Evaluating and Enhancing Georeferencing Accuracy in BIM and 3D GIS Models for Built Environment Digital Twins

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Abstract

The integration of Building Information Modelling (BIM) and Geographic Information Systems (GIS) through open standard models such as IFC and CityGML is fundamental to the development of a comprehensive digital twins for the built environment projects. Accurate georeferencing of these models is essential for performing reliable geospatial analyses, particularly in projects that employ a custom Coordinate Reference System (CRS) or are affected by significant distortion due to map projection. Although a considerable number of studies addressed georeferencing in the context of BIM-GIS data integration, limited attention has been given to the assignment of custom CRSs to both IFC and CityGML models. Moreover, the impact of BIM modelling and different georeferencing approaches on the final positional accuracy of the models remains under-investigated. This study addresses these gaps by proposing a methodology to enhance georeferencing accuracy through the assignment of custom CRS to both IFC and CityGML models, while also practically examining how BIM modelling practices and georeferencing approaches impact the overall positional quality of the models. The results demonstrate the effectiveness of the proposed methodology in enhancing georeferencing accuracy of IFC and CityGML models, offering a practical guideline for ensuring the spatial accuracy of the 3D models in the digital twin environment.

1. Introduction

Digital twins are increasingly being adopted in built environment projects, particularly in retrofitting and urban planning applications. BIM enables the representation of detailed geometric and semantic characteristics of the physical asset, while GIS provides information about its surrounding environment. Therefore, the integration of BIM and GIS is crucial for creating a comprehensive digital twin that supports these applications (Kang, 2023; Pan et al., 2020). BIM-GIS data integration processes enable the transformation of BIM models into GIS-compatible formats, which can then be imported into a GIS environment for conducting various geospatial analyses. Although BIM and GIS data are complementary, integrating data from these two domains is a challenging task and remains an active area of research (Karimi and Iordanova, 2021). One of the most critical aspects of this integration is accurate georeferencing, which ensures spatial coherence between both systems. Maintaining a high level of positional accuracy in the georeferencing process is paramount for increasing interoperability between both systems and creating more efficient digital twins.

Several studies have investigated georeferencing of BIM and/or 3D GIS models, including Zhu et al. (2017), Markič et al., (2018), Uggla and Horemuz (2018), Clemen and Görne (2019), Jaud et al. (2020), Jaud et al. (2022), and Hakim et al. (2024). However, the accuracy and quality aspects remain insufficiently explored (Ohori et al., 2018; Biljecki and Tauscher, 2019; Sun et al., 2019; Esfahani et al., 2021; Jeddoub et al., 2024). Assigning custom CRS to both BIM and GIS models, which is essential for accurate georeferencing, is scarcely discussed in the literature. This study addresses this gap by demonstrating the practical assignment of custom CRSs to both BIM and GIS data models.

Digital twins of the built environment can be created based on GIS models derived from as-planned BIM models (Zhu et al., 2021). However, since digital twins are developed to replicate the real-world assets and reflect existing conditions, GIS models must be derived from as-built BIM models. Therefore, to utilize BIM and GIS models for creation of digital twins, it is essential that the models represent as-built conditions. In that sense, as-built BIM model should first be created, then BIM/GIS integration techniques can be utilized to transform the as-built BIM models into as-built GIS models. However, since most of assets in the built environment lack as-built BIM models, geospatial data gathering and modelling techniques can be employed for creation of such models (Tang et al., 2010). The process of gathering of geospatial data and conducting parametric modelling to produce BIM models of as-built assets in the built environment is known as Scan-to-BIM (Bosché et al., 2015).

To share the as-built BIM model, produced from Scan-to-BIM processes, with GIS systems and to enhance interoperability between the two systems, it is essential to utilize open data standards. In this context, the most widely adopted open data standards are IFC for BIM and CityGML for GIS (Liu et al., 2017). Moreover, CityGML is considered the most suitable GIS standard for representing the built environment (Wittner, 2020) Therefore, to achieve the objectives of this study, IFC and

CityGML are selected as the open data standards for enabling data integration between both systems.

As-built BIM models can be imported in the GIS environment through the integration techniques, enabling their connection to various databases and supporting multidisciplinary applications (Pepe et al., 2021). The integration of BIM and GIS data is typically achieved through three main approaches: conversion (Donkers et al., 2016; Floros et al., 2018). unification (El-Mekawy et al., 2012; Herle et al., 2020), and linked data techniques (Karan & Irizarry, 2015; Usmani et al., 2020), each associated with certain advantages and limitations. Among the techniques, conversion is considered the most suitable for performing georeferencing due to two main reasons: (1) the user has more control over specifying the method and parameters of georeferencing, and (2) due to limitation of other techniques; unification creates a new model and introduces additional sources of error in the model, and the focus of linked data technique is mostly on semantic characteristics rather than geometrical. In this study, due to their flexibility and adaptability, conversion techniques were applied to enable BIM and GIS data integration.

The main aim of this study is to improve georeferencing accuracy by proposing a methodology for assigning custom CRS to IFC and CityGML models. In addition, this study investigates relevant tasks that influence this objective. These include evaluating the positional accuracy of the BIM models produced through the Scan-to-BIM process compared to real world data, and examining whether the point-and-direction approach is sufficient for georeferencing BIM models or if multi-point approach is required. The remainder of this paper is structured as follows: section 2 explores the IFC georeferencing and introduces the concept of scale factor; section 3 demonstrates the employed methodology in this study; section 4 presents the results of the study; section 5 discusses the findings and outlines the limitations of this study; and finally, section 6 concludes the paper by summarizing the findings.

2. IFC Georeferencing

Currently, there are three ISO-certified versions of IFC (Table 1). The georeferencing capabilities of each version is unique; therefore, it is essential investigate the details of each one.

Version	Name	ISO Publication	Published (yyyy-mm)
4.3.2.0	IFC 4.3 ADD2	ISO 16739-1:2024	2024-04
4.0.2.1	IFC 4 ADD2 TC1	ISO 16739-1:2018	2017-10
2.3.0.1	IFC 2x3 TC1	ISO/PAS 16739:2005	2007-07

Table 1. IFC versions and ISO publication.

In IFC2x3, georeferencing is performed using *IfcSite* entity by assigning appropriate geographical coordinates to the RefLatitude, RefLongitude and RefElevation attributes. This version of IFC is restricted to the global geographic CRS, and does not support the direct assignment of projected CRS to the models.

In IFC4.0, georeferencing is achieved using *IfcMapConversion* and *IfcProjectedCRS* entities. The former is used to perform coordinate system transformation from local CRS to target CRS (which may be either national or global CRS), while the latter defines the target CRS based on the EPSG code. BIM authoring software typically implements IFC georeferencing using a point-and-direction approach. This method requires obtaining the geodetic coordinates of a well-recognizable point in a model and the angular direction towards true north. However, since determining the north direction requires the coordinates of an additional point in the same CRS. Therefore, the overall georeferencing process requires a minimum of two points (BuildingSMART Australasia, 2021). In that sense, performing IFC georeferencing through *IfcMapConversion* is associated with two main sources of uncertainty. The first is related to inaccuracies in the coordinates of the origin point used for georeferencing. The second source concerns the deviation angle towards north, which depends on the accuracy of the second point. These potential sources of errors must be carefully investigated when utilizing this IFC entity for georeferencing.

In the latest version of IFC (IFC4x3), *IfcCoordinateReferenceSystem* and *IfcCoordinateOperatation* are the two primary entities responsible for assigning CRS and handling CRS transformation in IFC models (Figure 1). *IfcCoordinateRefrenceSystem* is the supertype entity that controls the CRS assigned to the IFC model. The attributes of this entity allow for specifying a CRS name using EPSG code, providing a description, selecting a geodetic datum, indicating whether there a CRS transformation is required (which must reference *IfcCoordinateOperation*), and finally defining a custom CRS using WellKnownText via *IfcWellKnownText.* Additionally, this entity is associated with two subtype entities: *IfcProjectedCRS* and *IfcGeographicCRS*, the former enables the definition of a map projection, while the latter can be used for specifying the parameters of geographic CRS when no projection is applied. Notably, both subtypes inherit all attributes from the supertype entity.

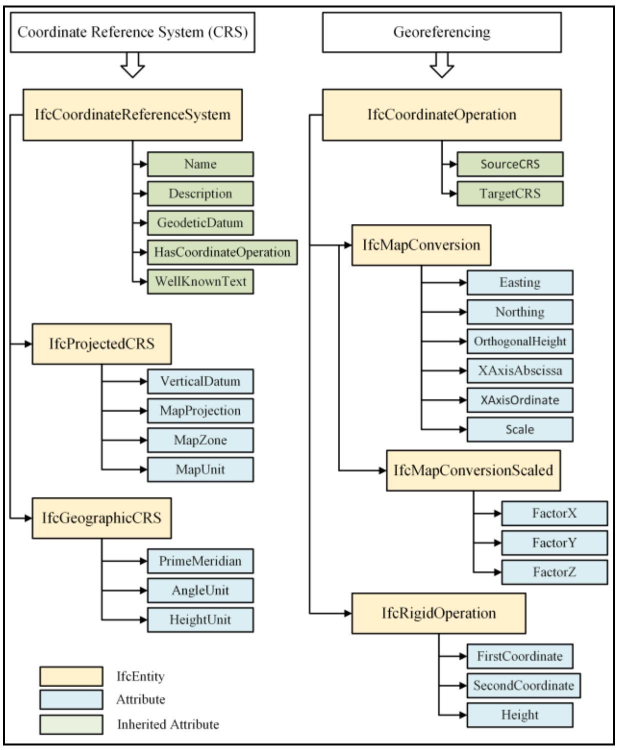

Figure 1. Relevant entities for georeferencing in the IFC4x3 schema (Source: buildingSMART).

IfcCoordinateOpertation is supertype IFC entity that enables CRS transformation. The attributes of this entity support the definition of parameters of the source and target CRS that facilitate the transformation process. This entity has two subtype entities: *IfcMapConversion* and *IfcRigidOperation*. The first one enables the point-and-direction transformation approach (introduced in IFC4.0) and also introduces *IfcMapConversionScaled*, which allows for specifying different scale factors along the X, Y, and Z axes instead of using a uniform scale. The second one supports simplified transformation method solely based on the translation, without requiring rotation or scaling.

2.1 Scale Factor

In Architecture, Engineering, and Construction (AEC) domain, the term "scale factor" typically has two meanings: the first refers to differences in mapping units, and second one is related to map projection distortion (Favretto, 2014). The former represents the ratio between measurement on the surface of earth to the same measurement represented on the map (Sisman & Sisman, 2017). The other one, which is more common in the geodetic field, is related to the distortions that arise when adopting a particular map projection. This type of scale factor can be classified into three categories: Grid scale factor, Elevation scale factor, and combined scale factor (Sickle, 2015). Grid scale factor defines the relation between measurements performed on the projected grid and its corresponding values on the surface of ellipsoid. Elevation scale factor relates measurements on the surface of ellipsoid to actual measurements performed on the surface of earth. Lastly, combined scale factor defines the ratio between measurements on the projected grid and those performed on the surface of earth (Figure 2).

In the context of BIM and GIS models, the scale factor affects the dimensions and the positional accuracy of the models. This impact becomes significant when the model is in areas of high distortion within the geodetic CRS. In such cases, if scale factor is not considered in the georeferencing process of these models, noticeable discrepancies between the model's dimensions and true values can occur.

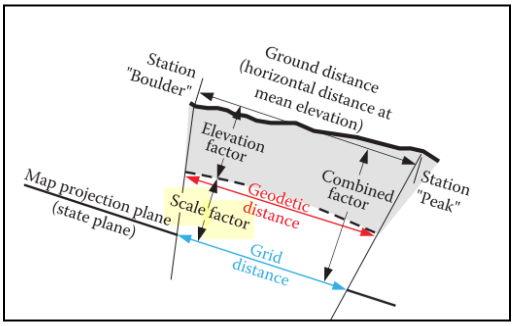

Figure 2. Combined scale factor (Source: Sickle, 2015).

3. Methodology

3.1 Study area

This study focuses on the development of a digital twin for the Greenway Hub building located on the Technological University Dublin (TU Dublin) Grangegorman campus (Figure 3). The campus is about 73 acres and is located 1.5 kilometres northwest of Dublin City Centre. A variety of geospatial surveying instruments were employed to perform data collection, including Global Navigation Satellite System (GNSS) receivers, total station, laser scanners and an Unmanned Aerial Vehicle (UAV). The GNSS receiver was Leica GS18, which is a dual-frequency receiver that supports different types of GNSS observation techniques. The total station was Leica TS16 with 1" angular accuracy and a 1mm + 1ppm distance measurement accuracy. The laser scanner was Leica RTC360, which has horizontal and vertical angular accuracy of 18" and distance accuracy error of 1.0mm + 10ppm. Finally, the aerial photogrammetry was conducted utilizing eBee X from Sensefly.

Figure 3. The Greenway Hub building located on the Grangegorman Campus.

3.2 Workflow

To achieve the objectives of this study, a 6-step workflow was developed (Figure 4). The details of each step are as follows:

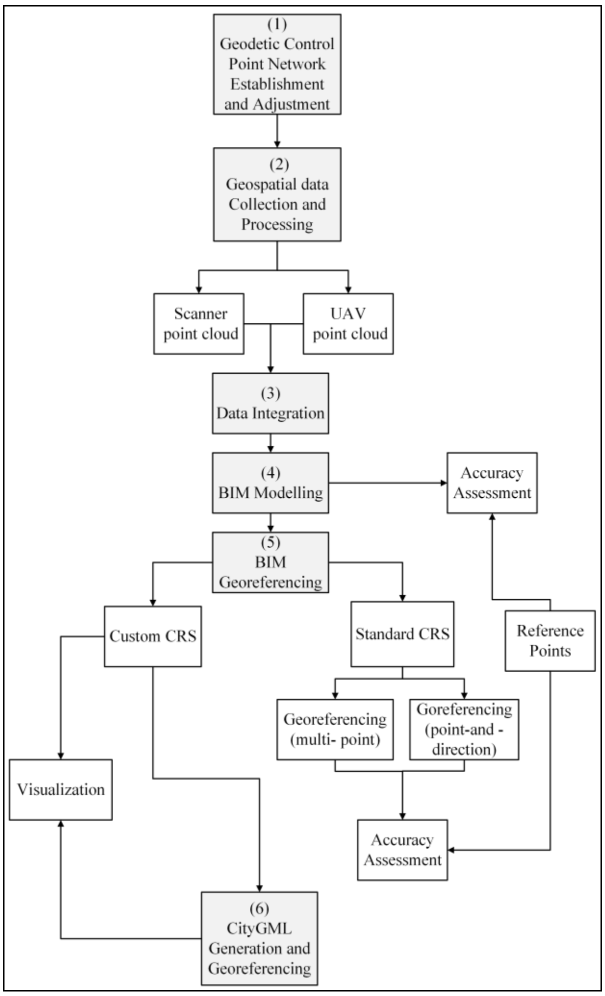

Figure 4. Overview of the workflow adopted in the study.

(1) Geodetic Control Point Network Establishment and Adjustment

The process started with the establishment of a control point network for study area based on Irish Transverse Mercator (ITM) system, which is a national CRS in Ireland. The Network Real-Time Kinematic (NRTK) GNSS observation technique was used to determine the baseline coordinates of the two primary control points for the network (S1 and S2). Subsequently, a traverse was conducted utilizing a total station to acquire the coordinates of remaining points in the network (S3-S7). The network was then adjusted using the Microsurvey StarNet software to compute the final set of adjusted coordinates of all points in the network. The control point network is shown in Figure 5.

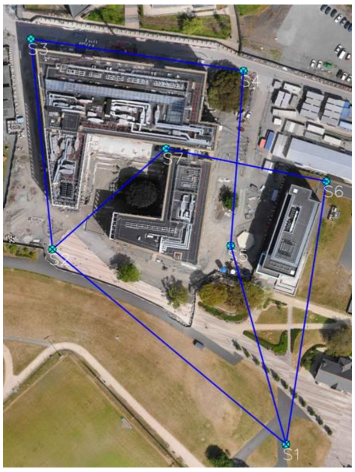

Figure 5. Control point network.

(2) Geospatial Data Collection and Processing

Following the acquisition of the adjusted coordinates, the total station was employed to measure two sets of points: the corners of the building and additional points on its façade. The corner points will be used as reference points in the accuracy assessment tasks in this study, enabling performing absolute accuracy comparison against derived coordinates from the BIM and GIS model. The additional points will be used to derive distances, allowing relative comparisons between the model dimensions and real-world measurements.

Subsequently, a terrestrial laser scanner was employed to capture point cloud data of the exterior of the building. Simultaneously, the total station was employed to measure the coordinates of the black and white registration targets based on already adjusted coordinates of the control points. However, since terrestrial laser scanner do not provide adequate coverage of roof of the building, a supplementary georeferenced point cloud data sets from UAV photogrammetry was obtained from a third party. The point cloud generated from the UAV photogrammetry covered all visible parts of the building including façades and roof surfaces.

(3) Data Integration

This step involves merging the point cloud datasets obtained from terrestrial laser scanning and UAV photogrammetry. Prior to merging, quality control procedures were applied to both data sets. This process revealed that the UAV-based point cloud was associated with high level of noise, therefore it was excluded from the calculations. Nevertheless, the portion that corresponds to the roof was retained, and merged with the laser scanner point cloud to enhance the visual completeness of the model. This integration was feasible since both datasets were georeferenced in the same CRS adopted for the project.

(4) BIM modelling

The merged point cloud was subsequently imported into BIM environment for creation of as-built BIM model. In this study, Autodesk Revit was utilized as the main software for BIM modelling. The resulting as-built BIM model is presented in Figure 6.

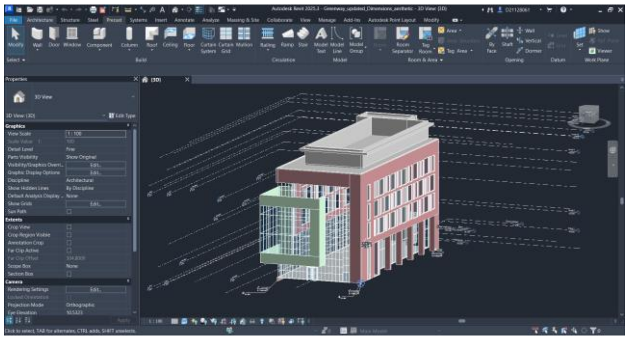

Figure 6. As-built BIM model of the Greenway Hub building.

At this step, the first task related to achieving the primary objective of this study was carried out. This task involved comparing the coordinates and distances obtained from the BIM model with the true values measured at the field. Specifically, the four corners of the building and two linear distances. These values enabled performing both absolute and relative comparison between the BIM mode and real-world measurements.

(5) BIM Georeferencing

This step addresses the comparison of the georeferencing methodologies, which is the second key task contributing to the overall aim of this study. To carry out this task, the BIM model was initially georeferenced using the common point-and-direction approach. Subsequently, a two-dimensional (2D) representation of the model was georeferenced using a multi-point method based on least squares adjustments. The impact of each approach on georeferencing accuracy is then analysed and presented.

Finally, this step investigates the main objective of this study: associating a custom CRS with 3D digital models. In this regard, the first consideration in this process is to determine whether performing such a task is necessary. This can be assessed by calculating the scale factor distortion associated with the adopted CRS in the project area. In this case study, the scale factor for the project site was calculated to be 0.99998 based on ITM coordinate system. This indicates that the distortion due to scale factor in this part of the country is negligible, and therefore, there is no need to define a custom CRS for the project. However, in other regions of the country or when employing alternative map projection systems such as Universal Transverse Mercator (UTM), this factor causes significant distortion. For example, the scale factor in the central parts of Ireland in ITM is around 0.9998, which could cause serious inaccuracies in measurements (Figure 7). To explore this effect, Autodesk Civil 3D was used to virtually move the building to city of Athlone, which has central location in Ireland.

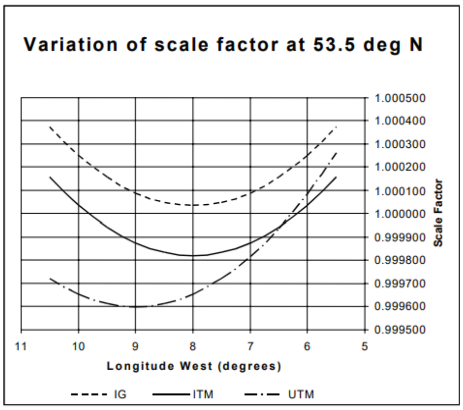

Figure 7. Scale Factor in ITM (Cory et al., 2001).

To associate a custom CRS with the IFC model, the following approach was adopted:

• The process commenced outside of BIM environment by modifying the parameters of the existing ITM coordinate system (EPSG=2157). To minimize the distortion in the project area, the longitude of the central meridian of the CRS was shifted to align with the center of the site (longitude = -7.968692) while keeping the scale factor of 1.0. In this case, no modifications were required for the latitude of origin. Additionally, the false Easting and Northing coordinates were left unchanged.

• IFC model was exported from the BIM Authoring software (Autodesk Revit) using the coordinates derived from the modified CRS, while preserving the north direction. Since Revit does not support the definition of custom CRS, the model was initially exported to IFC using the standard EPSG code. Subsequently, manual modifications were made on the IFC entities to reflect the created custom CRS.

The modified IFC entities included *IfcProjectedCRS*, *IfcMapConversion*, and *IfcWellKnownText*. Specifically, *IFCProjectedCRS* was used to name, describe and define the geodetic datum for the custom CRS; *IfcMapConversion* was employed to define the point of reference and the orientation angle towards north; and *IfcWellKnownText* was utilized to define the parameters of the custom CRS. The details of the modification are as following:

#28=IFCPROJECTEDCRS('Custom_ITM_7_58_7.17W','Custom ITM 7°58\'7.17"W','IRENET95',$,$,$,#27);

#29=IFCMAPCONVERSION(#22,#28,598151.334,742032.180,0.,0.95018231549955268,-0.31169467000882223,$);

#280= IFCWELLKNOWNTEXT('PROJCRS["Custom ITM 7°58\'7.17\"W",BASEGEOGCRS["IRENET95",DATUM["IRENET95",ELLIPSOID["GRS1980",6378137,298.257222101,LENGTHUNIT["metre",1]]],PRIMEM["Greenwich",0,ANGLEUNIT["degree",0.0174532925199433]]],CONVERSION["Custom Irish Transverse Mercator",METHOD["Transverse Mercator",ID["EPSG",9807]],PARAMETER["Latitude of naturalorigin",53.5,ANGLEUNIT["degree",0.0174532925199433]],PARAMETER["Longitude of natural origin",-7.968692,ANGLEUNIT["degree",0.0174532925199433]],PARAMETER["Scale factor at natural origin",1.0,SCALEUNIT["unity",1]],PARAMETER["False easting",600000,LENGTHUNIT["metre",1]],PARAMETER["Falsenorthing",750000,LENGTHUNIT["metre",1]]],CS[Cartesian,2],AXIS["Easting(E)",east,ORDER[1],LENGTHUNIT["metre",1]],AXIS["Northing(N)",north,ORDER[2],LENGTHUNIT["metre",1]]]',#28);

It is imperative that *IFCWellKnownText* references back to *IfcProjectedCRS*.

• The custom CRS was defined in the GIS environment using the same parameters specified in its WellKnownText (WKT) representation. Subsequently, the IFC model with custom CRS was imported into the GIS environment to enable visualization and geospatial analyses.

(6) CityGML Generation and Georeferencing

In this step, the IFC model associated with custom CRS was converted into CityGML and then visualized within a GIS environment. In this study, Feature Manipulation Engine (FME) by Safe Software was used to perform the conversion. Prior to this process, the custom CRS was defined in the FME environment utilizing the already defined parameters in the WellKnownText representation. The conversion workflow necessitates utilizing several key transformers: Rotator, to orient the model based on north direction angle; LocalCoordinateSystemSetter, to specify the coordinates of the reference point; and CmapProjector, to set the custom CRS as the target coordinate system for the resulting CityGML model. By following the outlined methodology, the defined custom CRS was successfully assigned to the exported CityGML model. As a result, the model can be accurately visualized in any GIS platform that supports defining a custom coordinate system.

4. Results

This section presents the results of the tests and accuracy assessment procedures conducted to address the primary objective of this study.

The comparison between coordinates derived from BIM model and those obtained from field surveying revealed that an absolute positional accuracy of less than 20 mm can be achieved (Figure 8). Moreover, evaluation of distances between real-world measurements and those extracted from the BIM model showed similar results (Figure 9).

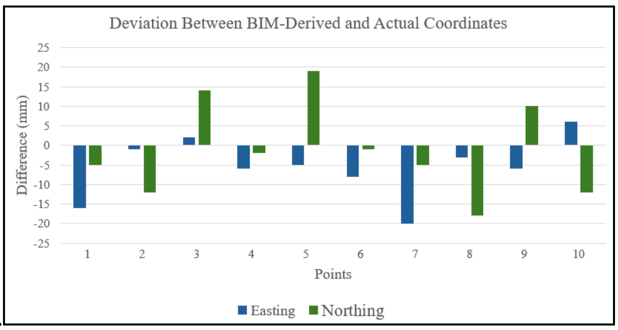

Figure 8. Comparison between coordinates derived from the BIM modelling and actual surveyed coordinates.

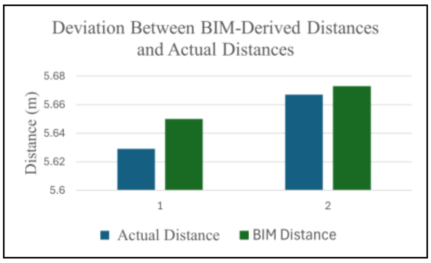

Figure 9. Comparison between distances derived from the BIM model and actual field-measured distances.

Regarding comparison of georeferencing methodologies, the results confirmed that applying multiple control points provides higher georeferencing accuracy than the point-and-direction approach (Figure 10). Moreover, utilizing multiple points for georeferencing has the advantage of detecting errors in the points, which is not possible with point-and-direction approach.

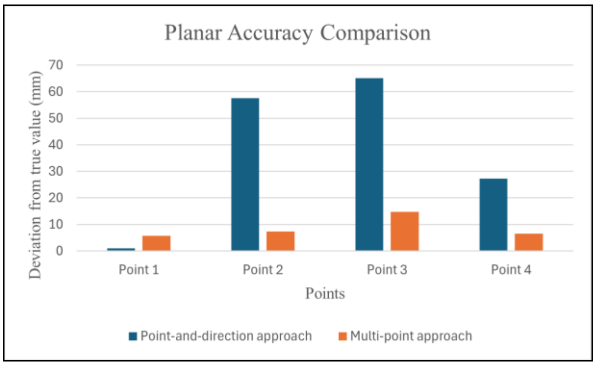

Figure 10. Comparison between georeferencing using the point-and-direction and the multi-point approaches.

Regarding assigning custom CRS to IFC models, the results demonstrated the feasibility of the proposed approach for assigning a custom CRS to IFC4x3 model and subsequently visualizing the model in GIS environment. In this study, ArcGIS Pro by ESRI was utilized as the GIS platform for visualization (Figure 11). Importing IFC model with the embedded custom CRS into GIS environment enabled accurate spatial positioning of the model within its real-world context.

Figure 11. Visualization of the IFC model with an embedded custom CRS in ArcGIS Pro.

The results also confirmed the applicability of the proposed approach for assigning a custom CRS to CityGML. The IFC model, embedded with custom CRS, was successfully converted CityGML while preserving the same customized CRS. QGIS was used to visulize and validate the CityGML model (Figure 12).

Figure 12. Visualization of the CityGML model with an embedded custom CRS in QGIS.

5. Discussions

This section discusses the factors that influence the quality of the obtained results and also outlines the limitations of the study.

The first task of this study was to evaluate the positional accuracy of the BIM model generated from point cloud, in comparison to real-world coordinates. The results of the analysis revealed that the accuracy of the produced BIM model depends on two main factors: the quality of the point cloud dataset and the skills of the BIM modeller. Several factors influence the quality of the point cloud, including the quality of the data acquisition instruments, the acquisition methodology, post-processing approach, data registration and data integration techniques. Given this complexity, minimizing the effects of this factor requires adherence to the best practices throughout data acquisition and processing. Regarding the skills of the modeller, as it has also been highlighted in Esfahani et al. (2021), the accuracy of the BIM models vary depending on the modelers skills and modelling methodology (manual or automated). Therefore, the discrepancies reported in this study between the BIM-derived coordinates and the field measurements could vary depending on the human and methodological factors.

With respect to the second task, the advantages of georeferencing BIM models using multi-point instead of depending on a point-and-direction approach become apparent. The point-and-direction approach carries the risk of undetected errors in either the reference point or in the secondary point used to calculate north direction. In contrast, when multiple points are utilized for georeferencing BIM models, a least squares adjustment can be applied, which not only detects errors in any of the input points but also minimizes the overall positional error. This approach ensures optimal placement of the model relative to all control points. However, in the context of as-built BIM generation, it is important to note that applying point-and-direction or multi-point georeferencing approach is only relevant when the point cloud dataset was acquired in a local CRS. Conversely, if the point cloud was captured using a national or international geodetic CRS, the most accurate georeferencing results can be achieved by extracting the parameters directly from the point cloud itself.

Regarding the assignment of a custom CRS to IFC model, this study highlights that the process remains complex and highly manual. This complexity originates from the fact that most BIM authoring tools support only standard CRSs that are identifiable by EPSG code. As a result, implementing a custom CRS requires manual modification of the IFC structure outside the BIM environment. While the proposed approach minimizes the scale factor distortion resulting from the map projection, it causes misalignment between the model and other geospatial datasets. In such cases, applying the custom CRS to the entire project is essential to maintain spatial coherence. Additionally, the effectiveness of this approach depends on the capabilities of the visualization platform for custom CRS definition and interpretation.

When assigning custom CRSs to CityGML model, although several commercial and open-source tools are available to perform IFC to CityGML conversion, it is paramount to choose a tool that supports the definition of a custom CRS within its system. In this study, FME was chosen due to its flexibility and robust support for CRS customization. However, it was observed that the process was highly manual and reliant on the point-and-direction georeferencing approach. When employing the multiple-points approach, it is necessary to extract the control point coordinates defined in the custom CRS and to recalculate the north direction accordingly.

This study presents several limitations that require further investigation. First, the proposed workflow for georeferencing and assigning custom CRS to IFC and CityGML models is predominantly manual. Which makes the process both time consuming and labour intensive. Future research should focus on developing automated and semi-automated methodologies. Second, the georeferencing approach in this study focused on planar coordinates of points; however, elevation and the geoid models have major impact on the georeferencing accuracy as well. Therefore, more research is needed to develop approaches that consider both horizontal and vertical components into the georeferencing process. Third, this study applied minor changes to CRS parameters to mitigate the scale factor distortion; more investigation is required to explore cases that require significant modifications to CRS parameters. Another limitation of this study is that CityGML version 2.0 was employed, however, it is important to focus on the latest version of CityGML (v3.0) in future studies. Finally, this study investigated the creation of a digital twin for a single building. However, since scale factor distortion becomes more significant in large-scale built environment assets that extend over large area, future research should focus on implementing the proposed methodology to infrastructure projects.

6. Conclusion

The objective of this study was to develop a methodology for accurately georeferencing IFC and CityGML models within the context of digital twin creation for the built environment projects. The proposed methodology focused on assigning a custom CRS to both IFC and CityGML models. Additionally, the impact of BIM modelling techniques and georeferencing approaches on positional accuracy of the models were investigated. The findings demonstrate the feasibility of assigning custom CRSs to both model types. Moreover, it it showed that BIM modelling practices and georeferencing approaches can significantly affect the final spatial accuracy of the models. This study can be utilized as a practical guideline for accurately georeferencing BIM and GIS models for creation of digital twins of building and infrastructure projects. The main limitation of this study lies in the manual implementation of the proposed methodology, which presents an opportunity for future research towards automation.

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