Requirements for geo-locating transnational infrastructure BIM models

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ABSTRACT: The transfer of design data into nature is a necessary task during the construction of a building. For this, the geodetic Coordinate Reference System (CRS) used during the design process needs to be accounted for and the induced distortions handled appropriately. In the context of Building Information Modelling (BIM), the CRS represents the metadata of the initial model which needs to be included and maintained throughout project's lifetime. When a project's construction site spans multiple countries, the initial data is available in different national CRSs and transforming them completely free of residuals is impossible. For the Brenner Base Tunnel between Austria and Italy, a new compound CRS was designed, representing a homogeneous reference system for all surveying and construction work. We present its definition and the rationale behind it. We highlight the requirements for BIM models and design systems and present current deficiencies.

1 INTRODUCTION

1.1 *Geolocation*

The transfer of design data into nature is a necessary task during the construction of a building. The structure must have correct dimensions and especially be placed on the correct land slot at the correct elevation. This task, also known as setting out, is the principal responsibility of surveyors. Setting out can be done within a local or a global context, depending on the building at hand, and generally counts as a solved and manageable problem.

For infrastructure objects (e.g. roads or railways) the setting out is primarily done in the global context. Shared elements with neighboring objects (like junctions or railway stations) represent compulsory points (i.e. geometric boundary conditions) which need to be considered and met. All objects that influence the design can be included within a large-scale geodetic Coordinate Reference System (CRS). These are generally provided by the surveying agencies of individual countries.

CRSs are split in two independent systems: the location and the height reference, named the geodetic and the vertical datum, respectively. A geometric projection of the geodetic datum flattens the Earth's curvature and together with the vertical datum establishes a well-defined CRS (Kaden & Clemen 2017, ISO 19111). A comprehensive collection of these systems and their combinations is the database of the European Petroleum Survey Group (EPSG), where nearly 6000 CRSs from around the world are listed together with datum definitions and transformations (EPSG 2018).

The CRSs usually do not provide sufficiently precise data for tunnel construction. Therefore, it is common to define a new, local CRS on the tunnel construction site, which provides a common ground for all documentation and construction. The geospatial data is then transformed from existing databases or measured anew ensuring high precision and quality.

When a construction project of a tunnel spans multiple countries, the initial data is available in different national CRSs. Consequently, problems arise already at the beginning of the design stage as transforming between the CRSs completely free of residuals is a demanding and peculiar task. Using project's own CRS, the need for handling the coordinates of each and every object in two different CRSs is avoided.

1.2 *Design*

The engineering design takes place in a right-handed three-dimensional (3D) Cartesian coordinate system – the Project Coordinate System (PCS). This is beneficial for visualization, perception, and performing calculations and hence less error-prone. Therefore, the definition of a suitable PCS is the first task in the engineering design. Knowing the axes, their point of origin, and their scale provides a common basis for all actors participating in a project.

For a long time, the design was done by hand and has been digitalized during the last century with the introduction of Computer-Aided Design (CAD). In the last decades, the Architecture, Engineering and Construction (AEC) industry has undergone an evolution from two-dimensional (2D) CAD drawings to three-dimensional (3D) object-oriented models. This new paradigm was branded Building Information Modelling (BIM) and has found quick adoption in the building sector (Borrmann et al. 2015).

buildingSMART International (bSI), formerly known as the International Alliance for Interoperability (IAI), is the international community behind the BIM standards. These range from the vendor-neutral BIM data formats *Industry Foundation Classes* (IFC) (ISO 16739:2013) and *BIM Collaboration Format* (BCF) to the *Information Delivery Manuals* (IDM) (ISO 29481) and *International Framework for Dictionaries* (IFD) (ISO 12006-3).

In the last years, the infrastructure sector has shown increased interest for the usage of BIM methods and the benefits they bring (Barazzetti & Banfi 2017). When considering BIM models of buildings with comparatively limited extends, the question about the underlying PCS has been handled by surveyors separately from the designers. However, when large linear objects are being modelled, aspects of geodetic CRS and the distortions they imply have a much more significant impact. These aspects need to be adequately addressed when expanding the established work flows and data formats (Markič et al. 2018).

1.3 *Goal*

The often-forgotten fact is that the well-defined CRS from Section 1.1 and the PCS from Section 1.2 are two sides of the same coin: the geodetic and the engineering perspective of the truth, respectively. This has significant implications as correcting such a mistake can be demanding and challenging. Its consequences are at best only shameful (Conchúir 2016) and at worst really expensive (Spiegel 2015).

This paper provides an insight at geo-location in general and geo-referencing BIM models in particular. The correct handling of transnational geospatial data is exemplary presented on the Brenner Base Tunnel (BBT) project. Following questions are in focus:

- How is a CRS defined?
- How do BIM systems handle geospatial data?
- How to exchange geo-referencing metadata in the BIM model?

The paper is structured as follows. This section provides a short introduction with our motivation. Geodetic background is briefly explained in Section 2. Section 3 provides a short overview of related recent works in the field of geo-referencing BIM models. The BBT project is presented in Section 4 followed by handling of geo-referencing data in BIM design systems in Section 5. The paper concludes with discussion in Section 6.

2 THEORETICAL BACKGROUND

In civil engineering, the PCS is a depiction of the real world by the chosen geodetic CRS. Having the underlying CRS and thus the PCS well-defined, geospatial data from different sources can be incorporated in the project by according transformations.

2.1 *Geodetic Datum*

The Earth is roughly a sphere and as such, the use of spherical coordinates offers itself as a way of referencing points on Earth surface. Since the Earth is a sphere squished at the poles (due to the rotational forces), a really good approximation is an oblate ellipsoid, which is an ellipse rotated around the minor axis (ISO 19111). The longitude Λ and latitude Φ denote the angles from the reference lines, e.g. the Greenwich meridian and the Earth's Equator, respectively. A pair of angles (Λ, Φ) defines a unique location on the ellipsoid.

Through the history, many ellipsoids have been defined and used with different areas of best fit. The "best fit" objective is to minimize the differences between the Earth's equipotential surface and ellipsoid in a specific area or globally. For example, the ellipsoid *WGS84* used in World Geodetic System 1984 geodetic datum is an Earth-centered ellipsoid and has a global best fit. It is widely used, e.g. by the Global Navigation Satellite System (GNSS).

It is common to describe ellipsoid shape in geodetic context by providing its major axis R_{major} and instead of its minor axis R_{minor} its inverse flattening f^{-1}, which is defined as (ISO 19111, EPSG 2018):

$$f^{-1} = \frac{R_{\mathrm{major}}}{R_{\mathrm{major}} - R_{\mathrm{minor}}} \tag{1}$$

2.2 *Coordinate System*

The Cartesian coordinates (X, Y) of the PCS are obtained by projecting the ellipsoidal coordinates (Λ, Φ) onto a plane using some sort of map projection. Since projecting the curved surface of an ellipsoid onto a plane without any deformation is not possible, a map projection can only preserve one of: either angles, distances or surface areas. The compromise most frequently chosen is to preserve angles by using the so-called conformal map projections, such as the Transverse Mercator (TM) or Universal Transverse Mercator (UTM) projections.

To keep the distortions of distances and surface areas in an acceptable range for applications like large-scale topographic mapping or cadastral surveying, strips of the ellipsoid are defined and projected onto a cylinder's surface. Figure 1 shows two conformal map projections that differ from each other in the radius of the cylinder and the width of the strips. The Gauss-Kruger projection (GK) (a type of TM) uses a cylinder that touches the ellipsoid at a meridian (see Fig. 1, left). Therefore, only the distances along the meridian are not distorted and get increasingly more distorted the further away from meridian the location is. This is why, the strips of the projection usually have a width of 3 degrees. In the UTM projection, the cylinder intersects with the ellipsoid 180 km east and west of the central meridian of a specific strip, which has a width of 6 degrees (see Fig. 1, right). To keep the distance distortions in an acceptable range, even at the borders of the strip, the central meridian is shortened with a scale of $m = 0.9996$.

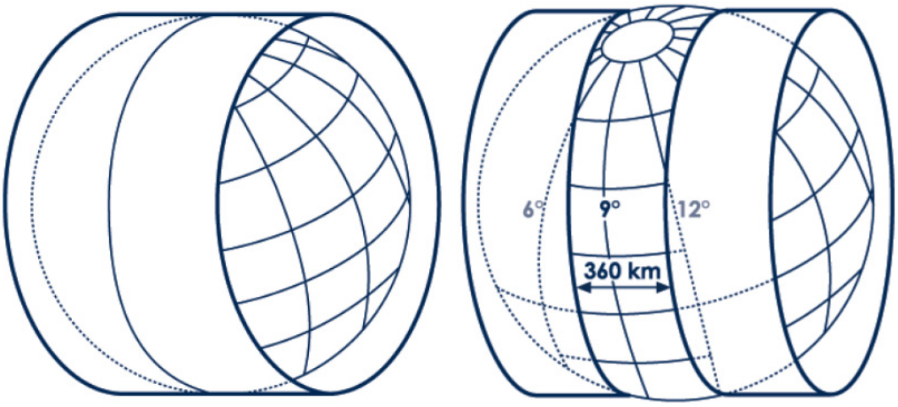


Figure 1: Different ways of projecting the ellipsoid on a cylinder: the Gauss-Kruger projection (GK) (left) and the Universal Transverse Mercator projection (UTM) (right) (Markič et al. 2018).

2.3 *Vertical Datum*

There are several possible definitions of elevation on Earth. One of them is to define the verticality on the Earth's surface as the (opposite) direction of the Earth's gravity pull. In this way, the water does not flow between two points with the same elevation which is very practical in construction. The vertical axis (*H*) follows the so-called plumb line and for easier notation, the coordinate value is usually given as a distance to some reference plane and not to the point of origin. This reference plane – the zero orthogonal height $H = 0$ – is the Earth’s equipotential gravity field and defines the geoid form (see Fig. 2). The most common plane is the mean sea level (ISO 19111).

The geoid and the ellipsoid forms disagree to a certain extent. This so-called undulation N can be determined with measurements and can amount to up to 100 m, which induces additional distortions in dimensions. Additionally, the plumb line from a point on the Earth's surface to the geoid (which follows the direction of gravity by its definition) and the perpendicular line from that same point to the chosen geodetic datum may not coincide. The reason for this is the gravity anomaly caused by variations in the density distributions within the Earth (Kaden & Clemen 2017). The ellipsoid height h is defined:

$$h = H + N + \Delta \tag{2}$$

where the error Δ comes from the influence of gravity anomaly and is determined from the deflection of the vertical direction (see Fig. 2). For small areas the gravity anomaly is constant $\Delta = const$, and can be added to coordinates of the whole project. However, elongated infrastructure objects like tunnels need to appropriately account for the changing environment by conducting additional measurements and adjusting their models accordingly.

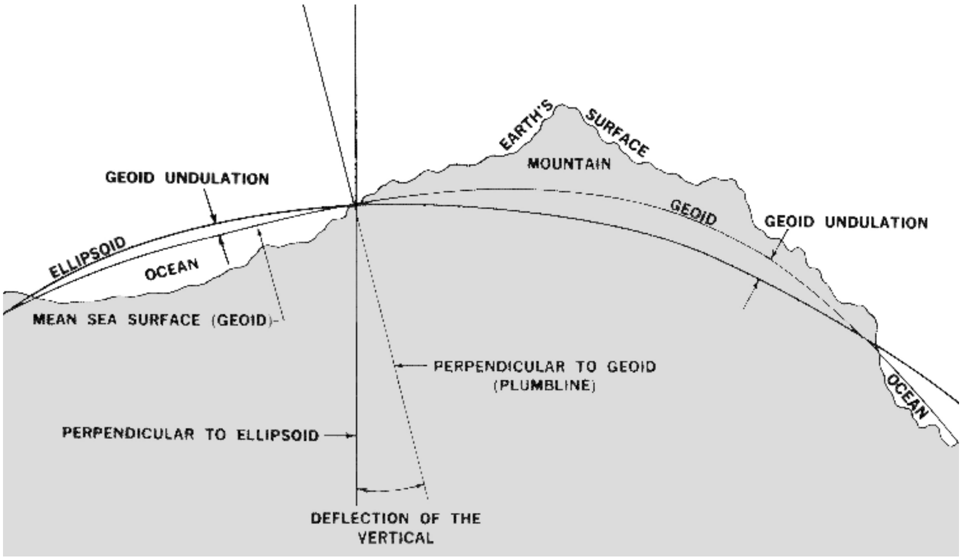


Figure 2: Depiction of the geoid, ellipsoid and Earth’s surface as well as the undulation of the geoid and the deflection of the vertical (National Imagery and Mapping Agency 2002).

2.4 *Projected and Compuond CRS*

To summarize, a CRS is composed of multiple parts. The choice of ellipsoid’s size, position and orientation together with the height reference define the geodetic and vertical datums, respectively. The chosen projection defines the transformation from a double-curved surface of ellipsoid to a Cartesian CS. The map projection together with a geodetic datum is called a projected CRS, which uniquely defines the transformation of the Cartesian CS to the ellipsoid surface as presented in Figure 3. In combination with a vertical CRS, the reference system is called a compound CRS (ISO 19111).

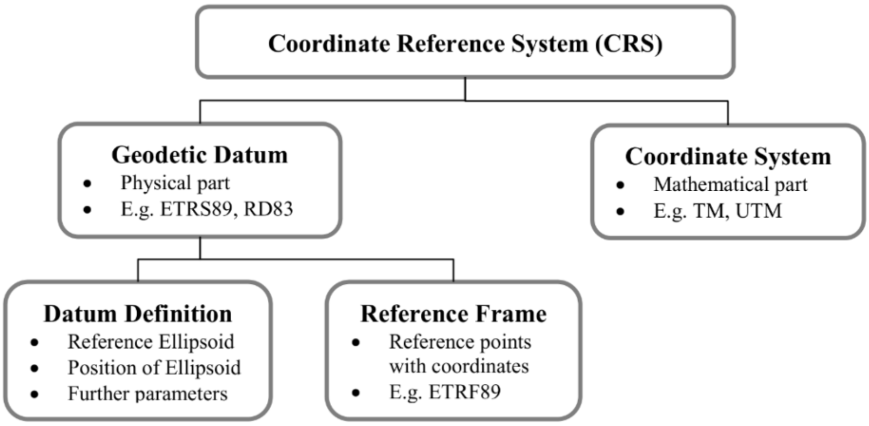


Figure 3: Components of a locational Coordinate Reference System (CRS) in the geospatial domain (ISO 19111:2007).

3 RELATED WORK

The geo-referencing of BIM models has become a topic of interest with the introduction of elongated objects from the infrastructure to the BIM context. bSI members have addressed this issue in one of their latest projects *Model Setup IDM*. The main focus of the project was the use case of geo-referencing. IFC versions 2x3 and 4 have been looked at in detail and a guideline for implementers has been published. As a general remark, they call for increased communication between all participants and free sharing of information (buildingSMART 2018).

Barazzetti & Banfi (2017) list multiple examples from all areas of AEC industry and evaluate the applicability of a bridge BIM model for traffic simulation analysis in detail. They conclude that an integration of geospatial data with parametric BIM modelling could simplify and speed up the design processes in the AEC industry.

Kaden & Clemen (2017) walk through an example study on the coordinate systems from the geodetic perspective. They noted that a correct understanding of geodetic CRSs is crucial for the success of BIM projects, especially in the infrastructure sector. However, in their words, *most CAD data is created without this consideration*. They go in great depth in linking the geodetic CRS and the BIM model using an intermediate CRS of a so-called local surveying coordinate system that represents a PCS.

Heunecke (2017) provides the equations and the reasoning behind the geodetic distortions of projections and even exemplarily calculates their exact values. For example, a curve's radius of $R_{\mathrm{BIM}} = 1000\,m$ in a BIM system changes to $R_{\mathrm{UTM}} = 999.46\,m$ when projected by a map prijection (here, to UTM) or transformed to $R_{\mathrm{real}} = 1000.54\,m$ when calculating the set-out values (here, from UTM). This distortion is location-dependent (!) and varies in different CRSs. Such differences influence the drive dynamics insignificantly; however, they can be the reason to violate a compulsory point's margin like a railway platform's edge.

Uggla & Horemuz (2018) argue that a BIM model is to be *viewed as a 1:1 representation of the terrain at the construction site* and that it is not described in a geodetic CRS. As such, the engineering system's agreement with the real world stays within given tolerances only within a small area (1 km) around the project base point. They conclude that the current implementation in the IFC schema is not usable and wishes for *addition of support for object specific map projections and separate scale factors for different axes*.

Markič et al. (2018) critically evaluate the IFC schema and its capability to store geospatial metadata. With the introduction of BIM-based exchanges of digital models the handling of this metadata needs to be addressed in the processes and correctly incorporated in the models. They argue that the current official version (IFC4) provides sufficient support for the typical case occurring in the majority of projects. However, based on two recent real-world infrastructure projects the implementation is rendered insufficient. They propose a solution by extending the IFC schema to support such peculiarities with the inclusion of grid shift parameter sets.

4 BRENNER BASE TUNNEL

The Brenner Base Tunnel (BBT) is a major European infrastructure project of the Helsinki (Finland) – La Valletta (Malta) North-South Trans-European Network (TEN) corridor. The BBT's two 55 km long, parallel, single-track railway tunnels enable freight and passenger trains to cross the Alps between Innsbruck (Austria) and Franzensfeste (Italy). At its completion, the 1371 m high Brenner Pass will be avoided, and the travel time reduced significantly while increasing the safety and throughput (Bergmeister 2011).

For historical reasons, most of the European major countries base their geospatial data in their own national CRSs. In the recent years, the European Union (EU) pushed for a common system and the member countries have started updating and transforming their systems accordingly. This is a long process that is nowhere near its end; the companies and public authorities have not yet adapted their processes and thus still provide geospatial data in the established data formats and (old) CRSs (Donaubauer & Kolbe 2017).

At the beginning of the project in 2001 the geospatial data of the construction site from the two countries participating in the project needed to be merged. This ensures a clear planning process and avoids mistakes during the underground construction. However, both countries used a completely different CRS as presented in Table 1 and as such three options were available.

1. Convert the Austrian geospatial data into Italian CRS and work in Italian CRS.
2. Convert the Italian geospatial data into Austrian CRS and work in Austrian CRS.
3. Plan in a third CRS and convert both Austrian and Italian data into it. This system may be an existing CRS or defined completely anew.

The project team decided for the third option and defined a completely new CRS named "*BBT_TM-WGS84*". A short overview of the properties is shown in Table 1, right column. The rationale behind the decision, as well as the chosen values, is explained in the following paragraphs.

Table 1: The properties of the geodetic and vertical datums and the projected CRSs used by the countries participating in and by the Brenner Base Tunnel (BBT) project itself (Mugnier 2005, Macheiner 2015). For each element its code and name from the European Petroleum Survey Group (EPSG) database as well as additional parameters are provided (EPSG 2018).

Property	Austria	Italy	BBT
Responsible authority	Bundesamt für Eich und Vermessungswesen (BEV)	Instituto Geografico Militare (IGM)	Prof. Ing. Franco Guzzeti*
Geodetic datum	MGI	Monte Mario	WGS84**
- EPSG	4312	4265	4326
- Ellipsoid	Bessel 1841	International 1924	WGS84**
○ EPSG	7004	7022	7030
○ R_{major}	6,377,397.155 m	6,377,388 m	6,378,137.0 m
○ f^{-1}	299.1528128	297	298.257223563
Projected CRS	Austria M28, M31 & M34	Italy zone 1 & 2	BBT_TM-WGS84
- EPSG	31,257, 31,258 & 31,259	3003 & 3004	not set
- Scale factor	1.0000	0.9996	1.000121
- False easting	150 km	1500 & 2520 km	20 km
- False northing	-5000 km	0 km	-5,105.739717 km
- Projection	Gauss-Kruger	Gauss-Boaga	TM
○ EPSG	9807	9807	9807
- Central meridian	10°20'E, 13°20'E & 16°20'E	9°0'E & 15°0'E	11°30'42.5775"E
- CS Origin***	48º16'15.29"N 16º17'41.06"E	41º55'25.51"N 12º27'08.40"E	46º58'50.7947"N 11º31'42.5775"E
Vertical datum	Trieste datum	Genova datum	EVRF2007****
- EPSG	1050	1051	5215

*Prof. Ing. Franco Guzzetti is associate professor at the Polytechnic University of Milan.

**WGS84 stands for World Geodetic System 1984 and is the name of the geodetic datum as well as its underlying ellipsoid.

***The reference lines are the Equator and the Greenwich meridian.

****EVRF2007 is the European Vertical Reference Frame 2007 realized by geopotential numbers and normal heights of the United European Leveling Network (UELN).

4.1 *Geodetic Datum*

Austria still uses a local best-fit ellipsoid *Bessel 1841*, while Italy uses one of the first global best-fit ellipsoids *International 1924*. These differ in all parameters (see Table 1) and a transformation between them – although possible – is computationally very demanding. With the introduction of GNSS the ellipsoid *WGS84* has become a global reference and the transformations from all other ellipsoids have been precisely calculated (EPSG 2018). The project team decided to use the *WGS84* as this simplifies the transformations for obvious reasons. Additionally, GNSS-based tachymetry results are more easily incorporated within the project as only the special projection needs to be applied. It also provides good basis for future maintenance works and enables portability in future scenarios.

4.2 *Vertical Datum*

The chosen vertical datum is the European Vertical Reference Frame 2007 (EVRF2007), realized through the United European Leveling Network (UELN). This again allows for easier future maintenance and redesign works.

4.3 *Reference Plane*

The undulation of the geoid to the ellipsoid *WGS84* spans from $N = 49$ *to* $51\ m$ in the area around the tunnel. To achieve better agreement between the nature and the geospatial data and to lessen the computational burden, the project's reference plane has been defined anew, which lies $H = 770\ m$ $(H_{ell} = 720\ m)$ above the ellipsoid (see Fig. 4). This scales the data from the ellipsoid by $m_{\text{ref.plane}} = 1.000121$, which was done at the beginning of the project.

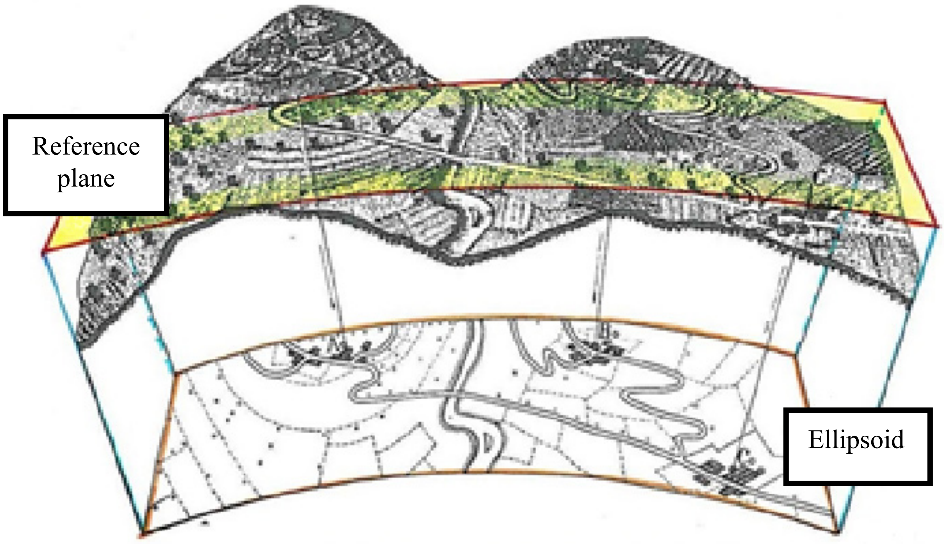


Figure 4: The *WGS84* ellipsoid in the project scope and the reference plane for the elevation, which lies $H = 770\ m$ above the ellipsoid.

4.4 *Coordinate Reference System*

There are many already defined projected CRSs based on *WGS84*, like the *WGS84 / World Mercator* (Eurocentric view of the world excluding polar areas, EPSG code 3395) and *WGS84 / UTM grid system* (EPSG codes 32600-32660). As the geospatial data was going to be transformed without regard for the chosen projection, it was optimal to choose the best suitable one. However, none of the available options was providing an extra edge over the others.

As presented by Markič et al. (2018), infrastructure projects sometimes opt for custom orientation and/or relative position of the projection plane. It is beneficial for the project area to be distorted as little as possible through projection operations. Because the project site extends primarily in the North-South direction, it was optimal to define a TM projection in such a way, that its meridian runs as close to the tunnel axis as possible to ensure a constant scale across the whole project area (see also Fig. 1, left). The chosen meridian was 11°31'42.5775"E from Greenwich as presented in Figure 5 which ensures the whole project lies within +/- 10 km of the meridian. Therefore, the distortions of the projection are neglectable.

4.5 *Deflection of the Vertical*

Because of the big variance in the direction of the gravity pull along the tunnel, these were separately recorded along the axis of the tunnel by Technical University Graz as part of the definition of the vertical datum. The corrections of the project height due to gravity anomalies lie between 5,5 cm and 17 cm and their detailed progression is shown in Figure 6.

Figure 5: Plan of the BBT project site, where the topography, the state border Austria-Italy, the axes of the tunnel together with the central meridian, project's origin, and coordinate axes are marked.

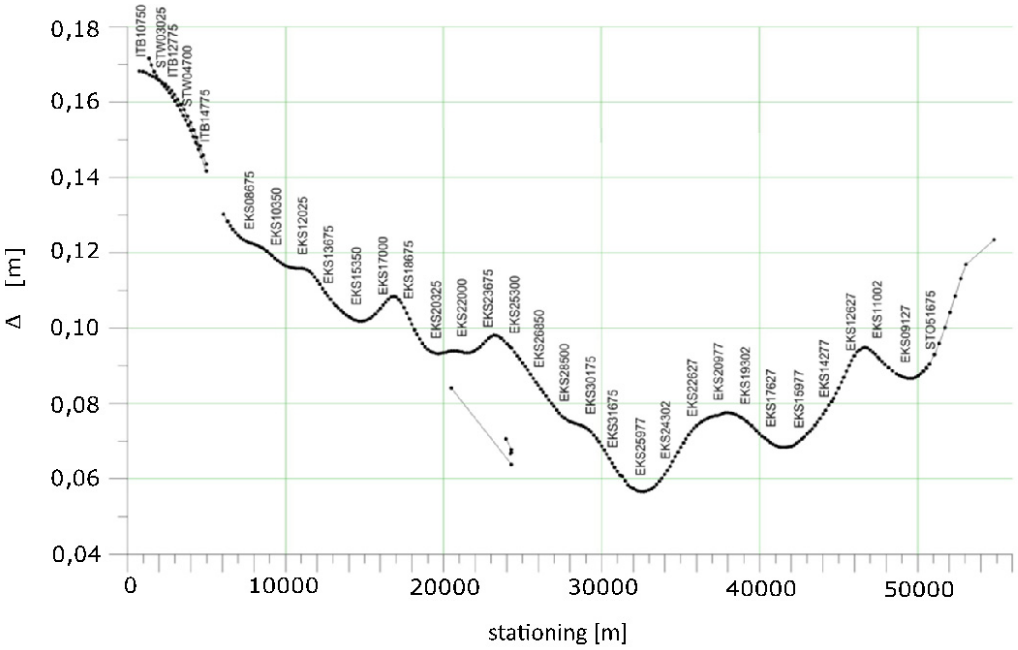


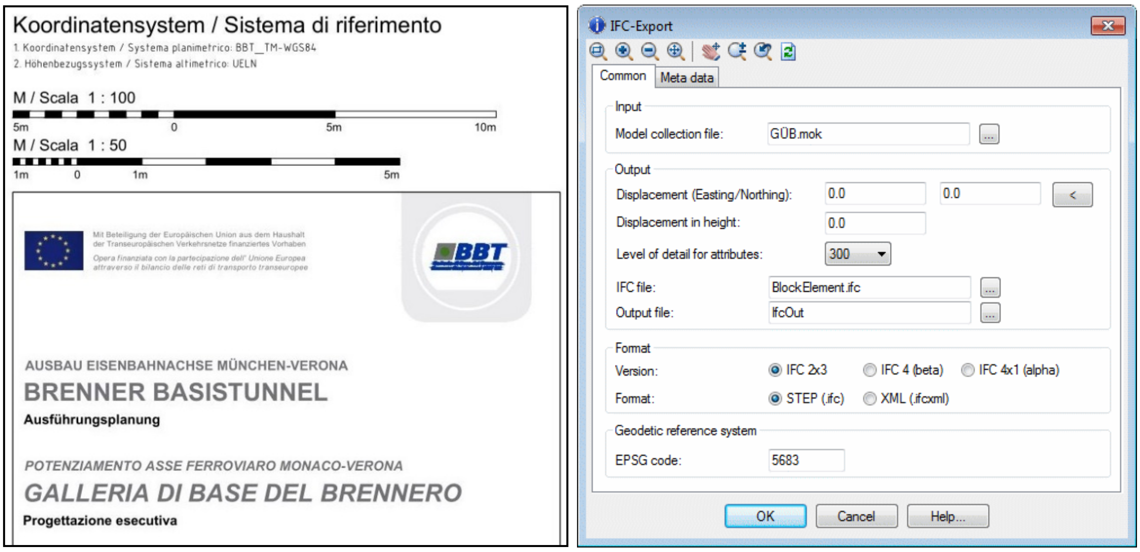
Figure 6: Detailed measurements of the deflection of the vertical resulted in precise height corrections along the tunnel axis which are presented together with identifiers of the individual points.

5 DESIGN WITH BIM TOOLS

The design data needs to be exchanged multiple times during the project and later archived for maintenance purposes. Currently, this is done by exchanging paper-based and digital blueprints together with additional supportive project information. Geo-referencing is one of the support-ing elements set at the beginning and looked at when setting-out the design. In the BBT project, every blueprint is labeled with the information about the underlying CRS (see Fig. 7, left).

In the long term, the blueprints will be succeeded by digital models (Borrmann et al. 2015). The goal is to make machine guidance and prefabrication possible directly from the model itself. Therefore, this supportive information needs to be addressed and considered properly (Markič et al. 2018). As such, the BIM design programs need to provide functionality to include and correctly handle the model's metadata. As the design takes place in the PCS *(X, Y, Z)*, the designers usually do not know about the discrepancies between their geospatial data. It is first recognized when including freely accessible ortho-photo images and finding misalignment between objects of interest. Additionally, some programs have a problem handling bigger coordinates. This can be fairly easily solved with introducing a new, local PCS, whose origin and rotation is known within the geodetic CRS (Kaden & Clemen 2017). For example, the user of software ProVI 6.0 can specify a displacement in location as well as elevation (see Fig. 7, right).

The IFC schema enables the exchange of geo-referencing metadata in its entities *IfcMapProjection* and *IfcProjectedCRS*. The former allows for diminishing of coordinates' values and the latter saves the information about the underlying geodetic CRS by providing its EPSG code (see Fig. 7, right) (ISO 16739, buildingSMART 2018). Although this covers most cases, this is not sufficient for the BBT project. Because the BBT project defined new projected and compound CRSs, that do not have an EPSG code (see Table 1) and thus cannot be exchanged using the popular IFC format. This inadequacy has been addressed by Markič et al. (2018) which have proposed a solution by extending the IFC schema accordingly. Currently, such information needs to be exchanged in an additional file attached to the project documentation.



Koordinatensystem / Sistema di riferimento

1. Koordinatensystem / Systema planimetrico: BBT_TM-WGS84
2. Höhenbezugssystem / Sistema altimetrico: UELN

M / Scala 1 : 100

M / Scala 1 : 50

Mit Beteiligung der Europäischen Union aus dem Haushalt der Transeuropäischen Verkehrsnetze finanziertes Vorhaben

Opera finanziata con la partecipazione dell' Unione Europea attraverso il bilancio delle reti di transporto transeuropee

AUSBAU EISENBAHNACHSE MÜNCHEN-VERONA

BRENNER BASISTUNNEL

Ausführungsplanung

POTENZIAMENTO ASSE FERROVIARO MONACO-VERONA

GALLERIA DI BASE DEL BRENNERO

Progettazione esecutiva

IFC-Export

Input

Model collection file: GÜB.mok

Output

Displacement (Easting/Northing): 0.0 0.0

Displacement in height: 0.0

Level of detail for attributes: 300

IFC file: BlockElement.ifc

Output file: IfcOut

Format

Version: ● IFC 2x3 ○ IFC 4 (beta) ○ IFC 4x1 (alpha)

Format: ● STEP (.ifc) ○ XML (.ifcxml)

Geodetic reference system

EPSG code: 5683

Figure 7: The geo-referencing metadata provided on a blueprint (left) and the parameters of IFC export in the infrastructure design software ProVI 6.0 (right). The metadata about the underlying compound CRS is clearly stated on the blueprint (top). Similarly, the software user can specify the translation vector as well as set the EPSG code of the underlying geodetic CRS used in the project by filling out the export mask.

6 CONCLUSIONS

Exchange of design data and its transfer to the construction site is currently done with paper-based and digital blueprints. With the introduction of Building Information Modelling (BIM) methods, the AEC industry will switch to model-based exchanges (Borrmann et al. 2015). This demands a careful definition of the structure of the BIM model in order to be clear about the data and its context. The focus of this paper is the geo-referencing of BIM models and its evaluation on a real-world example, the Brenner Base Tunnel (BBT).

The BBT project's surveyors decided to define a new, compound geodetic Coordinate Reference System (CRS) because of the benefits it brings to the accuracy and clearness of the data.

The CRS “*BBT_TM-WGS84”* was based on the *WGS84* ellipsoid (used by global navigation satellite systems) and projected using a Transverse Mercator (TM) projection. The vertical datum was based on the United European Leveling Network (UELN) and its corrections measured in detail along the axis of the tunnel. Each blueprint has been foreseen with the metadata about the chosen geodetic CRS (see Fig. 7, left).

A BIM model provided in the vendor-neutral format IFC can include data about the underlying geo-referencing context. However, there are still some missing functionalities if we wish to use IFC format in projects like the BBT. Since the defined CRS does not have an EPSG code foreseen to be included in the IFC file, this metadata needs to be exchanged in another way which is suboptimal. The software implementers should sign an agreement of how to handle such peculiarities in order to allow for clear and concise design processes.

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