Georeferencing of IFC Geometries

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Abstract

The problem of georeferencing building information modelling (BIM) models is complex and in need of a comprehensive solution. We focus on the open BIM data format Industry Foundation Classes (IFC) and its georeferencing specification. The requirements voiced by the domain experts during recent years have been collected and analysed. While IFC already covers some of the concepts, an extension to the IFC schema was proposed which handles the inadequacies. The proposal composes of several new entities, which support geographic coordinate reference systems (CRSs), a well-known text (WKT) representation of a CRS and a rigid transformation of BIM geometries within chosen CRS. The improvements assure much-needed semantically clear definitions of the georeferencing concept within the IFC data model. As such, the interpretation of IFC data content is unambiguous for stakeholders, software implementers, and end-users.

1 Introduction

The core of BIM is information management for the architecture, engineering and construction (AEC) domain. BIM is being increasingly implemented in the infrastructure sector within the AEC domain and replacing or enhancing established computer-aided design (CAD) workflows (BRADLEY 2016).

Since infrastructure assets are not autonomous structures residing on a limited land extent but rather span multiple kilometres, the curvature of the Earth plays a non-negligible role when defining the geometric context of the BIM model. The CRS conveys the definitions and parameters for the transformations between the digital geometries and the reality. While the geographic information system (GIS) domain is comfortable with the use of CRSs of various complexity, the same cannot be claimed for the BIM domain (WUNDERLICH 2020). However, a "*correct understanding [of CRS] is crucial especially in the infrastructure sector*" (KADEN & CLEMEN 2017).

This contribution expands on our previous contribution to the *19. Internationaler Ingenieurvermessungskurs*, which questioned if BIM models are distorted according to the underlying geospatial data or not (JAUD et al. 2020b). The main conclusion was a call for support of all scenarios occuring in the industry and thus amending the IFC standard appropriately. Three scenarios for transformation of coordinates between the digital data and the reality have been addressed by (JAUD et al. 2022) with critical evaluation and proposals for the IFC data model[1]. This contribution summarizes the changes to the IFC schema, with emphasis on documentation for practitioners and software developers.

The paper is structured as follows. This section presents our motivation and the goal of the contribution. Next section gives an overview of the possible scenarios as required by the stakeholders and practitioners. The possibilities of the IFC standard that address the requirements are described in Section 3. The paper concludes with a short discussion in Section 4.

2 Georeferencing Scenarios

The mathematical and semantic connection between model's geometries and the Earth's environment need clear and unambiguous definitions within BIM. There are three main georeferencing scenarios used in the industry as presented in Figure 1 (JAUD et al. 2020). This simplified representation assumes that models extend purely in West-East direction to the East of the projection's meridian. Additionally, only the projection's distortions are taken into considerations, thus neglecting other sources of distortions, for example the elevation and resulting height reductions.

This contribution focuses on the well-established CRSs used in practice, e.g. *DB_REF* used by German Railways. We acknowledge that a specialized CRS for a specific region can be designed which "flattens" the scale function of the CRS to be very close to 1, thus making all three scenarios equally viable in BIM projects. For example, *DB Station&Service AG* provides custom CRSs for each of their bigger passenger train stations around Germany (DB STATION&SERVICE AG 2023).

The following paragraphs describe the three scenarios in detail. The properties of the scale function between the digital geometries and their counterparts in nature for the three scenarios are summarized in Table 1. Additionally, the table lists the size of the deviation at the transition between the stations and the railway line.

Table 1: The properties of the three scenarios as depicted in Figure 1

	Scenario Name	Scale function	Scale value	Deviation
A	Undistorted	constant	$m = 1$	big
B	Distorted	variable	$m = m_{CRS}$	none
C	Averaged	constant	$m = \overline{m_{CRS}}$	small

[1]These proposals have been discussed and modelled in a shared public environment on Github (https://github.com/bSI-InfraRoom/IFC-Specification) with periodic involvement of the community in expert panels.

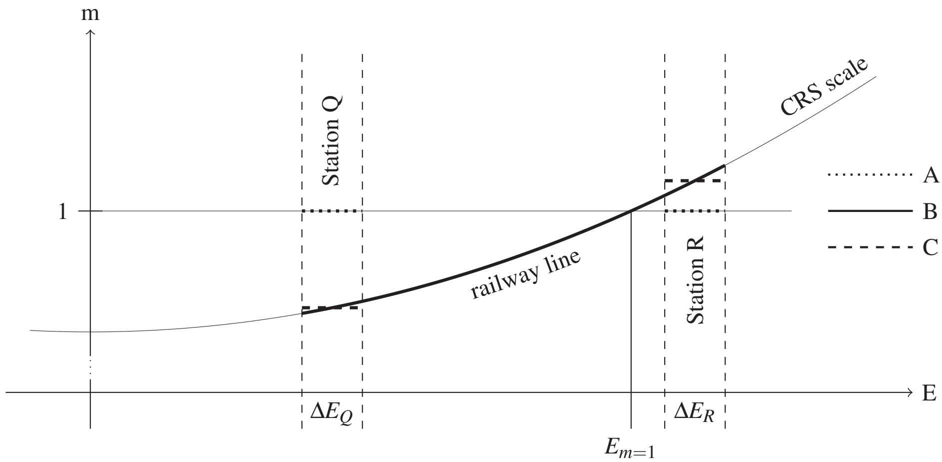

Fig. 1: A simplified visual representation of the different scenarios (A, B, and C) as presented in Table 1 for two locations (stations Q and R) and the railway line between them (adapted from JAUD et al. 2020). E denotes the Easting coordinate, m the scale factor between the digital model and reality. *CRS scale* denotes the scaling function m_{CRS} dependant only on the Easting location of a very simple CRS. In the general case, the resulting curve is not as smooth and dependant on many more factors.

Scenario A: BIM is undistorted. The geometric context of any BIM models has usually been interpreted as a local, three dimensional Euclidean space described with a Cartesian coordinate system (CS) for the representations of objects on site (e.g. WUNDERLICH 2020). The objects' geometries in the model as well as finalized objects in reality share the same dimensions and positions (up to a certain delta), i.e. the scale factor between them is 1.

As shown in Figure 2, the CS is defined as follows. The natural vertical direction at the chosen point of origin (PoO) defines the *up* axis (corresponds to z axis of the Cartesian CS). The direction of the local North defines the *North* axis, while the local East direction defines the *East* axis. These correspond to y and x axes of the Cartesian CS.

Such CRS is usually called a *topocentric* or an *engineering CRS*. (ISO 19111 2019) notes the limitation in size of such models. The tangential horizontal surface of the CRS drifts away from the curvature of Earth with increasing distance from the PoO as clearly seen in Figure 2. Thus, such CRS is only a viable approach for *compact* structures residing close to the PoO. Assuming the equality of horizontal planes in the model with equipotential surfaces in nature is fallacy (JAUD et al. 2020). The reason is the steady drift of the gravity direction from the *Up* direction defined by the topocentric CRS.

Scenario B: BIM is distorted with varying factor. With the introduction of (long) infrastructure objects in BIM, the interpretation in Scenario A is no longer viable. The locality of the topocentric CRS cannot be extended indefinitely as the Cartesian CS's vertical direc-

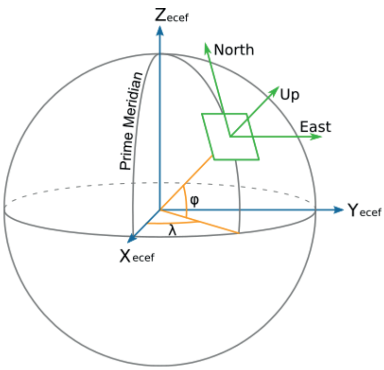

Fig. 2:
Depiction of a topocentric CRS (green) defined in a chosen point on Earth (PROJ 2023). Note the ever increasing discrepancy between the curved surface of the Earth and the $Up = 0$ plane of the CRS being tangential in PoO.

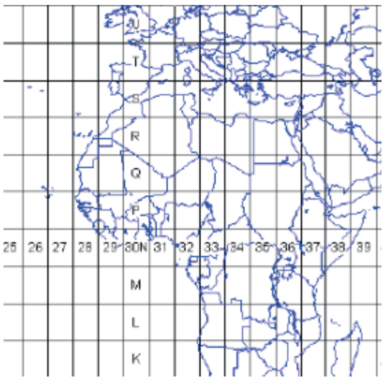

Fig. 3:
An example of a projected CRS UTM (MORTON 2023). Note that the distortion factor between the curved surface of the Earth and the projection surface of the CRS change with the position on the map.

tion and the direction of gravity drift apart further away from PoO. Additionally, geospatial data of the as-is situation in the field is usually set as the context of the BIM design in the infrastructure domain (JAUD et al. 2020). Thus, it shall be possible to model BIM geometries in the same CRS as the geospatial data resides.

Three-dimensional (3D) geospatial data resides in a combined CRS with a projected CRS and a vertical CRS as its components[2]. The latter is based on a chosen geoid and defines the meaning of the vertical axis, e.g. as the gravitational height. The former is based on a chosen ellipsoid and chosen projection method, defining the horizontal plane of the Cartesian CS. Figure 3 showcases the Universal Transverse Mercator (UTM) projection with the defined zones.

Consequently, using a projected CRS as the context of BIM geometries enables modelling of any size of structures, e.g. elongated structures from the infrastructure domain (cf. the railway line in Figure 1). However, the assumption of equal dimensions in the model and the reality (which holds true in scenario A) is broken. The magnitude of the distortions of the horizontal distances is a function of the location on the map, resulting from the chosen projection, height

[2]In this paper, whenever the term *projected CRS* is used, we mean a compound CRS with projected CRS for two-dimensional (2D) horizontal localization combined with a gravity-related height CRS to achieve a *projected 2D together with a vertical* CRS.

reduction, and other consequences of the chosen CRS. Thus it is not constant along any (longer) distance in the model.

Scenario C: BIM is distorted with a constant factor. The third scenario simplifies the transformation of geometries, while also accepting distortions in the BIM geometries. The varying scaling factor from Scenario B is averaged over the extent of the BIM model and assumed constant; however, it is rarely equal to 1 as in Scenario A. Thus, the extent of the BIM model may be much bigger before violating geometric consistencies. Scenario C: BIM is distorted with a constant factor.

The benefit of Scenario C over Scenario A lies in much smaller deviations at. These occur when federating geometrical data from different models, e.g. the stations with the railway line in Figure 2, without the necessary geodetic transformation applied to the geometries. This stems from the fact that there is a certain amount of error accumulated over the area of the (compact) structure. Thus, it has to be evened out at the transition zones, cf. the differences in scale factor at the edges of stations in Figure 1.

The benefit of Scenario C over Scenario B is the simplicity of transformation. The geodetic transformations needed in Scenario B are complex and computationally intensive. With a single constant factor, the transformation is straight-forward and thus the data easier to access.

Scenario C is common practice for engineering surveys. However, this engineering practice is not fully supported, neither in the current IFC standard nor in BIM modelling tools or collaboration software.

3 Solution in IFC

An important requirement on the BIM models is their preparedness for immediate use. In order to use BIM models (e.g. IFC datasets) without manual intervention involved, the interpretation of their content must be unambiguous across the AEC stakeholders and software solutions. Within the BIM model, the CRS is represented in the so-called georeferencing meta data of the BIM model. This meta data is commonly encoded using one of the unique CRS identifiers from the European Petroleum Survey Group (EPSG) database (IOGP et al. 2022).

Resulting from the scenarios described in Section 2, a single identification of the underlying CRS is deemed insufficient. As WUNDERLICH (2020) asserts, *"a scale fixed to 1 associated with BIM must collide with the necessary considerations for map projection and height"*. Thus, the definition of the horizontal coordinate plane and the location of BIM geometric context's PoO shall be specified independently from one another (JAUD et al. 2022). That is, the used coordinate operation (CO) with its properties shall be provided as well. In a nutshell, the mathematical and semantic connection between model's geometries and the Earth's environment need clear and unambiguous encoding possibilities within BIM.

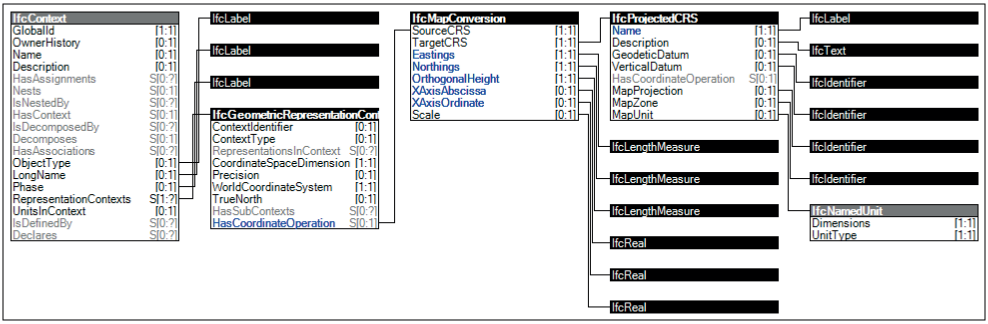

Fig. 4: *Project Global Positioning* concept template as defined in IFC4. Any IfcGeometricRepresentationContext has an optional inverse attribute HasCoordinateOperation pointing to an IfcMapConversion. This in turn has a direct attribute to an IfcProjectedCRS (ISO 16739-1 2016).

3.1 Status Quo in IFC4

The current official version of the IFC schema is IFC4 Addendum 2 Technical corrigendum 1 (IFC 4.0.2.1; ISO 16739-1 2018). The entities for georeferencing in a projected CRS are encapsulated in the *Project Global Positioning* concept template as presented in Figure 4. This template specifies a relation to map coordinates of a particular IfcGeometricRepresentationContext with all IfcShapeRepresentation occurrences referencing it.

A CRS is modelled with the abstract entity IfcCoordinateReferenceSystem. Its first and mandatory attribute Name encodes the CRS's identifier from the well-established EPSG registry (Jaud et al. 2022). The Description attribute optionally gives a human readable description of the CRS. Two additional EPSG codes can be provided for the underlying geodetic and vertical datums in GeodeticDatum and VerticalDatum, respectively. A projected CRS is modelled with IfcProjectedCRS and inherits from IfcCoordinateReferenceSystem. It encodes three properties of the used map projection: its name, its zone and the unit (ISO 16739-1, 2018).

IfcMapConversion conveys that the IfcGeometricRepresentationContext is a *topocentric* CRS. The first two parameters are inherited from IfcCoordinateOperation which connect a *source* CRS to a *target* CRS, e.g. the geometric context of BIM geometries with a projected CRS. The next three attributes (i.e. Eastings, Northings and OrthogonalHeight) specify the coordinates of the source CRS's PoO in the target CRS. Following, XAxisAbscissa and XAxisOrdinate define the orientation of the source's first coordinate axis within the target CRS. The source's and target's third coordinate axes coincide per definition. If these two attributes are omitted, this definition applies to the pairs of the first and second coordinate axes as well. Last, the optional attribute Scale allows for scaling between the used unit of measurement (UoM) in source and target CRSs, for example if BIM geometries are in feet and the underlying projected CRS is in meters. If omitted, the units are the same and the scale is 1.

In a nutshell, the current IFC georeferencing concept describes the CO for any geometry in the geometric context to the specified projected CRS, only using the insertion point (project base point) as translation and a horizontal rotation.

In a nutshell, this template describes the translating coordinates of any geometry in the geometric context to the specified projected CRS with the defined insertion point and horizontal rotation. Consequently, the BIM geometries in such context have their true dimensions in the model. Thus, the current state of the IFC specification already covers Scenario A from Section 2.

3.2 Additions

As described in Section 2, a semantically clear distinction before setting out in reality is needed between:

- BIM geometries being only translated and rotated into their place in the projected CRS with no scaling (and no re-projection) applied (Scenario A);
- BIM geometries being only translated and rotated into their place in the projected CRS with constant scaling (but no re-projection) applied (Scenario C); or
- a coordinate transformation being applied to BIM geometries by (re-)projecting according to their position in the CRS (Scenario B).

The first item is already supported by the IFC data model as presented in Section 3.1. However, the latter items (i.e. Scenarios B and C) require amendments of the IFC standard.

To support constant scaling in Scenario C, a new entity IfcMapConversionScaled inheriting from IfcMapConversion is introduced to the IFC schema. It adds three additional scaling factors ScaleX, ScaleY, and ScaleZ, which enable the constant scaling of BIM dimensions along *x*, *y*, and *z* axes of the geometric context.

To support Scenario B, a new entity IfcRigidOperation inheriting from IfcCoordinateOperation is introduced. This enables a mere translation of coordinates into the projected CRS as shown in Figure 5. The attributes FirstCoordinate, SecondCoordinate, and Height convey the offset values of BIM context's PoO in the projected CRS.

3.3 Related Changes

For the sake of completeness, we also include several related georeferencing proposals in this contribution. An EXPRESS-G diagram summarizing the existing and proposed entities is presented in Figure 6 (Jaud et al. 2022).

Jaud et al. (2019) called for support of WKT strings to codify the CRS's parameters. The explicit specification of a WKT to describe a CRS has many advantages: structure and content are standardized and established in the geospatial world (ISO 19162 2019). The parameters of the WKT are suitable to be interpreted by an algorithm in automated coordinate calculations. Thus, this avoids the problem where an EPSG code is not available for the CRS used in BIM project. The WKT string is modelled with the IfcWellKnownTextLiteral type and

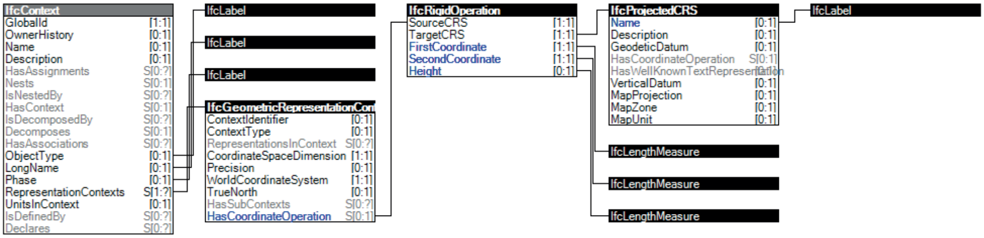

Fig. 5: *Project Global Positioning Mapped* concept template as proposed by IFC Tunnel project. Any IFCGEOMETRICREPRESENTATIONCONTEXT has an optional inverse attribute HASCOORDINATEOPERATION pointing to an IFCRIGIDOPERATION. This in turn has a direct attribute to an IFCPROJECTEDCRS.

connected to the chosen CRS with the IFCWELLKNOWNTEXT entity.

Moreover, we include the extension put forward by (JAUD et al. 2022) to allow the use of a 3D geographic CRS for the definition of PoO in addition to the established projected CRS. The geographic CRS is modelled with a new entity IFCGEOGRAPHICCRS as shown in Figure 7. Its attributes GEODETICDATUM, PRIMEMERIDIAN, and UNIT establish the CRS following (ISO 19111 2019). To connect the BIM geometries to the geodetic CRS, we extend the use of IFCRIGIDOPERATION to support plane angle offsets in its attributes FIRSTCOORDINATE and SECONDCOORDINATE. Thus, IFCRIGIDOPERATION allows for both length and angle measures for IFCPROJECTEDCRS and IFCGEOGRAPHICCRS, respectively.

4 Conclusion

This paper presents the proposed extensions to the official IFC4 data schema which enhance the support of georeferencing concepts:

- a new entity IFCGEOGRAPHICCRS to model geographic CRS;
- a new entity IFCMAPCONVERSIONSCALED to model a constant-scale tranformation between the geometric context of IFC geometries and a projected CRS;
- a new entity IFCRIGIDOPERATION to model a rigid transformation operation between the geometric context of IFC geometries and a CRS; and
- a new type IFCWELLKNOWNTEXTLITERAL and a new entity IFCWELLKNOWNTEXT to encode the WKT representation of CRS in IFC.

Together with already existing entities IFCMAPCONVERSION and IFCPROJECTEDCRS, these entities allow to model the three scenarios of georeferencing the geometric context of an IFC dataset as described in Section 2.

The extension provides semantically clear ways of defining georeferencing meta data of an IFC model, regardless of its content and extent. Figure 8 shows an overview of the existing and newly proposed entities together with their correct usage as applied to georeferencing

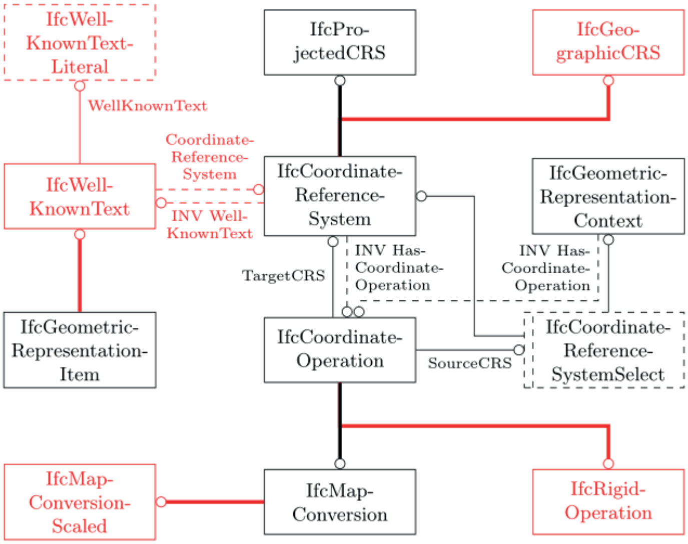

Fig. 6: EXPRESS-G diagram of existing (black) and proposed (red) entities for georeferencing with the IFC data model (JAUD et al. 2022)

between the real world coordinates and BIM model's context. Elongated objects following Scenario B (e.g. railway lines) can have their context set to lie in a projected CRS (see top path in 8). Objects with compact extent following Scenario A or C (e.g. buildings) may set their context in a topocentric CRS residing either in a projected or a geodetic CRS (see bottom and diagonal path in 8).

We call for buildingSMART International (bSI) and International Organization for Standardization (ISO) to ratify the extension in the next official IFC version. Additionally, the limitation of a single model context per IFC dataset shall be lifted. With this, buildings and infrastructure objects would be able to coexists within one IFC dataset with corresponding georeferencing metadata attached to their respective geometric contexts.

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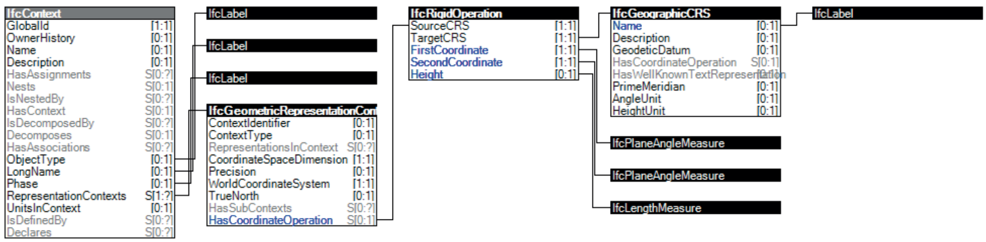

Fig. 7: *Project Global Positioning Geographic* concept template as proposed by IFC Tunnel project. Any IFCGEOMETRICREPRESENTATIONCONTEXT has an optional inverse attribute HASCOORDINATEOPERATION pointing to an IFCRIGIDOPERATION. This in turn has a direct attribute to an IFCGEOGRAPHICCRS.

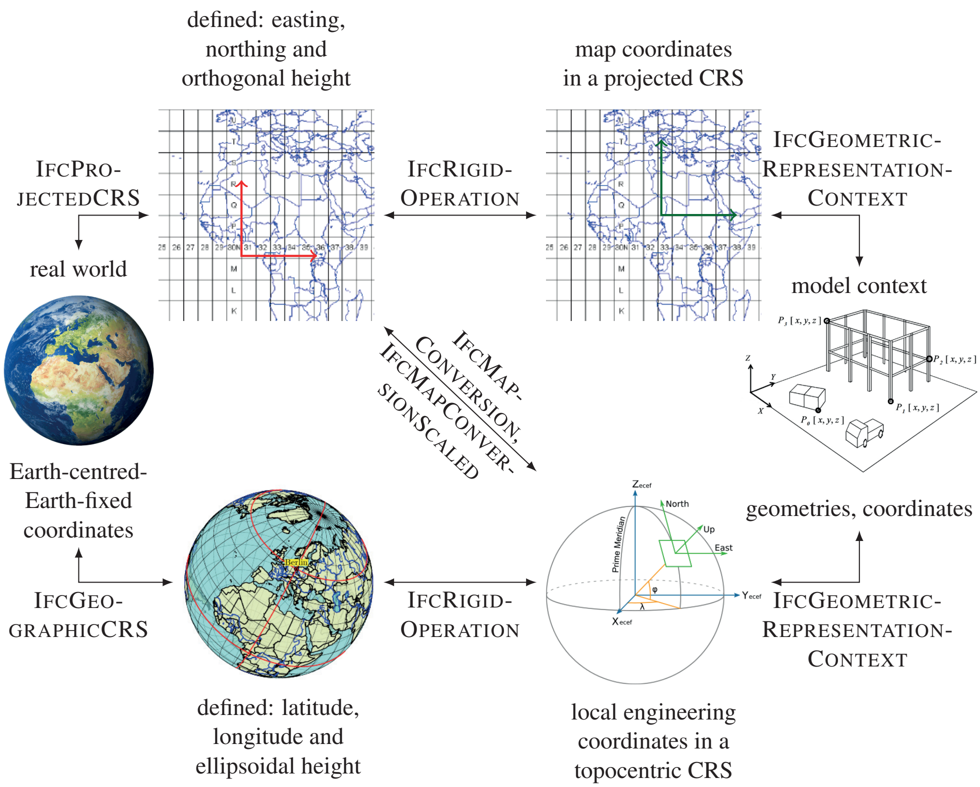

Fig. 8: A visual representation of the different possibilities described in Section 3. These show the three different transformation paths from real world coordinates (left) to BIM model's coordinates (right) or vice versa. In this way, any geospatial and BIM model data can be combined following semantically clearly defined transformations.

Bibliography

BRADLEY, A., LI, H., LARK, R. & DUNN, S. (2016): BIM for infrastructure: An overall review and constructor perspective. In: Automation in Construction 71, S. 139-152.

DB STATION&SERVICE AG (2023): Georeferenzierung von DB Personenbahnhöfen in BIM Projekten. https://infoplattform-personenbahnhoefe.deutschebahn.com/pb-hf/Georeferenzierung-fuer-DB-Personenbahnhoefen-in-BIM-Projekten-9561164 accessed 2023-02-02.

INTERNATIONAL ASSOCIATION OF OIL & GAS PRODUCERS (IOGP) (2022): Coordinate Conversions & Transformations including Formulas: Geomatics Guidance. Note Number 7, part 2: IOGP Publication 373-7-2.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO) (2018): ISO 16739-1: Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries – Part 1: Data schema. https://www.iso.org/standard/70303.html accessed 2023-01-02.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO) (2019): ISO 19111: Geographic information – Referencing by coordinates. https://www.iso.org/standard/74039.html accessed 2023-01-02.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO) (2019): ISO 19162: Geographic information – Well-known text representation of coordinate reference systems. https://www.iso.org/standard/76496.html accessed 2023-01-02.

JAUD, Š., DONAUBAUER, A. & BORRMANN, A. (2019): Georeferencing within IFC: A Novel Approach for Infrastructure Objects. In: CHO, Y. K., LEITE, F., BEHZADAN, A. & WANG, C. (Eds.): Computing in Civil Engineering 2019: Visualisation, Information Modelling, and Simulation, i3CE 2019 – ASCE International Conference on Computing in Civil Engineering, 17-19 June 2019, Atlanta, Georgia, USA.

JAUD, Š., DONAUBAUER, A., HEUNECKE, O. & BORRMANN, A. (2020a): Georeferencing in the context of building information modelling. In: Automation in Construction 118, S. 103211.

JAUD, Š., KOHLHAAS, A. & BORRMANN, A. (2020b): Do BIM models intrinsically possess geodetic distortions or not? In: WUNDERLICH, T. A. (Hrsg.): Ingenieurvermessung 20. Beiträge zum 19. Internationaler Ingenieurvermessungskurs München, 2020. Wichmann, Berlin/Offenbach.

JAUD, Š ., CLEMEN, C., MUHIČ, S. & BORRMANN, A. (2022): Georeferencing in IFC: Meeting the Requirements of Infrastructure and Building Industries. In: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences X-4/W2-2022, S. 145-152.

KADEN, R. & CLEMEN, C. (2017): Applying Geodetic Coordinate Reference Systems within Building Information Modeling (BIM). In: INTERNATIONAL FEDERATION OF SURVEYORS (FIG) (Ed.): Technical Programme and Proceedings of the FIG Working Week 2017: Surveying the world of tomorrow – from digitalisation to augmented reality, FIG Working Week 2017, 29 May – 2 June 2017, Helsinki, Finland.

MORTON, A. (2023): UTM Grid Zones of the World. https://www.dmap.co.uk/utmworld.htm accessed 2023-01-02.

PROJ LIBRARY (2023): Geocentric to topocentric conversion. https://proj.org/operations/conversions/topocentric.html accessed 2023-01-02.

WUNDERLICH, T. A. (2020): Misalignment – Can 3D BIM Overrule Professional Setting-out According to Plane and Height? In: KOPÁČIK, A., KYRINOVIČ, P., ERDÉLYI, J., PAAR, R. & MARENDIĆ, A. (Eds.): Contributions to International Conferences on Engineering Surveying, 8th INGEO International Conference on Engineering Surveying and 4th SIG Symposium on Engineering Geodesy, 22-23 October 2020, online.