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Framework of Scan to Building Information Modeling for Geometric Defect Localization in Railway Track Maintenance

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Abstract: Railway transportation plays a vital role in modern society, enabling the safe and efficient movement of people and goods over long distances. To ensure the longevity and safety of a railway infrastructure, the regular maintenance of tracks is crucial. Traditional track inspections, conducted manually to monitor geometric parameters and to identify defects, are time-consuming, labor-intensive, and prone to human error. Current Scan-to-BIM frameworks for railway maintenance also lack standardized methods for extracting geometric parameters that can be easily integrated into Building Information Modeling (BIM). Additionally, the Industry Foundation Classes (IFC) standard, used for BIM data exchange, does not support storing parameter values at specific chainage points along the track, limiting defect localization. A framework is proposed to address these challenges by standardizing the extraction of geometric parameters from point cloud data and ensuring seamless integration with BIM. The framework calculates parameters at station chainage points and generates additional chainage points along the track, associating the data with the corresponding chainage. A case study demonstrates the framework's ability to enhance defect localization, using the EN 13848-5 European Standard to identify defects at specific chainages. Ultimately, this approach contributes to the more effective lifecycle management of railway tracks.

Keywords: scan to BIM; railway track maintenance; geometric defect localization; parameter extraction; BIM-based maintenance

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Citation: Mahmood, B.; Kim, S. Framework of Scan to Building Information Modeling for Geometric Defect Localization in Railway Track Maintenance. *Buildings* **2024**, *14*, 3578. https://doi.org/10.3390/buildings14113578

Academic Editors: Junxiang Zhu and Paulo Santos

Received: 23 September 2024
Revised: 2 November 2024
Accepted: 8 November 2024
Published: 11 November 2024

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1. Introduction

Railway transportation is a crucial element of modern society that enables the movement of goods and people across long distances in a safe, efficient, and cost-effective manner. According to transportation statistics in 2022, the transportation of passengers by railway accounts for 9.1% of the total passenger transport, while the railway mode contributes to 17.1% of the total freight transport in European Union countries [1]. By considering this high demand for railways, the Korean government plans to invest KRW 114 trillion in expanding the rail network over the next 10 years [2]. The Ministry of Land, Infrastructure and Transport plans to increase the capacity of the rail network by 125%, which would extend the 4274 km network to 5341 km [2]. Railways play a crucial role in both the U.S. and Europe, with ongoing expansions to meet growing transportation demands. In the U.S., ambitious projects like the Brightline West and the Hudson Tunnel Project are underway [3], aiming to enhance connectivity and boost economic growth. Europe is also expanding its high-speed rail networks, with passenger rail traffic increasing significantly. These expansions require substantial investments, with maintenance costs in Europe already exceeding EUR 25 billion annually [4]. Effective maintenance is essential to ensure the safety and reliability of these expanding rail networks. These statistics show that railway maintenance is important for the efficient functioning of railway networks. In this maintenance, the cost of track maintenance is approximately 50% of the total maintenance cost, with track geometry accounting for approximately 10% of all track maintenance [5–7]. This maintenance ensures the safe and smooth travel of trains. A railway track is the longest-lasting

and most capital-intensive asset. Even a slight improvement in maintenance can have a large impact on its lifecycle cost. To increase the life cycle of railway tracks, the European Union spent approximately EUR 25.6 billion in 2023 for railway maintenance [8]. Usually, the maintenance of a railway involves the following steps: (1) The track is inspected by measuring critical track parameters, such as the track alignment, gauge, cant, and twist. This inspection helps ensure that these parameters remain within specified tolerances for safe operation. (2) Defects are detected and localized based on these measured parameters using acceptable tolerance strategies suggested by standards. (3) The track is repaired, which might include replacing the damaged rails or correcting the alignments of rails.

1.1. Traditional Methods of Inspection

In conventional railway maintenance practices, inspections are often carried out manually or with limited technological support [9]. These inspections rely on subjective assessments of a field inspector [10]. For instance, a railway inspector visually inspects the condition of railway tracks and identifies defects based on their judgment. Then, these assessments are manually entered into a database for collaboration with other teams. Due to the subjective assessment of railway tracks, a defect may be overlooked or misinterpreted. This misinterpretation may not be able to predict a repair of the track at the initial stage of the defect and may lead to the reactive maintenance of replacing the track. This reactive decision often leads to unplanned disruptions and higher maintenance costs due to unexpected issues. Also, this manual data entry system may be time-consuming and error-prone.

Modern railway companies use specialized track inspection vehicles equipped with various sensors, cameras, and laser scanners. These vehicles can inspect tracks at higher speeds and provide real-time data [11]. For example, [11] used Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU) sensors, attached to a trolley, to measure track geometry. Ref. [12] added an inertial navigation system to a trolley to improve geometry measurement. Ref. [13] added a laser scanner to improve measurement accuracy. Ref. [14] used the kinematics of a rail track to improve geometric measurement. These cars use lasers and sensors to measure track geometry. They can detect deviations and irregularities in real time. However, this measurement system is expensive and affects track availability by occupying the track during the inspection and stopping the train from using this track. This track unavailability disturbs the train's schedule. The use of these vehicles can be costly and may cause delays in train schedules [15]. From a data perspective, the data collected by these vehicles may not be interoperable with other data management systems such as BIM, which may hinder data sharing [15]. Additionally, managing the large amount of data generated by these vehicles can be challenging, requiring specialized data management techniques [15].

1.2. Maintenance-Related Data Management

The railway industry has been facing challenges in terms of the interoperability of data, particularly between maintenance and design data [16,17]. These issues arise because data from various sources may not be fully integrated into one platform, making it challenging to gain a holistic view of track conditions [16]. The fragmented nature of data exchange has resulted in a loss of approximately USD 15.8 billion [18,19] in the U.S. The European Union Agency for Railways (ERA) monitors the progress of the EU railway system in terms of safety and interoperability [20]. The 2022 edition of the ERA report highlights the need for a more efficient and effective railway system, and the transport budget for railways in Europe increased by EUR 10 billion for rail digitalization [20]. From a technical perspective, natural language processing techniques are being used to digitalize manual inspection reports [21,22], making this data consistent with BIM [23]. To store the large amount of data that is usually generated with regard to the maintenance of an infrastructure, cloud-based techniques are being used [24]. For an exchange of such large data with other stakeholders, cloud-based methods [25,26] and Industry Foundation Classes (IFC) file formats have

been developed. However, maintenance-related data are still not interoperable with these formats [16,17].

1.3. Scan to BIM in the Maintenance of an Infrastructure

Scan to BIM is the process of capturing the physical characteristics of a structure using a reality capture device like a laser scanner or photogrammetry and then converting that data into a detailed and accurate BIM model [27–29]. Specifically, if Scan to BIM is applied for the maintenance of an infrastructure, it will help in proactive maintenance planning, reducing repair costs and solving interoperability issues by seamlessly transferring the information among teams [30]. For example, by creating an as-is BIM model, maintenance teams can easily identify defects and plan maintenance activities in advance. This proactive planning may reduce unplanned disruptions and may lower maintenance costs.

Recently, Scan to BIM has been applied to the lifecycle management of road infrastructure [31,32], estimating the material quantity and maintenance cost of a project [30] and generating BIM for the maintenance of roads [33]. Although these proposed methods provide a generalized method for extracting maintenance-related parameters from a scanned point cloud and then integrating these parameters with BIM models, a detailed framework of Scan to BIM is required for railway track maintenance. The existing method of Scan to BIM cannot be used for extracting and managing the maintenance-related geometric parameters of railways. Specifically, a systematic framework is needed to standardize the extraction of geometric parameters that are required in the maintenance of railway tracks. An integrated method of these parameters in BIM is also required for an easy analysis of these parameters, which in return will help in defect identification and localization. This approach can help in the efficient maintenance of railway tracks and can reduce the cost of maintenance [34]. By integrating maintenance-related parameters into BIM, the BIM model becomes a dynamic representation of a railway track, which is continually being updated with the most recent data. In this way, maintenance decisions become proactive, as the BIM model provides an overview of track conditions in a timely manner, enabling predictive maintenance planning and cost savings [35].

This paper presents a framework of Scan to BIM for a railway track. In this framework, a standardized method for the extraction of geometric parameters from point cloud data is presented, and then, the integration of these parameters into BIM is proposed, specifically for the maintenance of railway tracks. The contribution of this work is twofold. First, it involves extracting geometric parameters at regular intervals that align with the station points in the BIM model. Second, it introduces new points along the station chainage to store these parameters. This additional step of introducing new points is essential, because standard BIM software (e.g., Civil3d 2022) do not allow for the dynamic values of these measurements to be directly integrated. This approach not only enhances the safety and reliability of railway tracks but also offers significant cost benefits by preventing critical issues and minimizing downtime. This approach also helps to give a holistic view of track conditions that will help with effective and proactive decision making.

2. Literature Review

The Scan-to-BIM process is used in the maintenance of civil infrastructures [31,32]. In this process, representative parameters are extracted from a scanned point cloud, and then, these parameters are integrated into BIM. This process results in an as-is BIM model.

2.1. Parameter Extraction from 3D Point Cloud Data

Recent studies have explored the potential of 3D point cloud data processing for various applications in construction and infrastructure. For instance, Mirzaei et al. [36] provide a comprehensive review of machine learning techniques applied to point cloud data, underscoring the advancements and future directions in this field. The geometry of a railway track, captured in a scanned point cloud, determines the performance, safety, and comfort of rail travel. This geometry is characterized by several parameters, including the

alignment, elevation profile, gauge, cant, and twist. These parameters are important for the maintenance and operation of a railway system, as they affect the track's quality, stability, and durability. One of the challenges in the measurement of these parameters is the extraction of the rail head from the point cloud data, obtained by laser scanners or other sensors. The rail head is the top surface of the rail, which is in contact with the wheel. Rail head extraction is essential for determining the gauge, alignment, and profile of the rail, as well as for detecting defects, wear, and damage. There are various methods for rail head extraction in point cloud data, which can be classified into two categories: segmentation-based methods and model fitting-based methods. Segmentation-based methods aim to separate the rail head points from the background points by using geometric features [37,38]. Model fitting-based methods aim to fit a geometric model, such as a line [39], or a cylinder [40], to the rail head points by using the RANSAC algorithm. Segmentation-based methods are usually faster and simpler than model fitting-based methods, but they may suffer from noise, outliers, and occlusion. Model fitting-based methods are usually more robust and accurate than segmentation-based methods, but they may require more computational resources and prior knowledge of the rail's geometry. Maintaining proper rail alignment is crucial for ensuring a smooth and safe journey.

Extracting rail alignment involves defining a centerline between railway tracks. In the case of a point cloud, various methods, such as using the average coordinate of each pair of points in both rails [18], RANSAC-based line fitting [41], and the minimum enclosing rectangle [40], have been employed for accurate alignment extraction. In these point-cloud-based methods, estimated alignment can be erroneous when some part of a track is not scanned and a corresponding point in a pair of rails is not available. The gauge of a railway track is the distance between the inner sides of the two rails. Gauge defects are the most common cause of derailments [42]. The gauge can be measured in a point cloud by using different methods, such as the smallest-distance method and the minimum enclosing rectangle method [43], which finds the minimum enclosing rectangle of the rail head points and then computes the distance between the opposite sides of the rectangle. However, this method may cause errors when a rail has irregularities, and the rectangle may not fit accurately. The cant and twist of a railway track are the parameters that describe the cross-level and the rate of change of the cross-level, respectively. The cross-level is the difference in elevation between the two rails of a track. The cant and twist are important parameters for ensuring the comfort and safety of a train's movement, as they affect the centrifugal force and the lateral stability of a train. The cant and twist can be measured by using different methods, such as (1) the height difference between two rails in a point cloud; (2) the inclination angle method, which measures the inclination angle of the rail by using an inclinometer or an IMU [44]; and (3) using a Global Navigation Satellite System (GNSS). These sensor-based measurements may not be compatible with BIM software, and the amount of data generated may also need additional storage and data management technology. Moreover, existing parameter extraction methods do not have a uniform approach, and these extracted parameters are inconsistent. The extraction of these parameters is a sequential process, because they depend on each other. This means that the determination of one parameter depends on the prior extraction of another parameter. For instance, alignment is extracted after rail head extraction, and the twist parameter can be extracted after the extraction of the cant parameter. This mutual dependency of parameter extraction requires a consistent pipeline of methods. Therefore, the method for parameter extraction needs to be standardized.

2.2. Data Management Systems

Data management systems have been developed to analyze and visualize maintenance-related data [45]. These systems provide a platform for enabling the prediction and optimization of maintenance activities. These management systems can be classified into two categories: centralized systems and distributed systems. Centralized systems store and process maintenance-related data in a single server or a cloud platform, which provides

unified access and analysis for users [46]. Distributed systems store and process railway track geometry data in multiple devices or nodes, which provide decentralized and parallel access and analysis for users [17].

These data management systems are being standardized by buildingSMART in the Industry Foundation Classes (IFC). The IFC standard is a data model that is used in the Building Information Modeling (BIM) industry to facilitate the exchange of information between different software applications. The latest version of IFC, IFC 4.3 [47], introduces specific elements to model a specific type of structure. Smaller structures (e.g., buildings) are modeled based on smaller elements like doors, windows, etc. [48]. Larger linear structures (e.g., railway, bridges, and roads) are modeled based on alignment line and geometric parameters. These geometric parameters define the shape of an infrastructure along the alignment line. Developments of these standards focus on the design stage, and maintenance-related parameters are not considered in these standards [49]. There is an active research area devoted to modifying these standards for the maintenance of an infrastructure during its lifecycle. In this struggle, information related to the physical defects of a building has been integrated into BIM for IFC 2.x standards [50,51]. For the maintenance of linear structures like bridges and railways, information related to physical defects has been also integrated into BIM [52–54] by defining shapes similar to defect shapes. However, these methods cannot be used for integrating geometric parameters and localizing geometric defects in railway tracks. These geometric parameters are measured along the alignment line of an infrastructure, in the latest IFC standard (version 4.3). Moreover, the nature of information is different for physical defects and geometric defects. A physical defect is usually described in the IFC by its location, type, and depth information. These properties are static and limited to a point. On the other hand, geometric defects are deformations in the geometry of a structure, and these defects are identified by analyzing geometric parameters. Geometric parameters, such as the gauge, cant, and twist, are dynamic and vary along the alignment. These parameters are measured multiple times along the alignment to provide a comprehensive understanding of a track's condition. The integration of these varying parameters in BIM at the maintenance stage is not possible [49]. Specifically, the integration of these varying parameters is not possible with the existing method of physical-defect integration. BIM-related software do not have the option to store measured values of these parameters corresponding to the measured location. Given these challenges, there is a need for further research to develop a method that can effectively integrate maintenance-related geometric parameters in BIM. Such a method would enhance the effectiveness of maintenance planning and analysis and would contribute to the safety and efficiency of railway operations.

In sum, the use of a point cloud for railway track inspections is becoming increasingly popular [55] due to its ability to capture the accurate geometry of a track. Geometric parameters can be extracted from this point cloud for the inspection of a railway track. However, existing methods for the extraction of these parameters are not mutually consistent [56]. There is a need for a standard pipeline of methods that are mutually consistent, and parameters are uniform. Also, the integration of geometric parameters extracted from point clouds into BIM is essential for efficient railway track maintenance. Geometric defects can be localized in BIM based on this integration. Scan to BIM provides a holistic view of the railway infrastructure, addresses interoperability issues, and improves the efficiency of maintenance operations.

3. Framework

The proposed method for Scan to BIM in railway maintenance consists of five steps (Figure 1): (a) the point cloud of a railway track is used as the input, (b) representative parameter extraction, (c) the integration of parameters in BIM, (d) defect detection criteria, and (e) creation of an as-is BIM-model representation with localized defects. The first step in the process involves scanning the railway track. This scanning will generate a point cloud, which is a set of data points on the surface of a track in a 3D coordinate system. In the

second step, representative parameters of a railway track are estimated. These parameters include the rail head, rail profile, alignment of the centerline, gauge, cant, and twist. In the third step, the estimated parameters are then integrated into a BIM model for maintenance planning and analysis. The integration method proposed in this study involves storing the measured parameters at station chainage points. In the fourth step, defect detection criteria are defined based on the selected standard. This defines the tolerance limit and threshold values. Lastly, an as-is BIM model is created for the visualization of a railway's current condition. In this as-is model, defects are localized by analyzing the parameters in this model.

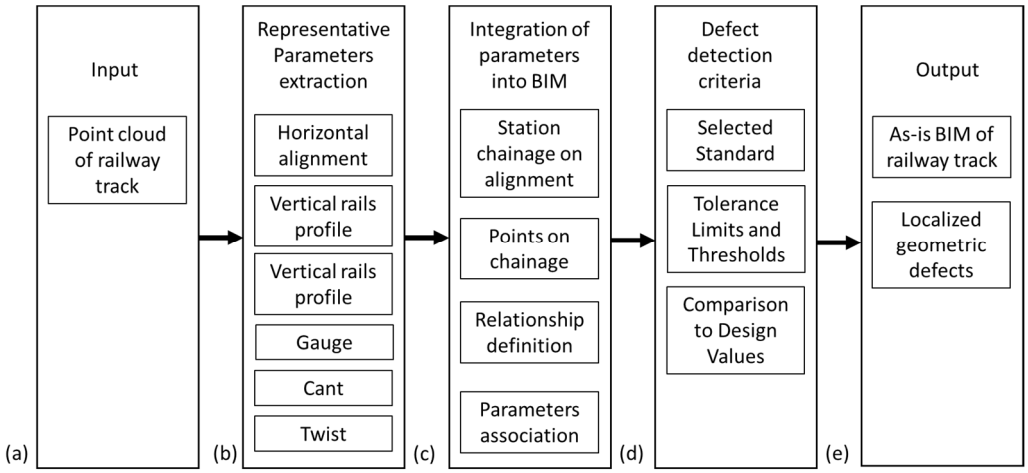


Figure 1. Framework of Scan to BIM for railway track maintenance.

In the following sections, the proposed framework will be discussed in detail. Section 3.1 focuses on the extraction of representative parameters, while Section 3.2 covers the integration of these parameters into the BIM model. The criteria for detecting geometric defects and their localization in railway tracks is discussed within Section 3.3.

3.1. Representative Parameter Extraction

This section focuses on the extraction of representative parameters from the point cloud of a rail's head, specifically, its geometric parameters are focused on here. These parameters include the horizontal alignment, vertical profiles, gauges, cant, and twist of rails. This process begins with the extraction of the inner boundaries of both rail heads. These delineated boundaries are subsequently utilized to find the vertical profile of the rails. The centerline of these lines is considered as the alignment. This alignment is segmented into a fixed interval of the station chainage for the extraction of other parameters. The gauges, cant, and twist are then computed corresponding to these station chainage points. Further details about this process are presented in subsequent paragraphs.

For the extraction of geometric parameters from a rail's head, the inner boundary of the rail's head is extracted. This boundary is considered as the edge of the top surface of the rail head (Figure 2a), inspired by [40]. This extraction of the inner boundary can be automatic or manual. For the automatic extraction of a rail's head (inner boundary), the first rails are segmented, and then, the inner boundary of the rail head is extracted. For extracting a rail's head automatically, a cylinder is assumed on the points, and such points are selected that do not have points above them and that do not have points around this point within a circular range. The height of the cylinder is supposed to be less than the rail's height, and the radius of the circle should be less than the distance between the rails. These parameters of the cylinder will ensure that only the points on top of the rail will be selected. For selecting the inner-boundary points, the smallest rectangle is fitted on these points. This method is repeated along the complete rail head. These selected points have 3D coordinates that can be decomposed into the rail's horizontal and vertical profile. In the second method of inner-boundary extraction, points are manually extracted, and a polyline

is fitted on these points (Figure 2b). Manual extraction tends to be more accurate than the automatic method, as it picks all the points. On the other hand, rectangle fitting may miss some points when there is noise irregularity in the rail. Additionally, the safety of railway tracks cannot be compromised. The resources and energy required to extract this line are worth compromising to ensure this safety. The accuracy of parameter extraction is ensured by accurately determining the inner boundary manually at the rail's head. In the proposed framework, the extraction of the boundary line on the rail's head is conducted manually to ensure accuracy.

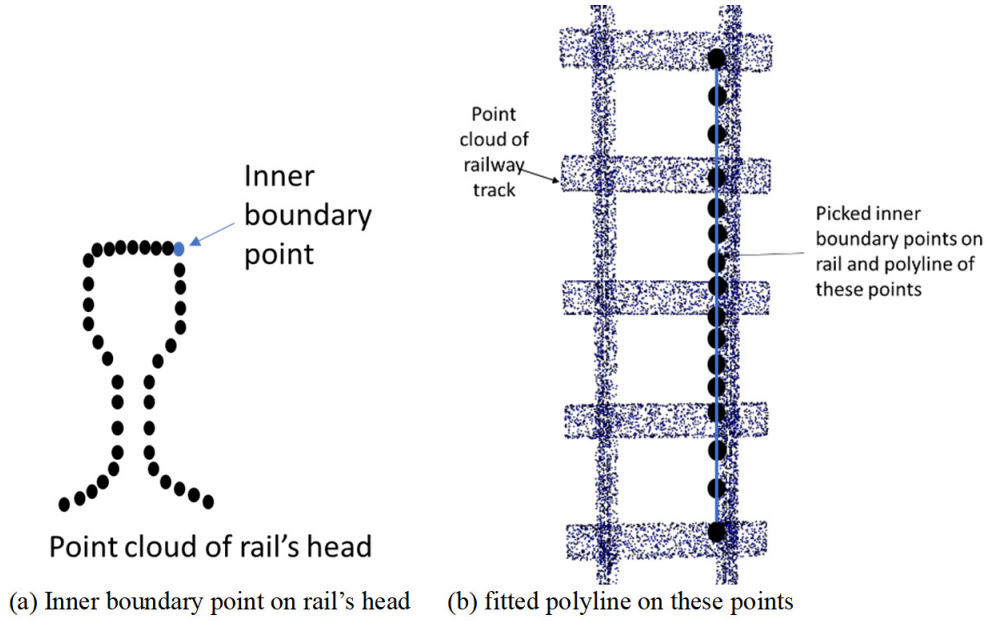


Figure 2. Manual process of inner-boundary extraction at rail's head.

For alignment extraction, a line is computed at the center of the track, which represents the alignment of a railway track (Figure 3a). For finding the centerline, which will represent the alignment, a rectangle is fitted on the points from the previous step [40]. However, this method may give an erroneous fitting of the rectangle when there are irregularities in the rail. To overcome this issue, circles are fitted on the polylines of the previous step (Figure 3b). These circles are drawn with varying diameters, until they touch the polylines. For this fitting, a point is picked on a polyline, and a perpendicular line is drawn on it. Then, a circle is drawn on this line, such that the circle touches the polyline, while the center point is perpendicular. The diameter of this circle keeps increasing until it touches another line. While increasing the diameter of this circle, the step size of this is kept small enough to maintain accuracy. Specifically, this step size was chosen to be 1mm based on the usual accuracy of point clouds [57]. The centers of these circles represent the centerline, also called the alignment. Along with this alignment, the vertical profile of the rails can be extracted with these polylines. These polylines have 3D coordinates of the rail's head. The third coordinate represents the elevation of the rail head in a local coordinate system. This third coordinate can be separated and represented as a profile.

In the past, geometric parameters were extracted by drawing a perpendicular line on a fitted polyline on the inner boundary of the rail head [38]. However, this method does not provide any location information about the measured point, making it difficult to integrate with BIM due to the absence of the measuring location. To address these limitations, the extraction of parameters along the alignment at station chainage is proposed. Station chainage in railways is just a way to measure and mark the distance along the tracks from a specific starting point. These extracted parameters are then associated with these station chainages to easily determine the location of a parameter. A station is a fixed reference point, once the structure and station chainage are the distance along the alignment from the station point to a specific point along the structure. Station chainage can be calculated based on the centerline

alignment and also on the vertical profile and, in a local coordinate system, using linear interpolation (Figure 4a,b). This station chainage can be converted to global coordinates using survey points available along the track by drawing a perpendicular line on the alignment from the control point, established by a surveyor (Figure 4c). To mark the chainage on the alignment line, a polyline of the alignment is selected. By considering this polyline as a linear line, the length of this line is calculated (Equation (1)). The number of segments is estimated based on the chainage interval (Equation (2)). Then, the coordinates of the chainage points are calculated using linear interpolation rules (Equations (3) and (4)). To estimate the elevation profile at the chainage points, elevation is interpolated in these points. To interpolate the elevation in a point, two triangles are considered, one with elevations of the end points of a polyline (z1 and z2 in Figure 3b) and the other with the start point and chainage point (z1 and z in Figure 3b). A tangent of the common trigonometric angle (α in Equation (5)) can give the elevation at a chainage. To convert this chainage of a station into a global coordinate system, a perpendicular line is drawn on the alignment line, such that this perpendicular line passes through the survey point (line STCP in Figure 4c). This point of the perpendicular line (ST in Figure 4c) gives the global coordinates of the alignment at that specific point. The remaining chainage can be converted into a global coordinate system then by interpolation. Survey points are marked along the railway track using reflective ball signs or plane reflector signs [58]. These signs can be detected in a manual inspection or terrestrial laser scanning. However, due to their small size, they may not be detected by drone-based point clouds. To overcome this small-size issue of such signs, [59] experimented with signs of a larger size that can be detected by a drone-based point cloud.

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (1)$$

$$n = d/i \quad (2)$$

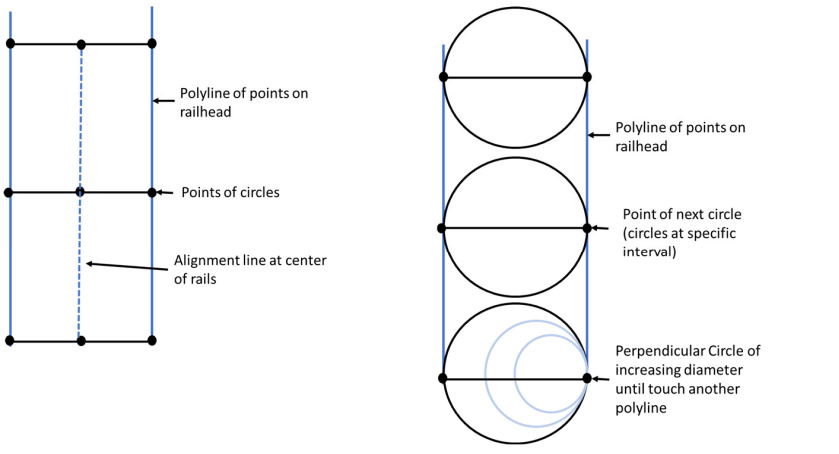
$$x = x_1 + n(x_2 - x_1) \quad (3)$$

$$y = y_1 + n(y_2 - y_1) \quad (4)$$

$$h = h_1 + (n \times \tan(\alpha)) \quad (5)$$

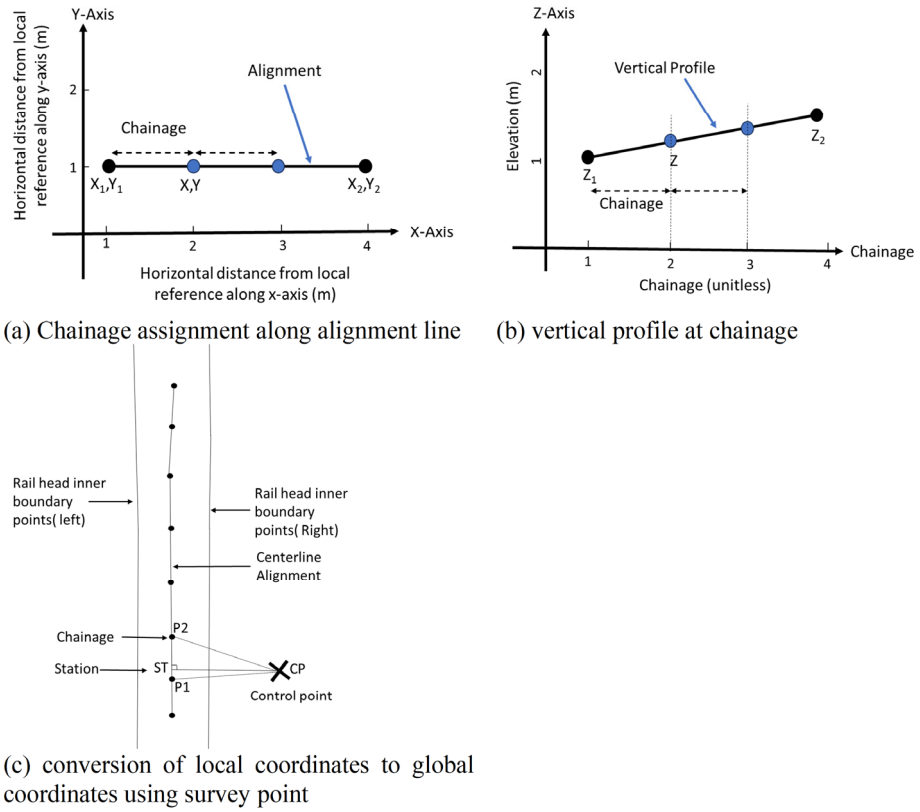
where

- d = the length of a line segment;
- n = the number of chainage points in a line segment;
- i = the distance between consecutive chainage points along the line segment;
- x, y = the horizontal coordinates of line segment;
- h = the elevation of a point;
- α = the vertical gradient of a line segment.



(a) extracted alignment of rails (b) fitting of circles that touches the polylines

Figure 3. Finding the alignment of rails.

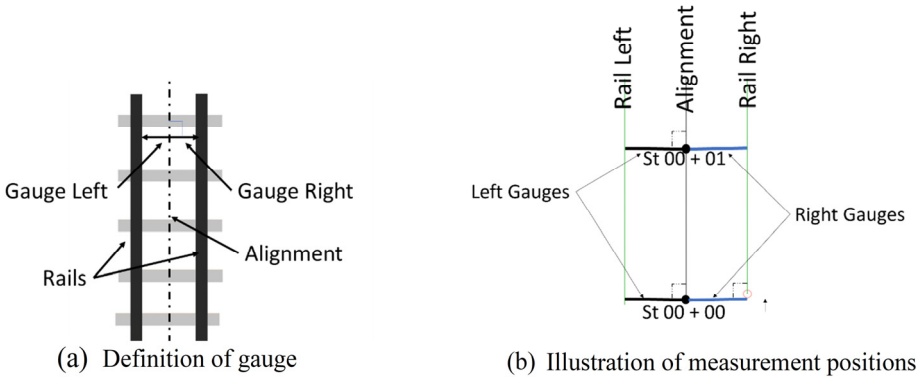


(a) Chainage assignment along alignment line (b) vertical profile at chainage

(c) conversion of local coordinates to global coordinates using survey point

Figure 4. Schematic of station chainage at extracted alignment. (**a**) illustrates the chainage on the horizontal axis, (**b**) shows the vertical axis and the definition of chainage, and (**c**) depicts the control point used to convert local coordinates to global coordinates.

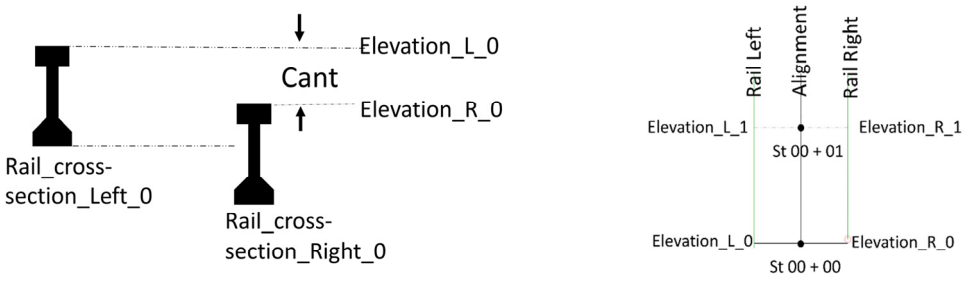
The subsequent step in the parameter extraction process concerns the gauge (Figure 5a). The gauge, which is the distance between two rails, can be extracted at chainage points. One common method to determine the gauge is by finding the closest point on a corresponding line [39]. However, this method may cause the gauge measurement line to be skewed and may cause erroneous results due to potential deformations of the rail, or if the corresponding part of a rail line was not scanned. To overcome this issue, the gauge is measured from the centerline alignment to the left and right side, separately (Figure 5b). This measurement approach was also emphasized by [60]. For each gauge measurement, a perpendicular line is drawn on the centerline alignment, by considering the tangent line on the alignment as the base line for the perpendicular line. Based on these measured gauges, defects in a railway track can be localized by thresholding the acceptable gauges. This acceptable range of gauges was developed by the European Committee for Standardization (CEN) in EN 13848-5 [61].



(a) Definition of gauge (b) Illustration of measurement positions

Figure 5. Measurement of gauges along alignment chainage.

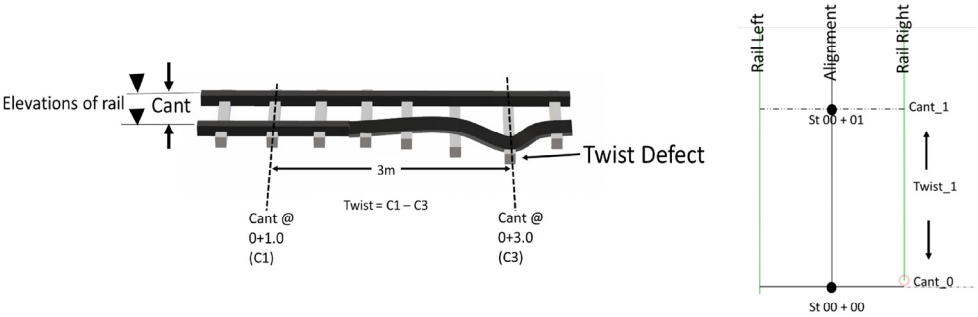
The next step in the parameter extraction process is cant extraction (Figure 6a). The cant of a railway track refers to the difference in elevation between the two rails. For cant extraction, the difference in elevation in the rail profile at station chainage points is proposed (Figure 6b). This provides a measurement of the cant at each chainage point along the track. For this property's extraction, the rail's vertical profiles are used. The elevation of a rail head point is subtracted from the corresponding rail head point in a second rail. For consistency, station chainage is used.



(a) cross section of rails for defining the cant (b) top view of rails

Figure 6. Extraction of cant along rail track alignment.

The final step in the parameter extraction process is twist extraction (Figure 7a). The twist of a railway track refers to the rate of change of a cant along the track. For twist extraction, the subtraction of consecutive cants is proposed. This provides a measurement of the twist at each chainage point along the track (Figure 7b). The usual practice of twist calculation is based on an interval of 3 m [62]. This 3 m interval is estimated using station chainage points. This measurement of the twist is conducted at each station chainage [62].



(a) Illustration of twist in rails (b) Illustration of twist extraction method and position

Figure 7. Extraction of twist along alignment chainage.

3.2. Parameter Integration into BIM

The accuracy of parameter extraction is ensured by accurately determining the inner boundary manually at the rail's head. The extracted parameters are integrated into BIM. For this integration, the Industry Foundation Classes (IFC) 4.3 standard is used. This standard is a comprehensive schema designed to facilitate the storage and exchange of BIM-related data across various software platforms. Tailored to model extensive infrastructures such as railways, roads, and bridges, IFC 4.3, however, is limited in its ability to store varying measurements or values for parameters at each chainage point, as it is primarily developed to record uniform property values. To overcome this limitation, two approaches can be adopted, (1) creating multiple segments of an alignment and associating a specific set of parameters to each segment (Figure 8) or (2) defining Cartesian points at chainage positions and associating measurement properties and their values to them (Figure 9). Cartesian

points can be thought of as coordinates on a map, indicating specific locations. Each point is defined by three numbers (x, z, and y), representing distances along the horizontal (x- and y-axis) and vertical (y-axis) directions from a starting point known as the origin. The first approach of multiple segments can lead to a redundancy of the data, especially when default values are used for parameters that are not measured. For example, in implementing this segmentation approach in the Civil 3D 2022, the alignment of a railway track is divided into multiple segments. Then, for each segment, properties are defined in a cross-section, called an assembly. This assembly has the complete geometric information of a track, including its underground part. By defining multiple assemblies, the irrelevant information that has not been measured is saved repeatedly. This repetition of data uses memory and slows the computer. Moreover, these assemblies are designed for design parameters, and maintenance-related parameters may not be stored in these assemblies.

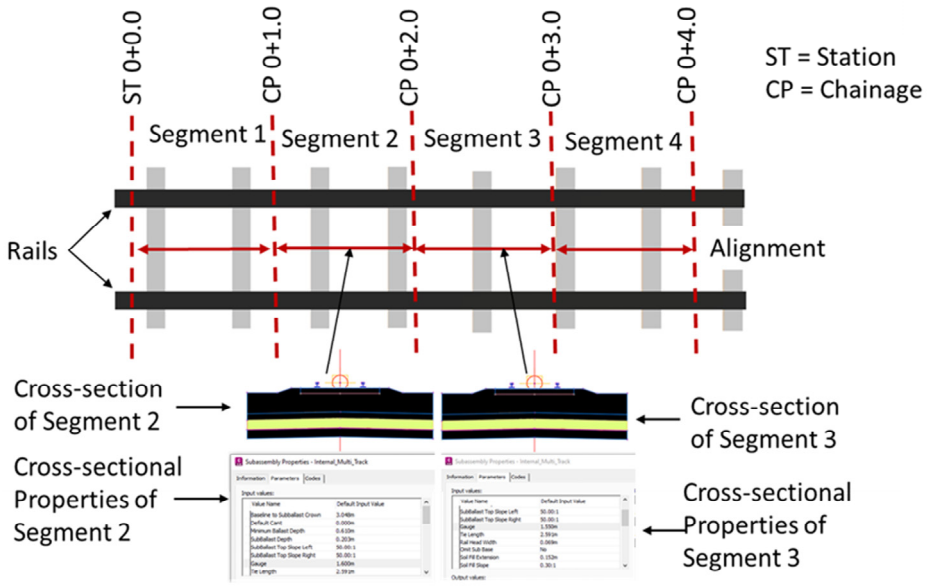


Figure 8. Railway track model segmented into parts.

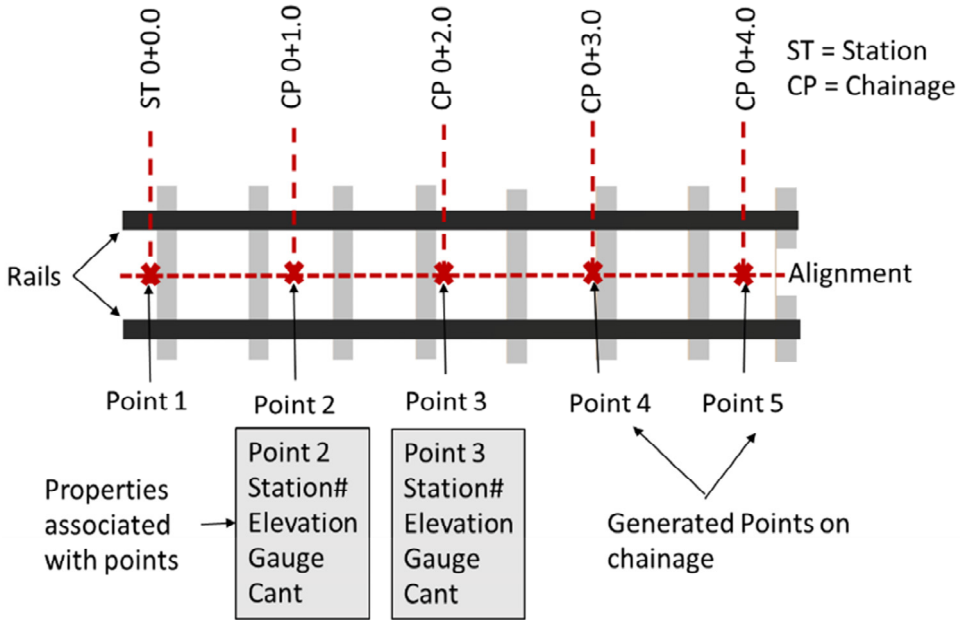


Figure 9. Illustration of the points generated at alignment stations.

For the point-based approach (Figure 8), points are generated at the station chainage, and then, maintenance-related parameters are described as properties of these points. Measured values of parameters can be stored in corresponding points. By introducing a point-based approach, the redundancy of data will be reduced. Furthermore, this approach allows for the use of the level-of-detail approach, in which these points, having parameters and measured values, can be turned off to speed up the visualization and loading of data. This will enhance the visual efficiency of the BIM model.

For describing these points based on IFC 4.3 standards, the schema is described as a unified modeling language (UML) in Figure 9. In this schema, an existing entity within the IFC 4.3 standards, the Cartesian points are introduced at a corresponding chainage (Figure 9). These points are shown as *IfcStationChainage* in Figure 10**.** These points have the following properties: *ChaingeId* for the differentiation of points and x, y, and z, coordinates for correspondence with the chainage. These points are then associated with the existing railway alignment element, named *IfcRailwayAlignemnt,* utilizing an association relationship, termed *IfcRelNest* [63]. In this association, an element of the railway alignment (*IfcRailwayAlignemnt*), being the parent object in this relation, is called the *RelatingObject* [63], and multiple Cartesian points, being the child object in this relation, are called the *RelatedObject* [63] (Figure 9). This association is shown as *hasPoints* on the arrows. By introducing this association, the *IFCRailwayAlignment* element now has a property, named *Stations*, that has a list of all these generated points. Subsequently, to associate maintenance-related geometric parameters with these chainage points and to store the measured values, *IfcPropertySingleValue* [64] is employed. Each Cartesian point has the *IfcPropertySingleValue* of the measured parameters, the elevation, gauge, cant, twist etc., and the measured values are stored in these parameters. This relationship is shown as an arrow, named *has*. For the measured gauges, *PsetRightGauge* and *PsetLeftGauge* are defined as the property set. These will store the right gauge and left gauge values, respectively. Similarly, for the profile of the right and left rails, *PsetRightRailElevation* and *PsetLeftrailElevation* are introduced. The measured values of the cant and twist are stored in property sets, named *PsetCant* and *PsetTwist*, respectively. Furthermore, their mutual dependency is also shown with a dotted arrow, named *use.* These mutual dependencies include a calculation of the cant using values of the left and right elevation. Similarly, the twist parameter is calculated by subtracting the cant values sequentially at 3 m intervals.

3.3. Defect Detection Criteria

Defect localization is a critical aspect of railway track maintenance. Defects related to geometric distortion cause functional, safety, and durability issues. If these defects are not corrected in a timely fashion, they can cause accidents too. To identify defects, geometric parameters, integrated into BIM in the previous step, are used. If the designed BIM model is available, the parameters of both models can be compared using a station chainage point. If the designed BIM model is not available, thresholding is applied to the parameters, and these parameters are considered defective if their value is above the tolerance limit. These tolerances are defined as the accepted amount of variations of geometry parameters from nominal values or design specifications [65]. Standards of acceptable tolerance limits established by organizations in Europe include the ISO 23054-1:2022 [66] and BS EN 13848 series [67]. These standards define track geometry parameters and specify the minimum requirements for track geometry measurements. The EN 13848-5 European Standard [67] defines the minimum requirements for the quality levels of a track's geometry. In Korea, the Design Standards of Korean Railroad [68] provides guidelines for railway construction, including a track's geometry. There is also research being conducted on the rectification of track geometry defects based on track deterioration modeling and derailment risk assessments [68]. In America, the Federal Railroad Administration and the Association of American Railroads [69] provide standards and recommend practices for the quality of a track's geometry. The Track and Rail and Infrastructure Integrity Compliance Manual [70]

provides track inspection standards and procedures. These standards help ensure the safety and efficiency of railway transportation in their respective regions.

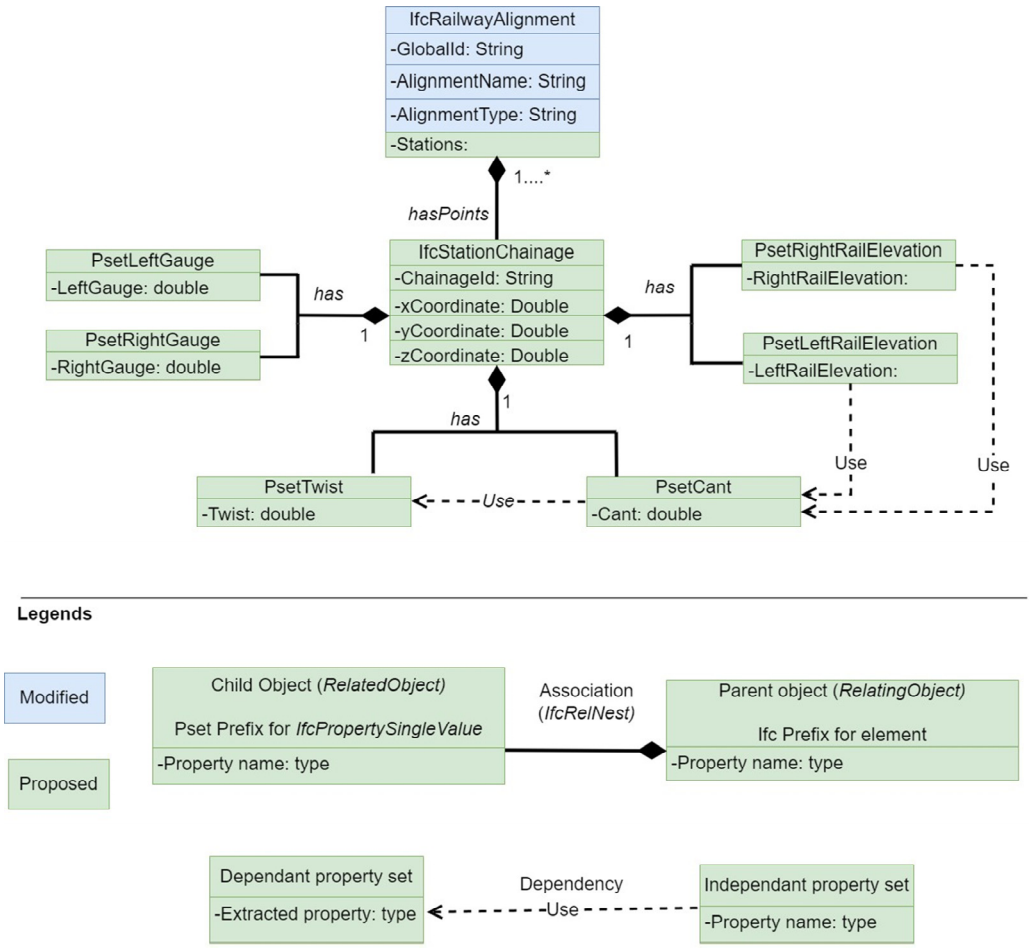


Figure 10. Proposed method of parameter integration into unified modeling language (UML).

4. Case Study

A case study was conducted on a 200 m segment of a railway track using a DJI Phantom drone in Uiwang, Korea, as a testbed (Figure 11). The drone was systematically programmed to capture images at 3-second intervals while maintaining a consistent altitude of 30 m above the ground level. The flight path, pre-defined within DJI's proprietary software, ensured thorough coverage of the railway track segment designated for this study. Subsequent to the aerial survey, a point cloud was generated using the Pix4D 4.9.0 software, leveraging the aerial imagery to construct a detailed 3D model of the railway infrastructure (Figure 11). In this case study, geometric parameters were extracted, and then, these parameters were integrated into BIM according to the proposed method. After this Scan-to-BIM process, the railway track was evaluated for geometric defect localization. The selected track segment was scanned using a drone camera, named DJI phantom. The images were captured by the drone at an elevation above the electrical system of the railway. These images were processed in a commercial software to generate a point cloud (Figure 11), which provided a 3D representation of the track. The point cloud was then used to extract key maintenance parameters such as the gauge, cant, and twist along the alignment. These parameters were measured at chainage station points along the 180.75-meter segment to provide a comprehensive understanding of the track conditions.



(a) Location of rail track (b) The rail track in real (c) Point cloud of rail track

Figure 11. Selected railway track segment for case study in Uiwang-si, South Korea.

In the first step of parameter extraction, a 3D polyline was fitted on the rail. For this line fitting, points were manually picked at the inner boundary of the rail head (Figure 12a). The interval between points was kept very small to increase accuracy. At curved sections, points were picked carefully at very small intervals. On the other hand, for straight tracks, point selection involved a relatively larger distance. Then, a polyline, a combination of linear line segments, was fitted on these selected points (Figure 12b).



(a) selected points on rails head that represent inner boundary (b) the fitted polylines on rail's head

Figure 12. Inner-boundary extraction of rail's head.

From this polyline, horizontal coordinates were separated to make a horizontal and vertical profile of the rails (Figure 13). Station chainage was calculated at these profiles by assuming the station 0 + 00 at the start of the profile. Station chainage was calculated using Civil 3D's built-in functionality of generating alignments. A centerline is generated by drawing circles on each chainage point and by increasing the diameter until the circle touches another polyline. The center of the diameter is the alignment point. The alignment was created by joining these points. This alignment is shown in Figure 13. Then, gauges were calculated at these station chainages. For calculating the gauges at chainages, a perpendicular circle is drawn from the alignment line that touches the rail. The left and right gauges were calculated separately. Other parameters include the following: the cant and twist were also calculated at this station chainage. For calculating the cant, vertical profiles of the rails were subtracted from each other at chainage points. Then, the twist was calculated by subtracting the cant at 3 m intervals.

In our case study, the station chainage of the railway track was marked on an electric pole, which is demonstrated in Figure 14. A specific railway pole, labeled as 0 + 154, was selected within the point cloud data. The reference point at this pole was projected onto the estimated alignment line. The distance between this projection point and the estimated station point was utilized as a correction factor. To rectify the estimated chainage, this correction factor was added to the estimated chainage number, ensuring the accuracy of the station's positioning along the railway track.

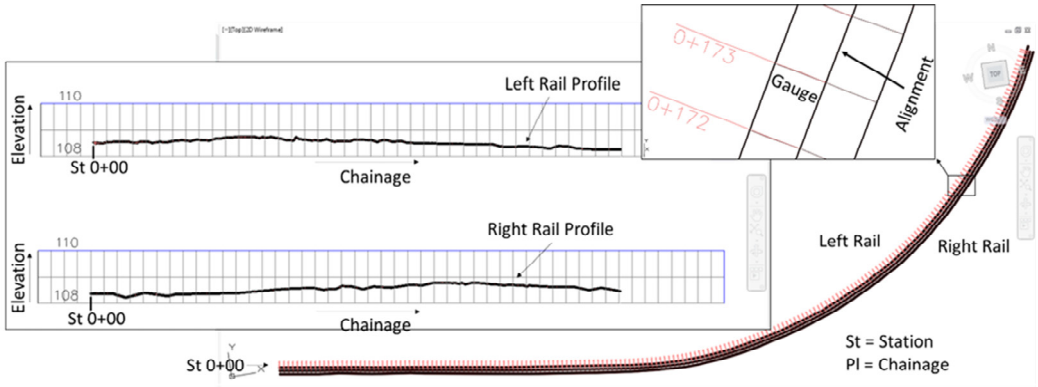


Figure 13. Extracted elevation profiles from 3D polylines of railway track, center alignment, and gauges at station chainage.

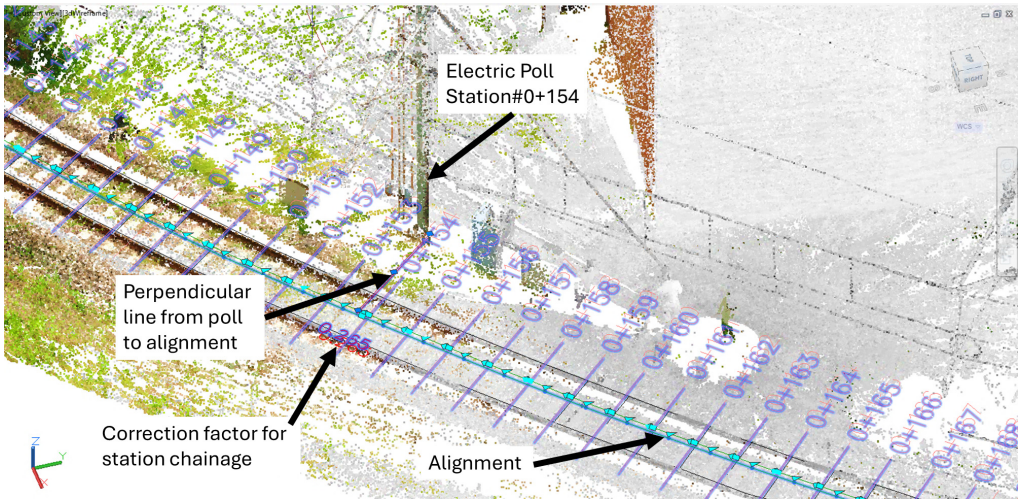


Figure 14. Correction of station chainage numbers by projecting reference point in point cloud on alignment line.

The extracted maintenance parameters were integrated into a BIM model using the proposed method. This involved storing the parameters at station chainage points and associating them with the corresponding points in the BIM model. The proposed method was implemented using a Python library, IFCOpenShell [71], and a model was generated according to IFC standards. A part of the generated file is shown in Table 1, where a Cartesian point was integrated into the alignment of the rail, and then, the corresponding value of the gauge was associated with this point.

Table 1. A generated IFC 4.3 BIM model from case study data using proposed method.

```
#24 = IFCALIGNMENT('1hyOK0yBg3',$,'Alignment',$,'Rail',#23,$,$);
#198 = IFCCARTESIANPOINT((100.,100.,0.));
#199 = IFCRELNESTS('1hylWBg33',$,'StationSubSetOfAlignment',$,#24,(#198));
#200 = IFCPROPERTYSINGLEVALUE('MaintenanceParameters','Gauge',IFCTEXT('1.51'),$);
#201 = IfcRelDefinesByProper-
ties('1hyOK0hab9SfkcUhlWyBg3y',$,'StationProperty','PropertyAssignedToStationChainagePoint',(#198),#200)
```

The framework was also implemented into Autodesk Civil 3D by using coordinated geometry points (Cogo points) as station chainages. In this implementation, Cogo points were generated on chainage points, and each Cogo point was assigned user-defined properties: the maintenance-related parameters. For this integration, a Dynamo program was made in Civil 3D (Figure 15) that loaded the database of the generated Cogo points and a datasheet

that extracted parameters. A Cogo point is selected from the database, and the corresponding parameter value is read from the datasheet. At the end, this value is updated in a property set of this Cogo point using the Object.*UpdateProperty* function. The integration process of one point is shown in Figure 15 for illustration of this process. The integration of all points was implemented by introducing loops at index nodes. The results are shown in Figure 16, where a 3D model of the railway track is shown, which was created with measured parameters. The associated properties are also shown for a point in Figure 16.

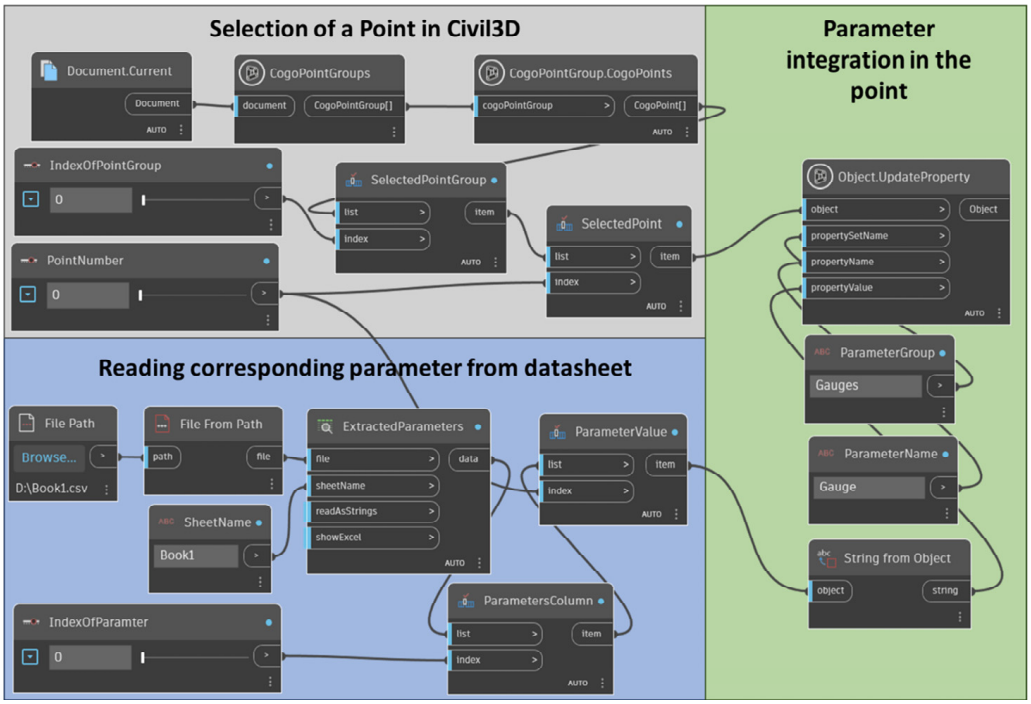


Figure 15. A Dynamo program for the integration of a parameter into a Cogo point of Civil 3D.

The track in this case study was evaluated using the European Standard EN 13848-5. This standard classifies geometric defects into three categories: alert limit, intervention limit, and immediate action limit. The alert limit indicates the initial stage, warning a closer monitoring and investigation of defects. The intervention limit means a serious level that needs urgent attention to repair the defect and to avoid it from getting worse. The immediate action limit means a situation that needs immediate actions to avoid accidents. These limits are related to the different speeds of trains. For an urban rail transit, the speed is usually about 80 km/h [72,73].

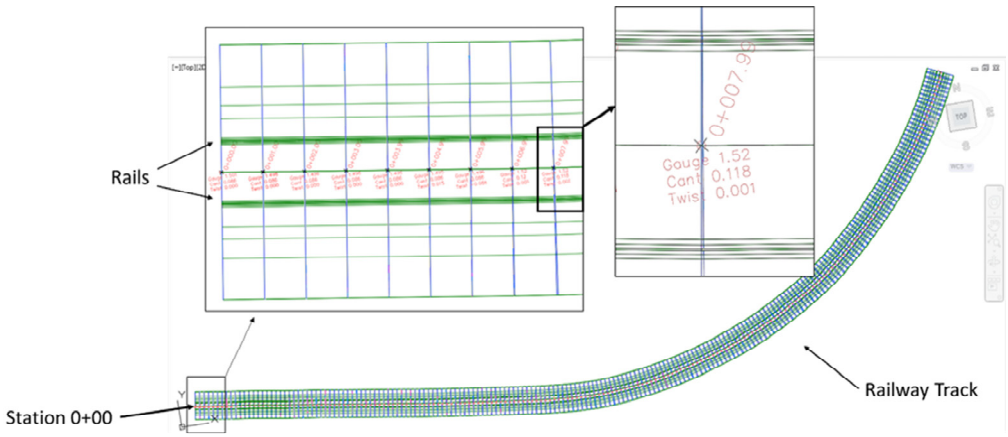


Figure 16. Implementation of proposed method in Autodesk Civil 3D for verification.

Table 2 shows the safety limits for this speed. The standard gauge value was assumed to be 1.435 m. In this case study, we estimated the defect location by finding the parameters that have values beyond the acceptable limits. The integrated parameters in BIM were extracted and are shown in Table 3, and defects are localized in this table based on EN 13848-5 thresholds. If the parameter value was beyond the acceptable limit, the value was colored according to the severity of the defect.

Table 2. Standard values and acceptable ranges of parameters in railway track.

Quality	Gauge (mm)		Twist (mm/m)
	Lower Limit	Upper Limit	
Alert limit	−7	25	4
Intervention limit	−9	30	5
Immediate action limit	−11	35	7

Table 3. Estimated and integrated parameters in BIM (Civil 3D implementation).

Point Index	Station	Gauge Left (m)	Gauge Right (m)	Gauge (m)	Left Elevation (m)	Right Elevation (m)	Cant (m)	Twist (m/m)
1	0 + 000.00	0.749	0.752	1.501	108.329	108.243	0.086	0.000
2	0 + 001.00	0.749	0.749	1.498	108.33	108.244	0.086	0.000
3	0 + 002.00	0.748	0.748	1.496	108.33	108.244	0.086	0.000
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
88	0 + 086.88	0.731	0.73	1.461	108.676	108.499	0.177	0.000
89	0 + 087.88	0.725	0.725	1.45	108.676	108.499	0.177	0.000
90	0 + 088.88	0.721	0.724	1.445	108.676	108.499	0.177	−0.012
91	0 + 089.88	0.723	0.724	1.447	108.676	108.499	0.177	−0.012
92	0 + 090.88	0.703	0.705	1.408	108.641	108.499	0.142	−0.007
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
180	0 + 178.75	0.704	0.71	1.414	108.514	108.329	0.185	0.016
181	0 + 179.75	0.703	0.723	1.426	108.515	108.329	0.185	−0.062
182	0 + 180.75	0.709	0.739	1.448	108.563	108.329	0.233	−0.078

To visualize the defect in the Civil 3D software, we employed a layer-based approach, detailed as follows:

- New layers were established within the Civil 3D project, each corresponding to different levels of defect severity (e.g., immediate, intermediate, and alert).
- The visual attributes (color and shape) of points were defined for each layer.
- A Dynamo script was developed to assess the geometric parameter values against the established limits.

Upon detecting a parameter value within a certain limit range, a new point was instantiated at the corresponding chainage location.

- This point was then assigned to the layer indicative of the identified limit range.

The Dynamo script's relevant segment, which facilitates the creation of points and their allocation to the respective layers, is illustrated in Figure 17. Additionally, a Python script related to this Dynamo implementation is presented in Table 4. This script includes a condition to identify defects based on the gauge value. If the gauge value exceeds 1.470 m or falls below 1.424 m, it identifies a defect and sets the geometry accordingly. The visualization of gauge defects within Civil 3D, as achieved through this methodology, is showcased in Figure 18.

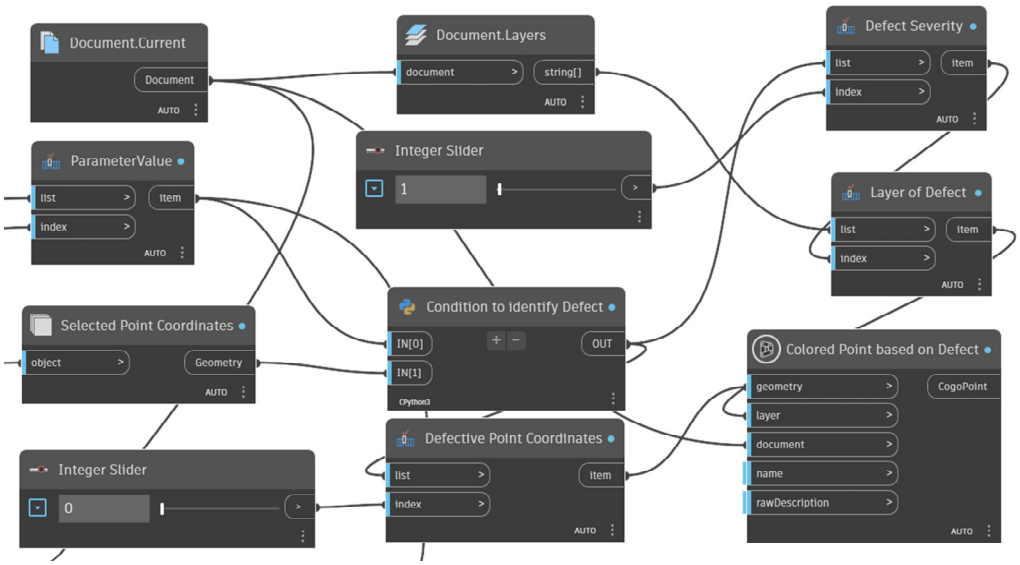


Figure 17. A Dynamo program for creating points at defects' location and assigning the corresponding layers.

Table 4. Dynamo node, named "Condition to Identify Defect" in Figure 17.

```
data = IN
gauge_value = data[0]
geometry = data[1]
output = []
if gauge_value > 1.470 or gauge_value < 1.424:
    # If the condition is true, set the geometry and #0 layer as the output
    output = [geometry, 0]
else:
    # If the condition is false, set both outputs to None
    output = [None, None]
OUT = output
```

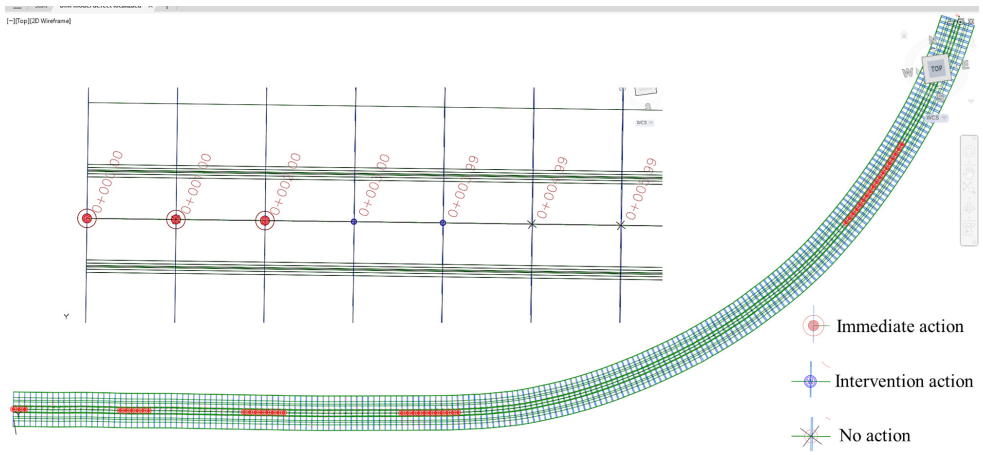


Figure 18. Visualization of severity of defects in BIM model.

5. Discussion

This study primarily focuses on using Scan to BIM for maintaining railway tracks. The key objective was to extract critical geometric parameters from point cloud data and then to integrate them into BIM. These critical parameters include the alignment, elevation profile, gauges, cant, and twist. The extraction of these parameters is essential for effective maintenance strategies. Additionally, for the integration of these parameters into BIM, the generation of points on station chainages and then the association of these properties on this corresponding point is proposed. This framework helps in identifying the specific points along the track (chainage) where defects have occurred.

The extraction of the alignment, elevation profile, gauges, cant, and twist from a point cloud is a noteworthy contribution of this research. For the extraction of the alignment, points are picked on the edge of the top surface of the rail. This approach was inspired by [40], by assuming a square-shape head of the rail. This square shape was assumed in this framework, because rail heads appear to be square due to the low resolution of a point cloud. The real shape of a rail head with curved corners at the top can be captured by high-resolution scanning [38]. In such cases where the real shape of the rail head can be scanned, a plane may be fitted on top of the head to find elevation-related parameters (i.e., profile, cant, twist, etc.), and a plane is fitted on the side of the rail to find the alignment and gauge. The proposed framework is also applicable in such scenarios by assuming a line at the center of these extracted planes. These calculated lines on planes will serve as inner boundary lines for parameter extraction.

In the Civil 3D environment, gauges were computed by drawing a perpendicular line from the alignment line to the rails. This approach solves the problem of underestimated or overestimated gauges, particularly on curved surfaces or during the uneven scanning of corresponding tracks. The cant is calculated by determining the difference in elevation at the same points used for gauge calculations. Importantly, the twist, a critical parameter in railway track maintenance, is computed by taking the difference of the cant at three-meter intervals for each point. In the EN 13848-5 standards, a cant defect is not evaluated, because cants vary along a track based on the curve angle, and the twist is accommodating of the defect of the cant in it.

In the second half of this paper, the focus shifted towards the integration of these parameters into BIM. The integration of extracted parameters into BIM provides a comprehensive view of a track's conditions, enabling informed decision making for maintenance activities. BIM integration serves as a holistic approach, where the extracted alignment, elevation profile, gauges, cant, and twist contribute to a dynamic and visual representation of the railway track within the BIM environment.

Furthermore, the integration of these extracted parameters into the IFC format and Civil 3D software is a significant aspect of this research. Points along the chainage points are defined, and a user-defined property is assigned at each station. This integration not only enhances the visualization of critical parameters but also facilitates BIM-based decision-making processes for track maintenance. The utilization of Civil 3D as a platform for parameter integration highlights the practical applicability of the proposed framework in real-world scenarios.

In a case study, the usage of this proposed approach of Scan to BIM was shown. In this case study, defects were identified based on a standard, EN 13848-5, and then, these defects were localized using the proposed framework. The defect type and location, in terms of chainage, can be seen in Table 3. The results show that the gauge values of the track were out of the acceptable range, indicating a severe deformation of the track. One possible reason for this abnormality is that this track has not been maintained in a while, as this track is used as a testbed in university settings. Technically, the widening that occurred in this case study may be due to the thermal expansion and contraction of the rails. Additionally, the decrease in ballast level leading to reduced lateral support could also contribute to this issue. Twist defects may be due to uneven settlements of the track.

The proposed framework is inherently scalable and adaptable. In terms of adaptability, our framework can be applied to BIM models at different developmental stages. Once the alignment line is established, our method can be utilized, making it suitable for both early-stage models and fully developed construction plans. Regarding scalability, the simplicity of our method enables its effective application to projects of varying sizes. The scalability of the proposed framework relies on extracting inner lines on rail heads and fitting circles at 1-meter intervals. These gauge and cant values are stored and integrated using a Dynamo program that iterates over stations to integrate data. For larger datasets, the efficient manual extraction of lines can be achieved by ensuring personnel are experienced. To manage larger data sets, high-capacity storage solutions, such as Azure, can be used effectively.

These advanced storage solutions have the capability of developing a digital twin that supports Dynamo's iterative calculations. By leveraging these components and using Dynamo's automation, this framework ensures its scalability and adaptability to longer tracks. Moreover, our framework demonstrates interoperability by successfully integrating it with common BIM languages like IFC 4.3 and commercial software like Autodesk Civil 3D. This ensures that our method can seamlessly integrate into existing BIM workflows without disruption.

6. Conclusions

In summary, using Scan-to-BIM technology for the maintenance of railway tracks provides an efficient approach for the lifecycle management of railway tracks. The detailed extraction of parameters from captured point cloud data allows for the more efficient planning of repairs, enabling maintenance teams to address issues proactively rather than reactively. Moreover, the incorporation of BIM into the inspection process provides a holistic view of the railway environment. This BIM-based inspection data storage not only streamlines the storage and retrieval of crucial information but also addresses interoperability challenges within existing management systems.

In conclusion, this academic paper presents a comprehensive framework for Scan to BIM in the context of railway track maintenance. The extraction of critical parameters from point cloud data and their subsequent integration into the Civil 3D and BIM environments, respectively, contribute to a robust methodology for informed decision making and proactive maintenance strategies in the realm of railway track infrastructure.

The proposed framework of parameter extraction depends on defining a line on the boundary of the rail's head. For accurate identification, the rail head should be clearly visible, with the point cloud having enough detail, low noise, and high accuracy. If the point cloud lacks these features, due to issues such as it being of a low resolution or having occlusions, our method may not work well.

In the proposed framework of Scan to BIM, the manual selection of points existing on the rail's head (inner boundary points) was proposed. This process is slow and tedious. In the future, automatic point selection will be studied. This automatic selection of points will focus on rail head segmentation and then inner-boundary-point extraction. Specifically, a previous study focusses on the parametric method for selecting these points in a point cloud [40]. In the future, this point selection method will be based on deep learning, in order to make it generalizable for all types of tracks. This parametric selection of parameters limits the applicability of this method to a specific type of railway track. Also, parametric methods are not sensitive to noise in point cloud. For the integration part in Scan to BIM, the proposed integration was not optimized for visualization. In the future, the level-of-detail (LOD) standards will be defined for faster loading times and for managing the data. A similar level of detail for maintenance-related data was proposed in [74]. However, that method does not define the standards for maintenance-related parameters.

In the case study, a curved railway track segment was selected due to its inherent complexities. Curved tracks pose unique challenges, including variations in the rail head boundary and heightened demands for accuracy. The successful implementation of our framework in this context supports its ability to handle complex geometries and establishes a basis for its adaptability to other railway configurations. We define reliability as the framework's consistency, accuracy, and repeatability across diverse scenarios. While only one case study is presented, the complexities of the curved track affirm the initial reliability of our framework. Future research should involve a broader range of track geometries, including straight and differently curved segments, to further validate its reliability.

The proposed framework not only enhances the accuracy and efficiency of geometric parameter extraction but also has broader implications for the future of railway maintenance. By ensuring interoperability with BIM, this framework can significantly influence policies by promoting standardized data-integration practices across the industry. This can

lead to the development of new industry standards that prioritize accurate, real-time data for maintenance and inspection tasks.

Author Contributions: Conceptualization, S.K. and B.M.; methodology, B.M.; software, B.M.; validation, B.M. and S.K.; formal analysis, B.M.; investigation, S.K.; resources, B.M.; data curation, B.M.; writing—original draft preparation, B.M.; writing—review and editing, S.K.; visualization, B.M.; supervision, S.K.; project administration, S.K.; funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2023R1A2C1004727). Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the funding agency.

Data Availability Statement: The original data are openly available on GitHub at the following link: https://github.com/bilawal-mahmood1/Scan-to-BIM-for-railway-maintenance (accessed on 7 November 2024).

Acknowledgments: We sincerely appreciate the suggestions from editors and reviewers.

Conflicts of Interest: The authors declare no conflicts of interest.

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