<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *Automation in Construction*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Uggla, G., Horemuz, M. (2018)

Geographic capabilities and limitations of Industry Foundation Classes

Automation in Construction, 96: 554-566

<https://doi.org/10.1016/j.autcon.2018.10.014>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-240760>

Geographic Capabilities and Limitations of Industry Foundation Classes

Gustaf Ugglå^{a,*}, Milan Horemuz^a

^a*Division of Geodesy and Satellite Positioning, School of Architecture and Built Environment, Royal Institute of Technology (KTH), SE-100 44 Stockholm, Sweden*

Abstract

Infrastructure design is conducted in a 3D Cartesian coordinate system with the assumption that the Earth is flat and that the scale is constant over the entire project area. Map projections are commonly used to georeference the designed geometries before constructing them on the surface of the Earth. The scale in a map projection varies depending on the position in the map plane, which leads to scale distortions between the designed geometries and the geometries staked out for construction. These distortions are exaggerated for large longitudinal projects such as the construction of roads and railroads because the construction site spans a larger area. Building Information Modeling (BIM) is increasing in popularity as a way to manage information within a construction project. Its use is more widespread in the building industry, but it is currently being adopted by the infrastructure industry as well. The open BIM standard IFC (Industry Foundation Classes) has recently developed support for alignment geometries, and full support for disciplines such as road and railroad construction is underway. This study tests whether the current IFC standard can facilitate georeferencing with sufficiently low distortion for the construction of infrastructure. This is done by performing georeferencing using three different methods, all using the information provided in the IFC schema, and by calculating the scale distortions caused by the different methods. It is concluded that the geographic capabilities of the IFC schema could be improved by adding a separate scale factor for the horizontal plane and support for object-specific map projections.

Keywords: Georeferencing, BIM, IFC

1. Introduction

The process of constructing infrastructure consists of making designs in a 3D Cartesian coordinate system but implementing those designs in construction on the stochastically shaped curved surface of the Earth, from now on referred to as the terrain. The design is conducted with the assumption that the Earth is flat, i.e. that any vector parallel with the vertical axis is pointing in the up direction, and that there is a constant scale between the designed and the constructed geometries [18]. In the terrain, the up direction depends on the direction of gravity, which is different in every location. This conceptual difference leads to geometric distortions when transforming between curvilinear and Cartesian coordinates because it is impossible to project a curved surface onto a plane without distortions.

The process of assigning geodetic coordinates, i.e. coordinates related to the physical Earth, to geometries is known as *georeferencing*. This is commonly done via

map projections, which are planar representations of the Earth's surface. All map projections are subject to scale distortions, the magnitude and character of which vary depending on the characteristics of the map projection [31]. In infrastructure design, the georeferencing is usually performed by setting the horizontal plane of the Cartesian coordinate system equal to the map projection plane. This disregards the assumption that the Cartesian system has a constant scale in relation to the terrain because the relationship between the terrain and the map projection varies depending on geographic location. A map projection surface (e.g. a cylinder) is defined at a specific height, usually tangent or secant, relative to a reference ellipsoid. The size of any geometry that is not located at the height at which the map projection is defined will be rescaled when represented in the map projection. These differences in scale are referred to as scale distortions and are the cause of the deformation of geometries. These distortions must be accounted for when combining data from different project sites, when combining new designs with existing geodata, and when

*Corresponding author, gustaf.uggla@abe.kth.se

staking out the design in the terrain [10].

In order to minimize scale distortions, different map projections are used for different areas of the Earth. In this article, map projections are divided into two groups – those that are well known and those that are object specific. A well-known map projection is identifiable by an EPSG (European Petroleum Survey Group) code [14], which is a global identifier for spatial reference systems. Typical examples are national map projections or UTM (Universal Transversal Mercator) zones [4]. An object-specific map projection is not identifiable by name or any other identifier, but is instead defined by a set of parameters. An object-specific map projection is tailored to produce very low scale distortions in a specific area, e.g. along a road or railroad geometry. The construction of infrastructure covers areas several orders of magnitude larger than the construction of buildings, and this makes the selection of map projection more important for infrastructure projects because there typically is a greater variation in scale distortion over a larger area. As a consequence, object-specific map projections are more commonly used when designing and constructing infrastructure [22].

All relevant coordinate systems and map projections are comprehensively explained in Section 2.1.

Building Information Modeling (BIM) is a combination of processes, technologies and policies [32], and it addresses information management within a construction project. Information is stored in an object-oriented data model instead of documents and blueprints, and this allows for greater collaboration between actors and more elaborate spatial analyses such as clash detection [13]. BuildingSMART, which is the organization that develops and maintains the most prominent BIM standard IFC (Industry Foundation Classes) [8], has recently created the extension *IFC Alignment* [7], which adds support for alignment geometries used for road and railroad design. However, IFC does not support the use of object-specific map projections, nor does IFC offer any means to compensate for the difference in scale between the construction site and the map projection. These limitations make IFC less than ideal for the construction of large longitudinal infrastructure, and the addition of such support would improve IFC’s usability for a wider range of construction projects.

The main research question investigated in this article is whether the IFC specification includes all relevant attributes for correct georeferencing. The georeferencing capabilities and shortcomings of the current IFC standard are evaluated by using three methods for georeferencing and calculating the resulting scale and angular distortions. The methods interpret the geographic infor-

mation provided in the IFC file and transform the geometries to a geodetic context from where the data can be staked out for construction or can be integrated with other geodata.

2. Background

This section provides a description of the coordinate systems relevant to this article, a description of how infrastructure is designed and constructed today, an explanation of the geographic entities and attributes available in the IFC standard, and a review of research related to the topic of georeferencing BIM models.

2.1. Spatial coordinate systems

The basis for most geodetic reference systems and map projections is a geocentric ellipsoid of revolution called the *reference ellipsoid*. The reference ellipsoid is an approximation of the physical shape of the Earth and is determined by its semi-major and semi-minor axes a and b , respectively, or by the semi-major axis a and the flattening f , where f is defined by

$$f = \frac{a - b}{a} \quad (1)$$

Position with respect to the ellipsoid is determined by latitude ϕ , longitude λ , and height over the ellipsoidal surface h . The latitude of point P is the angle between the equatorial plane and a line that passes through P in the direction of the ellipsoidal normal, and the longitude is the angle between the local meridian plane at point P and the Greenwich meridian plane, see Figure 1. Latitude, longitude, and height above the reference ellipsoid are in this article referred to as *geodetic coordinates*. A connection between the physical Earth and the reference ellipsoid is needed in order to formalize a relationship between the two because the reference ellipsoid on its own is just a geometric shape. This connection is known as a *geodetic datum*.

Figure 1: A reference ellipsoid with the definition of Greenwich meridian, latitude ϕ , longitude λ , height over ellipsoid h , the Earth Centered Earth Fixed (ECEF) coordinate system (X, Y, Z) , and the oriented engineering system (e, n, u) .

The coordinate system used for designing in BIM is a local 3D Cartesian coordinate system (x, y, u) in Euclidean space. IFC refers to this system as the *engineering system*. The origin of the engineering system has known geodetic coordinates (ϕ, λ, h) and is usually located close to the project area. The system consists of a horizontal (x, y) -plane, which is parallel to the tangential plane of the reference ellipsoid at the point of the origin, and a vertical u -axis, which is perpendicular to the (x, y) -plane and represents the "up" direction.

The engineering system can be transformed into another local horizontal system (e, n, u) with the n -axis pointing to the geodetic north, i.e. the North Pole on the reference ellipsoid, see Figure 1. This system is from now on referred to as the *oriented engineering system*. The transformation from the engineering system to the oriented engineering system is performed by the following equation [17]:

$$\begin{bmatrix} e \\ n \\ u \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ u \end{bmatrix} \quad (2)$$

where α is the angle between geographic north and the y -axis.

The oriented engineering system can be transformed to the Earth Centered Earth Fixed (ECEF) coordinate system (X, Y, Z) by rotation and translation using the following equation [17]:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + \begin{bmatrix} -\sin\lambda & -\sin\phi \cos\lambda & \cos\phi \cos\lambda \\ \cos\lambda & -\sin\phi \sin\lambda & \cos\phi \sin\lambda \\ 0 & \cos\phi & \sin\phi \end{bmatrix} \begin{bmatrix} e \\ n \\ u \end{bmatrix} \quad (3)$$

where X_0 , Y_0 , and Z_0 are the ECEF coordinates of the origin of the (e, n, u) -system and ϕ and λ are the latitude and longitude of the origin of the (e, n, u) -system.

The ECEF system consists of three orthogonal axes with their origin in the center of the reference ellipsoid. The X -axis is oriented towards the Greenwich meridian, see Figure 1.

The ECEF coordinates (X, Y, Z) can be transformed into the geodetic coordinates (ϕ, λ, h) in the following manner. Longitude λ can be calculated exactly by [17]

$$\tan(\lambda) = \frac{Y}{X} \quad (4)$$

and latitude ϕ and height h are obtained by iteration using the following equations [17]

$$\begin{aligned} \tan(\phi_n) &= \frac{Z}{\sqrt{X^2 + Y^2} (1 - e^2 \frac{\eta_{n-1}}{\eta_{n-1} + h_{n-1}})} \\ \eta_n &= \frac{a}{\sqrt{1 - e^2 \sin^2(\phi_n)}} \\ h_n &= \frac{\sqrt{X^2 + Y^2}}{\cos(\phi_n)} - \eta_n \end{aligned} \quad (5)$$

where η is the mean curvature radius at the given latitude, e is the first eccentricity, a is the semi-major axis of the reference ellipsoid, and n is the iteration number. The initial latitude ϕ_0 is calculated by [17]

$$\tan(\phi_0) = \frac{Z}{\sqrt{X^2 + Y^2} (1 - e^2)} \quad (6)$$

ECEF coordinates (X, Y, Z) can be obtained from the geodetic coordinates (ϕ, λ, h) in the following manner [17]

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} (\eta + h) \cos\phi \cos\lambda \\ (\eta + h) \cos\phi \sin\lambda \\ [\eta(1 - e^2) + h] \sin\phi \end{bmatrix} \quad (7)$$

A map projection is a transformation of the geodetic coordinates (ϕ, λ) into the planar Cartesian coordinates (E, N) . This can be written as

$$E = f_E(\phi, \lambda, a, b) \quad N = f_N(\phi, \lambda, a, b) \quad (8)$$

where f_E and f_N are projection functions and a and b are the semi-major and semi-minor axes of the reference ellipsoid. There are three main types of map projections – i) planar or azimuthal projections, ii) conical projections, and iii) cylindrical or Mercator projections. This article is focused on the use of various types of Mercator projections because they typically are more common for infrastructure design and construction. However, the principles presented here are general and can be applied to conical and azimuthal projections as well.

Mercator projections are conformal, which means that the scale distortion at a given point is equal in all directions and thus that the angles are maintained from the reference ellipsoid to the projection plane. The two types of Mercator projections relevant to this article are transverse Mercators and oblique Mercators. A transverse Mercator is a cylindrical projection where the map plane is tangent to the reference ellipsoid along a specific meridian, see Figure 2. This means that the scale factor between the map plane and the reference ellipsoid is 1 only along the central meridian. The UTM system, which uses the transverse Mercator projection, divides the Earth into 60 zones with a width of 6° . A scale factor of 0.9996 is applied, which makes the projection secant instead of tangent [4]. This means that there are two lines instead of one where there is no scale distortion between the map plane and the reference ellipsoid, but the central meridian becomes subject to scale distortion. An oblique Mercator is similar to a transverse Mercator, but the map plane can be tangent to the reference ellipsoid along any line and not just a meridian. The oblique Mercator is less common than the transverse Mercator, but due to its flexible nature the oblique Mercator is suitable for use as an object-specific map projection [22].

Figure 2: *Transverse Mercator - (E,N)-system*

An object-specific map projection is tailored to minimize scale distortion in a specific area, and the defining parameters will vary depending on the type of map projection. An oblique Mercator requires a reference ellipsoid, a datum, and a central line, where the central line can be defined either by two points on the reference ellipsoid or by one point together with an azimuth [31]. There are existing software implementations, such as PROJ.4, where this type of information can be written in a single string, which also means that the definition of an object-specific map projection can be stored as a single attribute in a data model. PROJ.4 [15] is an open-source geodetic library for calculations and transformations using both well-known and object-specific map projections and reference systems.

The height of an object is described by coordinates in a *vertical datum*. The reference surface of a vertical datum can be in the form of either a reference ellipsoid or a *geoid*. A geoid is a continuous equipotential surface that approximates the mean sea level and spans the entire Earth, including the continents. For a reference ellipsoid, the height h of a point P is defined as the distance between P and the surface of the ellipsoid along the ellipsoidal normal. For a geoid, the height H of a point P is defined as the distance between P and the surface of the geoid along the normal of the geoid. It is possible to transform heights between the two types of vertical datums, given that both of them are known.

Because a map projection surface is defined at a specific height relative to the reference ellipsoid, objects that are not located at that height are subject to scale distortion. The total or combined scale distortion at any given point within a map projection depends on the horizontal position of the point within the map projection, as well as the height above the reference ellipsoid, see Figure 3.

Figure 3: The relationship between three distances at varying heights above the reference ellipsoid – d_3 in the terrain, d_2 in the cartographic plane, and d_1 on the surface of the reference ellipsoid. d_1 is always shorter than d_3 if the terrain is above the reference ellipsoid. d_1 is equal to d_2 if both are tangent to the central meridian and d_1 gets shorter in comparison to d_2 with increasing distance to the central meridian. The map projection in this figure is a transverse Mercator, but the concept holds true for other types of map projections as well.

2.2. Infrastructure - Design and construction

When designing infrastructure and buildings, it is desirable to consider the Earth as flat and the engineering system to be a constant-scale representation of the terrain at the project site [22]. Because all computer software used in the design process operates in Cartesian coordinate systems, this requires some sort of transformation between the "flat" engineering system and the curved surface of the Earth.

The most common method today is to design infrastructure directly in a map projection [18]. This means that the (e, n) -coordinates in the oriented engineering system are seen as (E, N) -coordinates in a map projection. The u -coordinate in the engineering system is seen as height in a vertical datum. The scale in a map projection is not constant in all areas, which means that the distance between two points might differ depending on whether it is measured in the map projection or on the reference ellipsoid. This means that the assumption of a constant scale between the map projection and the terrain leads to geometric inconsistencies between the designed objects and their constructed counterparts. The character and magnitude of these deformations depend on the type of map projection used and the location of the project within the map projection.

In Sweden, most infrastructure projects are designed di-

rectly in the national map projections. Sweden is divided into 12 transverse Mercator projection zones, 6 in the south and 6 in the north, where the central meridians are spaced 1.5° apart [27]. The projections are based on the national geodetic reference system SWEREF 99, which is a Swedish realization of the European reference system ETRS 89 [26]. Scale distortion in a transverse Mercator projection depends on both distance to the central meridian and height above the reference ellipsoid, and the effects of these act in opposite directions, see Figure 3. The projection zones in SWEREF 99 were developed with the aim to keep the combined scale distortion below 50 parts per million (ppm) [27].

Some construction projects have a lower tolerance of scale distortion than what can be obtained by using the well-known map projections available for that area. Typical examples are bridge or tunnel projects between countries such as the Öresund Bridge between Sweden and Denmark and the Channel Tunnel between England and France, but projects within a single country such as the West Coast Main Line in the United Kingdom can also fall into this category [22]. In the United Kingdom there is only one official map projection, OSGB 1936, which is used for the entire country. This leads to large scale distortions for certain areas [18]. A solution for such projects that is used today is to create an object-specific map projection that minimizes scale distortions in the area of the project. This could, for example, be a transverse Mercator or oblique Mercator defined in such a way that its central meridian or central line is close to the project area.

A software solution based on object-specific map projections, SnakeGrid, was commissioned by Network Rail and developed by University College London [18]. SnakeGrid consists of an oblique Mercator projection combined with a residual model to counteract projection deformations along a 3D curve. The software that calculates the defining parameters of the map projection and the residual model is proprietary and requires licensing but the parameters and the residual model can be used freely by third-party software to transform between the SnakeGrid and other reference systems [22]. The use of SnakeGrid for the West Coast Main Line kept the scale distortion between the design and the terrain below 20 ppm. The same number would have been close to 400 ppm if OSGB 1936 had been used instead [18].

Planar coordinates in a well-known map projection combined with height coordinates defined in a vertical datum are typically used for engineering surveying and Automated Machine Guidance (AMG). This does not restrict the possible methods for transforming data from an engineering system to a geographic reference system. Accurate transformation between well-known reference

systems is possible, and it is therefore also possible to georeference data from an engineering system to, e.g. a reference ellipsoid before transforming to a map projection. The difference in scale between the map projection and the terrain can be compensated for during engineering surveying or AMG as long as the coordinates in the map projection are correct. This study focuses on the step prior to this, where the coordinates are transformed from a local Cartesian coordinate system to a map projection or geodetic coordinate system.

2.3. IFC

IFC is an open data format for BIM based on the STEP EXPRESS (ISO 10303) language and concepts. STEP is a language developed with the aim to provide a description of a product that is machine readable and unambiguous [24]. The IFC initiative started in 1994 and the latest full version, IFC 4, was released in 2012. IFC is intended to be a high-level data model independent of any software implementation [25]. IFC is developed by buildingSMART with the goal of allowing all involved actors to share information throughout the life cycle of any built environment asset. In terms of semantics, it should be possible to model objects present in a built environment asset in such away that the digital model and physical asset are essentially identical [6]. This means that IFC should cover every phase from design to operation across several disciplines such as architecture; structure; heating, ventilation and air conditioning (HVAC); etc.

IFC Alignment is an extension of IFC 4 and is the first part of buildingSMART's project *IFC for Infrastructure* [9]. IFC Alignment describes geometries as horizontal alignments, which can be lines, circular arcs, and clothoids, and vertical alignments, which can be lines, circular arcs, and parabolic arcs [29]. The alignment geometries will be used to describe the geometric shape of large longitudinal infrastructure objects in upcoming standards such as IFC Bridge and IFC Road [9].

Data in IFC are stored as instances of entities, which in turn have attributes assigned to them. The top node in all IFC files and databases is the entity *IfcProject* [28], which is a subtype of the abstract *IfcContext*. *IfcProject* contains the *IfcGeometricRepresentationContext*, which defines the spatial coordinate systems [6], and the highest spatial container, which commonly is *IfcSite* or *IfcBuilding* [28].

Geometries in IFC can be stored as either Constructive Solid Geometry (CSG), Swept Solid, or Boundary Representation (BREP) [12]. The geometries are parametric, and their placement is hierarchical in relation to the highest spatial container, e.g. *IfcSite*. A building might have a placement relative to the origin and orientation

of the site, while a wall is placed in relation to the origin of the building. This type of nesting is recursive through all levels [8].

The origin of the engineering system has known or derivable geodetic coordinates and the orientation of the engineering system relative to the geodetic (true) north is known or derivable. All descriptions of entities and attributes in the following paragraphs are based on the respective specifications of the standard IFC 4 [6] and the extension IFC Alignment [7].

The engineering system, which is described in Section 2.1, is defined by the attribute *WorldCoordinateSystem* under the entity *IfcGeometricRepresentationContext*. The geographic position of the origin of the engineering system is defined by either *RefLatitude* and *RefLongitude* under *IfcSite* or by *Eastings* and *Northings* under *IfcMapConversion*. *RefLatitude* and *RefLongitude* are defined as latitude and longitude in the reference system WGS 84, while *Eastings* and *Northings* are defined as easting and northing in a specified map projection. The map projection is specified by an EPSG code as the attribute *Name* under the entity *IfcProjectedCRS*. There are two additional attributes, *MapProjection* and *MapZone*, that can be used to define a map projection such as a specific UTM zone. Both attributes are text fields but there is no list of supported values, and the interpretation of the attributes therefore depends on the receiving software. Even if the interpretation were to be unambiguous, a projection type and a projection zone would not be enough to specify, for example, an oblique Mercator.

The height of the origin of the engineering system is defined by either *RefElevation* under the entity *IfcSite* or *OrthogonalHeight* under the entity *IfcMapConversion*. *RefElevation* is defined as height relative to sea level, but it is unclear which vertical datum this attribute refers to. *OrthogonalHeight* is defined as height in a specific vertical datum defined by *VerticalDatum* under the entity *IfcProjectedCRS*.

The (x, y) -plane of the engineering system is per definition always parallel to a plane tangent to the reference ellipsoid in the point of the origin of the engineering system. The rotation around the u -axis, i.e. the orientation of the engineering system relative to north, can be defined in two different ways. The first one, *TrueNorth* under the entity *IfcGeometricRepresentationContext*, specifies the angle between the y -axis and the geographic north, i.e. the direction towards the North Pole on the reference ellipsoid. The second one, *XAxisAbscissa* and *XAxisOrdinate* under the entity *IfcMapConversion*, describes the rotation of the engineering system relative to the cartographic north, i.e. the north direction in the

map plane. The attributes specify the abscissa and ordinate relative to the x -axis from which the rotation angle can be derived.

The uniform scale factor, *Scale* under *IfcMapConversion*, affects all three axes and can be used to alter the length unit used. Because the scale factor alters both planar

and vertical coordinates, it cannot be used to mitigate the scale distortion caused by georeferencing because this scale distortion only affects the horizontal plane.

The relationship between *IfcContext*, *IfcGeometricRepresentationContext*, *IfcMapConversion*, and *IFCProjectedCRS* is shown in Figure 4.

Figure 4: The relationship between *IfcContext*, *IfcGeometricRepresentationContext*, *IfcMapConversion*, and *IFCProjectedCRS*. Source: [5]

2.4. Related research

Borrmann et al. [3] have described the process of georeferencing IFC data from the engineering system to a geodetic reference system. The described process consists of a 2D translation of the origin of the engineering system to the appropriate easting and northing coordinates in a map projection, a translation in height with respect to the vertical datum, and a rotation around the u -axis.

BuildingSMART Australasia has published a report that offers best-practice recommendations regarding georeferencing for both small and large construction sites [10]. A small site is defined as a site under approximately 1 km for which the curvature of the Earth is negligible and allows the use of a local coordinates. The geometries in the model are transformed using a 2D Helmert transformation, which consists of a translation, a rotation around the u -axis, and a scaling of the (x, y) -plane. The report suggests the use of the IFC attribute *Scale* under the entity *IfcMapConversion* for this scaling. However, this is contradictory to the IFC specification because the attribute *Scale* also affects the u -axis, see Section 2.3. For sites larger than 1 km, it is suggested that the coordinates in the engineering system be transformed to coordinates in a map projection via a 2D Helmert transformation. The project should, if possible, be divided into several models because the scale factor between the engineering system and the map projection will be dif-

ferent depending on the geographic location. However, the issue of using the attribute *Scale* under the entity *IfcMapConversion* is still present.

Other related studies are found in the field of integration between BIM and Geographic Information Systems (GIS). The two domains are similar on a conceptual level but differ in terms of implementation. BIM is object oriented and aims to represent building elements in high detail, whereas GIS traditionally has been layer oriented and used to represent geometric features in a much larger geographic context. However, GIS have through the development of CityGML started to move towards more detailed representations of buildings and the built environment [23]. CityGML is an open data format used for semantic models of the built environment and is in that sense very similar to IFC. However, there is still no unambiguous method for the integration of the two standards. Successful integration of BIM and GIS requires harmonization in terms of semantics and geometric representations [21]. Georeferencing is an important aspect because BIM data are described in a local coordinate system while geodata are defined in a geographic reference system, but for some applications approximate georeferencing can suffice. This makes georeferencing a somewhat overlooked aspect in the integration process.

Isikdag et al. [20] investigated the use of BIM data for the purpose of site selection and fire response. Georeferencing was not considered an important aspect of site

selection because the model did not yet have an actual location but was fitted to the surrounding data. In the case of fire response, the coordinates of the building model were transformed from local to global coordinates just by translation. Hijazi et al. [16] proposed a system based on open-source software to use BIM data for geospatial analysis. The authors recognized georeferencing as a key aspect for successful integration but did not disclose the method used. Irizarry et al. [19] developed a system for supply chain control of a construction project. The geographic location of the construction site has a vital role in locating suitable suppliers, but again the need for accuracy is low. Rafiee et al. [30] proposed a method to integrate BIM models in a geographic context in order to use highly detailed building information for geospatial analysis such as view and shadow analysis. The building models were georeferenced using the known latitude and longitude together with the known orientation relative to north. Amirebrahimi et al. [1] proposed a framework for microscale flood damage assessment based on the integration of BIM and GIS. They used a georeferenced BIM model created in Autodesk’s Revit, but the method of georeferencing was not disclosed. Deng et al. [11] proposed an ontology-based approach for converting IFC to CityGML, and they used a georeferencing method proposed by Wu et al. [35] that consists of a three-axis rotation and a translation of origin.

The integration of BIM and GIS typically does not require the same geometric accuracy as the construction of large infrastructure projects, and the georeferencing method is therefore not seen as critical. However, less distorting georeferencing methods could be of value in the integration of BIM and GIS when working with datasets covering larger areas. The discrepancy between the constant scale in a BIM environment and the varying scale of a map projection used in a GIS environment could be significant over longer distances.

3. Georeferencing methods

Three methods for georeferencing IFC models are considered in this article for describing the transformation from the engineering system to the reference ellipsoid. Once the coordinates on the reference ellipsoid are established, it is possible to transform the data to any known map projection and vertical datum.

The aim of the georeferencing process is to transfer the geometries from the engineering system to the terrain with as little distortion as possible. Any two points on a vertical line, i.e. points with identical (x, y) -coordinates in the engineering system, should also be perpendicular to the surface of the reference ellipsoid thus sharing

(ϕ, λ) -coordinates once they are georeferenced. True verticality in the terrain is defined by the direction of the gravity vector, which can deviate slightly from the direction of the ellipsoidal normal, and this is known as deflection of the vertical. The size of this deviation is limited to roughly 20 arc seconds in flat terrain and roughly 70 arc seconds in mountainous areas [2]. Given the small magnitude, the deflection of the vertical is disregarded in this article. All three georeferencing methods presented in this article maintain the vertical qualities of the geometries, and since it is not possible to do so without introducing horizontal scale distortion, the georeferencing methods are assessed based on the magnitude of horizontal scale distortion caused by their use.

The three methods were developed based on three different conceptual views:

1. The horizontal plane of the engineering system is equal to a map projection
2. The engineering system is connected to the ellipsoid in Euclidean space
3. Horizontal distances are identical in the engineering system and in the terrain

The first view is what is mainly used for larger construction projects today, and also what is proposed by Liebich [29] and Borrmann et al. [3]. The second view does not comply with the premise regarding maintained verticality, and therefore certain alterations are made. These alterations are explained in Section 3.2. The third view is similar to an object-specific azimuthal map projection, but with the addition of a local ellipsoid that approximates the terrain at the height of the project. The local ellipsoid and how it is determined is explained Section 3.3. The three views, though not exhaustive, provide a wide approach to the problem of georeferencing.

The first step of all three georeferencing methods is to transform the engineering system (x, y, u) into the oriented engineering system (e, n, u) , see Equation 2. The remaining transformation steps for each method are explained in the following paragraphs, and an overview is shown in Table 1.

the same (e, n) -coordinates should also have the same latitude and longitude. Once the ECEF coordinates are transformed into latitude and longitude, the height above the reference ellipsoid for each point is set to the sum of the project height, which is the height of the origin of the engineering system, and the u -value from the oriented engineering system, see Figure 7.

The effect of this is that a vertical line in the oriented engineering system will remain vertical after transformation into geodetic coordinates. If the u -coordinates are not set to zero, two points with identical (e, n) -coordinates could be given different latitudes and longitudes thus breaking the second premise stated earlier in this section.

Figure 7: Visualization of Method 2. Points $P1$ and $P2$ have the coordinates $(e, n, 0)$ and (e, n, u) but they are both given latitude and longitude as if they were located at $(e, n, 0)$. The height above the reference ellipsoid is set to the sum of the project height and their u -coordinates giving the points $P'1$ and $P'2$ with the coordinates (ϕ, λ, h_p) and $(\phi, \lambda, h_p + u)$.

3.3. Method 3

Method 3 considers the horizontal coordinates of a point P in the oriented engineering system as polar coordinates (α, d) instead of Cartesian coordinates (x, y) , where α is the azimuth and d is the horizontal distance between the origin and P , see Figure 5. The horizontal distance is used instead of the slope distance in order to ensure that points with the same (e, n) -coordinates obtain the same latitude and longitude after the transformation. In this method, the horizontal surface of the terrain is approximated by a local ellipsoid. A local ellipsoid is different from a reference ellipsoid because it approximates the shape of a smaller portion of the Earth and not the Earth in its entirety. The geodetic coordinates (ϕ, λ) of each point are computed by solving the direct geodetic

problem¹ on the local ellipsoid, see Figure 8. The latitude and longitude calculated on the local ellipsoid are transformed into latitude and longitude on the reference ellipsoid by first transforming the coordinates to ECEF coordinates that in turn can be transformed into latitude and longitude on the reference ellipsoid, see Equations 4, 5, and 7. This is possible because both ellipsoids share the same center, and the definition of ECEF coordinates is therefore identical for both ellipsoids.

Figure 8: Visualization of Method 3. ϕ is the latitude of the origin of the engineering system, and d is the horizontal distance in the engineering system from the origin to point P . h_p is the project height, and u is the height of point P relative to the origin of the engineering system. P' is the georeferenced point P , and h is its height above the reference ellipsoid.

The local ellipsoid is created with the following two constraints: i) the normal vector at the origin of the engineering system should be the same on both the reference and the local ellipsoid and ii) the distance between the two ellipsoids along the normal vector should be equal to the project height.

The semi-major and semi-minor axes of the local ellipsoid are determined by the following procedure. Consider an engineering system with its origin located at (ϕ, λ, h_p) . The reference ellipsoid has the semi-major and semi-minor axes a and b . In order to determine the semi-major and semi-minor axes of the local ellipsoid, a' and b' , we will view the problem from the perspective of the meridian plane at the given longitude, see Figure 9.

¹The direct problem on the ellipsoid is the problem where the latitude and longitude of a second point are obtained from the latitude and longitude of a first point together with the azimuth from the first point to the second point and the distance between the points, i.e. $(\phi_1, \lambda_1, \alpha_{12}, d_{12}) \rightarrow (\phi_2, \lambda_2, \alpha_{21})$. The solutions to this problem are either approximative or iterative [33].

Figure 9: The relationship between the reference ellipsoid and the local ellipsoid. The semi-major and semi-minor axes of the local ellipsoid a' and b' are determined by the project height h_p and the shared slope of the normal vector at ϕ .

Figure 10: Relationship between latitude ϕ , reduced latitude β , and the point (x_1, y_1) .

Cartesian coordinates (x_1, y_1) are determined for (ϕ, λ) on the reference ellipsoid by first calculating the reduced latitude β using [33]

$$\tan \beta = (1 - f) \tan \phi \quad (9)$$

where f is the flattening of the ellipsoid. (x_1, y_1) are then determined by

$$\begin{aligned} x_1 &= a \cos \beta \\ y_1 &= b \sin \beta \end{aligned} \quad (10)$$

For a visual derivation of Equation 10, see Figure 10.

The normal vector of an ellipse

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \quad (11)$$

at the point (x_1, y_1) is determined by

$$a^2 y_1 x - b^2 x_1 y - (a^2 - b^2) x_1 y_1 = 0 \quad (12)$$

and the slope k of the normal vector is therefore

$$k = \frac{a^2 y_1}{b^2 x_1} \quad (13)$$

The Cartesian coordinates of (ϕ, λ) on the local ellipsoid, (x_2, y_2) , can be determined by

$$\begin{aligned} x_2 &= x_1 + \frac{b^2 x_1}{\|(a^2 y_1, b^2 x_1)\|} \cdot h \\ y_2 &= y_1 + \frac{a^2 y_1}{\|(a^2 y_1, b^2 x_1)\|} \cdot h \end{aligned} \quad (14)$$

where $\|\cdot\|$ denotes the norm of the vector.

Adding point (x_2, y_2) on the local ellipsoid to the equation of an ellipse gives

$$\frac{x_2^2}{a'^2} + \frac{y_2^2}{b'^2} = 1 \quad (15)$$

and the slope of the normal vector at (ϕ, λ) is per definition identical on both ellipses

$$\frac{a^2 y_1}{b^2 x_1} = \frac{a'^2 y_2}{b'^2 x_2} \quad (16)$$

The semi-major and semi-minor axes on the local ellipsoid, a' and b' , can be computed from Equations 15 and 16 as

$$\begin{aligned} b' &= \sqrt{\frac{b^2 \cdot x_1 \cdot x_2 \cdot y_2}{a^2 \cdot y_1} + y_2^2} \\ a' &= \sqrt{\frac{x_2^2}{1 - \frac{y_2^2}{b'^2}}} \end{aligned} \quad (17)$$

3.4. Inverse georeferencing

Sections 3.1, 3.2, and 3.3 cover the forward georeferencing of points from the engineering system to geodetic coordinates. All three methods can be applied inversely in order to transform geodetic coordinates into coordinates in the engineering system.

It is not possible to transform parametric curves and surfaces defined in a Cartesian coordinate system to geodetic coordinates or vice versa. This is true for all three methods, and any attempts at such transformations would require that the data be discretized into points and lines. It is possible to translate and rotate the engineering system into a map projection without discretizing the geometries because the (E, N, H) -coordinates are Cartesian in their nature. However, it is not possible to transform parametric data in a map projection into parametric data on a reference ellipsoid.

It is possible to bypass this limitation for the purposes of engineering surveying or AMG because the surveyed point is a single point that can be transformed into a point in the engineering system by using inverse georeferencing. The surveyed point can then be compared to the designed geometries in the context of the engineering system.

4. Evaluation of georeferencing methods

This section provides a description of the calculations performed and the aspects considered during the evaluation process. All calculations were performed for an engineering system with its origin at latitude 59° and longitude 18° , which is a rough approximation of Stockholm, Sweden. The project height was 0 m for all calculations that did not explicitly evaluate the impact of project height. A variety of project heights were used in the latter category. The map projection used in Method 1 was SWEREF 99 1800, a transverse Mercator projection with its central meridian at longitude 18° . The reference ellipsoid was GRS 80. Transformation between the ellipsoid and map projection as well as calculations of the direct and inverse problem on the ellipsoid were performed using *pyproj* [34], a Python interface to the geodetic library PROJ.4. The geographic location used in the calculations is to a large extent arbitrary, and the results and conclusions are applicable for any reference system and transverse Mercator projection. The impacting factors are which well-known map projections are available at the project location and where within those map projections the project site is located.

4.1. Scale distortion

The methods for georeferencing presented in Section 3 are evaluated in terms of scale distortion. The scale distortion is calculated as

$$SD(ppm) = \left(\frac{D_{Eng.Sys.}}{D_{Ellipsoid}} - 1 \right) \times 10^6 \quad (18)$$

A scale distortion of ± 1 ppm means that a distance of 1 km in the engineering system will be either 1 mm shorter or 1 mm longer after georeferencing. The absolute value of the difference is used because it is the magnitude and not the direction of the scale distortion that is considered to be important. The reasoning behind this is that it is the highest scale distortion caused by georeferencing, regardless of direction, that should be compared to the tolerance of a construction project.

The scale distortion for each method is calculated in the following manner:

1. A horizontal grid of equally spaced points is created in the engineering system. The grid ranges from $(-100 \text{ km}, -100 \text{ km}, 0)$ to $(100 \text{ km}, 100 \text{ km}, 0)$, and the origin of the engineering system is located at $(0, 0, 0)$. The distance between the origin and the point farthest from the origin is roughly 140 km.
2. A circle with a radius of 10 m is created around each point in the grid and points are placed 10° apart along the circumference of the circle.
3. The points on the circumference of the circle are georeferenced to the reference ellipsoid using Methods 1, 2, and 3.
4. The distance on the reference ellipsoid between two opposite points on the circle is calculated and compared to the distance between the corresponding points in the engineering system. The scale distortion between the engineering system and the reference ellipsoid is calculated using Equation 18.

The resulting scale distortion is visualized in two different ways. The first visualization shows the magnitude of the scale distortion in each direction. Points are placed at the same angular intervals that were used in the engineering system, but instead of using a constant radius, the distance from the center of the geometry is determined by the magnitude of the scale distortion in that particular direction. The resulting geometry will always be symmetrical because the scale distortion is calculated as the mean of the two opposing directions. For example, the scale distortion in the north-south direction for a given position is calculated by using the points placed at 0° and 180° , see Figure 11.

Figure 11: A geometry visualizing the relative magnitude of the scale distortion for each direction. The direction α has a scale distortion of size SD for the given position. In this case, the direction $\alpha = 0$ would have a scale distortion of 0.

The second visualization uses a much denser grid and only displays the maximum scale distortion for each given

position. A raster is created where each pixel represents a point on the grid and the value of the pixel represents the maximum scale distortion in any direction at the given location.

4.2. Angular distortion

The angular distortion (AD) is defined as the difference in angle between the engineering system and the ellipsoid and is calculated by

$$AD = \beta_{Eng.Sys.} - \beta_{Terrain} \quad (19)$$

The greatest angular distortion occurs for an angle between the directions having the largest difference in scale distortion. Method 1 is based on a conformal map projection and is therefore not subject to angular distortion. For Methods 2 and 3, the greatest difference in scale distortion occurs in directions perpendicular to each other, which means that the angular distortion can be calculated using a right triangle with legs of equal length oriented in the aforementioned directions, see Figure 12.

Figure 12: A right triangle with legs of equal length a . One leg is tangent to a line passing through the origin of the engineering system.

A scale factor (SF) between the engineering system and the terrain is calculated by

$$SF = SD(ppm) \times 10^{-6} + 1 \quad (20)$$

and the angle is then calculated using the scale factor

$$\tan \beta_{Ellipsoid} = \frac{SF_1}{SF_2} \quad (21)$$

Because the legs of the triangle are of equal length in the engineering system, the angle $\beta_{Eng.Sys.}$ is always 45° .

4.3. Project height

The horizontal distance between two points with given latitudes and longitudes depends on their heights above the reference ellipsoid. The impact of project height on the scale distortion can be determined by performing calculations for scale distortion with varying project heights. This is done by altering the height of the origin of the engineering system. The scale distortion, see Equation 18, is calculated by comparing a certain distance in the engineering system to its corresponding distance on the local ellipsoid adjusted to the origin of the engineering system. The parameters of this ellipsoid are determined in the same manner as in Method 3.

5. Results

In this section, results from the calculations described in Section 4 are presented.

5.1. Scale distortion

Figure 13 shows the relative magnitude of the scale distortion. This shows both how the scale distortion is affected by distance and direction relative to the origin of the engineering system and the relative magnitude between the different methods.

Figure 13: Relative magnitude of the scale distortion in different directions for Method 1 in blue, Method 2 in red, and Method 3 in green. Values along the x -axis and y -axis indicate coordinates in the engineering system in kilometers.

The results show that the scale distortion of Method 1 is equal in all directions, which is expected because SWEREF 99 1800 is a transverse Mercator projection and therefore conformal. It should be noted that this is

a property determined by the map projection and not the method itself. For Method 2, the scale distortion is greatest along a line that passes through both the point in the grid and the origin of the engineering system. The scale distortion is the lowest in the direction perpendicular to this line. Method 3 has a scale distortion of 0 along a line that passes through both the point in the grid and the origin of the engineering system. The greatest scale distortion is in the direction perpendicular to this line. The effect of the respective georeferencing method on the shape of the circle is visualized in Figure 14.

Figure 14: Illustration of the relative change in the geometry of a circle caused by the different georeferencing methods. The dotted line on the right side is the initial shape of the circle and the solid line is the georeferenced shape. Scale and magnitude are not considered.

The magnitude of the scale distortion of Method 1, used with a transverse Mercator projection, only depends on the distance to the central meridian of the map projection. The magnitude of the scale distortion for Methods 2 and 3 on the other hand depends on the distance to the origin of the engineering system. By comparing the relative magnitudes between the methods, we can see that the scale distortion of Method 2 is in all locations and directions larger than the corresponding scale distortion of Method 3. Method 1 can be compared to Methods 2 and 3 in terms of the magnitude of the scale distortion, but no absolute patterns can be observed because the scale distortion in the different methods are dependent on different factors.

Figure 13 shows the direction and the relative magnitude of scale distortion for each method. Figures 15, 16, and 17 show the greatest scale distortion rounded to whole ppm for each method and position on the grid.

Figure 15: The greatest scale distortion regardless of direction for each pixel displayed in ppm for Method 1. Values along the x -axis and y -axis indicate coordinates in the engineering system in kilometers.

Figure 16: The greatest scale distortion regardless of direction for each pixel displayed in ppm for Method 2. Values along the x -axis and y -axis indicate coordinates in the engineering system in kilometers.

Table 2: Absolute value of the greatest scale distortion regardless of direction, rounded to whole ppm. **D** is the distance from the central meridian for Method 1 and the distance from the origin for Methods 2 and 3.

D (km)	M1 (ppm)	M2 (ppm)	M3 (ppm)
10	1	2	0
20	5	10	2
50	31	61	10
100	123	245	41

In Figure 15 we can see that the scale distortion of Method 1 when used with a transverse Mercator projection ranges from 0 ppm for a project tangent to the central meridian to 123 ppm for a project 100 km from the central meridian. Table 2 shows the numerical values for selected distances from the central meridian for Method 1 and from the origin of the engineering system for Methods 2 and 3.

In Figure 16 we can see that the scale distortion of Method 2 ranges from 0 ppm at the origin of the engineering system to 488 ppm at roughly 140 km from the origin of the engineering system.

Figure 17: The greatest scale distortion regardless of direction for each pixel displayed in ppm for Method 3. Values along the x -axis and y -axis indicate coordinates in the engineering system in kilometers.

In Figure 17 we can see that the scale distortion of Method 3 ranges from 0 ppm at the origin of the engineering system to 81 ppm at roughly 140 km from the origin of the engineering system.

5.2. Scale factor

Another calculation is performed in order to show the impact of a scale factor for the horizontal plane. Method 1 as described in this article is the georeferencing method proposed by Liebich [29] and Borrmann et al. [3]. Adding a scale factor for the horizontal plane, which is not compatible with the current IFC schema, makes the method compliant with the best practices recommended by buildingSMART Australasia [10].

The maximum scale distortion for Method 1 in Section 5.1 is 123 ppm, and the mean scale distortion SD_{mean} is the maximum scale distortion divided by two. It is possible to reduce the maximum scale distortion over the entire area by a factor of 2 by multiplying all geometries in the engineering system by a scale factor SF , which is determined by

$$SF = \frac{1}{1 - \frac{SD_{mean}}{10^5}} \quad (22)$$

Figure 18 shows the maximum scale distortion regardless of direction caused by this method of georeferencing. The maximum scale distortion for the entire area is equal to half the maximum scale distortion caused by Method 1, see Figure 15. The highest scale distortion is found in the middle and on the edges of the area. It is possible to define the scale factor in other ways, e.g. to create a wider corridor in the middle of the area with low scale distortion but with higher scale distortion along the edges of the area.

Figure 18: The greatest scale distortion regardless of direction for each pixel displayed in ppm for Method 1 with the addition of a horizontal scale factor. This method is identical with the best practices recommended by buildingSMART Australasia [10]. Values along the x -axis and y -axis indicate coordinates in the engineering system in kilometers.

5.3. Angular distortion

The angular distortions for Methods 2 and 3 are displayed in Table 3.

Table 3: Absolute value of the maximum angular distortion (AD) for Methods 2 and 3 at varying distances from the origin of the engineering system, rounded to thousandths of a degree.

Distance from origin (km)	AD M2	AD M3
10	0.000°	0.000°
20	0.000°	0.000°
50	0.001°	0.000°
100	0.004°	0.001°

The magnitude of the angular distortion for both Methods 2 and 3 is limited to thousandths of a degree for distances up to 100 km from the origin of the engineering system, which is negligible for the majority of applications. The angles in the engineering system can be considered to be identical to those on the surface of the reference ellipsoid.

5.4. Project height

By calculating the scale distortion for various project heights, we can see that Method 1 is linearly affected by project height while Methods 2 and 3 are not affected by project height in any significant way. In the case of Method 1, every 100 m of project height contributes with a scale distortion of 15.7 ppm. This scale distortion is in the opposite direction of the scale distortion caused by the distance to the central meridian, meaning that a project with a height of 200 m above the reference ellipsoid will have zero scale distortion at roughly 50 km from the central meridian, see Table 2.

6. Discussion

It is not possible to give absolute numbers for what would constitute tolerable levels of scale distortions because these will vary depending on the requirements of each construction project. However, it is possible to get a rough idea from the development of SnakeGrid where Network Rail stated a requirement of 20 ppm, and from the development of the Swedish national map projections where the aim was to keep the scale distortion below 50 ppm. The UTM system applies a scale factor of 0.9996 to minimize scale distortion over a zone 6° wide, which makes the map projection secant instead of tangent. The scale distortion along the central meridian, which can be calculated using Equation 18, is 400 ppm. This is clearly not of the same order of magnitude as the previously stated tolerances, and relying on map projections such as UTM zones for the design and construction of infrastructure might prove problematic for certain areas.

Object-specific transverse or oblique Mercator projections follow the same pattern of scale distortion as the transverse Mercator used for Method 1. The benefit of the object-specific map projections is that they can be defined in such a way that the distance from the central meridian or central line to the relevant geometries is minimized.

A separate scale factor for the (x, y) -plane is needed in order to comply with the recommended best practices given by buildingSMART Australasia [10]. This allows

for the designed geometries to match the scale of the map plane and makes it possible to essentially eliminate scale distortion for large longitudinal projects parallel to the central meridian of the map projection, see Figure 18. For large longitudinal projects orthogonal to the central meridian, a scale factor of this type can reduce the scale distortion but cannot fully eliminate it. The same concepts apply for the vertical axis. The scale distortion for a project with constant height above the ellipsoid can be eliminated, while the scale distortion for a project with varying height can only be reduced.

The use of both object-specific map projections and a separate scale factor for the (x, y) -plane would make it possible to create an optimum projection zone for a large longitudinal project. The central line of the map projection would be aligned with the main axis of the construction project and would be defined in such a way that the distance between the geometries and the central line is minimized. The scale factor would then be used to minimize the scale distortion over the width of the zone and range of the heights in the same manner as shown in Figure 18. To further reduce scale distortion for a geometry deviating horizontally and vertically from the central line of a map projection, it would be necessary to use a residual model to compensate for the local variations.

Implementing support for object-specific map projections and a separate scale factor for the (x, y) -plane in IFC would require the addition of two attributes – a string for the map projection, which could be added under the entity *IfcProjectedCRS*, and a scalar for the scale factor, which could be added under the entity *IfcMapConversion*. The residual model could either be in the form of an external file that is referenced from the IFC file or included directly in the IFC file itself. It is possible that neither solution is desirable because the first would create a situation where the IFC file no longer contains all of the necessary information and the second could potentially make the IFC file bloated in terms of size.

Methods 2 and 3 are not used in practice today and are not implemented in any commercial software. Method 2 caused larger scale distortions than Method 3 for all cases and can therefore be disregarded. Method 3 produced lower scale distortions than the transverse Mercator projection used for Method 1 for some cases, and it might be beneficial to use in situations where no suitable well-known map projections are available. However, the described use of object-specific map projections and scale factors produces better results in terms of scale distortion and is closer to the common practices used today.

All three methods are compatible with parametric data for the purpose of engineering surveying or AMG because the surveyed point can be transformed into a point in

the engineering system using the inverse georeferencing methods. For the purpose of integrating several BIM models or combining them with geodata, there are two possibilities. If the BIM data are discretized, it is possible to georeference the data using any of the methods. If the BIM data are not discretized, the data can be georeferenced to a well-known map projection using translation and rotation as described by Liebich [29] and Borrmann et al. [3] where the data can be integrated with other models or datasets that have coordinates in the same map projection.

7. Conclusions

The scale distortion for large longitudinal construction projects that are designed in the IFC format could be reduced by adding support for object-specific map projections, a separate scale factor for the (x, y) -plane, and possibly also support for residual models such as the ones used by SnakeGrid. The magnitude of the reduction in

scale distortion would vary from project to project depending on the geographic extent of the project and the well-known map projections that are available for the area. Because it is relatively easy to implement the attributes needed for horizontal scaling and object-specific map projections in the IFC standard, it is recommended that these attributes are added. Support for residual models is a more complicated topic, and the benefits of using residual models compared to only using object-specific map projections are relatively small [22].

For the purpose of integrating BIM and GIS, the use of well-known map projections will likely suffice because the need for geometric accuracy is typically lower. The models and datasets that are relevant to each other can probably be combined using a single national map projection or UTM zone.

7.1. Acknowledgements

The financial support from the Swedish Transport Administration for this work is gratefully acknowledged.

- [1] Amirebrahimi, S., Rajabifard, A., Mendis, P., and Ngo, T. (2016). A framework for a microscale flood damage assessment and visualization for a building using BIM–GIS integration. *International Journal of Digital Earth*, 9(4):363–386. DOI: 10.1080/17538947.2015.1034201.
- [2] Bomford, G. (1980). *Geodesy, 4th edition*. Oxford University Press, Oxford. ISBN: 978-0-198-51946-1.
- [3] Borrmann, A., Amann, J., Chipman, T., Hyvärinen, J., Liebich, T., Muhič, S., Mol, L., Plume, J., and Scarponcini, P. (2017). IFC Infra Overall Architecture Project - Documentation and Guidelines. https://buildingsmart.org/wp-content/uploads/2017/07/08_bSI_OverallArchitecture_Guidelines_final.pdf, accessed 2018-05-15.
- [4] Buchroithner, M. F. and Pfahlbusch, R. (2017). Geodetic grids in authoritative maps – new findings about the origin of the UTM Grid. *Cartography and Geographic Information Science*, 44(3):186–200. DOI: 10.1080/15230406.2015.1128851.
- [5] buildingSMART (2013a). Industry Foundation Classes Release 4 - Addendum 2 - Reference View (IFC4 RV 1.1). <http://www.buildingsmart-tech.org/ifc/review/IFC4Add2/ifc4-add2-rv/html/schema/templates/project-global-positioning.htm>, accessed 2018-06-04.
- [6] buildingSMART (2013b). Industry Foundation Classes Release 4 (IFC4). <http://www.buildingsmart-tech.org/ifc/IFC4/final/html>, accessed 2018-06-04.
- [7] buildingSMART (2015). Industry Foundation Classes - IFC Alignment Extensions Release Candidate. <http://www.buildingsmart-tech.org/mvd/review/extension/alignment/candidate/html>, accessed 2018-06-04.
- [8] buildingSMART (2017a). Basic IFC knowledge. <http://www.buildingsmart-tech.org/implementation/ifc4-implementation/basic-ifc-knowledge>, accessed 2017-12-08.
- [9] buildingSMART (2017b). IFC Alignment - Project presentation. <http://www.buildingsmart-tech.org/infrastructure/projects/alignment>, accessed 2017-11-03.
- [10] buildingSMART Australasia (2017). Model Setup IDM - Vol 1: Geo-Referencing BIM v1.2. http://buildingsmart.org.au/wp-content/uploads/Vol-1-Geo-referencing-BIM_v1.2.pdf, accessed 2018-05-15.

- [11] Deng, Y., Cheng, J. C., and Anumba, C. (2016). Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison. *Automation in Construction*, 67:1–21. DOI: 10.1016/j.autcon.2016.03.006.
- [12] Donkers, S., Ledoux, H., Zhao, J., and Stoter, J. (2016). Automatic conversion of IFC datasets to geometrically and semantically correct CityGML LOD3 buildings. *Transactions in GIS*, 20(4):547–569. DOI: 10.1111/tgis.12162.
- [13] Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, 2nd Edition*. John Wiley & Sons, Inc., Hoboken, New Jersey. ISBN: 978-0-470-54137-1.
- [14] European Petroleum Survey Group (2018). <http://www.epsg.org/>, accessed 2018-05-18.
- [15] Evenden, G. (2005). libproj4: A Comprehensive Library of Cartographic Projection Functions. Retrieved from <https://github.com/OSGeo/proj.4/blob/master/docs/old/libproj.pdf>, accessed 2018-06-04.
- [16] Hijazi, I., Ehlers, M., and Zlatanova, S. (2010). BIM for geo-analysis (BIM4GEOA): set up of 3D information system with open source software and open specification (OS). *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 38:45–49. <https://repository.tudelft.nl/islandora/object/uuid%3Aadcb7fc18-208c-4e3b-bc2a-d24a2346d44b>.
- [17] Hofmann-Wellenhof, B., Lichtenegger, H., and Wasle, E. (2008). *GNSS – Global Navigation Satellite Systems*. Springer-Verlag Wien, 1 edition. ISBN: 978-3-211-73017-1.
- [18] Iliffe, J. C., Arthur, J. V., and Preston, C. (2007). The Snake Projection: A Customised Grid for Rail Projects. *Survey Review*, 39(304):90–99. DOI: 10.1179/003962607X165041.
- [19] Irizarry, J., Karan, E. P., and Jalaei, F. (2013). Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in Construction*, 31:241–254. DOI: 10.1016/j.autcon.2012.12.005.
- [20] Isikdag, U., Underwood, J., and Aouad, G. (2008). An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes. *Advanced Engineering Informatics*, 22(4):504–519. DOI: 10.1016/j.aei.2008.06.001.
- [21] Isikdag, U. and Zlatanova, S. (2009). Towards defining a framework for automatic generation of buildings in CityGML using Building Information Models. In Lee, J. and Zlatanova, S., editors, *3D Geo-Information Sciences*, pages 79–96. Springer, Berlin, Heidelberg. ISBN: 978-3-540-87395-2, DOI: 10.1007/978-3-540-87395-2_6.
- [22] Jonsson, T. (2015). Snake Grid och andra objektanpassade projektioner för svensk infrastruktur (Dissertation). *KTH, Geodesy and Satellite Positioning*. Retrieved from <http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-168092>, accessed 2018-06-04.
- [23] Kolbe, T. H. (2009). Representing and Exchanging 3D City Models with CityGML. In Lee, J. and Zlatanova, S., editors, *3D Geo-Information Sciences*, pages 15–31. Springer, Berlin, Heidelberg. ISBN: 978-3-540-87395-2, DOI: 10.1007/978-3-540-87395-2_2.
- [24] Kramer, T. and Xu, X. (2009). STEP in a Nutshell. In Xu, X. and Nee, A., editors, *Advanced Design and Manufacturing Based on STEP. Springer Series in Advanced Manufacturing*. Springer, London. ISBN: 978-1-84882-739-4, DOI: 10.1007/978-1-84882-739-4_1.
- [25] Laakso, M. and Kiviniemi, A. (2012). The IFC standard - A review of history, development, and standardization. *Electronic Journal of Information Technology in Construction*, 17(May):134–161. <http://www.itcon.org/2012/9>.
- [26] Lantmäteriet (2017a). SWEREF 99. <https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/GPS-och-geodetisk-matning/Referenssystem/Tredimensionella-system/SWEREF-99>, accessed 2017-12-06.
- [27] Lantmäteriet (2017b). SWEREF 99, map projections. <https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/GPS-och-geodetisk-matning/Referenssystem/Tvadimensionella-system/SWEREF-99-projektioner>, accessed 2018-08-23.

- [28] Liebich, T. (2009). IFC 2x Edition 3 - Model Implementation Guide. Retrieved from <http://www.buildingsmart-tech.org/downloads/accompanying-documents/guidelines/IFC2x%20Model%20Implementation%20Guide%20V2-0b.pdf>, accessed 2018-06-04.
- [29] Liebich, T. (2015). IFC Alignment – Conceptual Model v.1.0.1. Retrieved from <http://www.buildingsmart-tech.org/downloads/ifc/ifc5-extension-projects/ifc-alignment/ifcalignment-conceptualmodel-cs>, accessed 2018-06-04.
- [30] Rafiee, A., Dias, E., Fruijtier, S., and Scholten, H. (2014). From BIM to Geo-analysis: View Coverage and Shadow Analysis by BIM/GIS Integration. *Procedia Environmental Sciences*, 22:397–402. DOI: 10.1016/j.proenv.2014.11.037.
- [31] Snyder, J. P. (1987). *Map Projections: A working manual*. U.S. Government Printing Office, Washington, D.C. ISBN: 978-1-782-66222-8.
- [32] Succar, B. (2009). Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in Construction*, 18:357–375. DOI: 10.1016/j.autcon.2008.10.003.
- [33] Torge, W. (2001). *Geodesy - 3rd completely rev. and extended ed.* de Gruyter, Berlin; New York. ISBN: 978-3-11-087995-7.
- [34] Whitaker, J. (2016). pyproj 1.9.5.1. <https://pypi.org/project/pyproj/>, accessed 2018-05-18.
- [35] Wu, I. and Hsieh, S. (2007). Transformation from IFC data model to GML data model: Methodology and tool development. *Journal of the Chinese Institute of Engineers*, 6(30). DOI: 10.1080/02533839.2007.9671335.