# Feasibility Assessment of a BIM-Driven Robotic Rebar Cage Assembly Framework for Ballastless Railway Track Slab Construction

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**Abstract –**

**Ballastless track slab systems are increasingly adopted in metro and high-speed rail projects due to their superior geometric stability, reduced maintenance requirements, and long-term performance. Construction of such infrastructure is more mechanised, driven by stringent requirements on construction speed, dimensional precision, and repeatability in processes such as material handling, batching, concrete distribution, and slab handling. Despite this high level of mechanisation, rebar cage assembly for track slabs remains largely manual, time-consuming, and ergonomically demanding, and continues to represent a critical bottleneck in ballastless railway track construction. This challenge is further exacerbated by constrained possession windows and limited spatial envelopes typical of metro environments.**

**This paper presents a feasibility assessment of a BIM-driven process planning and robotic assembly framework for rebar cages used in ballastless railway track slab construction. The study adopts a process-level automation perspective, recognising that track slab reinforcement exhibits manufacturing-like characteristics with repetitive yet bounded geometric variability across a project. Parametric BIM models are used to extract rebar geometry and connectivity, which are translated into robot-executable assembly sequences while accounting for geometric feasibility, interim cage stability, and robotic reachability. Feasibility is evaluated using a high-fidelity digital twin implemented in CoppeliaSim, where collision-free robotic pick–move–place operations are demonstrated under representative railway track slab geometries and spatial constraints. The results show that BIM-driven process planning and simulation provide a technically viable pathway for deploying robotic rebar cage assembly systems in metro and high-speed rail construction, subject to further physical validation.**

**Keywords –**

**Construction robotics, rebar cage assembly, ballastless track slabs, BIM-to-robot integration, digital twin, automation**

## 1 Introduction

The growing need for fast and precise construction, as well as safety and scalability, in the expansion of metro and high-speed rail systems around the globe has led to the adoption of ballastless track slab systems like plinth track systems and precast slab track systems over ballasted track systems, especially in tunnels, viaducts, and urban areas. As a result, railway track construction has achieved a relatively high level of mechanization compared to conventional building projects, with activities such as rail welding, slab placement, and material handling being extensively mechanized.

Despite this progress, rebar cage assembly for track slabs remains largely manual and continues to form a critical bottleneck in otherwise mechanized workflows. In current practice, rebar cage preparation for cast-in-situ (CIS) track slabs requires large labor crews operating over extended durations. Similar challenges persist in precast slab manufacturing yards, where upstream processes such as batching and concrete distribution are automated, and Computer Numerical Control (CNC) machines are widely used for cutting and bending of rebars, yet cage assembly and tying remain predominantly manual. Figure 1 illustrates the typical manual preparation of rebar cages on site, highlighting the labor-intensive nature of reinforcement assembly that persists despite extensive mechanization in other track slab construction activities.

Unlike conventional building slabs, ballastless railway track slabs are designed with limited flexibility in geometry and detailing, as they must satisfy strict requirements related to track alignment, stiffness continuity, and long-term structural performance. Consequently, track slab reinforcement layouts are highly standardized within a project. Even where horizontal curves, transitions, turnouts, or station zones are present, the resulting variations are typically confined to a finite and well-defined set of slab and reinforcement configurations. This characteristic renders track slab construction closer to a manufacturing process than a one-off site activity, with repetition and uniformity dominating over ad hoc geometric variation.

Figure 1 Manual preparation of rebar cage assembly on site and prefabrication yard respectively

From an automation perspective, this bounded variability is advantageous. The repetitive nature of track slab reinforcement enables reuse of motion planning strategies and robotic behaviors across multiple slab instances, reducing the need for continuous reconfiguration. While this study evaluates a representative track slab case, the emphasis is on assessing whether a BIM-driven robotic approach is technically feasible and operationally compatible at the project scale, where multiple slab variants typical of metro construction can be accommodated through automated adaptation rather than manual reprogramming, rather than on optimizing productivity for a single instance.

At the same time, large-scale railway projects operate under strict possession windows with multiple construction fronts active simultaneously. Manual assembly of rebar cage under such conditions introduces schedule uncertainty, quality variability, and safety risks, as labor-intensive tasks are difficult to scale across parallel work zones. Recent studies report that physically demanding and repetitive construction work, such as reinforcement work, is one of the least preferred jobs in the industry, which has resulted in the use of migrant workers in large-scale construction projects. Such conditions further emphasize the need to explore the possibility of applying automation techniques in railway construction.

Recent developments in construction robotics, digital twins, and BIM-based automation offer promising pathways to address these challenges. Nevertheless, current robotic technologies are mostly restricted to single-task automation, most prominently rebar tying, or are applicable only in stationary factory environments. Fully integrated, BIM-driven cage assembly frameworks that explicitly address the repetitive yet spatially constrained nature of railway track slab construction remain underexplored.

Against this background, this paper investigates the feasibility of a BIM-driven process planning and robotic assembly framework for rebar cages used in ballastless railway track slab construction. Productivity aspects are explored only at a conceptual level and are not intended as definitive performance predictions while economic evaluation is not part of this paper. Building upon existing studies on BIM-driven robotic reinforcement assembly and feasibility-oriented sequencing algorithms, the objective of this work is to evaluate whether such a framework can be technically realized and deployed within railway-specific geometric, spatial, and operational constraints. The study employs digital process planning and high-fidelity simulation to assess reachability, sequencing feasibility, and collision-free execution, thereby providing an informed basis for future physical implementation in prefabrication yards and, potentially, on-site metro construction using alignment-guided deployment platforms.

## 2 Literature review

Automation in the construction sector has continued to receive considerable attention from research and industry fields over the last two decades, owing to the challenges of low productivity growth, labour shortages, safety concerns, and variability in quality related to traditional construction methods [1]; [2]. In contrast to manufacturing, the construction sector remains largely site-based, labour-intensive, and fragmented, making it difficult to scale traditional productivity enhancement methods. In this scenario, reinforcement work has been identified as a domain of particular relevance for automation, involving repetitive, physically demanding, and time-consuming activities with well-defined geometric and structural constraints [3].

Availability of labour has emerged as a key bottleneck in the delivery of infrastructure projects across the globe. Recent global studies have pointed out that the construction sector is facing one of the most serious shortages of skilled labour compared to other key sectors, due to an ageing workforce, reduced entry of youth into the skilled trades, rising labour costs, and increased regulatory and safety demands [1]. Such issues are even more acute in large metro and railway projects, which are implemented with very tight possession windows, limited site space, and intense schedule pressures. Under such conditions, automation is increasingly being considered not only as a productivity solution, but also as a response to labour dependence, safety, and delivery risks.

Rebar cage assembly is a key bottleneck in reinforced concrete construction. Manual handling, placement, and binding of rebars are prone to serious ergonomic hazards, introduce variability in quality, and often lie on the critical path of construction activities [4]. The physical workload associated with reinforcement installation has been shown to increase with spatial complexity and congestion, further reducing productivity and increasing execution time [5]. These limitations are amplified in slab-type infrastructure elements, such as metro and high-speed railway track slabs, where dense reinforcement layouts must be produced rapidly and within strict dimensional tolerances.

Automation of upstream processes of reinforcement preparation such as cutting, bending, and batching is relatively mature. CNC-controlled machines and digitally integrated fabrication systems are widely deployed in precast factories and rebar yards, and significant gains have been realized in terms of productivity, precision, and material efficiency [6]. However, the downstream processes, particularly sorting, sequencing, and rebar cage assembly, remain predominantly manual, offsetting gains achieved during earlier stages of mechanisation.

Significant advances have been made in task-oriented robotic systems, especially in the area of rebar tying.

Vision-based robotic tying systems using RGB-D sensing and learning-based perception have demonstrated high accuracy and industrial feasibility [7] [8], while commercial systems such as TyBOT confirm productivity and safety benefits for large planar reinforcement meshes [4]. More recent research has extended robotic tying to non-planar configurations using six-degree-of-freedom pose estimation [9]. However, these systems typically assume manual placement of rebars and do not address the assembly of rebar cages as an integrated process.

Robotic assembly of rebar cages has been investigated primarily under controlled laboratory or factory conditions. Early studies demonstrated feasibility for beams and columns [3], while more recent work proposed gantry-based robotic production cells validated through simulation and experimental trials [10]. A key challenge identified across these studies is the determination of a feasible installation sequence that avoids geometric blocking and ensures interim cage stability. Digital twin–based sequencing approaches, including depth-first search heuristics, have been proposed to address this challenge [11]. However, validation has largely been limited to generic or building-scale rebar cages and stationary production environments.

BIM-enabled robotic frameworks have further advanced automation by providing machine-readable representations of reinforcement geometry and enabling digital continuity from design to robotic execution. Several studies have demonstrated BIM-driven robotic workflows validated in simulation environments such as CoppeliaSim [10], [12]. Despite these advances, most BIM–robot pipelines still require manual refinement of sequencing logic and calibration, limiting their scalability for infrastructure-scale applications.

Importantly, existing studies do not explicitly address the specific characteristics of ballastless railway track slab construction, which is governed by elongated slab geometries, repetitive yet bounded reinforcement layouts, linear deployment conditions, and strict spatial constraints imposed by railway infrastructure. Unlike conventional building structures, track slab reinforcement exhibits limited design variability within a project, resulting in manufacturing-like repetition along the alignment. This characteristic suggests that automation feasibility in railway applications is governed less by geometric complexity and more by effective process planning, sequencing logic, and integration with construction workflows.

Against this backdrop, the present study builds on established principles of BIM-driven robotics and feasibility-oriented sequencing, but repositions rebar cage assembly within the context of railway track slab construction. The study focuses on integrating BIM-based data extraction, constraint-informed installation order assignment, and high-fidelity digital twin validation to evaluate whether robotic rebar cage assembly can be practically deployed under railway-specific spatial, operational, and constructability constraints.

## 3 Methodology

Figure 2 illustrates the overall methodology adopted in this study, showing the end-to-end workflow from BIM-based data extraction and installation sequence assignment to robotic simulation and digital validation. The workflow begins with parametric data extraction from BIM models, where reinforcement geometry and connectivity are automatically retrieved from Bar Bending Schedule (BBS) inputs. A feasible rebar installation sequence is then assigned using constraint-based & Depth-first-search (DFS) logic informed by prior robotic assembly research. The extracted data and sequencing information are subsequently integrated into a robotic simulation environment, where inverse kinematics, collision-aware motion planning, and gantry-based robot control are implemented. The complete process is validated using a digital twin to assess reachability, collision-free execution, and operational feasibility under railway track slab constraints.

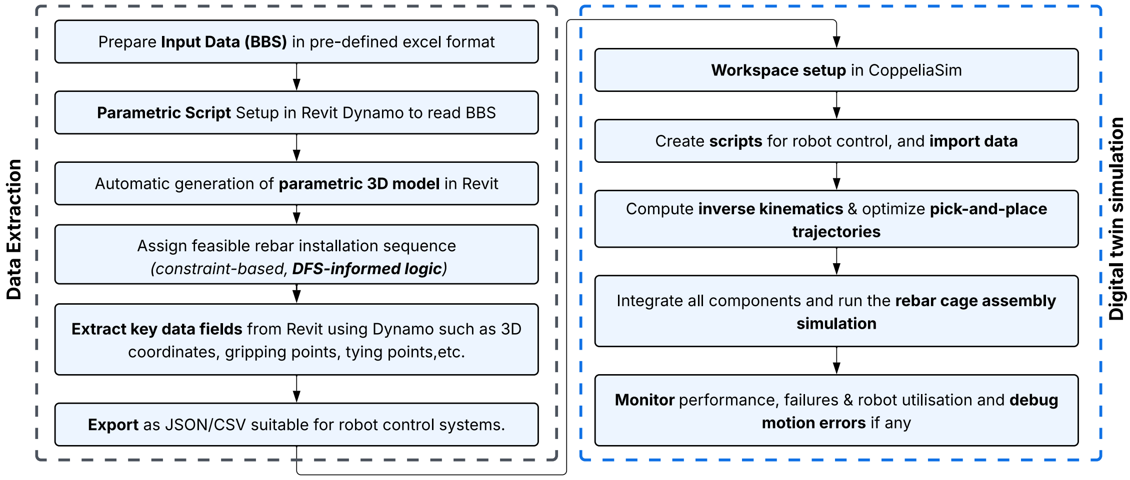


Figure 2 Methodology flow chart

## 4 BIM-Based Data Extraction for Railway Track Slab Reinforcement

The proposed framework relies on BIM as the authoritative source of reinforcement information for robotic process planning and simulation. A parametric rebar cage model corresponding to a ballastless railway track slab is developed as shown in figure 3 in accordance with typical BBS (figure 4) used in metro construction. The model captures the geometric definition of individual rebars, including bar diameter, length, bending shape, spatial coordinates, and layer information, as well as connectivity at intersections.

Assignment of the rebar installation order is formulated as a process planning problem rather than an optimisation task. In robotic rebar cage assembly, this sequencing problem can be represented as a constrained graph traversal problem, where individual rebars are treated as nodes and feasibility constraints such as geometric accessibility, collision avoidance, and interim structural stability-define precedence relationships. A Depth-First Search (DFS) based logic is employed to explore this solution space and generate a feasible installation sequence, consistent with established practices in robotic reinforcement assembly research. Similar DFS-based sequencing concepts have been previously reported for automated rebar cage fabrication in International Symposium on Automation and Robotics in Construction (ISARC) literature [11], where feasibility-oriented installation orders were shown to be sufficient for robotic execution.

In this study, rebars are grouped into layers based on their vertical position relative to the track slab base, with installation proceeding from lower to upper levels. Within each layer, the sequence is determined based on the distance from reference fixtures to ensure accessibility and avoid geometric blocking. The DFS algorithm incrementally builds the sequence while respecting constraints such as layer-wise progression, non-blocking placement, and support-first logic.

Compared to rule-based or layer-wise approaches, DFS offers greater flexibility in handling complex connectivity and non-uniform layouts, particularly where multiple valid sequences exist, while ensuring identification of at least one feasible, robot-executable sequence. The approach focuses on generating a consistent and repeatable sequence rather than outperforming human practices, enabling adaptability across varying slab geometries without manual reprogramming. Although DFS does not guarantee optimality in execution time or motion efficiency and may be sensitive to initial conditions, it is adopted here as the objective is feasibility validation. Given the bounded and repetitive nature of railway track slab reinforcement, identification of a single valid sequence is sufficient, making the approach computationally robust and well-suited for integration with BIM-derived data and digital twin environments.

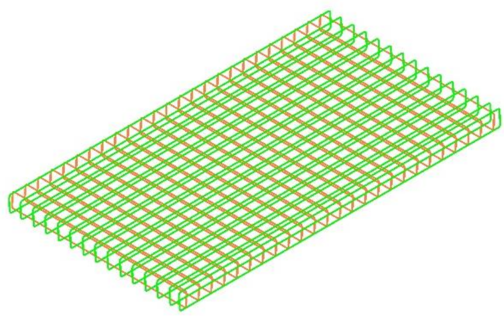

Figure 3 3D model of rebar cage

| Slab Logitudinal/Transverse Reinforcement | | | | | | | |
|---|---|---|---|---|---|---|---|
| Description | Diameter (mm) | Spacing (mm) | a(mm) | b(mm) | c(mm) | Length (m) = a+b+c | No. of bars |
| Longitudinal Slab Top | 12 | 200 | 150 | 4820 | 150 | 5.12 | 15 |
| Longitudinal Slab Bottom | 12 | 200 | 150 | 4820 | 150 | 5.12 | 15 |
| | | | | | | | |
| Transverse Slab Top | 10 | 200 | 150 | 2620 | 150 | 2.92 | 25 |
| Transvere Slab Bottom | 10 | 200 | 150 | 2620 | 150 | 2.92 | 25 |

Figure 4 BBS of the rebar cage

This combined BIM-based data extraction and sequencing approach ensures design-to-execution continuity while accommodating the repetitive yet constrained nature of railway track slab reinforcement. Following the assignment of a feasible installation order using DFS-based sequencing logic, the required reinforcement data are automatically extracted from the BIM environment using parametric scripting implemented through Dynamo within Autodesk Revit. This process eliminates manual interpretation of reinforcement drawings and manual data entry for robotic execution.

The extracted dataset includes unique rebar identifiers, bar diameter, assigned installation order, three-dimensional coordinates of grasp points defined at L/3 and 2L/3 locations along the rebar length for two-point gripping and the corresponding tie or placement points required for assembly so that deflection at ends of the rebar is minimum when picked up. These attributes are derived directly from the parametric BIM model, ensuring consistency between design intent and robotic process planning. The extracted information is structured and exported in a machine-readable format (JSON), enabling direct integration with robotic control and simulation environments without intermediate manual processing.

In addition to data extraction, Dynamo is used to parameterise the reinforcement model itself, allowing installation logic and attribute assignment to be embedded within the 3D model. This enables efficient handling of multiple slab variants with bounded geometric differences, such as those arising from curves, transitions, or station zones, by automating both parameter assignment and data extraction. As a result, clerical effort associated with repetitive data preparation is significantly reduced, and the framework supports scalable application across project-level variations in track slab geometry without the need for manual reprogramming of robotic tasks.

## 5 Simulation based evaluation for railway track slab

The proposed BIM-driven robotic rebar cage assembly framework is evaluated through simulation in CoppeliaSim using a high-fidelity digital twin configured for ballastless railway track slab construction. The digital twin models a gantry-based robotic system equipped with three six-degree-of-freedom (6-DOF) robotic manipulators mounted on a movable trolley, enabling movement in both longitudinal and lateral directions of the frame through linear actuators to ensure reachability within the assigned workspace. Of these, two robotic arms are dedicated to rebar pick–move–place operations, while the third arm is equipped with a specialised tying end-effector for executing reinforcement tying tasks. No vision sensors are required for tying as exact coordinates of tying points are being extracted from 3D model enabling accurate execution. This configuration supports coordinated operation while avoiding excessive workspace congestion.

The gantry–trolley system provides coarse positioning across the slab length and width, while the robotic arms perform localised manipulation tasks. This arrangement reflects the linear nature of railway track slab construction and enables efficient access to reinforcement locations distributed along elongated slab geometries without repositioning the entire system.

Motion planning is implemented using a hybrid strategy. First, the gantry and trolley perform coarse positioning to bring the robotic arm into the vicinity of the target rebar location in the longitudinal and/or lateral directions. Subsequently, fine positioning is achieved through inverse kinematics–based control of the 6-DOF robotic arm to execute precise grasping, placement, and tying operations. This layered approach reduces unnecessary arm motion, improves reachability, and reflects established practice in robotic reinforcement assembly research. The motion planning logic and kinematic modelling are inspired by previously reported robotic cage assembly frameworks, particularly the feasibility-oriented approaches presented by Momeni et al., while being adapted to the geometric scale and spatial constraints of railway track slabs. Conservative velocity and acceleration profiles are applied to ensure stable handling.

When importing BIM-derived reinforcement data into the simulation environment, a coordinate transformation formulation is applied to map BIM global coordinates into the local reference frame used in CoppeliaSim. This transformation accounts for differences in origin, orientation, and scale between the BIM model and the simulation environment, ensuring that rebar positions, grasp points, and placement targets extracted through scripting are accurately represented during robotic execution within the digital twin.

The simulation setup reflects typical railway site constraints, including limited lateral workspace, longitudinal deployment along the track direction, and interaction with rail-seat regions and embedded components. Spindles are planned to be temporarily placed at designated locations to fix the rail-seat base during casting and to ensure that reinforcement does not infringe upon the designed spacing. To accommodate railway-specific spatial restrictions, the complete robotic system including gantry structure, trolley, manipulators, and end-effectors is constrained within a predefined kinematic envelope representing the worst-case available construction space. This envelope is defined to prevent infringement with adjacent railway infrastructure such as overhead electrification (OHE) systems, cable trays, parapets, and other permanent or temporary civil works commonly present along metro alignments.

Collision-aware motion planning is enabled throughout the simulation to ensure safe interaction between robotic arms, partially assembled reinforcement cages, fixtures, and surrounding structural elements. The simulation experiments focus on evaluating robotic reachability, sequencing feasibility, and motion stability under conditions representative of metro construction, rather than on optimising cycle times or factory throughput. In addition to prefabrication yard scenarios, the simulation environment is intentionally constrained to reflect conditions applicable to cast-in-situ (CIS) track slab construction. By ensuring that the entire robotic system operates within the railway kinematic envelope, the framework demonstrates potential compatibility with deployment on alignment-guided platforms such as rail-mounted or road–rail vehicles (RRVs). This highlights the flexibility of the proposed approach to support both stationary prefabrication environments and mobile, track-based operations, which are essential for automation in linear railway infrastructure projects. To maintain focus on process-level feasibility and ensure comparability with existing robotic reinforcement studies, the following assumptions are adopted in the simulation:

1. The BIM-derived rebar geometry and connectivity accurately represent the as-designed reinforcement cage, and rebars are assumed to be geometrically rigid during handling and placement.
2. A feasible rebar installation sequence exists, and identification of a single valid sequence is sufficient for evaluating automation feasibility, recognising that multiple valid sequences may be possible.
3. Installation order assignments follow DFS-based, constraint-informed logic, which is not optimum but one feasible order
4. The robotic system operates in a controlled environment with known geometry; perception uncertainty, sensing noise, and real-time error correction are not considered at this stage.
5. Temporary fixtures and supports required to maintain interim cage stability are assumed to be available and correctly positioned throughout the assembly process.
6. Fixtures are provided on both directions of the table setup so that two different rebar can be placed on fixtures in their repsection directions. At any given fixture location, rebars are fed one by one to the system to eliminate the risk of pose uncertainty.

These assumptions are consistent with common practice in early-stage construction robotics research and allow the study to isolate the feasibility of BIM-driven process planning and robotic execution under railway-specific geometric and operational constraints.

When these assumptions are relaxed, several practical uncertainties arise. Rebar deflection during handling may influence placement accuracy; however, two-point gripping at one-third span locations reduces deflection, and the use of jigs helps maintain the rebars in a straight alignment during placement. Tolerance accumulation across sequential placements may affect overall cage geometry, although jigs used for spacing and cover control mitigate this effect under bounded variability. Pose uncertainty remains a limitation due to the absence of perception systems, while fixture misalignment and reinforcement congestion may further affect stability, accessibility, and placement precision. These factors indicate that incorporation of sensing, compliance control, and tolerance management strategies will be necessary for reliable real-world deployment. Key robot, gantry parameters used in the digital twin are summarised in Table 1 to ensure clarity and reproducibility.

Table 1 Robot and Gantry System Parameters Used in Simulation

| Parameter | Specification | Remarks |
|---|---|---|
| Robotic arm-payload capacity | 25 kg | Selected base on rebar + end effector weight including dynamic effect |
| Maximum reach of robotic arm | 1.3 m | Sufficient for placement within slab region with the help of linear actuators |
| Gantry longitudinal travel (X-axis) | 6 m | Covers slab length + margin |
| Gantry lateral travel (Y-axis) | 3 m | Covers slab width + margin |

## 6 Results and Discussion

Simulation results confirm that the proposed framework enables collision-free robotic rebar placement for railway track slab cages across all planned installation steps. All BIM-defined rebar target poses are reachable within the gantry workspace while maintaining compliance with railway spatial constraints. The process planning and sequencing logic successfully prevents geometric blocking and ensures interim cage stability, which is critical for elongated slab-type reinforcement assemblies typical of ballastless track systems.

Robotic motion remains stable throughout the simulation, with no kinematic singularities or unintended interference between manipulators or previously placed reinforcement. These results demonstrate that BIM-driven sequencing and digital validation are essential enablers for adapting robotics to railway reinforcement workflows, where precision, repeatability, and strict adherence to possession windows are more critical than maximising raw production speed. The framework is shown to be adaptable to both precast track slab manufacturing yards and on-site cast-in-situ (CIS) construction, subject to project-specific deployment strategies. A summary of key simulation-based performance indicators is presented in Table 2.

Table 2 Summary of Simulation-Based Performance Indicators

| Parameter | Value |
|---|---|
| Number of rebars | 80 |
| Assembly completion | 100 % |
| Average pick–move–place time (per bar) | ~35 s |
| Total placement time | ~2800 s (~47 min) |
| Number of ties | ~750 |
| Estimated tying time (per tie) | ~ 2- 3 s (Based on literature/industrial systems) |

The pick–move–place cycle times observed in the simulation are indicative and scenario-specific, as task duration is influenced by payload, travel distance, motion constraints, and placement accuracy requirements. Since the simulation assumes idealised conditions, observed cycle times are considered moderately reliable for comparative and feasibility assessment, but not as direct predictors of field performance.

In conventional practice, reinforcement cage assembly for ballastless track slabs is reported to achieve approximately 0.125 track m per man-hour, reflecting the labour-intensive and sequential nature of manual operations under constrained site conditions. Based on the simulation results for the representative slab configuration, the equivalent system-level production rate corresponds to approximately 2.5 track m per hour under idealised conditions. However, this value represents a theoretical upper bound, as the simulation does not account for real-world factors such as handling delays, coordination with other site activities, perception uncertainties, and operational interruptions. Therefore, the comparison should not be interpreted as a direct productivity gain, but rather as an indication of the potential for improved execution efficiency and reduced variability through automation. The primary contribution of this study remains the demonstration of technical feasibility, while quantitative productivity validation requires further experimental and field-based investigation.

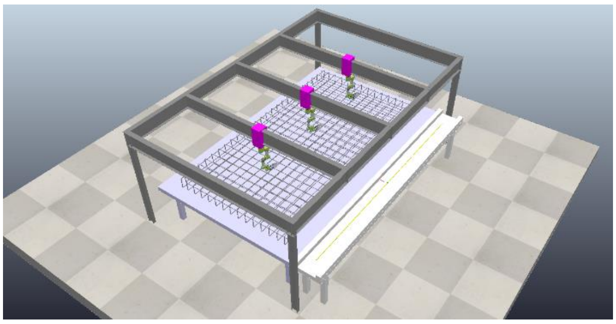

Figure 5 Simulation of rebar cage of metro track slab in CoppeliaSim

It is therefore emphasised that the objective of the simulation study is to evaluate the technical feasibility and deployability of the proposed robotic system under railway-specific spatial and operational constraints. Detailed cycle time optimisation and productivity assessment are outside the scope of this work, as reliable estimation would require physical prototyping, perception integration, and field validation. By constraining the system within the railway kinematic envelope, the framework demonstrates potential compatibility with deployment on alignment-guided platforms, such as rail-mounted or road–rail vehicles. When combined with coordinated logistics and alignment-guided mobility, the proposed approach offers a viable pathway for integrating robotic rebar cage assembly into metro construction workflows.

## 7 Conclusions and Future Work

This study presents a railway-specific feasibility assessment of a BIM-driven process planning and robotic assembly framework for rebar cages in ballastless track slab construction. It addresses a key gap in metro and high-speed rail projects, where rebar cage assembly remains largely manual despite mechanisation of other activities. By adapting established BIM-driven robotic sequencing approaches to railway-specific geometric and spatial constraints, the study reframes rebar cage assembly as a process planning and digital integration problem.

Simulation using a high-fidelity digital twin confirms the feasibility of collision-free and stable robotic assembly under representative metro track slab conditions. The results demonstrate that BIM-derived data, feasibility-oriented sequencing, and hybrid motion planning can be effectively integrated to enable robotic execution without geometric blocking or kinematic conflicts. The findings highlight that feasibility in railway applications is governed primarily by sequencing logic, spatial compliance, and digital workflow continuity rather than optimisation of hardware or cycle times. The framework is applicable to linear railway infrastructure projects characterised by repetitive yet bounded reinforcement layouts and strict possession constraints. Compatibility with prefabrication yards and on-site cast-in-situ construction is demonstrated, with potential for deployment using alignment-guided platforms such as rail-mounted or road–rail vehicles and automated guided vehicles (AGVs), enabling scalable and mobile robotic operations.

Future work will focus on physical prototyping, integration of perception-based feedback for tolerance management, and validation under real or semi-controlled site conditions. Further investigation is required to evaluate coordinated operation with alignment-guided systems and to assess productivity, safety, and constructability impacts. A key limitation of this study is its reliance on simulation-based validation under controlled conditions. While the digital twin enables evaluation of reachability, sequencing feasibility, and collision-free execution, real construction environments introduce additional uncertainties, including geometric tolerances, bar deflection, fixture misalignment, and operational variability. These factors may influence positioning accuracy and system performance. Consequently, the applicability of the proposed framework to real-world deployment requires further validation through physical prototyping and field implementation.

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