero, whereas at the end of the clothoid it is 5%. The curve of the wingwalls is obvious on the floor plan. For this test case there is no gradient for the vertical alignment. However, the superelevation of the clothoidal axis element results in a longitudinal inclination, as depicted in Fig.2.5. This inclination is upwards for the right wingwall, as seen in Section 4, whereas it is downwards for the left wingwall, as shown in Section 3. In the front view of the abutment (Section 1), it is obvious that both wingwalls are located at the same height, since the superelevation at the start of the clothoid is zero. In the back view (Section 4) however, the wingwalls have a height difference, which corresponds to a superelevation of 5%.

Fig.5.20 illustrates another interesting test case. This abutment is based on a horizontal arc line and has a decreasing inclination of -6%, as one can note from the side view. Again, the effects of the 4% superelevation are clearly seen in the front view, with the right abutment placed at a higher position than the left one.

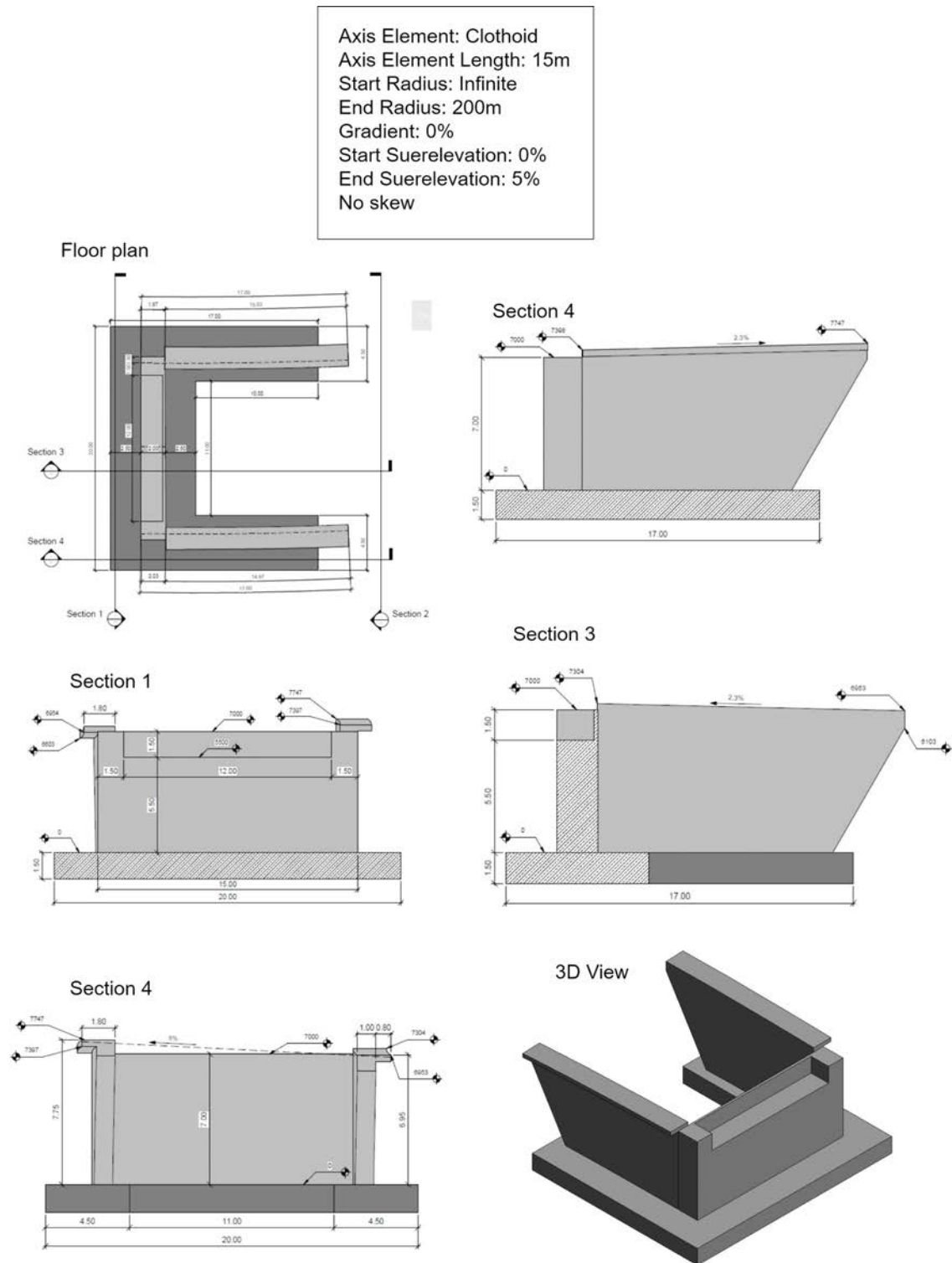


Figure 5.19: Abutment on a clothoid axis element

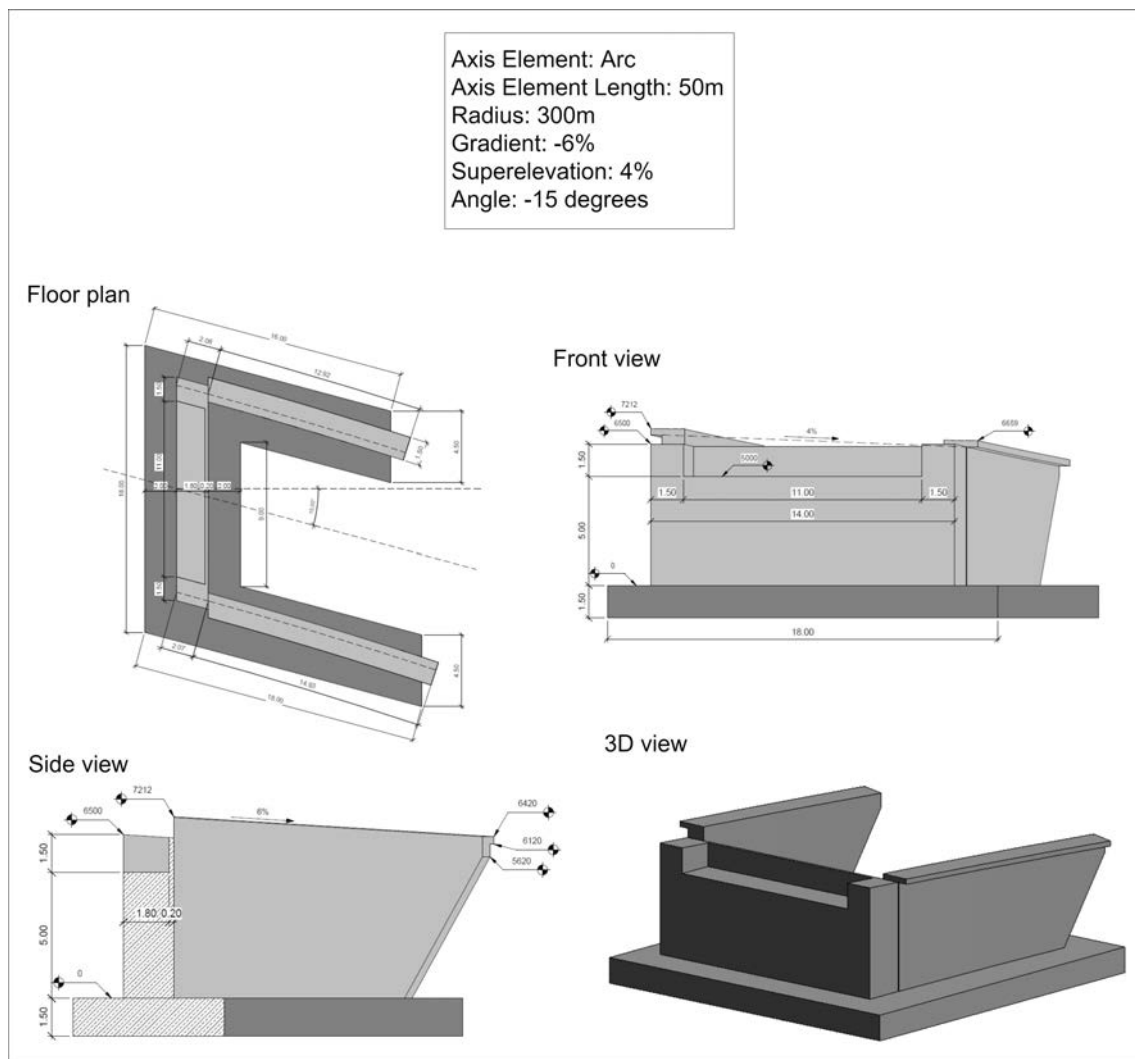


Figure 5.20: Left: Abutment with curved wingwalls in the x-y plane. Right: Abutment with curved wingwalls in the x-z plane

5.4.1 Considerations for Modeling Structural Properties of the Abutment

Creating an abutment in Revit with accurate geometry according to the curved horizontal and vertical alignments is one aspect of the Abutment-Tool. In addition, semantic information should be included, more specifically structural information. One of the original considerations about the Abutment-Tool was not only to create a geometrically correct abutment, but also to include the analytical model of the abutment. This option would make it possible to create a model that would include necessary information for further analysis, for example statical calculations. It is important to mention that, in cases of curved abutment wingwalls, the slightly curved surfaces do not play an important role for the statical calculations in comparison to fully planar surfaces. However, it is important that the abutment is modeled as a

structural component of the bridge too. Structural elements of Revit contain the analytical model.

The definition of the analytical model given in the Revit manual is following (Revit, 2019):

“An analytical model is a simplified 3D representation of the full engineering description of a structural physical model. The analytical model consists of those structural components, geometry, material properties, and loads, that together form an engineering system.”

The analytical model is an integral part of any structural element in Revit, namely for the following family categories:

- Structural Column
- Structural Framing: Beam and Brace
- Structural Wall
- Structural Floor
- Structural Foundation: Isolated, Wall, Slab

In other words, the analytical model is automatically created at the same time when the user creates the physical structural model. It is not possible to create an analytical model without its physical form. Furthermore, it is not possible to create either analytical lines or nodes with the Revit [API](#).

As mentioned before, the Abutment family and its nested families are created as Generic Adaptive families, meaning that they can not hold any analytical lines and nodes. The first consideration to tackle this problem was to change the family category of the wingwalls and backwall to the category “Structural Wall”. Unfortunately, whereas it is possible to change the category to other, non-structural categories, it is not possible to change it to any structural category. A second workaround to confront this problem was to create a so called “WallByFace”. This function can place wall instances on non-planar faces of a generic model. However, the Revit user has the option to place only non-structural wall instances with this function.

In conclusion, the current version of Revit does not provide any options to enable the analytical model for curved surfaces. The only way to include any structural information in the abutment model is by creating relative structural parameters and activating the option “Can host rebar”.

5.5 IFC Export of the Abutment Model

When choosing the appropriate settings for exporting an IFC file, it is essential to first consider the future use of the file. In other words, it is important to decide whether it will be used only for the purposes of coordination, or if it will be processed by a different modeling software. In the case of the exported abutment we concentrate mainly on exporting an IFC file suitable for coordination purposes. Therefore, the Export options described in the following subsection focus on the geometrical properties of the abutment.

5.5.1 Export Options in Revit

Generally, Revit allows to export the Revit project model into an IFC file with the use of the “Export IFC” dialog box (File → Export → IFC) as shown in Fig.5.21. By default, the mapping of the Revit instances to the IFC building objects is controlled by the “IFC Export Classes” dialog box (File → Export → Options → IFC Options). The default mapping for Generic Families in Revit to an IFC entity is the *IfcBuildingElementProxy*.

Definition from IAI: “The *IfcBuildingElementProxy* is a proxy definition that provides the same functionality, as an *IfcBuildingElement*, but without having a defined meaning of the special type of building element, it represents. NOTE: The building element proxy should be used to exchange special types of building elements, for which the current IFC Release does not yet provide a semantic definition” (BuildingSmart, 2019b).

However, the default mapping in Revit can be overridden and the user can define to which IFC entity each element will be exported. This is done by simply creating a shared parameter for each family instance, called “IfcExportAs”. In our case, the most suitable IFC entity for the abutment family would be the *ElementAssembly*, as depicted in Fig.3.9. In addition, both the wingwall and the backwall families are exported as *IfcWall*, whereas the footing family is exported as an *IfcFooting*.

The export options can then be configured in Revit from the dialog box, however, only a few of them have a potential impact on the geometry of the entities in an IFC file. The “Current selected setup” gives the user a choice between a few predefined options of IFC version and Model View Definitions (MVD) (Manual, 2019). Currently, the most commonly used schema is IFC 2x3 Coordination View 2.0, as it is supported by most programs, which is chosen for the abutment family and its components. One of the most important options are the “Property Sets”. The “Property Sets” tab of the advanced IFC export settings can be used in order to access further key settings (see Fig.5.21).

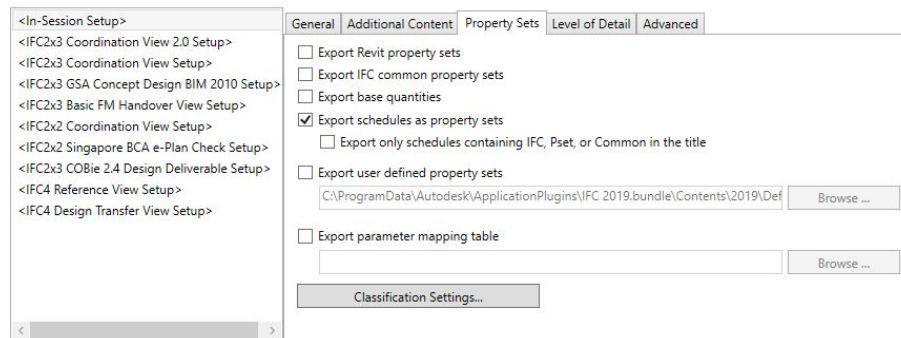


Figure 5.21: Revit Dialog for the customisation of the IFC export

Following options are provided in the Revit IFC advanced exporter (Manual, 2019):

- **Export Revit property sets**

This option allows the export of all the properties of a component. Although it might seem the most suitable option at a first glance, this function is not recommended for exchanging specialist IFC models. It augments the data model with lots of unnecessary information and thus results in huge file sizes. According to (Manual, 2019), a data model exported via this option could end up being 70% larger than the one exported with another method.

- **Export IFC common property sets**

This option includes the default properties that are defined in the IFC schema and should always be activated.

- **Export base quantities**

This option provides base quantities as a basis for the determination of quantities and the suitable information required by simulations.

- **Export user defined property sets**

is another way of exporting specific selected properties. The user has the option to exactly define which parameters will be exported in a text file.

More specifically, Fig.5.22 illustrates the relationships between the various objects that can be used in IFC PSETs.

For the coordination purposes, exporting the Revit property sets would be suitable, but it is recommended to be avoided due to the extra included, unnecessary information. Therefore, the parameters of the Abutment that need to be exported were specified in a text file in order to create the custom property set PsetAbutment. The exported IFC file was then imported in the IFC viewer BIM Vision in order to control and visualize the IFC file, as illustrated in Fig.5.23.

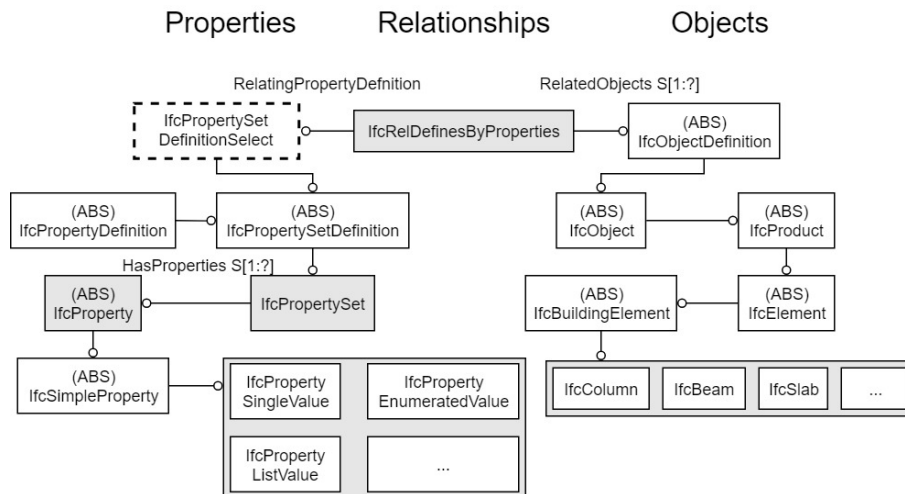


Figure 5.22: EXPRESS-G schema of the PSET, from Park *et al.* (2018)

After the first check, it is obvious that the host Abutment family and its parameters is not exported, whereas the nested families Wingwall, Backwall and Footing are exported with their parameters correctly. After some investigation this error was traced back to the Revit Ifc Exporter. Since there is no new geometry created inside the Abutment family, but only nested families that are imported in it, the Abutment family, as well as its parameters, can not be exported as an IFC entity. This poses a major disadvantage for the current Revit Ifc Exporter.

The proposed workaround is to create a geometrical form in the Abutment family, in the sense that it is virtual, with no material assigned. This virtual shape now represents the Abutment element. The IFC is now successfully exported, with the Abutment as an IFC entity *IfcElementAssembly*.

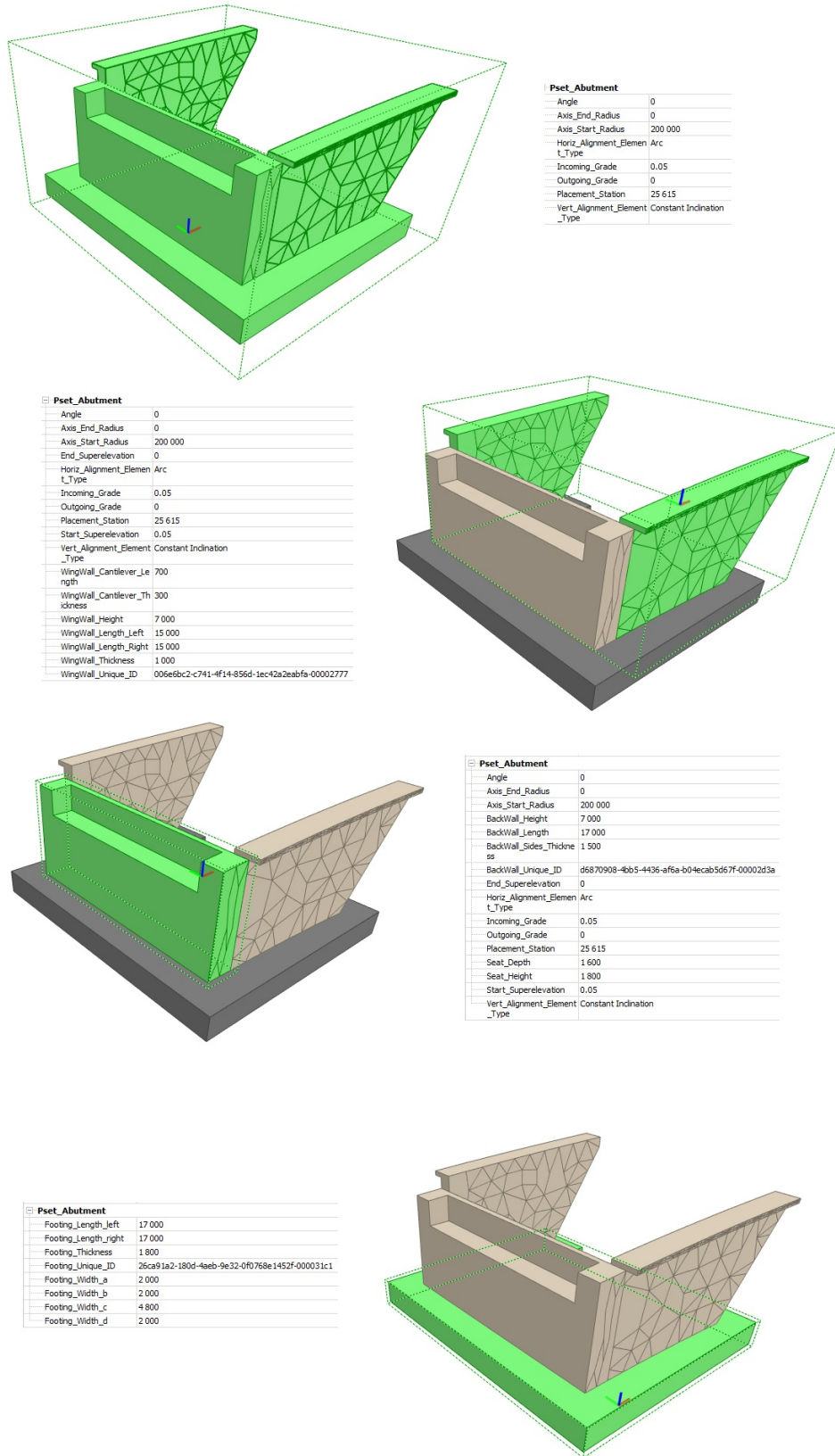


Figure 5.23: The abutment in BIM Vision

5.6 Considerations for handling the abutment modifications

Besides the accurate geometry creation of the abutment and its suitable IFC export, part of the present thesis is to develop a workflow for the proper editing of the created abutment. As mentioned in section 2.1, the whole process for designing a bridge includes a lot of changes in the alignment, which means that the bridge structure needs to be constantly adapted to the changes. Similarly the geometry of the created abutment must be modified accordingly. However, even with changed geometry this component still remains the same element of the bridge: the bridge abutment. Certain considerations need to be made for this purpose, but firstly some basic terms are explained in the following paragraphs.

5.6.1 Revit Unique ID and IFC Guid

Globally Unique Identifiers (**GUIDs**) are an essential component of collaborative BIM. Generally a **GUID** is a 16-byte, i.e. 128 bit number. It is commonly written in groups of 8-4-4-4-12 hexadecimal characters, meaning a total of 32 characters to represent the 16 bytes or 128 bits. The most important feature of a GUIDs is that they allow the precise tracking of information. Some of the characteristics of GUIDs are following (Bimtoolbox.org, 2019):

- Every single element of a model should have a GUID, for example the facility, slabs, walls, columns etc.
- Changes of objects in different model versions can be tracked down, since the object retains its GUID.
- Data can be associated with objects via a reference to the object GUID.
- GUIDs are essential part of the referencing mechanism of a BIM.
- The GUID should not be edited or modified under any circumstance.

Revit provides a UniqueID for every element. This UniqueID is not a GUID, but a string. Part of the string is a GUID, but the whole thing is not, which means that it needs to be treated as a string identifier. In the Online Revit Dokumentation it is stated (RevitApiDocs, 2019)

“The UniqueID can be used to store an identifier in an external database and to retrieve the same element in the future if it still exists. This id can be passed to the Document’s Element property to retrieve the element. The UniqueId is stable across upgrades and workset operations such as Save To Central, while the ElementId property may change.”

Every element has such a unique identifier, which is formatted in groups of 8-4-4-4-12-8 hexadecimal characters. It is thus similar to the standard GUID format, but has 8 additional

characters at the end. These 8 additional hexadecimal characters are sufficient for storing 4 bytes or a 32 bit number, which is exactly the size of a Revit “Element ID”. The Online Revit Dokumentation also states (RevitApiDocs, 2019):

“The Value within the ElementId is only unique within a single project. It is not unique across several projects. The Id can be used to retrieve a specific element from the database when needed. However ids are subject to change during an Autodesk Revit session and as such should not be retained and used across repeated calls to external commands.”

For instance when the Revit user creates several walls in a row, one can note that the GUID part of the UniqueId is the same for all of them, whereas the last 8 bytes are different, as they represent the individual element ids. Below, several ids of two instances of walls created in Revit are shown (Tammik, 2016):

```
ID=130315; Class=Wall; Category=Walls; Name=Generic - 200mm;  
UniqueID = 60f91daf-3dd7-4283a86d-24137b73f3da-0001fd0b;  
IFC GUID = 1W_HslFTT2WwXj91DxSWxH
```

```
ID=130335; Class=Wall; Category=Walls; Name=Generic - 200mm;  
UniqueID = 60f91daf-3dd7-4283a86d-24137b73f3da-0001fd1f;  
IFC GUID = 1W_HslFTT2WwXj91DxSWx5
```

One can see that, the first 16 bytes or 32 hex characters of the unique identifiers are identical. This part is internally called “EpisodeId” in Revit. The unique IDs only differ in the 4 byte or 8 hex character suffix at the end. In the example case shown above, the two differing suffixes for the walls represent their element ids in hexadecimal form, as 130315 equals 0x1fd0b, and 130335 equals 0x1fd1f (Tammik, 2016).

5.6.2 Edit Button for the Abutment Tool

With the information from the previous subsection it is concluded that each instance of the nested families Backwall, Wingwall and Footing are assigned a Revit UniqueID when placed in the host Abutment family. Thereafter, the instance of the Abutment family receives a Revit UniqueID when placed in the Project.

Currently, this version of the Abutment-Tool creates the Abutment family and its subcomponents, namely the nested families, from scratch and automatically places it in the Revit project. This means that, the Abutment instance has a UniqueID with every run of the Tool, which contradicts the use of the GUIDs mentioned at the beginning of the previous subsection. To confront this important obstacle certain considerations are made for the implementation of an “Edit” button for the Abutment Tool.

With the “Edit” button the user will be able to select the abutment that needs modification. By clicking on the abutment, the Abutment family editor opens. Again the Input dialogs presented in section 5.3 pop up, allowing the user to insert the new values for the wingwalls, backwall and footing. The Abutment Tool then recalculates and remodels the geometries of the wingwalls, backwall and footing and places the instances of the newly created nested families in the Abutment family. As a result the nested instances receive also new UniqueIDs. However, when the family editor of the Abutment family closes and we return back to the project environment, there is no new instance of the abutment family placed. As a consequence, the UniqueID of the Abutment remains the same.

Chapter 6

Conclusions

6.1 Considerations for further Improvements

The current version of the Abutment-Tool was developed in the scope of the present thesis and its academic purposes. However, in order to use the Abutment-Tool in a professional level, certain considerations for future improvements are made and presented in this section.

First of all, it is obvious that the current version of the Abutment-Tool can create abutments with wingwalls according to the first variant given in the German guidelines, e.g. wingwalls with a cut of constant 60 degrees. It would be very useful to implement the second variant for the wingwalls, so that the user can choose between the two different types. This can be easily done by creating a suitable void form in order to trim the wingwall and result in the desired geometry, as illustrated in Fig.6.1.

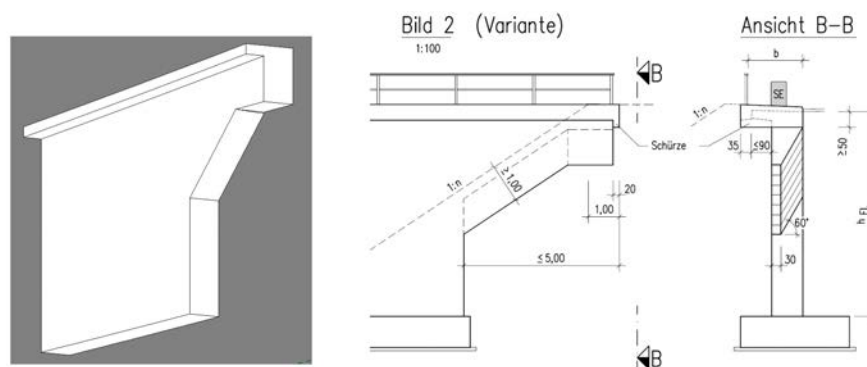


Figure 6.1: Implementing the second variant of the wingwall geometry, based on BVDI (2017)

Secondly, certain improvements can be made considering the user interface of the Abutment-Tool. It would be much easier and faster for the user to sketch the necessary profiles for the wingwalls and the backwall instead of inserting the various dimensions in the current window dialogs of the UI. The wall profiles should be created in the same way as the bridge deck

profiles used in the tolls presented in Chapter 4, meaning that the wall profiles need to be assigned with various parameters. The user will be able to import the profile family and use it directly for the geometry creation. Besides the advantage of an easier profile creation, this option makes it possible to control some features of the created geometry with the parameters of the profile.

Furthermore, considerations for improving the computation time are necessary. An important aspect that would greatly influence the computation time during the creation of the abutment geometry is the reduction of the number of profiles used. For instance, in case of a straight horizontal alignment and a constant gradient (e.g. also straight vertical alignment) only two profiles for the creation of the wingwall geometry are needed: one at the start and one at the end. As a result, by optimizing the number of profiles used, the computation time can be drastically reduced, which would allow the creation of several variants of the abutment in less time. For this purpose, it should be also investigated, which is the minimum number of profiles to achieve a certain accuracy.

Moreover, the current version of the Abutment-Tool is based on the German technical regulations of road design. Future updates will include the technical specification of railway design, in order to enable the creation of parametric abutment suitable for railway bridges.

Another significant consideration is made with regard to the IFC Alignment schema. Instead of creating the alignment on which the abutment is placed from scratch in Revit, it would make sense to input the alignment data as an IFC-Alignment, described in subsection 3.4.2. For this purpose, a special importing tool needs to be provided in Revit.

6.2 Outlook

The move towards a complete BIM workflow on infrastructure projects demands a high level of commitment and effort. The changes in the processes are significant when compared to the conventional methods. However, the rewards far outweigh the initial investment and, as both private firms and public sector become more up to date with the use of new BIM technologies.

Improvements in the current data exchange formats for BrIM

These process and workflow changes can be enabled by the technology progression that nowadays centers BIM in infrastructure. This technology provides integration and interoperability that break down any barriers between the different software applications. However, the need for the development of suitable exchange data formats for bridge structures is more than evident and there is still a lot of room for improvement, as presented in Chapter 3.

Improvements in the current modeling software for BrIM

Various software vendors have initiated only the previous couple years to develop programs suitable for the parametric modeling of bridges. Current applications have a lot of limitations and are not very easy to use (Chapter 4). In addition, substructures of bridges such as abutments and piers are not taken into consideration. The Abutment-Tool presented in this thesis may fill the gap of the creation of parametric bridge abutments. Still, further gaps need to be investigated, especially in case of non-standardised bridge structures, such as cabled bridges.

Improvements in the education of civil engineers and CAD planners

Last but not least: It is essential that civil engineers and drafters receive the proper education considering BIM tools and processes, not only students, but also professionals. Information and education on BIM will help senior engineers stand aside any doubts considering the efficiency of BIM implementation in infrastructure. Moreover, the support of the government is important in this topic. BIM information managers or companies could play an important role in promoting and facilitating the new business processes of BIM.

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Declaration of Originality

With this statement I declare, that I have independently completed this Master's thesis. The thoughts taken directly or indirectly from external sources are properly marked as such. This thesis was not previously submitted to another academic institution and has also not yet been published.

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