Georeferencing within IFC:
A Novel Approach for Infrastructure Objects

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ABSTRACT

The transfer of design data into nature is a necessary task during the construction process. For this, the geodetic Coordinate Reference System (gCRS) used during the design process needs to be accounted for and the distortions included need to be handled appropriately. In the context of Building Information Modelling (BIM) and the vendor-neutral data format Industry Foundation Classes (IFC), the gCRS represents an important metadata item of the model which is included and maintained throughout the project's lifetime. Although the IFC4 supports gCRSs by providing the option to refer to an identifier of the European Petroleum Survey Group (EPSG) database, it is not able to handle custom gCRSs, which can be defined for large infrastructure projects, such as the Brenner Base Tunnel (BBT). We highlight these deficiencies of the schema and propose a novel approach by expanding the IFC schema with the Well-Known Text (WKT) notation.

INTRODUCTION

Motivation. The Architecture, Engineering and Construction (AEC) domain is in its transition from two-dimensional (2D) planning processes to three-dimensional (3D) object-oriented modelling. Building Information Modelling (BIM) is steadily gaining importance replacing the conventional Computer Aided Design (CAD) practices and getting implemented in many aspects of the software and stakeholder landscape (Borrmann et al. 2018). Lately, the infrastructure sector has shown increased interest in adopting BIM methods (Barazzetti & Banfi 2017).

The transfer of design data into the field is a necessary task in the construction process. For this, the geodetic Coordinate Reference System (gCRS) used during the design process and the distortions included need to be handled properly. The gCRS denotes the model of the Earth, the chosen elevation reference as well as the used map projection. In the context of BIM, the vendor-neutral data format Industry Foundation Classes (IFC) developed by buildingSMART International (bSI) is getting increasingly popular (ISO 16739, Borrmann et al. 2016). The used gCRS represents the metadata of the Project Coordinate System (PCS) and thus the IFC model which should be included and maintained throughout the project's lifetime (Markič et al. 2018).

Within this study we investigate one of the biggest construction projects in Central Europe – the Brenner Base Tunnel (BBT) between Austria and Italy (Bergmeister 2011). It is designed in a dedicated compound gCRS, representing a homogeneous reference system for all surveying, design, and construction work. Whenever BIM methods are applied for the design, construction and maintenance processes in the project, the format allowing for exchanges between different stakeholders must be able to include the metadata about the BBT's underlying custom gCRS. However, as we show in this paper, this is not possible with the current version of the IFC schema. We propose a solution to define the gCRS with the standardized Well-Known Text (WKT) notation which allows for more customization (ISO 19162).

Related work. Georeferencing in the BIM context has increasingly been addressed in recent years. bSI members have discussed this issue in one of their latest projects *Model Setup IDM* (bSI 2018). The focus of the project was the use case of georeferencing in simple and complex projects. IFC versions 2x3 and 4 have been looked at in detail and a guideline for implementers has been published. Kaden & Clemen (2017) walk through an example study on the coordinate systems from the geodetic perspective. They noted that a correct understanding of gCRSs is crucial for the success of BIM projects in the infrastructure sector, where large extents lead to potentially large distortions. However, in their words, *most CAD data is created without this consideration*.

The shortcomings of the IFC schema have already been addressed by the authors in their previous study (Markič et al. 2018). However, the proposed solution of including grid-shift datasets in the IFC schema does not provide the needed accuracy in a large tunneling project such as the BBT. Additionally, producing such data would be cumbersome in a mountainous area (Markič et al. 2019). Uggla & Horemuz (2018) present their understanding of the georeferencing by means of the IFC schema from another point of view. They highlight 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 gCRS. They conclude 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*. Although we do not agree with the claim of the 1:1 representation, we agree with their conclusions.

Structure of the paper. This section provides a short introduction with related work. Next section introduces the reader to the topic of georeferencing. Section 3 explains how the current IFC4 schema handles the metadata about the gCRS, its deficiencies, and a proposed solution. The BBT case study with its custom gCRS and its representation in WKT is presented in Section 4. We conclude the paper with discussion in Section 5.

BACKGROUND ON GEOREFERENCING

In infrastructure design, the PCS is a depiction of the real world by the chosen gCRS. Having the underlying gCRS and thus the PCS well-defined, geospatial data from different sources can be incorporated in the project by applying the respective transformations.

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. More precisely, the Earth is a sphere squished at the poles (due to the rotational forces) and a really good approximation is an oblate ellipsoid – an ellipse rotated around its minor axis. 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 history, many ellipsoids have been defined and used. A geodetic datum relates an ellipsoid to the Earth, e.g. by setting the center of the ellipsoid to the Earth's center of gravity and its minor axis to coincide with Earth's rotational axis. The ellipsoid is described in geodetic context by providing its major axis R_{major} and instead of its minor axis R_{minor} its inverse flattening, which is defined as (ISO 19111, EPSG 2018):

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

Projected Coordinate Systems. 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 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).

To keep the distortions of distances and surface areas in an acceptable range, strips of the ellipsoid are defined and projected onto a cylinder's surface. The TM projection (for example, the Gauss-Kruger projection) uses a cylinder that is tangential to the ellipsoid at a meridian. 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 have a width of 3 degrees only. 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. Thus, the central meridian is shortened with a scale of $m = 0.9996$ which keeps the distance distortions in an acceptable range, even at the borders of the strip (ISO 19111, Kaden & Clemen 2017).

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 corresponds to the human notion of elevation and is very practical in construction. 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 orthogonal height $H = 0$ – is the Earth's equipotential gravity field (the most common is 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 100 m, which induces additional dimensional distortions (ISO 19111, Markič et al. 2019).

Projected and Compound gCRS. To summarize, a gCRS is composed of multiple parts. The choice of ellipsoid's size, position and orientation with regard to 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 a Cartesian CS. The map projection together with a geodetic datum is called a projected gCRS, which uniquely defines the transformation of the PCS's X and Y axes to the ellipsoid surface. In combination with a vertical gCRS, the reference system is called a compound gCRS (ISO 19111, ISO 19162).

Well-Known Text (WKT) representation. The WKT can be used to represent geometric shapes and features as well as conveying information about a gCRS in a customizable and parametric manner (ISO 19162). The concept is well established within the geospatial community and already supported by major Geographic Information Systems (GISs) (EPSG 2018).

The WKT notation is an object-oriented representation of a gCRS. It is made up from tokens, which are keywords (classes) followed by a set of attributes (of the class) within square brackets separated by commas. Attributes can be literal texts, numbers, or other tokens, the nesting is unlimited. The whole string is saved in a notation that is easily readable by both machines and humans. All geodetic concepts described above have a parametric notation, for example the token for an ellipsoid is defined as follows (ISO 19162):

ELLIPSOID[<name>,<major axis>,<inverse flattening>,<length unit>]

ISSUES OF THE CURRENT IFC DATA MODEL

The vendor-neutral data format IFC has included support for georeferencing in the version IFC4 (ISO 16739). The abstract entity *IfcCoordinateReferenceSystem* and the *IfcProjectedCRS* deriving from it provide information about the chosen geodetic and vertical datums as well as the chosen projection method. The main identifier represents the code from the European Petroleum Survey Group (EPSG) database saved in the obligatory *Name* attribute (EPSG 2018). Additionally, the EPSG codes of the geodetic and vertical datums can be optionally saved in *GeodeticDatum* and *VerticalDatum* attributes, respectively. According to the IFC specification, only one *IfcProject* and thus one *IfcProjectedCRS* per file can be defined (Uggla & Horemuz 2018, Kaden & Clemen 2017, ISO 16739).

The abstract *IfcCoordinateOperation* class links the geometric context of the *IfcProject* in the *TargetCRS* attribute with the gCRS defined with *IfcProjectedCRS* in the *SourceCRS* attribute. The derived *IfcMapConversion* class defines the transformation's parameters for the coordinate origin and the orientation of the project's PCS within the gCRS with its 6 attributes (*Eastings*, *Northings*, *OrthogonalHeight*, *XAxisAbsissa*, *XAxisOrdinate* and *Scale*) (Kaden & Clemen 2017).

The Problem and its Solution. Despite the functionalities described above, it is currently not possible to correctly exchange IFC data of a project where an EPSG code of the gCRS is not available. This particularly applies to infrastructure projects where a custom gCRS is in use. Thus, the exchange of project data with the IFC format is imperfect. To overcome this issue, we propose to extend the IFC schema to include the possibility for WKT notation of the underlying gCRS. The coverage by GIS and the parametric possibilities to describe any gCRS makes WKT the perfect candidate over property sets because of its clear and unambiguous semantic definitions of geodetic elements (ISO 19162). A new entity *IfcWellKnownTextCRS* is proposed:

```
ENTITY IfcWellKnownTextCRS
    SUBTYPE OF (IfcCoordinateReferenceSystem)
        WKT:     IfcText;                         // holds the WKT string
END ENTITY;
```

TEST STUDY – BBT

We test our proposal on a real-world project where the gCRS used in the project does not have an EPSG code (Markič et al. 2019). The BBT project is a major European infrastructure project of the Helsinki (Finland) – La Valletta (Malta) North-South Trans-European Network (TEN) railway corridor (Bergmeister 2011). At the beginning of the project in 2001 the geospatial data of the project area from the two participating countries – Austria and Italy – needed to be merged to ensure a clear planning process and to avoid mistakes during the underground construction. An overview of the project's site is shown in Figure 1 (Markič et al. 2019**)**.

For historical reasons, most of the major European countries base their geospatial data in their own national gCRS. Both participating countries use a completely different gCRS as presented in Table 1 and as such three options were available. Either i) convert all relevant Austrian geospatial data into Italian gCRS and work in Italian gCRS; ii) convert all relevant Italian geospatial data into Austrian gCRS and work in Austrian gCRS; or iii) choose or define a new custom gCRS and convert both Austrian and Italian relevant data into it. The project team decided for the third option and defined a completely new projected gCRS named "*BBT_TM-WGS84*" which allows for both, low distortion values in the project area and good integration with satellite-based measurements. The chosen geodetic datum is WGS84 and the chosen vertical datum is the European Vertical Reference Frame 2007 (EVRF2007), realized through the United European Leveling Network (UELN). An overview of the properties of *BBT_TM-WGS84* is presented in Table 1, right-most column (Markič et al 2019).

Figure 1. Plan of the BBT project's site with topography, the state border Austria-Italy and the tunnels. Central meridian, project's origin, and coordinate axes are also marked (Markič et al 2019).

Table 1. The properties of the geodetic and vertical datums and the projected CRSs used by the countries participating in and by the BBT project itself. For each element its code and name from the EPSG database as well as additional parameters are provided (Markič et al 2019).

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** + 720
○ EPSG	7004	7022	7030
○ R_{major}	6 377 397.155 m	6 377 388 m	6 378 137.0 + 720 m
○ f^{-1}	299.1528128	297.0	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	-5105.739717 km
• Projection	Gauss-Kruger	Gauss-Boaga	TM
○ EPSG	9807	9807	9807
• Central meridian	10°20', 13°20' & 16°20'	9°0' & 15°0'E	11°30'42.5775"E
• Origin***	48°16'15.29"N 16°17'41.06"E	41°55'25.51"N 12°27'08.40"E	46°58'50.7947"N 11°31'42.5775"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. It is widely used by Global Positioning System (GPS) and a reference for all other ellipsoid definitions.
***The reference lines are the mean equatorial plane and the Greenwich meridian.

To achieve better agreement between the nature and the geospatial data and to lessen the computational burden, the project team did some modifications to the well-established gCRS. The undulation reaches from N = 49 to 51 m in the area around the tunnel. Therefore, the WGS84 ellipsoid's reference surface has been lifted to H = 770 m (H_{ell} = 720 m) above the ellipsoid. Because the project site extends primarily in the North-South direction, it is optimal to define a TM projection in such a way, that its meridian runs as close to the tunnel axis as possible to ensure minimal distortions across the whole project area. The chosen meridian was 11º31'42.5775"E from Greenwich which ensures the whole project lies within +/- 10 km of the meridian (see Figure 1). Accordingly, the distortions of the TM projection are neglectable within the project's area.

The WKT string of BBT's gCRS is provided below. The important tokens are explained on the right side and the parameters from Table 1 are highlighted. This whole string without the comments and line-breaks can be included within the *IfcWellKnownTextCRS::WKT* attribute as proposed above.

```
COMPOUNDCRS["BBT_TM-WGS84-EVRF2007",                                          // compound gCRS
  PROJECTEDCRS["BBT_TM-WGS84",                                                // projected gCRS
    BASEGEODCRS["BBT_TM-WGS84-BaseCRS",                                       // geodetic datum
      DATUM["BBT_WGS84",
        ELLIPSOID["WGS84+720",6378857.0,298.257223563,LENGTHUNIT["metre",1.0]]]],
    CONVERSION["BBT_TM",                                                      // map projection
      METHOD["Transverse Mercator",ID["EPSG",9807]],                          // method
      PARAMETER["Latitude of natural origin",0,
        ANGLEUNIT["degree",0.0174532925199433],ID["EPSG",8801]],
      PARAMETER["Longitude of natural origin",11.5118270833,                  // projection's meridian
        ANGLEUNIT["degree",0.0174532925199433],ID["EPSG",8802]],
      PARAMETER["Scale factor at natural origin",1.000121,                    // meridian's scale
        SCALEUNIT["unity",1.0],ID["EPSG",8805]],
      PARAMETER["False easting",20000.0,                                      // false easting
        LENGTHUNIT["metre",1.0],ID["EPSG",8806]],
      PARAMETER["False northing",-5105739.717,                                // false northing
        LENGTHUNIT["metre",1.0],ID["EPSG",8807]]],
    CS[Cartesian,2],AXIS["(Y)",north,ORDER[1]],AXIS["(X)",east,ORDER[2]],     // CS' x and y axes
      LENGTHUNIT["metre",1.0]],
  VERTCRS["EVRF2007",                                                         // vertical CRS
    VERTICALDATUM["European Vertical Reference Frame 2007",ID["EPSG",5215]], // vertical datum
      CS[vertical,1],AXIS["(H)",up,ORDER[3]],LENGTHUNIT["metre",1.0]]]]       // CS' z axis
```

CONCLUSIONS

In this paper, gCRS along with a complex example from the BBT project are presented. In the context of BIM and the vendor-neutral data format IFC, the gCRS's definition is a part of the BIM model's metadata. We highlight the deficiencies of the current IFC schema to save a gCRS which is not included in the EPSG database such as BBT's *BBT_TM-WGS84*. We propose a novel solution by expanding the IFC schema to include a new entity *IfcWellKnownTextCRS*. Within its attribute *WKT* a string in the WKT representation is saved which allows for a fully parametric description of a gCRS definition.

We verify our solution on BBT's complex gCRS by translating the peculiarities listed in Table 1 to the WKT notation. This string would be included in the new entity and thus enable the exchange of complete georeferencing metadata of BBT's gCRS. With our solution, any gCRS which is not (yet) included in EPSG database can be referenced in an IFC file. Thus, the infrastructure sector can more clearly adapt BIM methods, even in the more complex projects.

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