Deploying 3D scanning based geometric digital twins during fabrication and assembly in offsite manufacturing

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Abstract

Verifying geometric compliance in offsite manufacturing (OSM) is key for ensuring adequate fit-up, structural integrity, building system performance, and assembly alignment on site. The use of a geometric digital twin (gDT) from 3D scanning can be used to digitize an assembly to detect and resolve potential problems in a prescient manner. The contribution of this article is the development of a framework for deploying and comparing three distinct gDT approaches for use during fabrication and assembly in OSM: (1) a scan-vs-BIM approach, (2) a scan-to-BIM approach and (3) a parametric BIM updating approach. Results from a commercial building project show that scan-vs-BIM is the most accurate approach, parametric BIM updating produces the most semantically rich gDT, and scan-to-BIM is a middle-tiered option, striking a balance between representational accuracy and semantic enrichment. This study concludes that future research should develop a hybrid solution of these gDT approaches and additional more accurate measurement technologies for optimal deployment in OSM.

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Introduction

In projects utilizing offsite manufacturing, reliance on a tightly controlled fabrication process is essential for ensuring adequate aggregation capabilities (Arashpour et al. 2019; Lawson, Ogden, Goodier 2014; Zhang et al. 2016). Recently, ‘digital twins’ have been popularized in academia and industry, referring to the complete digital replica of physical assets, systems and processes (Parrott and Warshaw 2017). Digital twins are intended to span the lifecycle of a product or system in order to simulate, collect information and create a feedback loop for continuous design, production and operation improvements (Lim, Zheng, Chen 2019). The ability to create and maintain a geometric digital twin (gDT), i.e., the geometric component of a digital twin, during fabrication and assembly enables dimensional quality control to be done digitally and in a prescient manner. In general, digital twins provide a mechanism for stakeholders to simulate, optimize and perform timely adjustments during production to correct for out-of-tolerance issues (Söderberg et al. 2017). For these reasons, gDTs have great potential as quality control tools during fabrication and assembly in OSM.

This paper demonstrates how gDTs can be employed in offsite manufacturing during fabrication and assembly. The current state of geometric digital twinning in construction relies on as-built data collection (e.g., laser scanning, photogrammetry, structured light imaging, etc.) and 3D geometry from a building information model (BIM). While there is growing literature surrounding the development and application of gDTs in construction, no studies to date compare the various ways they can be deployed to maintain and manage the as-built status of constructed works in OSM.

Background

Fabrication and assembly processes in OSM

Offsite manufacturing (OSM) is a process whereby the majority of traditional site-based construction works occur in a climate-controlled facility, allowing advanced production techniques to be used to prefabricate building elements, assemblies and buildings in a highly efficient manner (Sahin, Miller, Mohamed 2018; Yin et al. 2019). Applications of OSM include kit-of-part assemblies, structural insulated panels, bathroom pods, industrial pipe spool modules, panelised curtainwalls, and volumetric building modules (Choi, Chen, Kim 2019). In each of these applications, the construction process is discretized along a manufacturing line. In volumetric modular systems for instance, the overall construction process can be expressed in a series of six distinct production stages: (1) structural assembly, (2) MEP subsystems, (3) walls, floors, partitions, (4) MEP fixtures, (5) finishes and millwork, and (6) enclosure and service tie-ins (Figure 1). For each of these phases to flow seamlessly with one another, adequate project controls for fabrication and assembly must be used. These controls differ from traditional construction projects and are rooted in achieving a high level of dimensional quality.

[Figure 1 here]

Dimensional quality control in OSM

The control of dimensional quality in OSM has myriad purposes including safety, constructability, aesthetics and functionality (Rausch, Edwards, Haas 2020). Dimensional errors are inevitable in OSM as a result of assembly complexity, human and equipment precision, and capabilities of dimensional inspection processes (Nahangi and Haas 2014). In structural assemblies, proper fit-up between components is critical for ensuring there are no excessive gaps between interfaces. In the event of large gaps between interfaces, joining processes such as welding can introduce secondary stresses due to eccentric loading through the connection which can cause structural safety and performance issues (BCSA 2017). Dimensional deviations in prefabricated piping systems have a profound impact on the operation of plants and building systems (Nguyen and Choi 2018). As such, it is imperative to utilize robust dimensional quality control processes. By capturing the as-built status of systems during construction and comparing it to the as-designed intent, it is possible to detect and resolve conflicts in a digitized manner (Noruwa, Arewa, Merschbrock 2020). The deployment of gDTs can address many of the current challenges faced by manual dimensional quality control practices in OSM.

Geometric Digital Twins (gDTs)

The concept of digital twins is not new (Akanmu, Anumba, Messner 2014) and can be traced back to the manufacturing industry at the turn of the century (Grieves and Vickers 2017). The role of geometry in digital twins is essential – without geometric representations, digital twins lack the predicate for initialization or developing further (Borrmann and Berkhahn 2018). Lu & Brilakis (2019) recently coined the term ‘gDT’ to reflect the fundamental geometric attribute of a digital twin.

The deployment and level of abstraction contained within a gDT varies across intended uses, workflows, and end-users. For asset inventory management, smart city development, conceptualization, and design, it is not necessary to mirror every element or to digitally replicate all irregularities, textures, and physical anomalies to millimeter precision. This means the accuracy of the corresponding gDTs in this context is not overly stringent. In contrast, for operations and maintenance (O&M) and for fabrication and assembly control, accuracy as well as the level of granularity of the resulting gDTs is imperative (Lu, Q. et al. 2020). While a BIM functions as a static digital representation created to certain levels of detail during the design-construction lifecycle (e.g., BIM LOD 100, 200, 300, 350, 400 and 500), the role of a gDT is to be a dynamic geometric representation, based on BIM, but also incorporating geometric data collected during the construction and operation of an asset (Figure 2). As such, a gDT evolves and updates as the geometric status of an asset changes over time (i.e., gDT_1, gDT_2, gDT_3, …, gDT_n).

[Figure 2 here]

Mechanisms for creating and maintaining gDTs

There is no one single solution or platform for creating a gDT. It is rather predicated on the procedure and methodology employed for a particular application. This paper derives three unique approaches for geometric digital twinning, which are based on collecting geometric data from laser scanning and tailored specifically towards fabrication and assembly control in OSM.

Scan-to-BIM

Scan-to-BIM has emerged as a dependable process to generate geometrically accurate BIMs according to three main steps: (1) scanning, (2) registration, and (3) modelling. During the first two steps, the 3D as-built conditions are captured and distilled into a 3D point cloud. Object modelling, categorization (e.g., walls, doors, and pipes), and definition of topological relationships (e.g., adjacency, connectivity, and membership) are three main activities that should be conducted during the modelling step (Brilakis et al. 2010; Tang et al. 2010). Since many of these steps must be conducted manually (which is time consuming, tedious and error prone), research is being dedicated to automating the modelling process (Bosché et al. 2015; Ochmann, Vock, Klein 2019). The process of automated geometry modelling includes the following three tasks: (1) spatial correlation, which is the process of meshing the point cloud to approximate the complex geometries with polygonal meshes, (2) object recognition, which is the process of recognizing distinct objects, and (3) object classification and size fitting, which assigns parametric primitives to the recognized objects (Pătrăucean et al. 2015; Tang et al. 2010). Object recognition is the critical task of automated geometry modelling and many research studies have utilized different methods and assessed their ability to recognize objects with different shapes.

Scan-vs-BIM

Rather than converting a 3D point cloud into a new BIM, this method directly overlays collected data on a BIM to quantify discrepancies. This method has become the de-facto approach for dimensional inspection in OSM, with the most common applications being applied to structural systems, industrial piping and other MEP systems (Guo, Wang, Park 2020; Nguyen and Choi 2018; Rausch, Edwards, Haas 2020). The general approach for this method involves registering (aligning) the 3D point cloud to a BIM using feature-based or global best-fit methods. Then, discrepancies between the two datasets are colourized based on the Euclidean distance between individual points in the point cloud and the closest features in the BIM (FARO 2019). This type of analysis cannot produce discrete or ‘parametric’ deviations but is rather used to generate general out-of-tolerance issues in OSM (Rausch, Edwards, Haas 2020).

Parametric BIM updating

In parametric BIM systems, the classification of objects as being ‘parametric’ extends beyond just representational form and has unique attributes to facilitate use across the entire construction lifecycle. In addition to geometric attributes, parametric objects also include semantic information in the form of associative data, rules, topology and material-specific data (Eastman et al. 2011). Parameters are also used to classify objects into categories, families, types and instances, which is stored as data in the form of text, integers, numbers, area, volume, angles, URLs, or binary data (Meadati and Irizarry 2010).

Parametric BIM has only very recently been posited as a gDT method (Lu, Q., Chen et al. 2020), however it has long since been used as a powerful design tool (Eastman et al. 2011). Given how the modification of local parameters can propagate global changes to update a pre-existing BIM (Singh, Sawhney, Borrmann 2019), it can dynamically assess potential assembly conflicts in near real time. Previous research has investigated how such an approach has significant advantages for the construction industry (Akcamete, Akinci, Garrett 2009), and how laser scanning can be used as the basis for propagating changes (Gao et al. 2015). However, no research to date has explored or demonstrated how this approach can be used as a gDT.

Research Approach

This research outlines the necessary requirements of deploying gDTs for fabrication and assembly control in offsite manufacturing (OSM) and for producing an as-built BIM, where feasible. This is accomplished in three steps: (1) conducting a review to identify the necessary geometric accuracy requirements of gDTs, (2) identifying capabilities of existing gDT methods, and (3) conducting a series of functional demonstrations from an OSM project for comparison and evaluation purposes.

Materials and methods

Geometric requirements of gDTs for fabrication and assembly control in OSM

The accuracy of a gDT should reflect dimensional tolerances of elements and features as outlined in codes, standards, and project documentation. Table 1 highlights several key tolerances for structural systems, walls, floors, partitions, MEP components and overall envelope requirements in prefabricated assemblies. As seen, the strictest requirements are typically placed on the structural system. This is important not only for the structural safety of an assembly, but also for controlling deviations in typical construction sequencing, since error propagation and or tolerance stack-up of the final assembly is heavily influenced by the geometric status of the structural system.

While tolerance requirements for structural systems are well documented and outlined in numerous sources, the same cannot be said for other building subsystems. One possible reason for this is that performance of these systems is typically not tied to strict adherence to installation tolerances. For instance, wire gauge is often not modelled upfront in the BIM, since the inherent flexibility enables it to avoid in-field clashes as opposed to wiring conduit and cable trays which are modelled to resolve potential clashes with building components (Eastman et al. 2011). In some cases, HVAC and MEP guides and codes provide specific cases where building performance is directly tied to dimensional compliance. Naturally, these specific dimensional tolerance requirements need to be captured by the accuracy of a gDT. In plumbing systems, drains must have a minimum slope for proper drainage, which must be dimensionally verified during fit-up and installation. Since many MEP systems can accommodate a range of building tolerances (Figure 3), a gDT of these systems does not need to be as accurate as the structural system.

[Table 1 here]

[Figure 3 here]

In general, gDTs for fabrication control should focus on high fidelity digitisation of aggregation features that have the greatest impact on fabrication and assembly. Other items which are not constrained by strict fidelity requirements but are nonetheless important items to verify (e.g., rough stud placement and count) can be subject to low fidelity capture. In order to perform high fidelity twinning, the initial 3D model from the design stage must have a sufficient level of detail (e.g., LOD 400: information sufficient for fabrication) of critical features so that as-built data can be directly abstracted for dimensional comparison purposes (AIA 2008; BIMForum 2018).

Outlining the Capabilities of Existing gDT Methods

Guo et al. (2020) outline existing approaches for using laser scanning to perform quality assessments on prefabricated assemblies: without an as-designed model, with a CAD model (i.e., only the geometric information) or with a semantically rich BIM. In this paper, these approaches are further refined into: (1) scan-vs-BIM gDT, (2) scan-to-BIM gDT, and (3) parametric BIM updating gDT.

In the first approach, at each stage of production where the geometric status of the assembly needs to be geometrically twinned, a 3D laser scan is collected. This data is then is registered to a pre-existing geometric model (BIM). A scan-vs-BIM deviation analysis is carried out for the subsystem of interest to assess dimensional quality. Then, the parts of the geometric model that pertain to the subsystem that was scanned are replaced by the 3D point cloud. A subsequent assessment is conducted to identify clashes with remaining subsystems.

In the second approach, a 3D laser scan is also collected, but rather than directly overlaying the 3D point cloud on the pre-existing geometric model (BIM), a new model is generated using scan-to-BIM. This re-created assembly is then compared with the isolated subsystem of interest to visualize dimensional quality. In addition, this recreated model is replaced to form a hybrid model which can be used to assess potential clashes with downstream processes. This approach has become feasible given the progression in automated scan-to-BIM methods, which continue to improve.

The third approach builds upon the two previous ones, by taking information generated by a 3D point or a re-created assembly, and rather than simply replacing this data in the initial geometric model (BIM), parametric updates are instantiated. The core feature of this approach is that semantic information contained in the initial geometric model is preserved. This method takes advantage of not only the evolving status of scan-to-BIM and the fidelity of information generated in scan-vs-BIM, but also that of the parametric attributes of BIM.

A summary of each gDT method is shown in Figure 4. In this illustration, a gDT is developed for the geometric status of a particular subsystem of interest, after its fabrication is complete, prior to commencing subsequent subassembly fabrication. There are two key assessments depicted here: (a) a deviation analysis for the system of interest, and (b) an impact assessment for downstream production.

[Figure 4 here]

Enumerating Factors Affecting Geometric Accuracy

Accuracy of a 3D scanning based gDT is based principally on the as-built data collection process, which is subject to device calibration errors, environmental conditions, and device measurement errors (Anil et al. 2013). Accuracy is also based on the registration of datasets. For scan-vs-BIM, the alignment or registration of the point cloud with the BIM will accrue errors. Depending on the approach used for registration, such as best-fit alignment or feature-based alignment, different errors can occur. In addition, the alignment of geometric models (such as in a BIM-vs-BIM analysis) are also a potential source of error.

Another factor affecting the accuracy of a gDT is the characteristics of elements being twinned (Rebolj et al. 2017). Unique material conditions (texture, shape, colour, reflectivity, etc.) may impact the accuracy of as-built data capture, especially for lidar laser scanners (Anil et al. 2013). In addition, the geometric characteristics of elements also play a role. Since most BIM software tools employ use of rigid-body (idealized) parameters for defining construction elements (e.g., universal parameters defining cross sectional shape, and length, width, and height parameters), the ability to model or capture non rigid-body deformations is very challenging. While finite element analysis and multi-physics engines can be used to predict elastic and plastic distortions in materials, current digitization workflows that produce parametric objects such as scan-to-BIM cannot capture distortion such as bowing in a beam, welding distortion in steel frames, or bent flanges on pipe spools. Consequently, one solution is to ‘best-fit’ parametric idealized shapes to distorted shapes, at the expense of representational accuracy.

Where appropriate, the BIM level of development (LOD) also plays a key role in the ability to assess the accuracy of fabrication. For instance, if the LOD for a typical interior wall assembly is at LOD 300, then an overall thickness for the assembly is shown along with major penetrations for doors, windows and large mechanical equipment are detailed (BIMForum 2018). At this level of detail, individual components such as studs, bracing, insulation, sheathing and smaller penetrations for MEP equipment are not provided and as such cannot be parametrically updated. Without these additional details, the accuracy of verifying fabrication for items such as wall penetrations which are important for MEP coordination and clash avoidance cannot be measured.

To date, no known studies have derived an amalgamated error function for gDTs. This likely stems from the fact that the objective factors affecting accuracy are difficult or not feasible to homogenize since some factors are only available as average, standard deviation or absolute (i.e., maximum/minimum) values. For instance, laser scanner manufacturers often report ranging error in terms of absolute upper/lower limits (e.g., +/- 2 mm), noise errors as standard deviation values, and registration errors as root mean square (RMS) values. This creates obvious challenges for trying to establish a single amalgamated error function. In some research, a point cloud is used as a the single ‘ground truth’ metric, however as explained in detail by (Lu, R. and Brilakis 2019), such approach requires abstracting local model features (e.g., quadratic model surfaces) since direct computation methods such as nearest neighbour have flaws (point cloud sparsity and noise erroneously increase deviations). Rather than proposing a homogenization strategy, this research uses the following abstracted function for reporting the error of 3D scanning based gDTs (E_{gDT}):

$$E_{gDT} = f(E_{AB}, E_{DC}, E_{RD}, E_{LOD}) \tag{1}$$

where E_{AB} is the overall error resulting from the raw as-built data (e.g., scanner accuracy, registration error, noise, occlusions, etc.), E_{DC} is the error from data comparison (i.e., alignment of scan with BIM), E_{RD} is the rigid deformation abstraction error (difference between the as-built rigid deformations and the accuracy capabilities of the gDT method), and E_{LOD} is the error introduced from discrepancies between model LOD and as-built geometry LOD. Depending on the gDT method being employed, not every factor in this error function is applicable. As mentioned, due to intricacies and potential interrelations between these factors, it may not be feasible to derive an explicit algebraic expression (as factors may not always be mutually exclusive). As such, when investigating errors of gDT methods, this paper presents each of the individual terms listed in Eqn. 1.

Case study – background and research approach

The structural system of a previous offsite manufactured building is used to demonstrate and evaluate each gDT method. This building is comprised of prefabricated steel chasses that are subsequently fit-out with other building systems (MEP, walls, floors, fixtures, finishes and millwork). During the fabrication process (Figure 1), it was necessary to perform a series of dimensional quality control inspections to ensure clash-free assembly of subsystems within each chassis and to ensure adequate inter-module assembly on site. To this end, the fabricator was intent on determining the best approach for maintaining a gDT for their fabrication and assembly control needs. The following describes the specific data and software inputs used to evaluate each gDT method in this case study.

An initial BIM was created using Autodesk Revit®, and as-built data was collected using a FARO laser scanner at key fabrication stages. Two commercial software packages were used for supporting the gDT approaches: FARO® BuildIT Construction and ClearEdge3D® Edgewise. Given its ability for highly customized feature-based registration, FARO® BuildIT Construction was used to perform scan-vs-BIM analyses. Feature-based registration is important for OSM, since datums are employed during fabrication for controlling and measuring dimensional variability. Performing a global best-fit registration, such as through the *Iterative Closest Point* algorithm, does not account for datums on the assembly even though it does yield a global minimization of errors between the point cloud and BIM. In contrast, feature-based registration enables a user to localize key features and using primitive fitting on the point cloud for a series of features such as planes, extract coordinates that can be used for registration. ClearEdge3D® Edgewise was used to perform scan-to-BIM processes. While there is a range of existing research into automated scan-to-BIM processes, ClearEdge3D® Edgewise was chosen for this particular study given its graphical user interface, and intuitive review process for verifying the dimensional fit between idealized 3D model features and the raw unstructured point cloud data.

Results

Approach 1: Scan-vs-BIM gDT

A deviation analysis was first performed after scanning the fabricated structural system and registering the resulting point cloud to the BIM. Feature-based registration was used by extracting intersection points from three planar features located at each of the four bottom corners of the structural system. This deviation analysis revealed that variations of the structural system ranged up to 25 mm. To determine the impact of these variations, a subsequent assessment was undertaken to identify clashes that may occur for the next subsystem to be fabricated: the installation of doors. It was found that the position of one particular beam resulted in a clash with a door assembly by roughly 20 mm (Figure 5). Other smaller clashes were also identified for gypsum wallboard elements that wrap around the vertical columns. This information gives the fabricator the ability to make informed decisions whether to correct the position of parts of the structural system before proceeding with downstream production.

Enumerating the accuracy of this gDT is performed as follows. According to the laser scanner manufacturer, the maximum ranging error is equal to +/- 2mm at a distance of 25 m, and the standard deviation of ranging noise is between 0.5 mm and 1.35 mm for surface reflectivity of 90% and 10% respectively (FARO 2007). Both of these factors contribute to the raw as-built data error. The error in extracting planar features (required for registration) from the point cloud were reported in FARO® BuildIT Construction as 0.75 mm. Then the error in registering the point cloud to the BIM was quantified as 2.45 mm. It should be noted that both planar feature extraction and BIM registration are properties of the physical assembly and not based on the software employed. While there is no explicit error associated with parametric feature extraction, both previous enumerated errors are implicit forms of parametric feature extraction. For this gDT, there are no errors associated with the BIM LOD, since the BIM was developed to a fabrication level of detail (i.e., LOD 400).

[Figure 5 here]

Approach 2: Scan-to-BIM gDT

In this approach, the structural system was scanned in the same manner as the first approach. However, rather than directly using the resulting point cloud to overlay on the BIM, a subsequent model was (semi) automatically generated in ClearEdge3D® Edgewise. The result of this scan-to-BIM process was validated by manually confirming the parametric primitive fitting process of each structural component. This recreated model of the structural system was then aligned to the original BIM using features on the base frame that correspond to the datum used during fabrication. After alignment, an assessment was performed between the two models (the as-designed and the as-built) by extracting parameterized deviations (i.e., positional deviations in each of the principal component directions) for the main structural components as shown in Figure 6. Deviations for the beams and columns range up to 25 mm, which is similar to the information produced in the scan-vs-BIM assessment of the first gDT method. However, an additional part of this assessment is the parameterized deviation extraction of interface plates (used as inter-module connections). Based on the way deviations are produced in scan-vs-BIM, when components have gross positional errors (e.g., > 50 mm) or if deviations cannot be captured using Euclidean distance measurement (e.g., if a window is shifted 'in-plane' rather than 'out-of-plane'), these cannot be captured in the typical heat-map visualization produced in scan-vs-BIM (Anil et al. 2013; Lu, R. et al. 2020). However, when performing a BIM-vs-BIM assessment as in this gDT approach, one-to-one comparisons between all elements is made. In this case, the fabricator incorrectly placed two interface plates, P4 and P5 by 281 mm and 142 mm, respectively. Having access to such information directly after fabrication of the interface plates gives the fabricator the ability to correct the placement before enclosing in the structure further, and before invoking much larger rework costs downstream. In terms of assessing clashes with downstream processes, the initial model of the structural system was replaced by the recreated model. Then, clash detection was performed in a similar manner to the first gDT approach. This clash detection captured the same issue with the doorway assembly, and well as clashes with gypsum board elements as shown in Figure 7.

The enumeration of the accuracy of this gDT is as follows. The same raw as-built data errors from the first gDT apply. After performing scan-to-BIM, the resulting model was compared back to the point cloud according to the process outlined by Anil et al. (Anil et al. 2013) to quantify the accuracy of the process for generating the as-built BIM. In this case, the scan-to-BIM error was quantified as 8.89 mm. Finally, the alignment process (of the recreated BIM to the original BIM) was reported to have an error of 4.11 mm – this was determined by the average Euclidean distance between the outermost points on the base frame.

[Figure 6 here]

[Figure 7 here]

Approach 3: Parametric BIM Updating gDT

The final gDT approach performs parametric updates to an initial BIM. While deviations can be extracted using either a scan-vs-BIM approach or a BIM-vs-BIM approach as per Figure 4, this particular demonstration uses the BIM-vs-BIM approach, where two separate 3D models are overlaid, and parameterized deviations extracted along the main axes (Figure 6). In the scan-to-BIM process, elements are best fit to the point cloud, but are kept as idealized objects (i.e., only pose deviations captured). As such, errors from non-rigid deformations (e.g., welding distortion) are ‘smoothed’ by best-fitting idealized elements to the point cloud.

All geometric deviations were constrained to transformations about the axes used in creation of the initial 3D model (these axes are displayed in Figure 6). This ensures that the previously established topological relations are maintained during the updating process. Since subsystem components are based on geometric and spatial attributes of the structural system, updating the as-built geometry of the structure enables an update of subsystems to analyse issues pre-emptively. Clashes can be detected for groups of objects that are not parametrically related, indicating that certain relationships cannot be maintained based on changes to geometric and spatial configurations (Figure 8).

Enumerating the accuracy of this gDT is as follows. The same raw as-built data errors from the previous approaches apply. Since scan-to-BIM is used to generate parametric updates, the same error from the scan-to-BIM process applies (average error of 8.89 mm) as well as the error from aligning the recreated BIM to the initial BIM (average error of 4.11 mm). One additional source of error stems from constraining the parametric updates about the axes used to construct the initial BIM. This error is quantified by manually comparing deviations between elements, which resulted in an average error of 5.5 mm. Both the parametric update constraint and the scan-to-BIM error are combined into one overall error for rigid deformation (E_{RD}) of 14.39 mm.

[Figure 8 here]

Comparison and Summary of Results

Each gDT approach can be compared and evaluated based on the following criteria: ability to capture non-rigid deformations, error factors, level of data fidelity (i.e., semantic preservation), and ability to directly facilitate as-built BIM creation. A summary of these metrics is provided in Table 2.

Of the three gDT approaches, scan-vs-BIM is the only one to capture non-rigid deformations. This is because scan-to-BIM and parametric BIM approaches currently do not support modelling of deformation for elements (all elements are assuming to prescribe to parametric primitives). As such, a scan-vs-BIM gDT must be used when trying to quantify non-rigid deformation such as welding distortion. This approach also achieves the best overall accuracy, since the other gDT approaches rely on making parametric assumptions which impact accuracy. Each of the gDT approaches have the same error from raw as-built data, but as shown in Table 2, scan-to-BIM and parametric BIM gDT approaches have larger data comparison errors (E_{DC}), and the parametric BIM gDT has the largest overall error. Based on the laser scanner used in the case study, even the most accurate gDT (scan-vs-BIM) has larger errors than several of maximum permitted deviations for various OSM elements – especially for the structural system (Table 1). Even by employing one of the most accurate terrestrial laser scanners on the market (e.g., +/- 1mm), the overall error would still larger than key deviations in Table 1. As such, for elements requiring very precise dimensional verification (< 5 mm), additional measurement devices such as laser trackers must be deployed. However, these devices cannot produce the same rich data from laser scanners, which is why 3D scanning based gDT approaches are still efficacious. The parametric BIM updating gDT boasts the highest fidelity, since all initial semantics associated in the as-designed BIM are preserved. This also means that it can produce the most semantically rich as-built BIM, can be used for fabrication and assembly control and for generating an as-built BIM. The scan-to-BIM gDT is positioned as a middle-tier approach, and while it does not have the best overall accuracy, it can generate an as-built BIM in a more accuracy manner than the parametric BIM updating gDT (albeit at the expense of lower semantic richness). It is also the best positioned gDT for capturing missing components since a one-to-one comparison between design elements and as-built elements is performed.

[Table 2 here]

Discussion

The prevalence of offsite manufacturing (OSM) in modern construction systems is continuing to grow due to advancements in physical and digital technologies (Hou et al. 2020; Mostafa et al. 2018). In recent years, digital twins have emerged as a way of capturing the complete digital status of an asset or system. The geometric framework of a digital twin, (i.e., gDT) has been the focus of several research studies which employ use of 3D scanning to obtain accurate and dense information from a physical asset. This research explores three distinct ways that 3D scanning data can be used to produce a gDT; each having unique advantages and disadvantages based on the ability to capture non-rigid body deformations, accrual of error, fidelity or richness of semantic information, and the ability to generate an as-built BIM. This paper presents the requirements for using gDTs in OSM based on geometric accuracy semantic information requirements. Using a case study, the capabilities of each gDT approach are presented in terms of how they can be deployed for distinct analyses, their ability to generate as-built BIM and enumerated factors that affect their accuracy.

The case study found that scan-vs-BIM produced the highest average accuracy since it eliminates potential errors accrued through reconstructive processes in twinning. Furthermore, this approach can capture non-rigid body deformations (e.g., Figure 9 depicts the ability for each gDT to capture and abstract non-rigid deformations for a particular beam with non-negligible midspan deflection – for which, scan-vs-BIM is superior). However, the main disadvantage of this gDT approach is its inability to directly create an as-built BIM or produce semantically rich information – currently these must be generated manually. On the other hand, the parametric BIM updating gDT was found to generate the most semantically rich as-built BIM since it can preserve initial semantics (the original geometry is updated parametrically). The main downside with this approach is that it relies on making several parametric assumptions, and as such, has the lowest average accuracy. While this gDT method can be used directly for as-built BIM creation, it is significantly more challenging to use for generating information required for fabrication and assembly control. Finally, the scan-to-BIM gDT had balanced trade-offs with respect to the other gDTs. It has a slightly better accuracy than the parametric BIM updating, and likewise can directly produce an as-built BIM (albeit not to the same semantic richness).

[Figure 9 here]

Based on the observed accuracies of the gDT methods in this paper and the required dimensional tolerances for many elements in OSM, it can be concluded that even by using the most accurate laser scanners on the market, more accurate additional technologies may be required (e.g., laser trackers, robotic total stations, etc.) for certain quality control tasks. Laser scanning offers a significant advantage for dimensional verification over legacy technologies such as tape measures since mass-measurements can be obtained automatically and in a relatively short duration. However, to achieve the stipulated dimensional tolerance requirements for OSM, additional measurement techniques need to augment the digital twins created solely by laser scanning.

Limitations and future work

Since the enumeration of accuracy is based on several factors that are difficult or not feasible to homogenize (some factors are only available as average values, while others are absolute), it was not feasible to obtain an overall amalgamated error value. The other key limitation deals with the way in which parametric updates are executed in BIM. Depending on the nature of the geometric changes that need to be made, the topological relations and constraints cannot be maintained. Errors can occur for off-axis transformations, resulting in loss of topological semantics. In such a case, it can be challenging or infeasible to make updates to BIM.

Apart from the geometric accuracy requirements, raw geometric information must also be interpreted and assessed in a highly semantic fashion as per fabrication and assembly control requirements. Verifying a component has been correctly installed is not solely a matter of verifying accurate placement but is also based on verifying correctness in terms of its material, visual integrity, connection requirements, etc., which are semantically derived. The semantic verification of offsite manufactured assemblies can be inferred from a gDT, as long as adequate fidelity of geometry and texture information is available.

The process of employing scanning based gDTs for fabrication control is comprised of a range of semi-automated and manual steps which should be fully automated, given the amount of effort required to apply specific changes. Given its rich preservation of semantic information, parametric BIM updating is the most compelling gDT method to generate an as-built BIM. As such, future work will examine how to improve the dimensional accuracy of this approach and to develop an automated approach to perform parametric updates.

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Declaration of interest statement

No potential conflict of interest was reported by the authors.

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Table 1: Maximum permitted deviations for select features, components, and assemblies in OSM

Element/feature dimensional	Subsystem	Maximum permitted deviations (tolerances)	Source
Fit-up of bolted connections	Structural	2mm once interfaces have been joined	(BCSA 2017)
Cast steel connection defects	Structural	Defect depth <5mm with length <10mm	(Iwashita, Packer, Oliveira 2012)
Length of structural members	Structural	2mm (due to mill processes), 3mm (due to fabrication processes)	(BCSA 2017)
Position of fittings (critical to load transfer)	Structural	3mm	(BCSA 2017)
Position of fittings (non-critical to load transfer)	Structural	5mm	(BCSA 2017)
Camber deviation from intended curve	Structural	L/500 or 6mm (whichever is greater)	(BCSA 2017)
Position of bolt holes	Structural	2mm	(BCSA 2017)
Structural member position on baseplate eccentricity	Structural	5mm	(BCSA 2017)
Squareness of plate girder cross section	Structural	4mm	(BCSA 2017)
Twist in plate girder section from welding distortion	Structural	L/700 or 4mm (whichever is greater)	(BCSA 2017)
Precast column alignment from design-based gridline	Structural	9mm	(Ballast 2007)
Concrete floor slab thickness (cast in place or precast)	Structural	6mm	(ACI 2002; Ballast 2007)
Precast concrete	Structural	5-10mm	(Kim et al. 2016)
Concrete slab on grade	Structural	19mm	(ACI 2002; Ballast 2007)
Position of concrete foundations	Structural	30 mm	(CONSTRUCT 2010)
Position of slab edges	Structural	10 mm	(CONSTRUCT 2010)
Position of core walls	Structural	At base 10 mm, at any other level 25 mm	(CONSTRUCT 2010)
Position of openings in core walls	Structural	Relative to grid 25 mm, relative to nearest point of reference on core 15 mm	(CONSTRUCT 2010)
Wood partition wall stud position and plumbness	Walls, Floors, Partitions	6mm	(Ballast 2007)
Steel partition wall stud position and plumbness	Walls, Floors, Partitions	3mm	(Ballast 2007)

Floor framing flatness (wood framed)	Walls, Floors, Partitions	6mm	(Ballast 2007)
Gypsum wallboard plumbness and levelness	Walls, Floors, Partitions	6mm	(Ballast 2007)
Rough openings for doors and windows	Walls, Floors, Partitions	1mm to 5mm (additional flexibility since caulking gaps range up to 20mm)	(Ballast 2007)
Drainage pipe minimum slope	MEP subsystem	1 in 50 (e.g., 20mm for every 1000mm length)	(Government of Ontario 2018)
Positional deviation of MEP component from	MEP subsystem	10mm	(Guo, Wang, Park 2020)
Deviation (angular and positional) between interfaces of prefabricated MEP systems.	MEP subsystem	3mm or 1% of outer diameter of pipe. Adaptable module joints, threaded rods and other flexible coupling devices can be employed.	(BCA 2018)
Positional accuracy of plumbing systems, including the final position of interfaces for fixtures.	MEP subsystem	Connection elements (i.e., flanges that connect pipes and fixtures) require precise alignment (1-2mm error) since these connections are often watertight through threaded flanges. The pipe assembly leading up to a connection point can accommodate larger variations in the spatial position of the fixture (>10mm).	Refer to Figure 3.
Horizontal out-of-alignment due to manufacturing (for overall module envelope)	Overall assembly (in modular construction)	6mm	(Lawson, Ogden, Goodier 2014)
Vertical out-of-alignment due to manufacturing (for overall module envelope)	Overall assembly (in modular construction)	3mm	(Lawson, Ogden, Goodier 2014)

Table 2: Summary and comparison of the gDT approaches used in the case study

gDT Approach	Scan-vs-BIM gDT	Scan-to-BIM gDT	Parametric BIM gDT
Enumerated accuracy factors	E_{AB}: $R_E = \pm 2$ mm^A 0.8 mm < R_N < 1.4 mm^B E_{DC}: 2.45 mm^C E_{RD}: 0.75 mm^C E_{LoD}: NA	E_{AB}: $R_E = \pm 2$ mm^A 0.8 mm < R_N < 1.4 mm^B E_{DC}: 4.11 mm^C E_{RD}: 8.89 mm^C E_{LoD}: NA	E_{AB}: $R_E = \pm 2$ mm^A 0.8 mm < R_N < 1.4 mm^B E_{DC}: 4.11 mm^C E_{RD}: 14.39 mm^C E_{LoD}: NA
Non-rigid deformation capture	Yes	No	No
Data fidelity	Low	Med	High
As-built BIM creation	No	Yes	Yes

A: absolute ranging error (R_E), B: standard deviation of noise error (R_N), C: average error

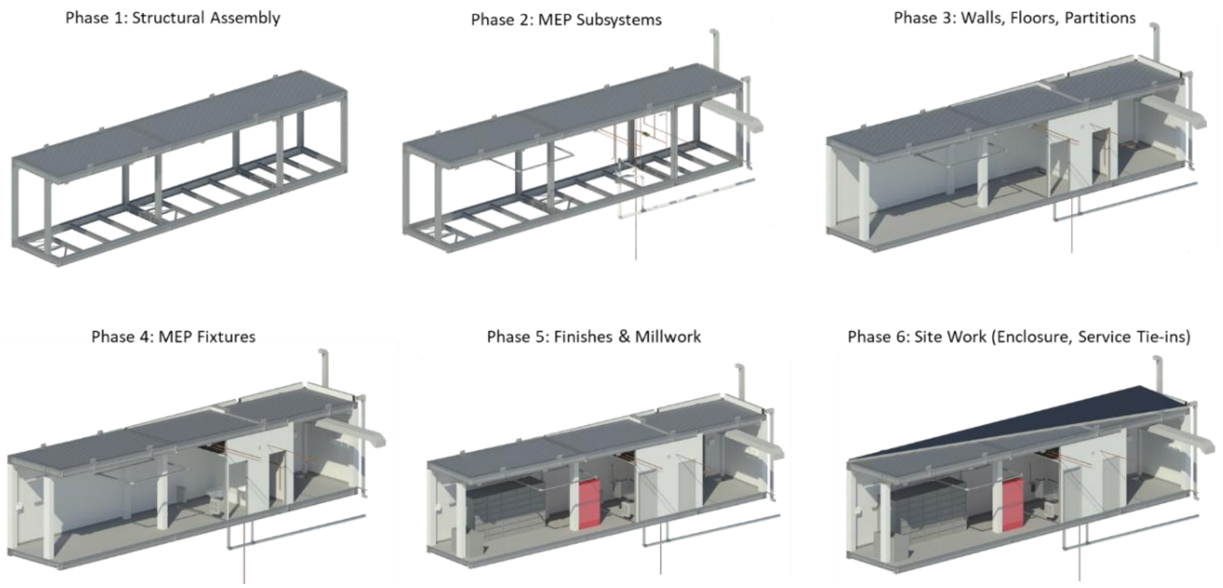
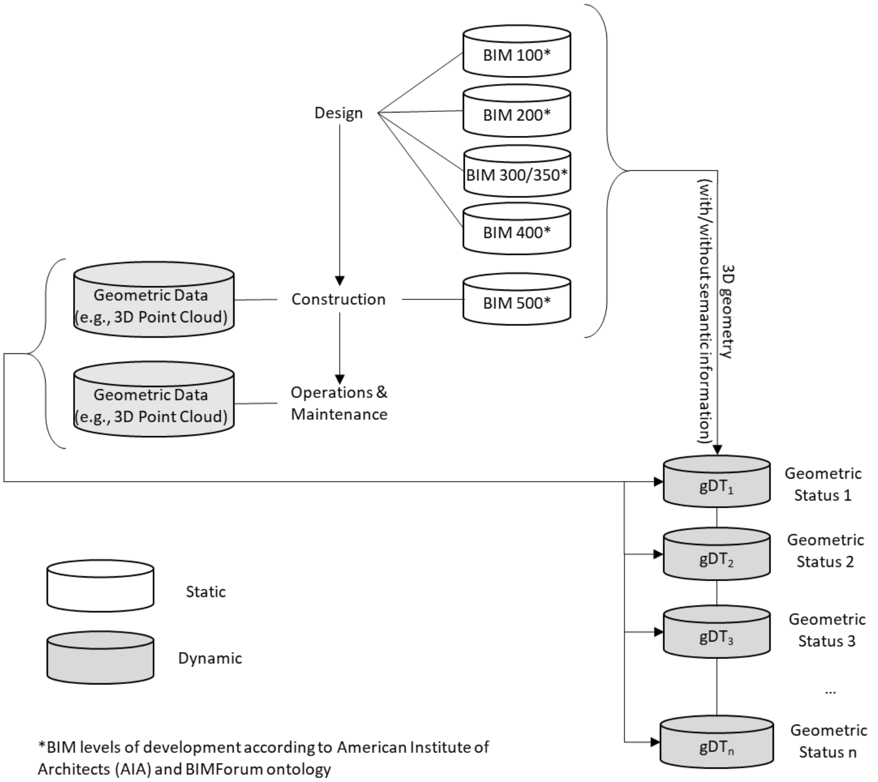


Figure 1: Fabrication and assembly phases for a volumetric offsite manufactured assembly



*BIM levels of development according to American Institute of Architects (AIA) and BIMForum ontology

Figure 2: Context for a geometric digital twin (gDT) with respect to project stages, BIM and geometric data collected during the asset lifecycle

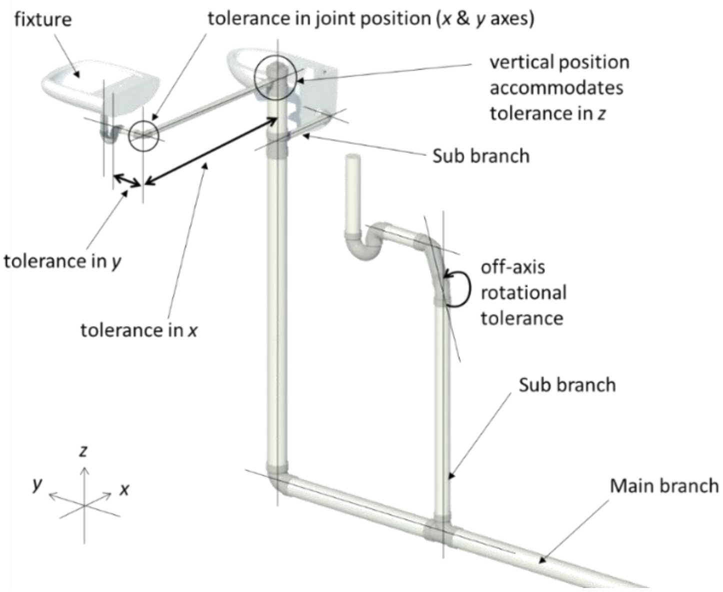


Figure 3: Dimensional tolerances from main branch to sub-branches and fixtures in plumbing systems.

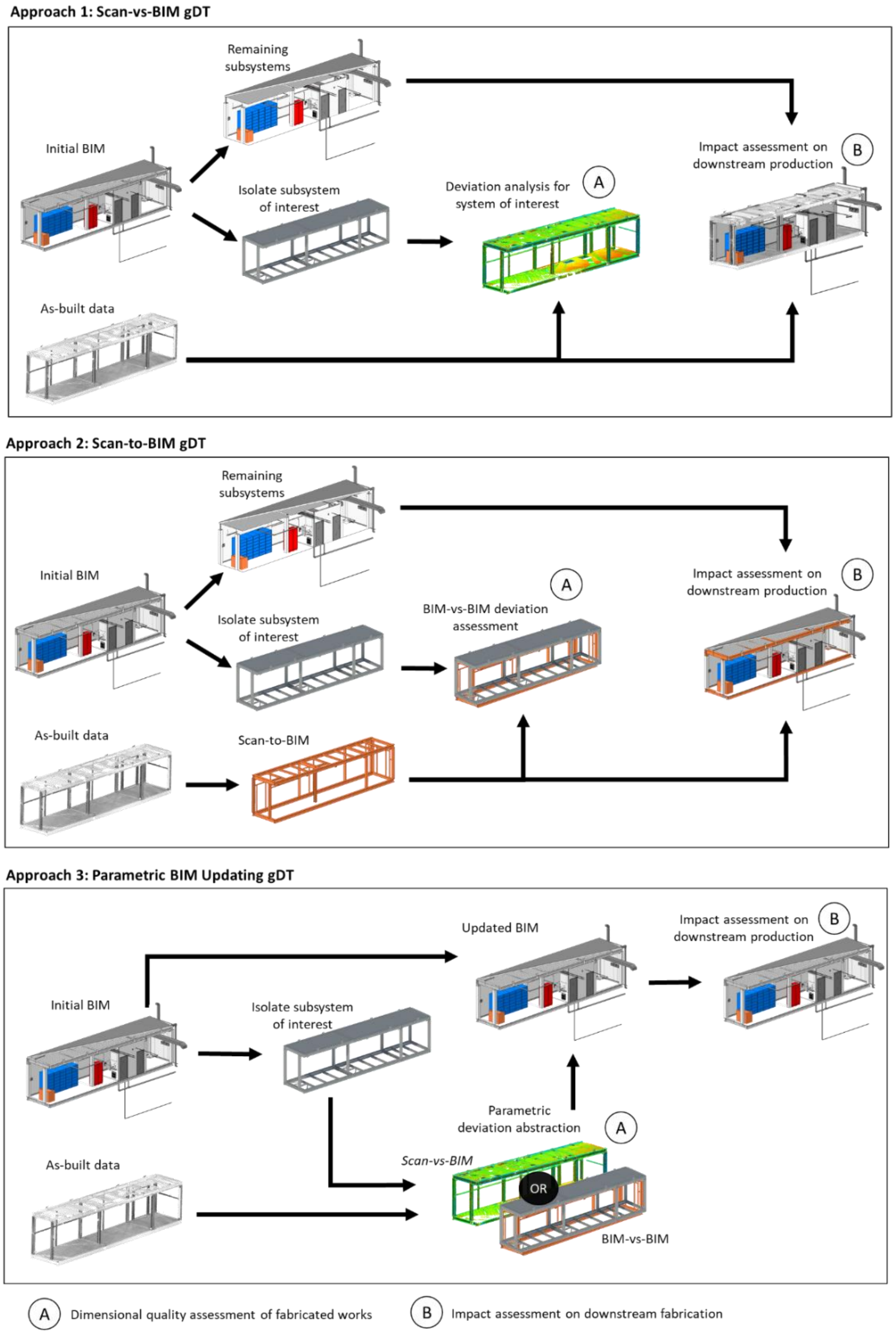


Figure 4: Geometric digital twinning approaches to support fabrication and assembly control assessments in offsite manufacturing using as-built data capture and BIM

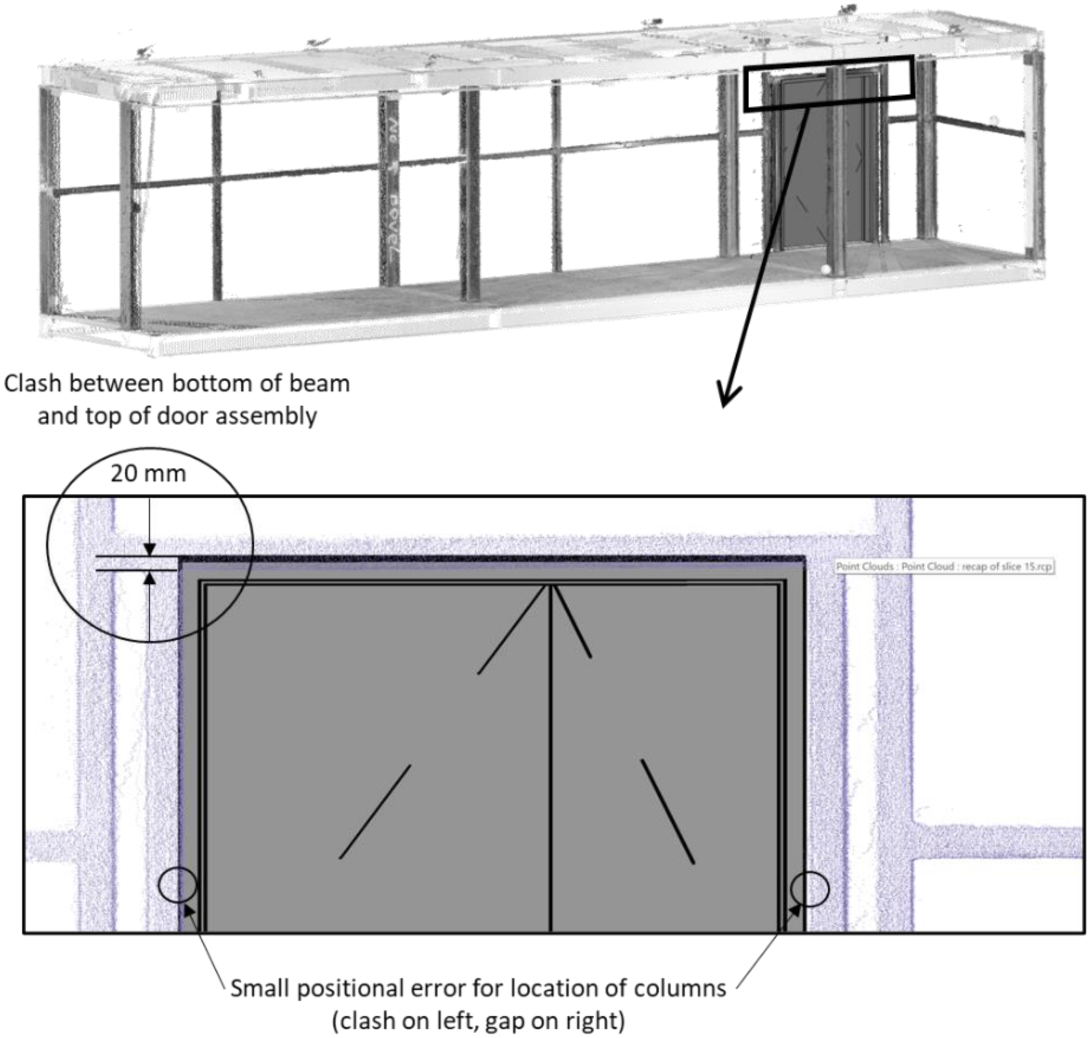
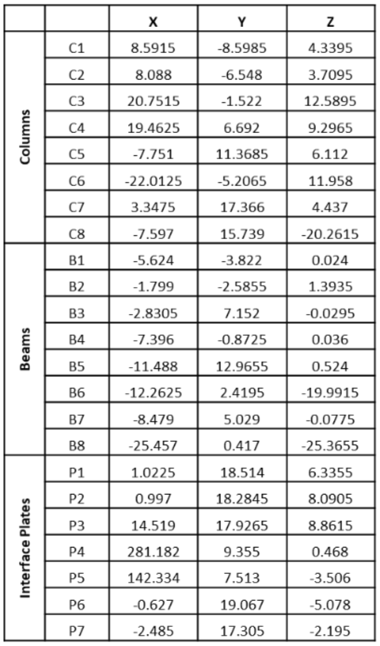


Figure 5: Scan-vs-BIM gDT: identification of a clash between a beam and door assembly.



		X	Y	Z
Columns	C1	8.5915	-8.5985	4.3395
	C2	8.088	-6.548	3.7095
	C3	20.7515	-1.522	12.5895
	C4	19.4625	6.692	9.2965
	C5	-7.751	11.3685	6.112
	C6	-22.0125	-5.2065	11.958
	C7	3.3475	17.366	4.437
	C8	-7.597	15.739	-20.2615
Beams	B1	-5.624	-3.822	0.024
	B2	-1.799	-2.5855	1.3935
	B3	-2.8305	7.152	-0.0295
	B4	-7.396	-0.8725	0.036
	B5	-11.488	12.9655	0.524
	B6	-12.2625	2.4195	-19.9915
	B7	-8.479	5.029	-0.0775
	B8	-25.457	0.417	-25.3655
Interface Plates	P1	1.0225	18.514	6.3355
	P2	0.997	18.2845	8.0905
	P3	14.519	17.9265	8.8615
	P4	281.182	9.355	0.468
	P5	142.334	7.513	-3.506
	P6	-0.627	19.067	-5.078
	P7	-2.485	17.305	-2.195

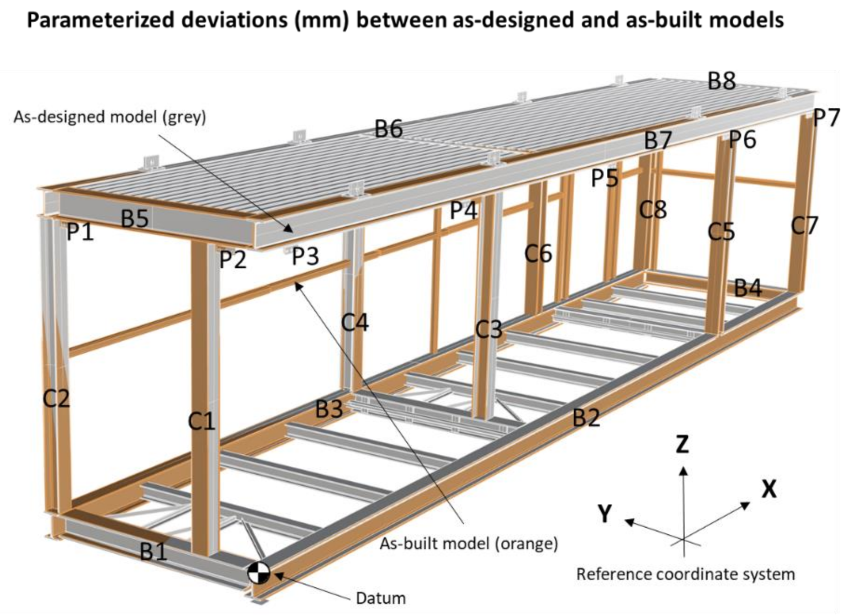
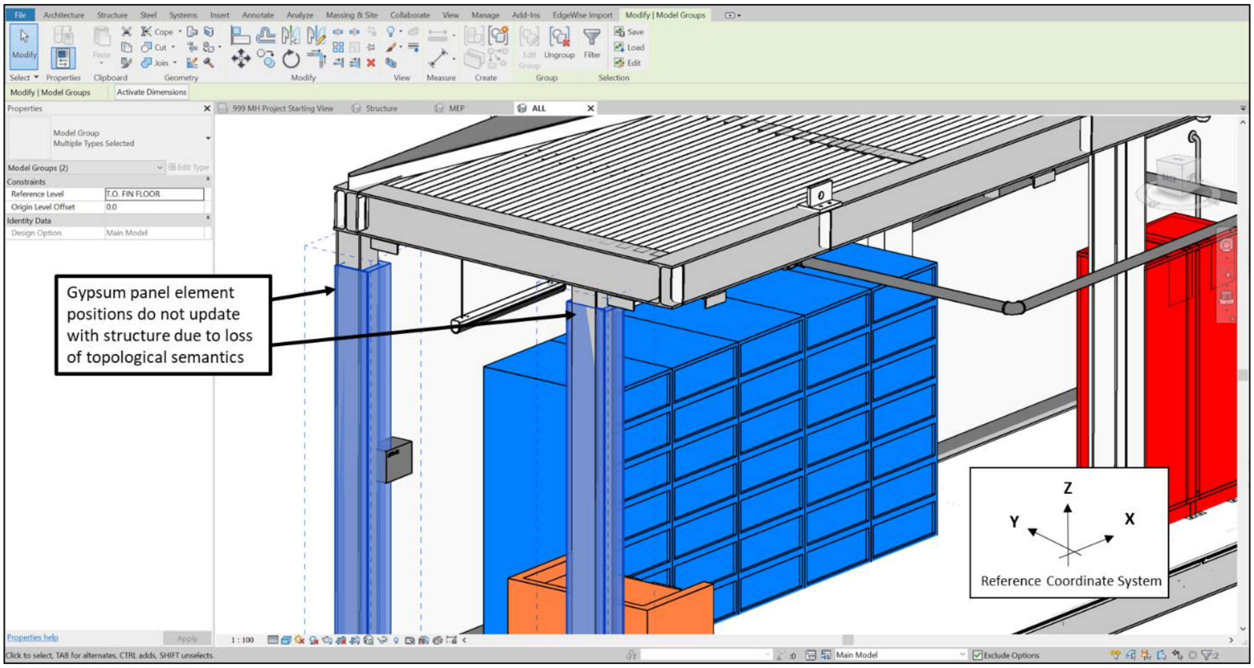


Figure 6: Parameterized deviations for main structural components by comparing a 3D model of the as-built state captured through digitization and registered to the as-designed state using a reference datum and best-fit rotations about the reference coordinate system axes. All deviations are in mm.



Model Group
Multiple Types Selected

Model Groups (2)

Constraints

Reference Level	T.O. FIN FLOOR
Origin Level Offset	0.0

Identity Data

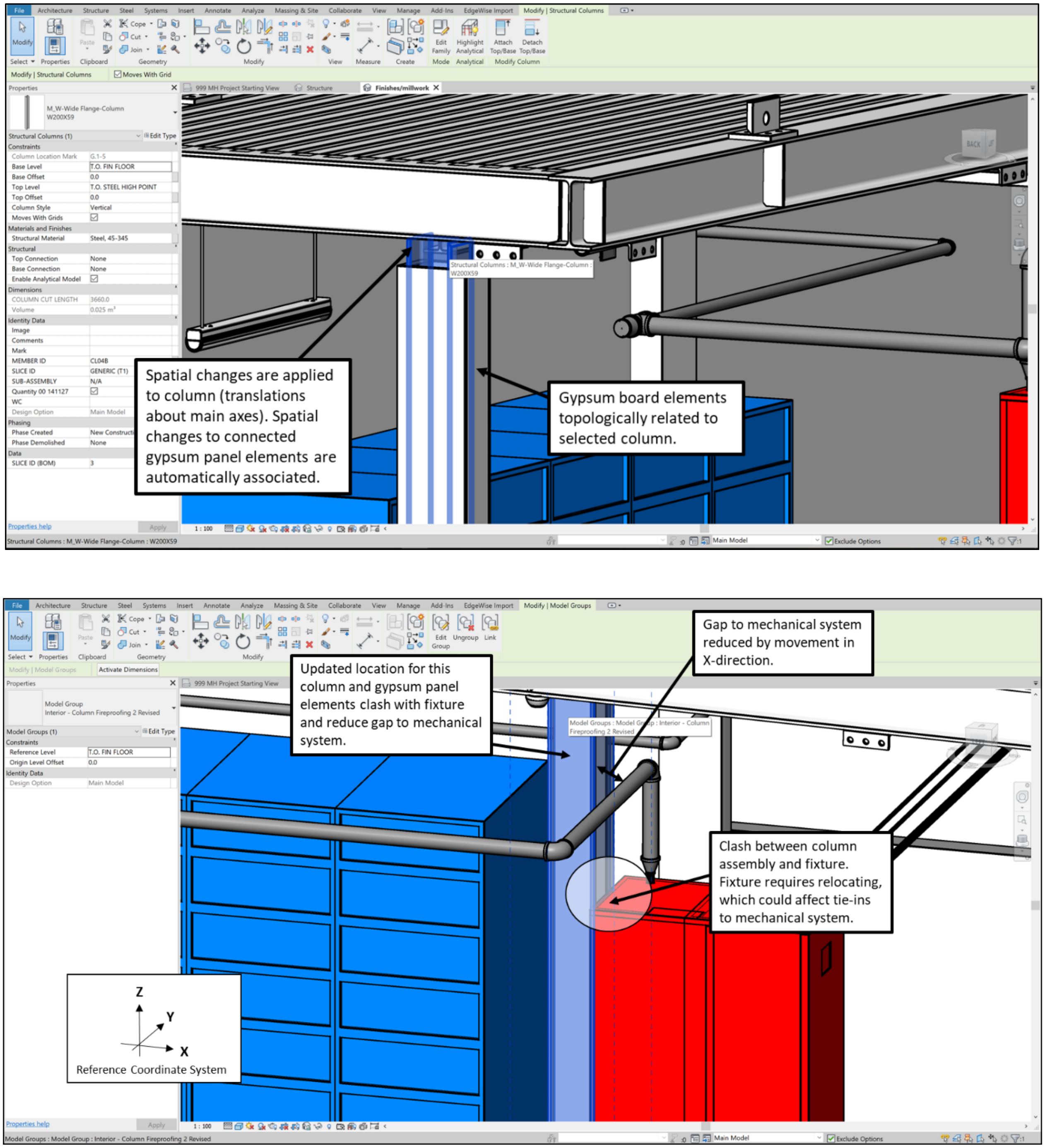
Design Option	Main Model

Main Model

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Gypsum panel element positions do not update with structure due to loss of topological semantics

Figure 7: Depicting clashes captured using scan-to-BIM approach. Note how topological relations between gypsum elements do not update when the structural system is replaced in the BIM.



Properties

M_W-Wide Flange-Column
W200X59

Structural Columns (1)

Constraints	
Column Location Mark	G.1-5
Base Level	T.O. FIN FLOOR
Base Offset	0.0
Top Level	T.O. STEEL HIGH POINT
Top Offset	0.0
Column Style	Vertical
Moves With Grids	☑
Materials and Finishes	
Structural Material	Steel, 45-345
Structural	
Top Connection	None
Base Connection	None
Enable Analytical Model	☑
Dimensions	
COLUMN CUT LENGTH	3660.0
Volume	0.025 m³
Identity Data	
Image	
Comments	
Mark	
MEMBER ID	CL04B
SLICE ID	GENERIC (T1)
SUB-ASSEMBLY	N/A
Quantity 00 141127	☑
WC	
Design Option	Main Model
Phasing	
Phase Created	New Constructi
Phase Demolished	None
Data	
SLICE ID (BOM)	3

Spatial changes are applied to column (translations about main axes). Spatial changes to connected gypsum panel elements are automatically associated.

Gypsum board elements topologically related to selected column.

Properties

Model Group
Interior - Column Fireproofing 2 Revised

Model Groups (1)

Constraints	
Reference Level	T.O. FIN FLOOR
Origin Level Offset	0.0
Identity Data	
Design Option	Main Model

Updated location for this column and gypsum panel elements clash with fixture and reduce gap to mechanical system.

Gap to mechanical system reduced by movement in X-direction.

Clash between column assembly and fixture. Fixture requires relocating, which could affect tie-ins to mechanical system.

Figure 8: Automated changes propagate in BIM through parameter updating (top), are used to predict hard clashes (i.e., physical conflicts) and soft clashes (i.e., gap violations) in the assembly (bottom).

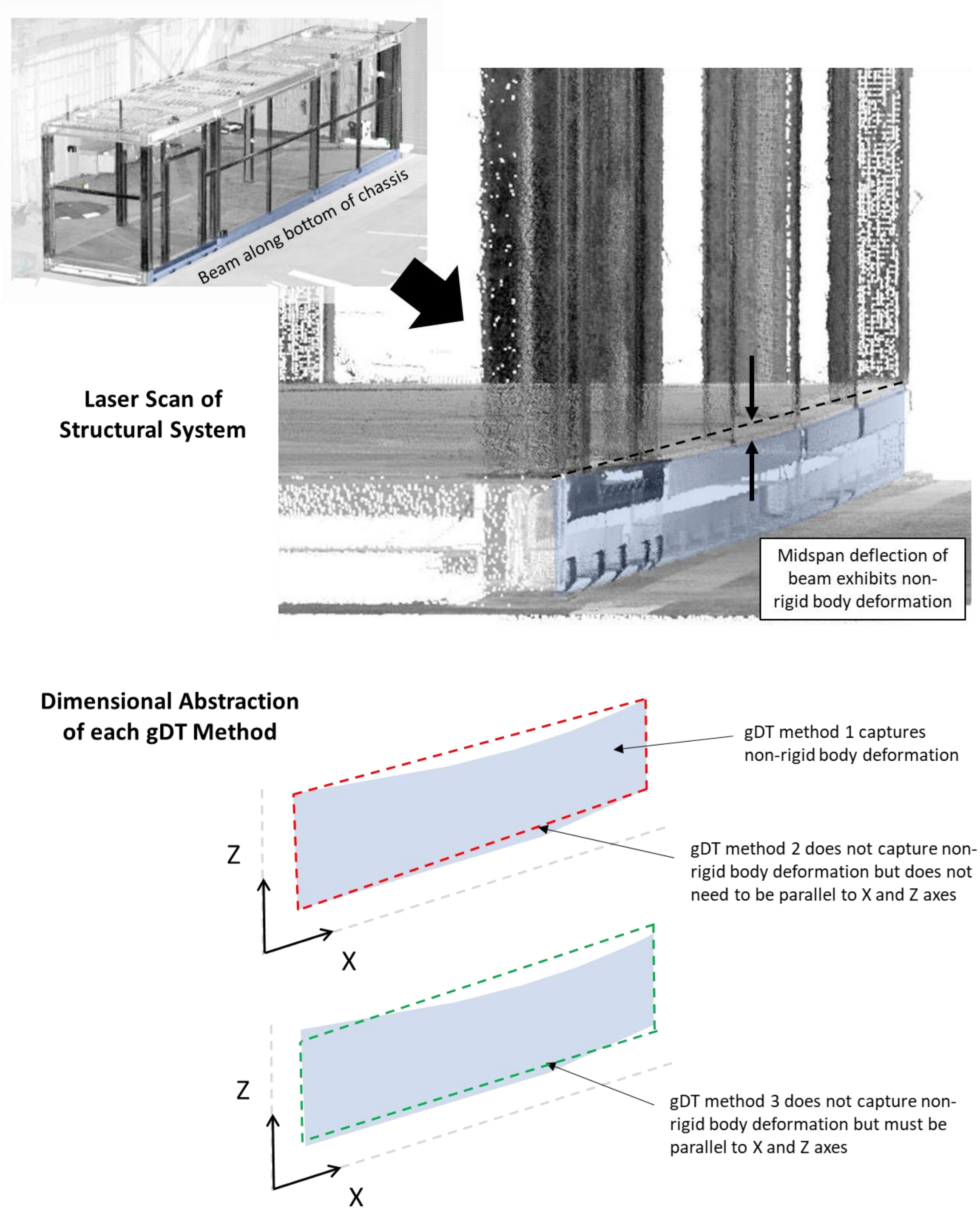


Figure 9: Depiction of each gDT's ability to capture (and abstract) non-rigid body deformation of a beam with midspan deflection located at the bottom of a chassis.

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