Do BIM models intrinsically possess geodetic distortions or not?

Štefan JAUD, Andreas KOHLHAAS and André BORRMANN

Abstract: With the introduction of infrastructure objects to the Building Information Modelling (BIM) developments, an interesting problem (re)appeared. Are BIM models intrinsically distorted in the same manner as the underlying geospatial data used during the design processes or should they be interpreted as a true-to-scale representation of the real world? Literature review shows the latter to be the case among researchers and practitioners, although many do not even recognise this dilemma exists. We present three possibilities of interpretation of a BIM model: distorted, not distorted or a combination of the two. We highlight the differences and their advantages and disadvantages over the other. More importantly, we depict the consequences of false interpretation and evaluate their extent. We find that there is no right or wrong answer to this question; rather, the knowledge among the experts is partially missing or simply not stressed enough. It is of utmost importance to address this issue in the areas of linked data, BIM coordination processes, as well as Scan-to-BIM approaches, as these connect different models among themselves but tend to oversee the issue presented.

Keywords: building information modelling, coordinate reference systems

1 Introduction

1.1 Motivation

Building Information Modelling (BIM) is steadily gaining acceptance in the Architecture, Engineering and Construction (AEC) domain. Object oriented modelling in a three-dimensional (3D) coordinate system (CS) is successfully replacing two-dimensional (2D) drawings and getting implemented in the complex stakeholder and software landscape (BORRMANN et al., 2015). Lately, the infrastructure sector has shown interest in the benefits and increased productivity promised by BIM methods (BARAZZETTI & BANFI, 2017).

With the introduction of infrastructure objects to the BIM developments, an interesting problem (re)appeared. The BIM model's project coordinate system (PCS) is a right-handed, orthogonal Cartesian CS, where each plane with constant height coordinate ($z = const.$) represents an equipotential surface. This is the intuitive human understanding of horizontality, where the Earth seems flat in observer's close surroundings. For example, the two pylons of the Golden Gate bridge in San Francisco, USA, are seen as standing vertical and parallel to each other.

However, the Earth's equipotential surfaces are shaped more like a "potato" and the gravity field vectors can be assumed parallel only in a small area. Thus, in the global sense, the aforementioned pylons are not standing parallel, but rather both follow the direction of the gravity vector at their corresponding positions.

1.2 Problem Statement

Obviously, the transfer of design data into the field is a necessary task in the construction process. For that, the BIM model is placed within its geospatial context and the set-out values calculated from established reference points. Since the Earth is not flat, the Euclidean geometry on its surface fails and discrepancies between the BIM model and its true form occur. However, when the model is designed, this fact tends to be neglected by, or hidden from, the designer. Therefore: how to handle georeferencing of BIM models in a transparent, correct and unambiguous manner?

1.3 Related Works

The problem of georeferencing of BIM models has not yet been thoroughly addressed in the literature, to the best of our knowledge. buildingSMART International (bSI) handled this issue in the *Model Setup IDM* project (bSI, 2018). The focus of the project was the use case of georeferencing in simple and complex projects and how to successfully federate models from different construction sites in a single model. The vendor-neutral data format Industry Foundation Classes (IFC) versions 2x3 and 4 have been looked at in detail and a guideline for software vendors has been published on how to properly use georeferencing entities within the IFC standard.

KADEN & CLEMEN (2017) walked through an example study on the CSs from the geodetic perspective. They noted that a correct understanding of CRSs is crucial for the success of BIM projects in the infrastructure sector, where large extents lead to potentially large distortions. However, most CAD data is created without this consideration. In their later study, CLEMEN & GÖRNE (2019) proposed different Levels of GeoReferencing (LoGeoRef). This establishes a metric of maturity and quality of georeferencing meta data within a BIM model in IFC format. They noted, that only LoGeoRef 50 provides enough information needed for geodetic activities directly from a BIM model.

UGGLA & HOREMUZ (2018) presented their understanding of the georeferencing by means of the IFC schema from another point of view. They highlighted that the BIM model *is to be viewed as a 1:1 representation of the terrain at the construction site* and that it is not distorted by a CRS. They concluded that the current implementation in the IFC schema is not usable and wish for addition of support for object specific map projections and separate scale factors for different axes. Similarly, WUNDERLICH & BLANKENBACH (2017) see the BIM model as a 1:1 representation of the built asset.

An important study naming the three options presented in Section 3 has been published by HEUNECKE (2017). He provides the necessary background and goes in depth on the reasons and the rationale behind the three solutions presented. However, he does not provide any criteria or clues as to which solution is most suitable for AEC projects.

Similarly, in our latest study, we present the three options together with an exhaustive background on the topic (JAUD et al., 2020). We critically evaluate the options and consider the consequences of neglection of georeferencing. We provide a decision tree to help practitioners determine the correct interpretation of a BIM model as well as a nomograph to deduct the maximum horizontal extent of a structure, where a misinterpretation of the BIM model does not lead to significant errors.

1.4 Structure of the Paper

This section introduces the reader to the topic with our motivation and related works from the academia. Next section shortly summarises the theoretical background needed to understand the research question at hand. Section 3 presents possible solutions as first introduced by HEUNECKE (2017). We evaluate the solutions in Section 4 and conclude the paper with Section 5.

2. Theoretical Background

2.1 Coordinate Reference System

All geospatial data lies in a well-defined coordinate reference system (CRS). Every object is correctly located on Earth, which includes its location in a CRS and the meta data about this underlying CRS. This meta data is composed of parameters of the geodetic transformations undertaken when producing the CRS. We call such geospatial data georeferenced.

CRSs are split in two independent systems: the location and the height reference, named the geodetic and the vertical datum, respectively. A geodetic datum relates an oblate ellipsoid to the Earth, which represents its mathematical model. The longitude, λ, and latitude, φ, denote the angles from the reference lines, e.g. the Greenwich meridian and the Earth's mean equatorial plane, respectively. A pair of angles, (λ, φ), defines a unique location on the ellipsoid (ISO 19111). 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 ellipsoid with its origin in Earth’s centre of mass and has a global best fit.

The vertical datum defines the physical model of the Earth – the geoid. The vertical axis, H, follows the plumb line and the coordinate value is usually given as a distance to some reference surface and not to the point of origin. This reference surface – the physical elevation, $H = 0$ – is one of the Earth’s equipotential surfaces. It is most common to take the mean sea level. It defines the geoid form which disagrees with the ellipsoid form to a certain extent. This so-called undulation, N, can be determined with measurements and can amount to up to $\pm 100\,m$ from a globally best-fitting ellipsoid (ISO 19111, JAUD et al., 2020).

The Cartesian coordinates Eastings und Northings, $(E, N) = (X, Y)$, 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 either angles, distances or surface areas. The compromise most frequently chosen in large scale topographic applications or cadastral surveying is to preserve angles by using the conformal map projections, such as the Transverse Mercator (TM) or Universal Transverse Mercator (UTM) projections (ISO 19111).

A geometric projection of the geodetic datum flattens the Earth’s curvature and both together with the vertical datum establish 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).

To summarize, a CRS is composed of multiple parts. The choice of ellipsoid's size, position, and orientation regarding the Earth together with the height reference define the geodetic and vertical datums, respectively. The chosen projection defines transition from the double-curved surface of the ellipsoid to an orthogonal Cartesian CS. The map projection together with a geodetic datum is named a projected CRS, which uniquely defines the transformation of the PCS's X and Y axes to the ellipsoid surface. In combination with a vertical CRS which defines the interpretation of the PCS's Z axis, the reference system is called a compound CRS (ISO 19111, ISO 19162).

2.2 Distortions

Because of the projections and reductions induced by the chosen CRS, the geospatial data possesses a well-defined discrepancy from the real world denoted with a scale factor, m_{CRS}, usually measured in parts-per-million (ppm): $1\ \% = 10000\ ppm$:

$$m_{CRS} = \frac{\text{geospatial distance}}{\text{real world distance}} \tag{1}$$

This scale applies only to horizontal distances. This scale factor is composed of two sources of the distortions as presented in Figure 1. First, the elevated data is reduced to the ellipsoid's surface inducing the reduction factor, m_h, (HEUNECKE, 2017):

$$m_h = m_h(\lambda, \varphi, \mathrm{h}) = 1 - \frac{h(\lambda, \varphi)}{R(\varphi)} = 1 - \frac{H(\lambda, \varphi) - N(\lambda, \varphi)}{R(\varphi)} \tag{2}$$

where h is the elevation above the reference ellipsoid depending on the normal height, H, and the undulation, N, and $R(\varphi)$ the Earth's Gaussian radius of curvature at latitude φ.

Second, the reduced data is projected from the ellipsoid to a plane inducing the projection factor, m_{proj} (HEUNECKE, 2017):

$$m_{proj} = m_{proj}(m_0, \varphi, \mathrm{X}) = m_0 \left(1 + \frac{X}{2m_0^2 R(\varphi)^2}\right) \tag{3}$$

where m_0 is the scale of projection at the projection's meridian; $R(\varphi)$ the Earth's Gaussian radius of curvature at latitude φ; and X is the Easting coordinate of the point without offset and prepended zone number.

The combined scaling factor from (1) can be calculated using both factors in (2) and (3) (HEUNECKE, 2017):

$$m_{CRS} = m_h(\lambda, \varphi, \mathrm{h})\, m_{proj}(m_0, \varphi, \mathrm{X}) \tag{4}$$

It is obvious that the scaling factor can only be calculated for a specific point. The overall scale, m_{CRS}, is through the linear combination in (4) dependent on all three coordinates of a point in space and changes continuously when moving from one coordinate to another (HEUNECKE, 2017). With this in mind, m_{CRS} would more correctly be called the scaling function and not merely a scaling factor.

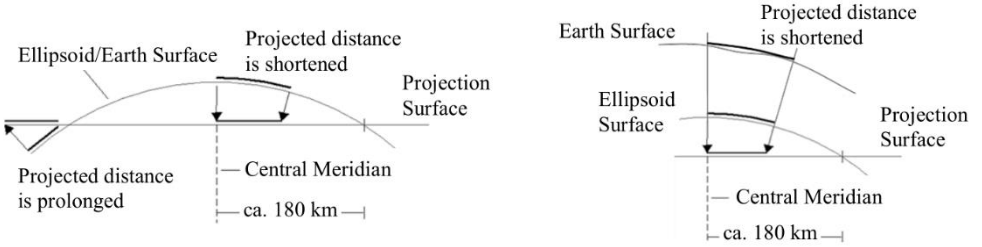

Fig. 1: The main sources of the distortions of geospatial data. The projection may prolong or shorten the distances depending on the distance to and the projection scale at the meridian of the chosen projection (left). The vertical reduction may prolong or shorten the distances, depending on the elevation above the reference ellipsoid (right) (KADEN & CLEMEN, 2017).

We stress again that the scaling factor applies only to horizontal distances as indicated in (1) and has no influence on vertical distances. However, following (4), the scaling factor of the horizontal axes depends on the elevation coordinate as well. Additionally, let it be noted on this place that a circular arc in nature may not be circular in the combined CRS and vice versa.

3. Interpretations

The focus of our paper is the correct interpretation of a BIM model considering georeferencing consequences. Following the nature of geodetic transformations as described in Section 2, georeferencing only influences the geometry and positioning of BIM data (see (1)). Therefore, the main concern is the definition and the meaning of the PCS and how it relates to the Earth. Specifically, we wish to unambiguously define the model scale, m_m, and its relation to the CRS of the geospatial data used during the design process.

We see three possibilities for an interpretation of a BIM model:

1. distorted with $m_m = m_{CRS}$,
2. not distorted with $m_m = 1$ or
3. a combination of the two (HEUNECKE, 2017).

While the literature review shows general preference for the second option, infrastructure objects can only be designed in the first because of their great horizontal extent. Since the third option merely combines the first two, the evaluation focuses on the former and is consequently valid for the third option as well.

We highlight the differences in the handling of geometric data in Figure 2. Recall that all geospatial data lies in a well-defined CRS which defines the parameters for the scaling function, m_{CRS}. In Option 1, the model's scale factor, m_m, is equal to the scaling function, $m_m = m_{CRS}$, resulting from the underlying geodetic transformations and is thus continuously changing throughout the whole BIM model. In Option 2, the scaling factor is $m_m = 1$, which denotes no difference in position as well as geometry between the model and the reality.

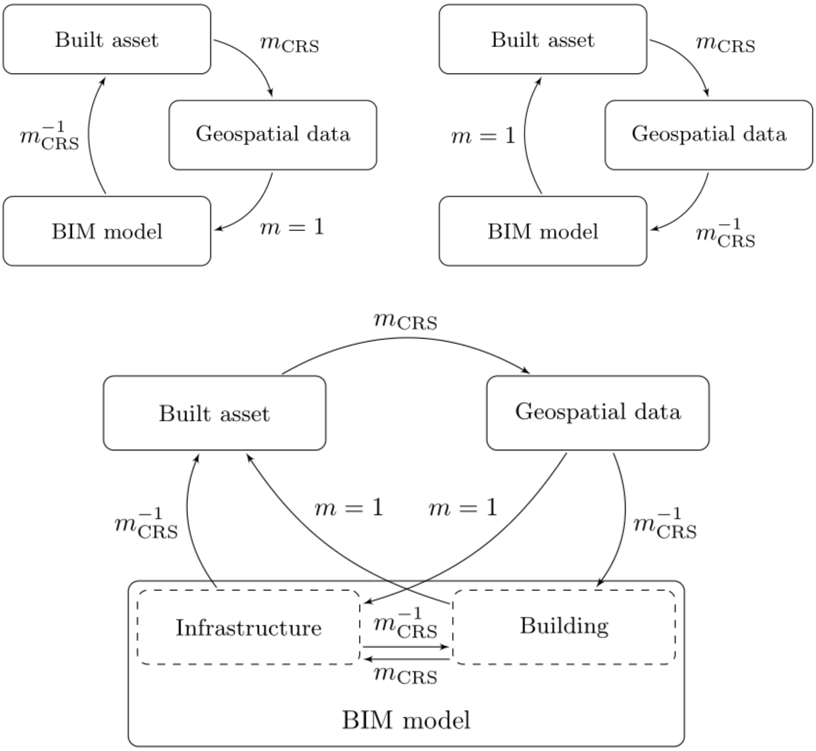

Fig. 2: The flow of data and its transformations between the real world (built asset), the geospatial analysis (geospatial data) and the design processes (BIM model). Top left represents Option 1 ($m_m = m_{CRS}$), top right Option 2 ($m_m = 1$) and bottom Option 3 (a mix of Options 1 and 2) (Jaud et al., 2020).

In the first option, the geospatial data is used as-is in the design processes. Thus, the BIM models themselves possess the same distortions as the geospatial data and cannot be used without previous manipulation for stake out or prefabrication processes. As seen on Figure 2, top left, they need to be inversely transformed to their true geometry using the inverse of the scaling function, m_{CRS}^{-1}.

On the contrary, the second option allows the BIM model to be used directly for stake out and prefabrication processes without any preprocessing. However, the geospatial data needs to have been inversely transformed with m_{CRS}^{-1} before being included in the design process as seen on Figure 2, top right. Additionally, there is a limit to the horizontal extent of such model as described by Uggla & Horemuz (2018).

The third option foresees the (inverse) transformation to happen between the designers themselves (see Figure 2, bottom). Structures with significantly larger horizontal than vertical dimensions count as infrastructure objects (for example, roads or railways), whereas structures with comparatively similar extent as well as very high buildings count as building objects (for example, short bridges or skyscrapers). We name the former *horizontal* BIM and the latter *vertical* BIM, and the geospatial data must be transformed when switching among them.

4. Evaluation

The problem addressed in this paper is of systematic nature and can be easily averted if every project stakeholder acknowledges it and acts accordingly. However, this is not always the case, especially in the vertical BIM community, where BIM models are generally interpreted according to Option 2 (see Section 1.3). If the geospatial data is not inversely transformed before the design processes as presented in Figure 2, top right, the introduced mistake may at first not be noticed. As such, its source could be hard to pinpoint when the design is staked out at the construction site at a later stage.

The consequences of such false interpretation depend on the position of the asset as well as the underlying CRS of the geospatial data as presented in Section 2. The magnitude of misinterpretation at a specific location can be calculated using (4). As an approximation, an average magnitude over the whole project site can be calculated with average coordinate values of the far-most corners (marked with indices 1 and 2) (HEUNECKE, 2017):

$$\begin{aligned}\overline{m_{CRS}} = m_h &\left(\frac{\lambda_1+\lambda_2}{2},\frac{\varphi_1+\varphi_2}{2},\frac{h_1+h_2}{2}\right)\\ &m_{proj}\left(m_0,\frac{\varphi_1+\varphi_2}{2},\frac{X_1^2+X_1X_2+X_2^2}{3}\right)\end{aligned} \tag{5}$$

The distortion can be knowingly neglected in special cases. Determining the (average) distortion at the construction site expressed as $\Delta = m_{CRS} - 1$ and knowing the construction precision strived for, the maximal horizontal extent of the construction site can be determined using the diagram in Figure 3. If the far-most corners of the construction site lie closer than the determined length, then the distortions of the CRS may be neglected, as the mistake induced does not exceed the construction precision. Only in this case the BIM model can be interpreted according to Option 2, even though the geospatial data may not have been inverse transformed with m_{CRS}^{-1} as depicted in Figure 2, top right (JAUD et al., 2020).

Section 3 introduced a differentiation between the horizontal and the vertical BIM models. For a clear definition, the diagram in Figure 3 helps to determine where to draw the border. If the distortions of the model can be neglected as described above, the model may be a *vertical* BIM model. If the distortions cannot be neglected, it is definitely a *horizontal* BIM model and the distortions induced by the CRS must be considered following Option 1.

It is possible to circumvent the obligations of a horizontal BIM model by choosing a CRS carefully. For that, one can use an existing CRS as provided by EPSG (2019) or define a new CRS, such that it minimizes the distortions of the CRS at the construction site. Preferably, this CRS is chosen in a way, where the tolerances imposed throughout the project exceed the CRS's distortions at every location. How to design such a CRS is not a part of this research paper and the reader is advised to consult geodetic literature.

An additional problem occurs when interpreting a BIM model according to Option 3 (e. g., a confederated BIM model which includes both types of sub-models). If there are parts of the model which neglect the distortions, the mistakes induced by neglection need to be smoothen out between the different types. These transition zones require special care when setting out at the construction site. This is not handled by this paper and needs further consideration.

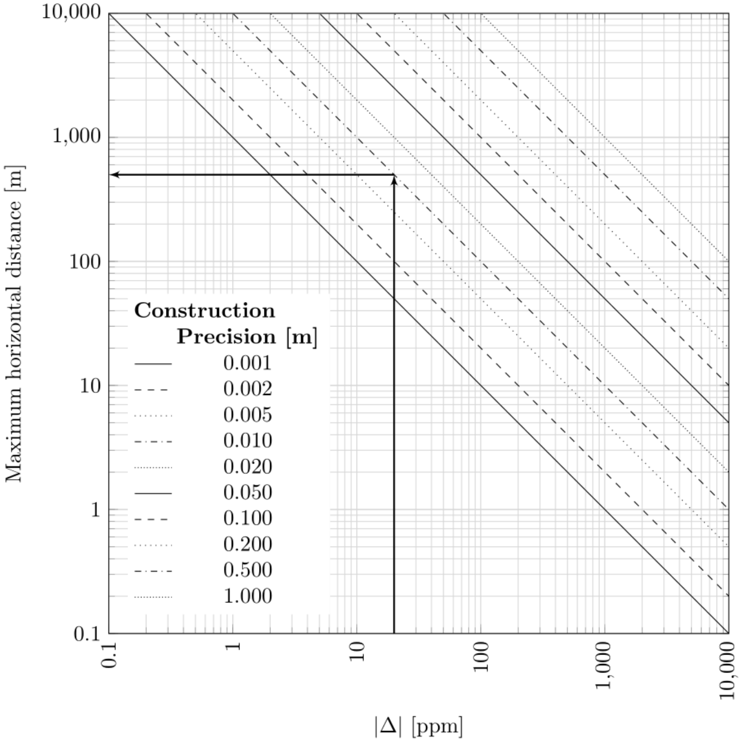

Fig. 3: The maximum horizontal extent of a BIM model, where the distortions can be knowingly neglected. It depends on the construction precision and the absolute (average) CRS's distortions on the construction site expressed as $\Delta = m_{CRS} - 1$. For example, with construction precision of 1 cm and distortion of 20 ppm, the maximum horizontal extent is 500 m (see black arrows) (JAUD et al., 2020).

5. Conclusions

This paper aims at addressing the question posed in the title and outlined in Section 1.2: Are BIM models intrinsically distorted in the same manner as the underlying geospatial data used during the design, or are they to be interpreted as a 1:1 representation of the real world? Literature review shows that no clear consensus is present, but that the 1:1 view seems to be the preferred case among researchers and practitioners for vertical BIM models.

We present three possibilities of how to interpret a BIM model in Section 3. Option 1 interprets the BIM model in the same way as the underlying geospatial data: distorted. Option 2 perceives the BIM model as a true representation of the built asset. Option 3 is a combination of the previous two, regarding horizontal and vertical models as Option 1 and 2, respectively.

We provide a graph to determine the maximal horizontal extent of a BIM model, where to draw the line between vertical and horizontal BIM models as well as where the geodetic distortions can be ignored. This is dependent on the construction precision and on the (average) scale factor of CRS at the construction site. This comes especially useful, if the meta data of the BIM model's CRS is not available and thus a correct interpretation is questionable.

We find that there is no right or wrong answer to the question posed in the title; rather, the knowledge among the experts is partially missing or simply not stressed loudly enough. We call for increased transparency among the project stakeholders. Every surveying, design or stake-out contract should explicitly specify the CRS of the models and how they are to be interpreted. In this way, disputes can be solved quickly, and costly errors averted.

The meta data of BIM models need to be adapted accordingly, in order to correctly incorporate CRS parameters. It is of utmost importance to address this issue in the areas of linked data, BIM coordination processes, as well as Scan-to-BIM approaches. These fields connect or transform models with different CRSs among themselves and tend to oversee the issue presented, which can lead to systematic errors, although easily averted.

References

BARAZZETTI, L. & BANFI, F. (2017). BIM and GIS: When Parametric Modelling meets Geospatial Data. ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences 4.

BORRMANN, A., KÖNIG, M., KOCH, C. & BEETZ, J. (2015). Building Information Modeling: Technologische Grundlagen und industrielle Praxis. VDI-Buch, Springer Fachmedien, Wiesbaden.

bSI, buildingSMART International (2018). Model Setup IDM, Vol I: Geo-referencing BIM. https://bsi-intranet.org/kos/WNetz?art=Folder.show&id=5568 (31.08.2018).

CLEMEN, C. & GORNE, H. (2019). Level of Georeferencing (LoGeoRef) using IFC for BIM. Journal of Geodesy, Cartography and Cadastre 2019, pp. 15–20.

EPSG (2019) The European Petroleum Survey Group homepage. http://www.epsg.org/ (30.11.2019).

HEUNECKE, O. (2017). Planung und Umsetzung von Bauvorhaben mit amtlichen Lage- und Höhenkoordinaten. In: zfv 142, pp. 180–187.

ISO 19111:2007 (2007). Geographic information – Spatial referencing by coordinates. Standard International Organization for Standardization Geneva, CH.

ISO 19162:2015 (2015). Geographic information – Well-known text representation of coordinate reference systems. Standard International Organization for Standardization Geneva, CH.

KADEN, R. & CLEMEN, C. (2017). Applying Geodetic Coordinate Reference Systems within Building Information Modeling (BIM). In: Technical Programme and Proceedings of the FIG Working Week 2017, Helsinki, Finnland.

JAUD, Š., DONAUBAUER, A. HEUNECKE, O. & BORRMANN, A. (2020). Georeferencing in the Context of Building Information Modelling. Automation in Construction. [In press].

UGGLA, G. & HOREMUZ, M. (2018) Georeferencing Methods for IFC, in: Proceedings of the 2018 Baltic Geodetic Congress, BGC–Geomatics 2018, Institute of Electrical and Electronics Engineers Inc. pp. 207–211.

WUNDERLICH, T. & BLANKENBACH, J. (2017) Building Information Modeling (BIM) und Absteckung, in: Ingenieurvermessung 2017, TU Graz.