GEOREFERENCING IN IFC: MEETING THE REQUIREMENTS OF INFRASTRUCTURE AND BUILDING INDUSTRIES

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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 implementation. The requirements voiced by the domain experts during recent years have been collected and analysed. While IFC already covers some of the concepts, we propose an extension to the IFC schema to handle the inadequacy. Our proposal composes of two new entities: one supports geographic coordinate reference systems (CRSs) and the other enables a rigid transformation of BIM geometries. We showcase the possibilities with three examples, one for each of the required scenarios. 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 and software implementers.

1. INTRODUCTION

1.1 Motivation

The core of building information modelling (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 et al., 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.

Geospatial data of the as-is situation sets the context of the BIM design. It is usually provided in a coordinate reference system (CRS) that relates the data to the Earth's form and gravity field. Thus, the CRS conveys the definitions and parameters for the transformations between the BIM geometries and the reality. 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 (International Association of Oil & Gas Producers, 2021; Jaud et al., 2020).

1.2 Problem Statement

The problem of georeferencing BIM models is complex. A "*correct understanding [of CRS] is crucial especially in the infrastructure sector*" (Kaden and Clemen, 2017). The perspectives on its complexity are listed from abstract (top) to pragmatic (bottom) in Table 1. The mathematical-physical models from geodesy are scientifically sound and a priori do not have to be discussed in the context of BIM. In order to interface between the BIM and geospatial domains, it is necessary to determine the information standards from the geospatial domain that can be used in a compatible way in BIM projects and workflows.

To achieve interoperability, georeferencing must be implemented at the application level through software as well as at the exchange level through suitable exchange formats. This means, the concepts and tools must be actually and correctly applied. Our research focuses on the exchange level, more precisely, on the most prominent open BIM data format Industry Foundation Classes (IFC) and how georeferencing is implemented in it. All other perspectives from Table 1 are out of scope of this paper.

In the official version of the IFC standard, a single concept template is available that specifies georeferencing to a CRS (ISO, 2018). It has been put through evaluation by the IFC infrastructure extension projects and deemed insufficient to cover all the requirements of data exchange in infrastructure use cases (e.g., Rives et al., 2020). In particular, additional options for specifying a CRS as well as a coordinate operation (CO) are required. That is, referencing a base point in a geographic CRS and defining a CO without the implicit (re-)projection of coordinates. The goal of this paper is to present the issues found and address them with a comprehensive solution.

1.3 Structure of the Paper

The paper is structured as follows. This section presents our motivation and the problem statement. Next section briefly summarizes related works. Section 3 gives an overview of the current capabilities of the official IFC4 standard. We list the collected requirements of the IFC infrastructure extensions projects in Section 4. Our proposed extensions that address the requirements are described in Section 5. We showcase the usage

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Table 1. A phenomenological classification indicates the many aspects on georeferencing in the context of BIM/GIS interoperability.

Layer	Concepts
A priori level: maths and geodesy	• coordinate systems and coordinate conversion • reference body (e.g. ellipsoid), map projection, . . . • geodetic datum and coordinate transformation • CRS (e.g. ETRS89/UTM, . . .) • geometric-physical concepts for height (geometric height, geoid, . . .)
Enabling level: geospatial and BIM	Standards (by OGC, ISO, . . .): • ISO 19111, ISO 19112, ISO 19148, . . . • OGC WKT-CRS & ISO 19162 • EPSG codes • ISO 19650, ISO 10303, . . . Open data formats: • OGC CityGML • ISO 16739: IFC ← focus of this paper Software: • concepts included and properly implemented • concepts included in native exchange formats • means of configuration for user and clients
Pragmatic level: users	• problem awareness • quality assurance (information requirements, model checking, . . .) • engineering skills and mutual understanding • geospatial and BIM software skills

on multiple examples in Section 6. The paper concludes with a discussion and an outlook in Section 7.

2. RELATED WORKS

An inadequacy of the IFC schema in addressing georeferencing has been noted by Uggla and Horemuz (2018): "*The current implementation in the IFC schema is suitable for infrastructure design in areas where sufficiently accurate well-known map projections are available, and which are not too high above the reference ellipsoid*". The authors also call for support of "*object specific map projections*" and "*separate scale factors for different axes*" (Uggla and Horemuz, 2018).

Clemen and Görne (2019) analysed the possibilities in the IFC4 version to specify the BIM model's position on Earth. They defined five levels of georeferencing (LoGeoRefs) and asserted that only the highest level (LoGeoRef50) provides sufficient information for precise surveying work.

Markič et al. (2018) have presented multiple suggestions for IFC schema improvement. They found that the IFC4 version provides adequate support for typical georeferencing cases occurring in the majority of projects. However, based on two recent real-world infrastructure projects, the IFC4 data model is deemed insufficient. To support these cases, they proposed two new IFC entities which encode grid-shift parameter datasets.

Jaud et al. (2019) analysed the Brenner Base Tunnel (BBT) project where a project-specific CRS was designed to minimize geodetic distortions at construction site. However, the CRS was defined in a way that accentuated the need for an extension of the IFC schema. Introducing well-known text (WKT) strings (ISO, 2019a) provided the needed flexibility to support even such peculiarities. The explicit specification of a WKT to describe a CRS has many advantages: structure and content are standardized and established in the geospatial world. 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 proposal was tested on the custom CRS of the BBT, with irrefutable results.

The need for different COs was voiced by recently Jaud et al. (2021). The authors describe three different possibilities of relating the Earth to the coordinate system (CS) of the construction site and their ideas are further developed in this study. They conclude that "*the topic [of georeferencing] needs a thorough analysis and a good understanding about the implications from all AEC stakeholders*" (Jaud et al., 2021).

Looking outside of academia, the standardization and professional bodies have been active as well. The importance of CRSs for the success of BIM projects was noted by Mitchell et al. (2020). Here, members of buildingSMART International (bSI) produced a manual to georeferencing in IFC and provided a guideline for IFC schema software implementers. It covers both the currently most wide-spread version, IFC2x3, and the latest official release, IFC4.

Multiple standards published by International Organization for Standardization (ISO) received an update in recent years (e.g., ISO, 2019a,b,c, 2021a). Additionally, ISO (2021b) examines barriers and suggests measures to improve the interoperability between geospatial and AEC data. It gives a comprehensive overview of current standards intersecting BIM and geographic information system (GIS) domains and aims to align them. As a result, three standardization projects are proposed: i) linking abstract concepts in BIM and GIS standards, ii) developing a geospatial and BIM dictionary, and iii) producing information exchange guidelines between BIM and GIS, the latter of which explicitly mentions the task of georeferencing. Annex C contains a comprehensive representation of the georeferencing status-quo with IFC from Clemen and Görne (2019). In parallel, but not unrelated, Gilbert et al. (2020) developed and published their report *Built environment data standards and their integration: An analysis of IFC, CityGML and LandInfra*. This report focuses on the file-based data exchange level and comes to very similar conclusions as listed above.

The IFC-Tunnel requirements analysis report addresses the georeferencing inadequacy with a simple IsDistorted flag applied to an appropriate entity (Rives et al., 2020). Despite the impression that the solution is a minor interference, it is a schema change and requires all related concept templates to be adjusted. With that in mind, a more IFC compliant solution was considered which differentiates between semantically distinguishable concepts and provides dedicated classes (i.e., entities) for them. These proposals have been discussed and modelled in a shared public environment on Github[1] with periodic involvement of the community in expert panels.

3. CURRENT STATE OF THE IFC STANDARD

The current official version of the IFC schema is IFC4 Addendum 2 Technical corrigendum 1 (IFC 4.0.2.1; ISO, 2018). The entities for georeferencing in a projected CRS are encapsulated in the *Project Global Positioning* concept template as presented in Figure 1. This template specifies a relation to map coordinates of a particular IFCGEOMETRICREPRESENTATIONCONTEXT with all IFCSHAPEREPRESENTATION occurrences referencing it. The template describes the CO converting coordinates of any geometry in the geometric context to the specified projected CRS.

A CRS is modelled with the abstract entity IFCCOORDINATEREFERENCESYSTEM (see Algorithm 1). Its first and mandatory attribute NAME encodes the CRS's identifier from the well-established EPSG registry (International Association of Oil & Gas Producers, 2021). 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, 2018).

Algorithm 1 Definitions of IFCCOORDINATEREFERENCESYSTEM and IFCPROJECTEDCRS in current IFC4 version (ISO, 2018).

```
ENTITY IfcCoordinateReferenceSystem
 ABSTRACT SUPERTYPE OF(IfcProjectedCRS);
  Name : IfcLabel;
  Description : OPTIONAL IfcText;
  GeodeticDatum : OPTIONAL IfcIdentifier;
  VerticalDatum : OPTIONAL IfcIdentifier;
 INVERSE
  HasCoordinateOperation : SET [0:1] OF
   IfcCoordinateOperation FOR SourceCRS;
END_ENTITY;
ENTITY IfcProjectedCRS
 SUBTYPE OF (IfcCoordinateReferenceSystem);
  MapProjection : OPTIONAL IfcIdentifier;
  MapZone : OPTIONAL IfcIdentifier;
  MapUnit : OPTIONAL IfcNamedUnit;
 WHERE
  IsLengthUnit : NOT(EXISTS(MapUnit)) OR
   (MapUnit.UnitType=IfcUnitEnum.LENGTHUNIT);
END_ENTITY;
```

IFCMAPCONVERSION restricts the IFCGEOMETRICREPRESENTATIONCONTEXT in its type to be *projected* CRS. Its transformation parameters are presented in Algorithm 2. 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 point of origin (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 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. The conversion between source (s_1, s_2, s_3) and target (t_1, t_2, t_3) coordinates is calculated as (Markič et al., 2018):

$$\lambda = \text{SCALE}\,, \tag{1}$$

$$\gamma = \arctan(\text{XAXISABSCISSA}, \text{XAXISORDINATE})\,, \tag{2}$$

$$t_1 = \lambda \cdot [(\cos\gamma \cdot s_1) - (\sin\gamma \cdot s_2)] + \text{EASTINGS}\,, \tag{3}$$

$$t_2 = \lambda \cdot [(\sin\gamma \cdot s_1) + (\cos\gamma \cdot s_2)] + \text{NORTHINGS}\,, \tag{4}$$

$$t_3 = \lambda \cdot s_3 + \text{ORTHOGONALHEIGHT}\,. \tag{5}$$

Algorithm 2 Definitions of IFCCOORDINATEOPERATION and IFCMAPCONVERSION in current IFC4 version (ISO, 2018).

```
ENTITY IfcCoordinateOperation
 ABSTRACT SUPERTYPE OF(IfcMapConversion);
  SourceCRS : IfcCoordinateReferenceSystemSelect;
  TargetCRS : IfcCoordinateReferenceSystem;
END_ENTITY;
TYPE IfcCoordinateReferenceSystemSelect = SELECT(
 IfcCoordinateReferenceSystem,
 IfcGeometricRepresentationContext);
END_TYPE;
ENTITY IfcMapConversion
 SUBTYPE OF (IfcCoordinateOperation);
  Eastings : IfcLengthMeasure;
  Northings : IfcLengthMeasure;
  OrthogonalHeight : IfcLengthMeasure;
  XAxisAbscissa : OPTIONAL IfcReal;
  XAxisOrdinate : OPTIONAL IfcReal;
  Scale : OPTIONAL IfcReal;
END_ENTITY;
```

4. REQUIREMENTS

An important requirement on the BIM models is their preparedness for immediate use. In order to use IFC models without manual intervention involved, the interpretation of their content must be unambiguous across the AEC stakeholders and software solutions. Moreover, the definition of the horizontal coordinate plane and the BIM geometric context's PoO shall be specified independently from one another Jaud et al. (as already noted by 2021).

In a nutshell, the mathematical and semantic connection between model's geometries and the Earth's environment need clear and unambiguous encoding possibilities within IFC. Thus, we focus only on LoGeoRef50, as it *provides the highest quality regarding the georeferencing of an IFC [dataset]* (Clemen and Görne, 2019). Other levels (< 50) do not provide any information about the CRS that is underlying the model data. As such, other levels require manual work to be able to correctly perform precise surveying work directly from the model.

The geometric context of any BIM model is usually seen as a local, three dimensional Euclidean space described with a

[1] https://github.com/bSI-InfraRoom/IFC-Specification

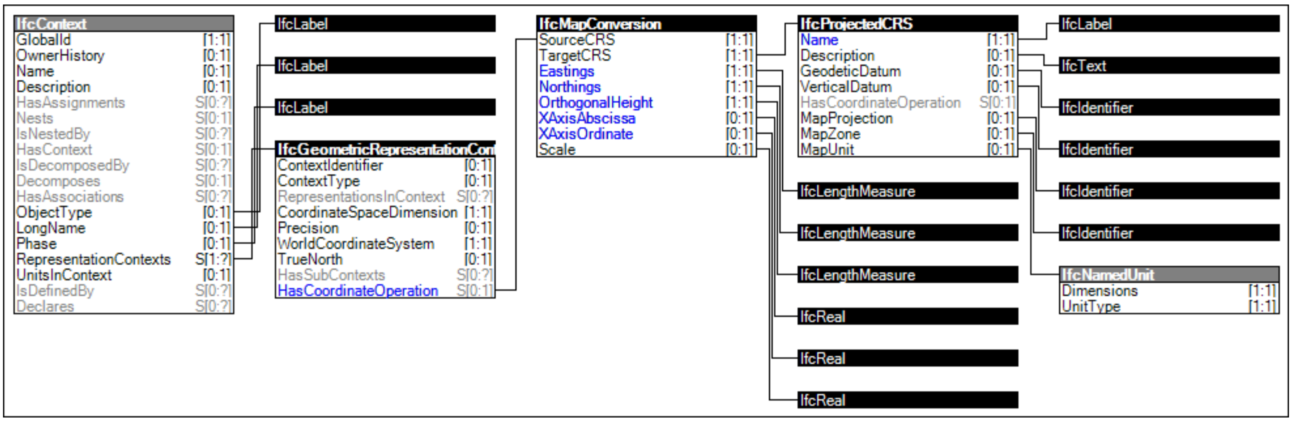

Figure 1. *Project Global Positioning* concept template as defined in IFC4. Any IFCGEOMETRICREPRESENTATIONCONTEXT has an optional inverse attribute HASCOORDINATEOPERATION pointing to an IFCMAPCONVERSION (see Algorithm 2). This in turn has a direct attribute to an IFCPROJECTEDCRS (see Algorithm 1) (ISO, 2018).

Cartesian CS for the representations of objects on site (Jaud et al., 2020). It is expected that 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 between the real world and the model is 1. ISO (2019b) speaks of an *engineering CRS* in such case; however notes the limitation in size of such models.

With the introduction of (long) infrastructure objects in IFC, this interpretation is no longer viable. The reason is that the locality of the Cartesian CS cannot be extended indefinitely as the Cartesian CS's vertical direction and the direction of gravity drift apart. Thus, it shall be possible to model geometries in a projected CRS additionally to the already existing engineering CRS. Moreover, we extend the requirements put forward by Jaud et al. (2021) to allow the use of a three-dimensional (3D) geographic CRS for the definition of PoO in addition to the established projected CRS.

To formalize the requirements, we employ the different CRS types defined in ISO (2019b): I) the geometric context of a BIM model shall be possible to define within an engineering or a projected CRS[2], and II) the engineering CRS's PoO shall be possible to reference within a geographic or a projected CRS.

The requirements can be formulated using the *Project Global Positioning* concept template described in Section 3. An additional clear and semantically appropriate identifier is needed to convey the information whether only a translation or a translation and transformation of coordinates into the projected CRS is to be applied. Moreover, it shall be possible to describe that no CO is supposed to be performed on coordinates.

These requirements are in-line with the discussion in technical weekly meetings during the *IFC Infrastructure Deployment* project. There, a distinction between a mere translation of the project's PoO compared to a translation and transformation of coordinates into a projected CRS was discussed.

5. PROPOSED EXTENSION

We describe our solutions by listing all changes to the existing IFC entities as well as defining new entities needed for both CRS and CO, respectively. The section concludes with an overview summarizing and diagrams visualizing the changes.

5.1 Coordinate Reference Systems

We have developed two solutions that address the requirements for CRSs presented above. These differentiate in a major data modelling decision: incur breaking changes or not. For the sake of completeness, we also include the proposal of Jaud et al. (2019) in our solutions.

Solution A: No breaking changes. This solution was developed with the main goal in mind: all changes shall be *backwards compatible*. This means that all existing IFC4 files remain valid datasets. The changes and additions to the encodings of CRSs are presented in Algorithm 3 with black, blue, and green colour.

In order to introduce the possibility of a geographic CRS, the definition of IFCCOORDINATEREFERENCESYSTEM needs to be amended. The attributes GEODETICDATUM as well as VERTICALDATUM have been moved to the IFCPROJECTEDCRS as these are not needed in a generic CRS.

A new optional attribute WELLKNOWNTEXT has been added to IFCPROJECTEDCRS to allow for provision of WKT strings. A new where rule NAMEORWKT ensures that at least one of NAME or WELLKNOWNTEXT attributes is set. These changes incur no breaking changes in the serialization of IFC models, as introducing optional attributes at the end of the attribute list does not invalidate existing files.

The geographic CRS is modelled with a new entity IFCGEOGRAPHICCRS as defined in Algorithm 3. Its attributes GEODETICDATUM, PRIMEMERIDIAN, and UNIT establish the CRS following ISO (2019b). Additionally, the last attribute WELLKNOWNTEXT allows for the CRS's definition using a WKT string if an EPSG code is unavailable. Parallel to IFCPROJECTEDCRS, the unit as well as identification have formal rules ensuring data's validity.

Solution B: Breaking changes. If breaking changes to the serialization of IFC data are permissible, the previous solution can be optimized from the data modeling point of view. As such, the WELLKNOWNTEXT attribute can be introduced already to the abstract IFCCOORDINATEREFERENCESYSTEM

[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 + vertical* CRS.

Algorithm 3 Changes and additions to encodings of CRSs. Existing definitions are colored black (cf. Algorithm 1), solution A blue and green, solution B red and green.

```
ENTITY IfcCoordinateReferenceSystem
 ABSTRACT SUPERTYPE OF (ONE OF
   (IfcProjectedCRS, IfcGeographicCRS));
  Name : OPTIONAL IfcLabel;
  WellKnownText : OPTIONAL IfcText;
  Description : OPTIONAL IfcText;
 INVERSE
  HasCoordinateOperation : SET [0:1]
   OF IfcCoordinateOperation FOR SourceCRS;
 WHERE
  NameOrWKT : EXISTS(Name)
   OR EXISTS(WellKnownText);
END_ENTITY;
ENTITY IfcProjectedCRS
 SUBTYPE OF (IfcCoordinateReferenceSystem);
  GeodeticDatum : OPTIONAL IfcIdentifier;
  VerticalDatum : OPTIONAL IfcIdentifier;
  MapProjection : OPTIONAL IfcIdentifier;
  MapZone : OPTIONAL IfcIdentifier;
  MapUnit : OPTIONAL IfcNamedUnit;
  WellKnownText : OPTIONAL IfcText;
 WHERE
  IsLengthUnit : NOT(EXISTS(MapUnit)) OR
   (MapUnit.UnitType=IfcUnitEnum.LENGTHUNIT);
  NameOrWKT : EXISTS(WellKnownText) OR
   EXISTS(SELF\IfcCoordinateReferenceSystem.Name);
END_ENTITY;
ENTITY IfcGeographicCRS
 SUBTYPE OF (IfcCoordinateReferenceSystem);
  GeodeticDatum : OPTIONAL IfcIdentifier;
  PrimeMeridian : OPTIONAL IfcIdentifier;
  Unit : OPTIONAL IfcNamedUnit;
  WellKnownText : OPTIONAL IfcText;
 WHERE
  IsPlaneAngleUnit : NOT(EXISTS(Unit)) OR
   (Unit.UnitType=IfcUnitEnum.PLANEANGLEUNIT);
  NameOrWKT : EXISTS(WellKnownText) OR
   EXISTS(SELF\IfcCoordinateReferenceSystem.Name);
END_ENTITY;
```

entity, following the NAME attribute as presented in Algorithm 3 with black, red, and green colour. Additionally, the formal proposition NAMEORWKT can be enforced at this level as well. The definition of IFCGEOGRAPHICCRS remains equal to Solution A, except for the WELLKNOWNTEXT attribute.

5.2 Coordinate Operations

The changes and additions to the encodings of COs are presented in Algorithm 4. With the introduction of new children to the abstract IFCCOORDINATEREFERENCESYSTEM, the usage of IFCMAPCONVERSION shall be restricted in the schema to only allow IFCPROJECTEDCRS entities being referenced by the attribute TARGETCRS. Thus, the SOURCECRS refering to a IFCREPRESENTATIONCONTEXT uses projected coordinates with elevation.

As required in Section 4, a semantically clear distinction is needed between:

a) BIM geometries being only translated and rotated into their place in the projected CRS with no scaling (and no projection) applied, or
b) a coordinate transformation shall be applied to BIM geometries by scaling and (re-)projecting according to their position in the CRS.

In order to achieve this, three *backwards compatible* options have been identified:

1) introduction of a flag on the existing CO entity IFCMAPCONVERSION (e.g., ISDISTORTED proposed by Rives et al., 2020),
2) an enumeration to cover the three specific cases that can occur (e.g., TRANSLATION, TRANSLATION_PROJECTION, PROJECTION), and
3) introduction of a new entity IFCRIGIDOPERATION inheriting from IFCCOORDINATEOPERATION.

The latter presents the semantically clearest solution, especially taking into account the already circulating IFC files using IFCMAPCONVERSION. It is unclear, what the intention of the original authors of these files was and thus impossible to determine a correct default value for either the flag or the enumeration value.

The proposed IFCRIGIDOPERATION restricts the IFCGEOMETRICREPRESENTATIONCONTEXT in its type to be a *topocentric* CRS. Its PoO may be defined within any IFCCOORDINATEREFERENCESYSTEM since the attributes FIRSTCOORDINATE and SECONDCOORDINATE allow for both length and angle measures for IFCPROJECTEDCRS and IFCGEOGRAPHICCRS, respectively. The topocentric Cartesian coordinate axes *East* and *North* are perpendicular to Earth's gravity with *Up* being its negative direction in the defined PoO. Consequently, the BIM geometries in such context have their true dimensions in the model.

Algorithm 4 Changes and additions to encodings of COs. Existing definitions are colored black (cf. Algorithm 2), and changes in green.

```
ENTITY IfcCoordinateOperation
 ABSTRACT SUPERTYPE OF(ONE OF
   (IfcMapProjection, IfcRigidOperation));
  SourceCRS : IfcCoordinateReferenceSystemSelect;
  TargetCRS : IfcCoordinateReferenceSystem;
END_ENTITY;
ENTITY IfcMapConversion
 SUBTYPE OF (IfcCoordinateOperation);
  Eastings : IfcLengthMeasure;
  Northings : IfcLengthMeasure;
  OrthogonalHeight : IfcLengthMeasure;
  XAxisAbscissa : OPTIONAL IfcReal;
  XAxisOrdinate : OPTIONAL IfcReal;
  Scale : OPTIONAL IfcReal;
 WHERE
  CorrectCRS : 'IFCPROJECTEDCRS' IN
   TYPEOF(SELF\IfcCoordinateOperation.SourceCRS);
END_ENTITY;
ENTITY IfcRigidOperation
 SUBTYPE OF (IfcCoordinateOperation);
  FirstCoordinate : IfcMeasureValue;
  SecondCoordinate : IfcMeasureValue;
  Height : IfcLengthMeasure;
 WHERE
  SameCoordinateType :
  ('IFCLENGTHMEASURE' IN
     TYPEOF(FirstCoordinate) AND
   'IFCLENGTHMEASURE' IN
     TYPEOF(SecondCoordinate)) OR
  ('IFCPLANEANGLEMEASURE' IN
     TYPEOF(FirstCoordinate) AND
   'IFCPLANEANGLEMEASURE' IN
     TYPEOF(SecondCoordinate));
END_ENTITY;
```

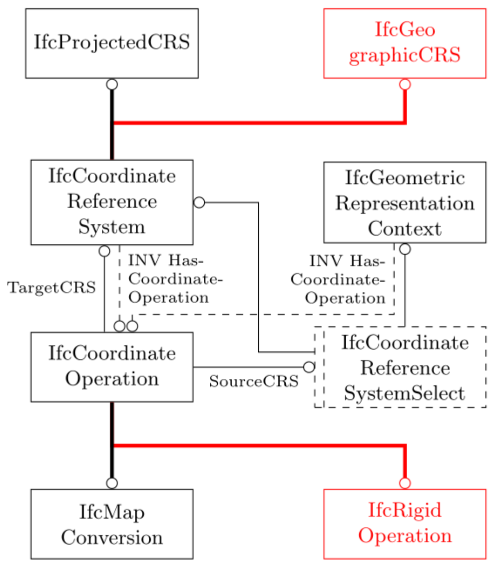

Figure 2. EXPRESS-G diagram of existing (black) and proposed (red) entities for georeferencing with the IFC data model. The definitions of the depicted entities are given in Algorithms 1 to 4.

5.3 Summary of changes

An EXPRESS-G diagram of the existing and proposed entities is presented in Figure 2. This diagram is valid for both solutions A and B from Section 5.1, since these differentiate only in the order of attributes. Additionally, Figure 3 shows an overview of the existing and newly proposed entities together with their correct usage as applied to georeferencing between the real world coordinates and BIM model's context.

It shall be mentioned on this place, that the usage of IFCRIGIDOPERATION is limited to small models placed in relative proximity 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.

Next, if IFCPROJECTEDCRS or IFCGOEGRAPHICCRS is defined with a WKT string, the CRS encoded in WKT must be of correct type, i.e., COMPOUNDCRS or GEOGCRS, respectively.

6. EXAMPLES

To showcase all the possibilities of the extended IFC schema, we devised three examples for each of the possible connections between the real world and BIM coordinates from Figure 3. We focus only on the IFC entities of interest and assume that these are a part of an otherwise valid IFC dataset. All examples make use of a common geometric context and a project defined in Algorithm 5.

The first example shown in Algorithm 6 uses the entities from the current official IFC4 version. It places the context in front of the main entrance to the Technical University of Munich, Germany. Here, all geometries within the IFCGEOMETRICREPRESENTATIONCONTEXT are in the compound CRS with EPSG code 5834 which is combining CRS with codes 5684 and 5783 (bSI Infra Room, 2022). According to the scale function implicit to the used projection and height reduction, the extent of geometries and their relative location are not equal between the model and reality. The correct dimensions must be calculated with the meta data from IFCPROJECTEDCRS.

Algorithm 5 The basis definitions of an IFCPROJECT and IFCGEOMETRICREPRESENTATIONCONTEXT references by all three examples in Algorithms 6 to 8 (based on ProjectSetup-1 example from bSI Infra Room, 2022).

```
#1=IFCPROJECT('2DAvEupIz0HQr73cMaawtY',
 $, $, $, $, $, $, (#21), #11);
#2=IFCDIRECTION((1., 0., 0.));
#4=IFCDIRECTION((0., 0., 1.));
#5=IFCCARTESIANPOINT((0., 0., 0.));
#7=IFCDIRECTION((0.,1.));
#11=IFCUNITASSIGNMENT((#12, #15));
#12=IFCSIUNIT(*, .LENGTHUNIT., $, .METRE.);
#13=IFCSIUNIT(*, .PLANEANGLEUNIT., $, .RADIAN.);
#14=IFCMEASUREWITHUNIT(
 IFCPLANEANGLEMEASURE(0.017453292519943295), #13);
#15=IFCCONVERSIONBASEDUNIT(#16,
 .PLANEANGLEUNIT., 'degree', #14);
#16=IFCDIMENSIONALEXPONENTS(0, 0, 0, 0, 0, 0, 0);
#21=IFCGEOMETRICREPRESENTATIONCONTEXT($,
 'Model', 3, 1.E-6, #22, #7);
#22=IFCAXIS2PLACEMENT3D(#5, #4, #2);
```

Algorithm 6 Georeferencing metadata of an IFC dataset in a projected CRS (based on Georeferencing-1 example from bSI Infra Room, 2022). The IFCPROJECTEDCRS follows Solution A from Algorithm 3. The construction site with this context lies in front of the main entrance to the Technical University of Munich, Germany.

```
#101=IFCPROJECTEDCRS('EPSG:5834',
 'DB_REF [...] + DHHN92 height', 'EPSG:5684',
  'EPSG:5783', 'Gauss-Kruger', '4', #12, $);
#102=IFCMAPCONVERSION(#21, #101, 4468005.,
 5334600., 515., 1., 0., 1.);
```

The second example presented in Algorithm 7 makes use of two additions proposed in this paper, i.e., the definition of a CRS using a WKT string as well as a definition of a topocentric CRS with the help of a projected PoO. The WELLKNOWNTEXT attribute is filled with a truncated WKT string of the CRS used by the BBT project as showcased by Jaud et al. (2019). The coordinates of the topocentric PoO are close to the southern portal of the tunnel and span a local, distortion-free CS for the portal. The shift parameters from IFCRIGIDOPERATION must not be confused with the axis translation (e.g., x-offset) of the WELLKNOWNTEXT string.

Algorithm 7 Georeferencing metadata of an IFC dataset in a topocentric CRS with its PoO defined in a projected CRS (truncated example from Jaud et al., 2019). The IFCPROJECTEDCRS follows Solution B from Algorithm 3. The context lies close to the south portal of the BBT tunnel in Italy.

```
#201=IFCPROJECTEDCRS($,
 'COMPOUNDCRS["BBT_TM-WGS84-EVRF2007", ... ]',
 $, $, $, $, $, #12);
#202=IFCRIGIDOPERATION(#21, #201,
 IFCLENGTHMEASURE(35010.),
 IFCLENGTHMEASURE(1560.), 0.);
```

The third and last example is shown in Algorithm 8. It demonstrates the use of the last entity proposed in this paper: IFCGEO-

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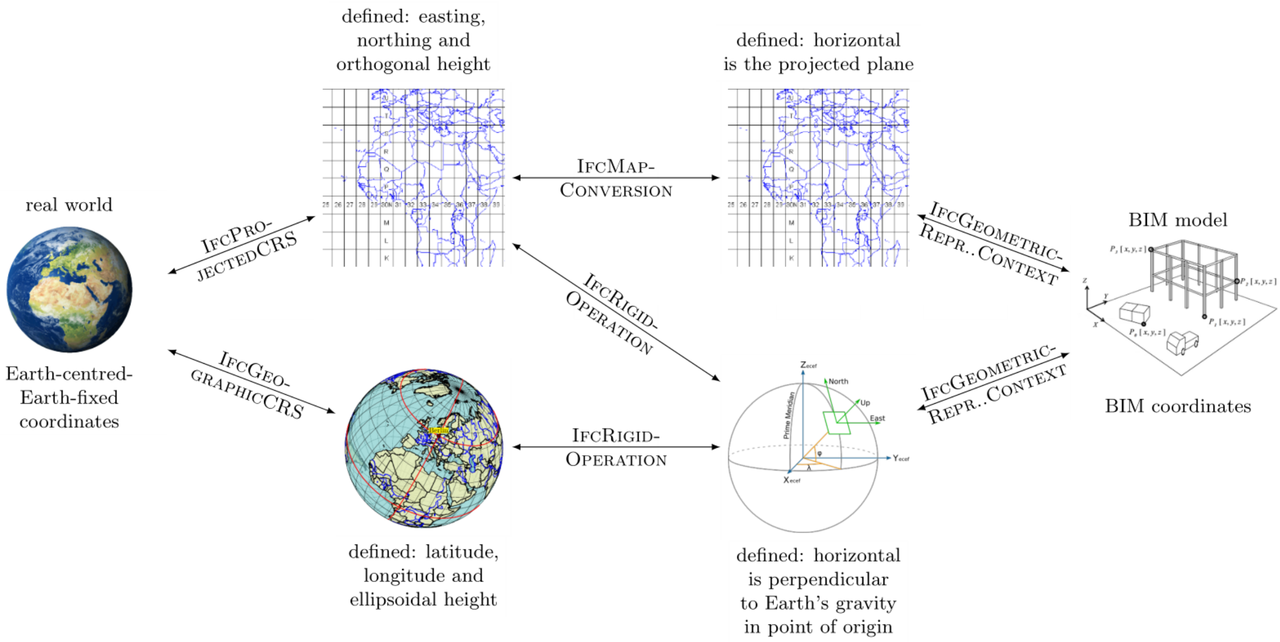

Figure 3. A visual representation of the different possibilities described in Section 5. These show the three different transformation paths from real world coordinates (left) to BIM model's coordinates (right) or vice versa. In this way, any geospatial and BIM model data can be combined following semantically clearly defined transformations.

GRAPHICCRS. The geographic CRS European Terrestrial Reference System (ETRS) has the EPSG code 4258. The topocentric CRS is placed on top of the Bell tower on the island of lake Bled in Slovenia using IfcRigidOperation with angle measures.

Algorithm 8 Georeferencing metadata of an IFC dataset in a topocentric CRS with its PoO defined in a geographic CRS. The IfcGeographicCRS follows Solution B from Algorithm 3. The geometries with this context lie at the Bell tower on the island of Lake Bled in Slovenia.

```
#301=IFCGEOGRAPHICCRS('EPSG:4258', $, $,
 'EPSG:6258', 'EPSG:8901', #15);
#302=IFCRIGIDOPERATION(#21, #301,
 IFCPLANEANGLEMEASURE(14.0902217),
 IFCPLANEANGLEMEASURE(46.3623297), 475.);
```

7. CONCLUSIONS

This paper presents an extension to the official IFC4 data schema to enhance the support of georeferencing concepts. As described in detail by the IFC-Tunnel project (Rives et al., 2020), it covers the requirements put forward by the infrastructure sector of the AEC domain. The extension proposes (cf. Section 5.3):

1) a slight reorganization of the attributes of the existing IfcCoordinateReferenceSystem and IfcProjectedCRS entities,
2) a new entity IfcGeographicCRS to model geographic CRS, and
3) a new entity IfcRigidOperation to model a rigid transformation operation between the geometric context of IFC geometries and a CRS.

Together with IfcMapConversion, these entities allow to model three possibilities of georeferencing the geometric context of an IFC dataset as presented in Figure 3. Additionally, we incorporate the proposal of Jaud et al. (2019) to include WKT strings to describe CRSs in IFC.

The proposal provides semantically clear ways of defining georeferencing meta data of an IFC model, regardless of its content and extent. Elongated objects (e.g., railway lines) can have their context set to lie in a projected CRS (see top arrows in Figure 3). Objects with small extent (e.g., buildings) may set their context in a topocentric CRS (see bottom and diagonal arrows in Figure 3).

The three examples from Section 6 showcase the versatility of our proposal. The two designed solutions differ in the modelling paradigm of introducing breaking changes to the serialization of IFC datasets. Of the three examples, the first follows Solution A, where no breaking changes are introduced (cf. Algorithm 6), while the latter two examples follow Solution B with breaking changes (cf. Algorithms 7 and 8).

We call for bSI and ISO to implement either of our proposals in the next official IFC version. Additionally, the limitation of a single 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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