# An OpenBIM-based Framework for Lifecycle Management of Steel Reinforcement

**Mingkai Li[1], Yuhan Liu[2], Boyu Wang[2] and Jack C. P. Cheng[1]**

[1]Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR
[2]China State Construction Science and Technology Limited, Hong Kong SAR
mlicj@connect.ust.hk (Mingkai Li), cejcheng@ust.hk (Jack C. P. Cheng)

**Abstract –**

**Reinforced concrete (RC) is commonly used in modern building construction. Steel reinforcement (or rebar) design and fabrication are important tasks for the construction of RC buildings. However, these processes are currently conducted semi-automatic, requiring large human effort and processing time. Besides, there is a lack of efficient approach for progress monitoring of onsite rebar installation, and the deviation between actual rebar layout and as-design model can not be accurately analyzed and recorded. Therefore, this study aims to develop an openBIM-based framework for rebar lifecycle management, concerning the design, manufacturing, assembly, renewal and demolition. Firstly, an automatic clash-free rebar design optimization approach is proposed integrating optimization algorithms and AI techniques. Secondly, A open digital workflow based on information delivery manual (IDM), model view definition (MVD), and Industry Foundation Classes (IFC), and the integration with machine fabrication code is developed to support rebar prefabrication. Thirdly, a BIM-based progress monitoring approach is proposed integrating laser scanning, while the rebar BIM model is updated with as-built data. Moreover, the applications of as-built rebar BIM model in maintenance, renewal and demolition are discussed.**

**Keywords –**

**Steel reinforcement design; Design optimization; Building information Modelling (BIM); Progress monitoring; Prefabrication; Graph Neural Network**

## 1 Introduction

Reinforced concrete (RC) stands as a prevalent construction material in modern building construction. The design and fabrication of steel reinforcement (commonly known as rebar) are important and necessary tasks for the construction of RC buildings, significantly affecting the constriction time, material consumption and waste generation. Current rebar design process relies heavily on manual participation, which is time-consuming and error-prone. Structural engineers usually conduct rebar design using structural analysis results, and the optimality of rebar design is largely influenced by the experience and expertise of engineers. Besides, the existing rebar design approach operates at the individual member level, often overlooking potential clashes and buildability challenges arising from the interaction between RC members. The identification and resolution of rebar clashes typically rely on manual efforts at the construction site, resulting in time-intensive processes. Sometimes, achieving a clash-free layout is challenging within the given rebar design. Moreover, the manual conversion of rebar detailing into machine codes for automated rebar prefabrication necessitates additional time and labor. As the industry promotes prefabrication and low-carbon construction, there is a pressing need to devise a novel approach for automated rebar design optimization and prefabrication.

There have been some related research efforts in the past attempting to solve some aspects of the above problems. Mangal et al. [1] proposed an automatic rebar design optimization approach for RC frames using two-stage genetic algorithm and BIM. Eleftheriadis et al. [2] developed an automated rebar specification method for flat slabs using BIM and finite element analysis (FEA). Some customized constructability considerations are integrated into the method to generate realistic rebar layout. Genetic algorithms were also incorporated into other studies for rebar design optimization of RC components [3-4]. Vaez and Qomi [5] presented a continuous optimization approach for the rebar design of RC shear walls. However, all the above methods are time-demanding and cannot accumulate the design experience from previous design cases like a human engineer does, hence they are generally computationally inefficient. Some studies tried to identify and resolve the rebar clashes. Mangal et al. [1] defined an indicator called clash number to count the number of clashes in beam-column joint and leveraged metaheuristic algorithm (MA) to reduce this indicator and thereby resolve clashes. However, this method assumes that beam and column rebar cannot be directly adjacent to each other, and produces a loose arrangement, which may not be applicable to those joints with large amount of steel. Liu et al. [6] proposed to formulate rebar clash avoidance as a path planning problem. However, the generated path may not satisfy the rebar shape code, undermining its practicality. Considering the above shortcomings, it is necessary to develop an automatic clash-free rebar design optimization approach.

To realize automatic rebar prefabrication, a rebar BIM model is the first step, with which the prefab-related information in it can be further extracted and transformed to fabrication machine codes for rebar fabrication. Following this, other materials like rebar detailed drawing can also be automatically generated with customized plugins to facilitate the assembly. However, currently in industrial practice, there is no a universal program/tool to automatically import rebar design results into commonly used BIM software like Revit or Tekla. Worse still, though the rebar design and prefabrication involve a lot of software and customized tools, there is a lack of mature software ecosystem or pipeline to ensure smooth and accurate information passing among them.

As for the progress monitoring of rebar installation, Turkan classified rebars as secondary construction objects and conducted preliminary experiments on automated rebar recognition and tracking for RC columns using laser scanning [7]. However, the approach has not been validated in other types of components and could not satisfy the practical use. Moreover, research on the applications of as-built rebar BIM model is still lacking.

The objective of this paper is to develop a openBIM-based framework for rebar lifecycle management. an automatic clash-free rebar design optimization approach is proposed integrating MAs and graph neural networks (GNN). Besides, a open digital workflow based on information delivery manual (IDM), model view definition (MVD), and Industry Foundation Classes (IFC), and the integration with BundesVereinigung der Bausoftware (BVBS) code is developed to support rebar prefabrication. In addition, a rebar installation progress monitoring method is developed using 3D laser scanning. Last but not least, the applications of the as-built rebar BIM model in building maintenance, renewal and demolition are discussed.

## 2 Methodology

This paper proposes a BIM-based framework to support the automation of clash-free rebar design optimization and prefabrication, as shown in Figure 1, which consists of 4 main modules, namely (1) automatic clash-free rebar design optimization, (2) BIM-based rebar prefabrication automation, (3) BIM-based progress monitoring, and (4) BIM-supported building renewal and demolition.

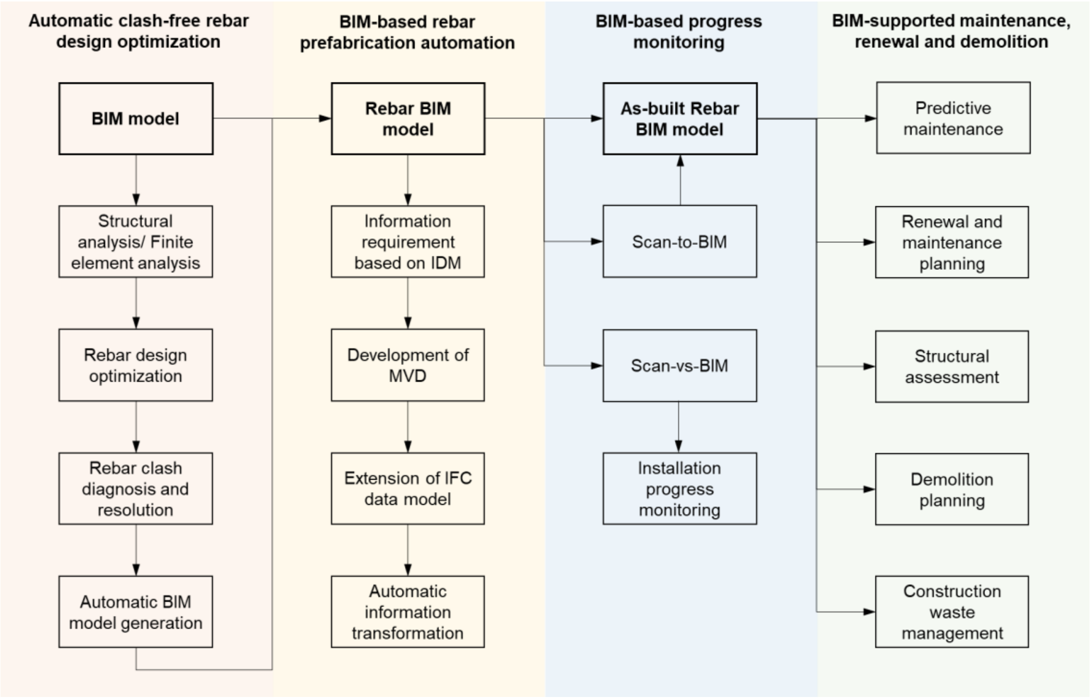


Figure 1. Proposed openBIM-based framework

## 2.1 Automatic Clash-free Rebar Design Optimization

To realize rebar design optimization, the first step is the establish the optimal formulation of rebar design, based on which optimization algorithms can then be leveraged to achieve the optimal design for a given design case. We also propose to adopt GNN to accelerate the design process and realize rebar clash avoidance.

### 2.1.1 Optimal Design Formulation

The optimal formulation for rebar design specifically includes the identification of design variables, searching space and design constraints, and the establishment of objective function.

***Design variables***: The general process to identify the design variables for one type of RC components include 3 steps: (1) collecting the typical rebar layouts, (2) dividing the rebar layouts into rebar groups, and (3) assigning design variables to each rebar group to describe the layout. For elongated RC components, the division of rebar groups are usually more intuitive. For example, the typical longitudinal rebar layout for a two-span continuous beam is shown in Figure 2(a), and 5 rebar groups can be identified. Each number in the figure refers to a rebar group. For each rebar group, since the number of rebar layers and number of rebars are variable, it is inconvenient to determine the number of design variables if each rebar is treated as a design variable. Therefore, we simplify the problem by assigning only 1 variable called rebar combination index to each rebar group, which refers to a detailed rebar layout in our rebar combination dataset. On the other hand, strip method is usually used for the rebar design of flat RC components like slab and walls, which separates components into several strips (as shown in Figure 2(b) with different colors), and assigns rebar layout to each strip.

***Searching space***: To ensure the optimized rebar design can be found on the market and comply with the industry practice, we establish a dataset containing all practical combinations of rebars with market-supplied diameters. This dataset is set as the searching space for optimization, and can be customized according to the need and preference of users. For example, if the user prefers using only one kind of rebar diameter in one rebar layer, those rebar layouts considering two or more kinds of diameters can be removed to generate a new dataset.

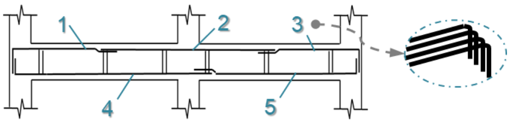
***Design constraints***: First of all, the steel area of selected rebar layout in each section should not be less than the required steel area. Besides, the rebar layout should follow requirements specified in building codes. Other code-stipulated requirements are also needed to be incorporated into the formulation, such as lapping and anchorage length, which are not all listed here.

***Objective function***: Most existing optimization methods take material consumption or total weight as the objective. However, as the construction industry faces labor shortages and increasing labor costs, buildability has become a increasingly important metric. We incorporate the evaluation of the buildability of rebar design into optimization, which is quantified by calculating the time required to install a specific rebar design. Therefore, the multi-objective optimization is formulated as follows.

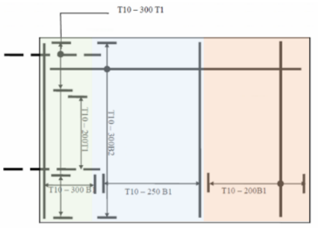
$$C = w \times M_s \times c_s + (1 - w) \times T_i / \tau \times c_l \tag{1}$$

$$T_i = T_P + T_t = N_{bar}/p_p + N_{tie}/p_t \tag{2}$$

where $w$ is the weighting factor to take account of two objectives – material consumption and buildability, $M_s$ refers to the mass of steel rebar (in ton), $c_s$ refers to the unit price for steel (in \$/ton), $T_i$ refers to the time required for installation, $\tau$ is a constant 480 min/man-day for unit conversion considering 8-hour work for one day, $c_l$ refers to the labor cost per man-day (in \$/man-day). In Equation (2), $T_p$ and $T_t$ refer to the time (in min) of rebar placing and rebar tying, $N_{bar}$ refers to the number of rebars, $N_{tie}$ represents the number of ties, which can be easily counted for the given longitudinal and transverse rebar layouts, $p_p$ and $p_t$ denote the production rates for rebar placing and rebar tying, respectively [8].



(a) Typical longitudinal rebar layout for continuous beams



(b) Typical rebar layout for RC slabs based on strip method

Figure 2. Typical rebar layouts for common RC components

### 2.1.2 GNN-based Design Proposal

GNNs are a class of machine learning models designed to analyze and make predictions on graph-structured data, such as social networks, molecular structures, or citation networks [9]. GNNs operate by learning representations of nodes and edges in a graph, capturing relational information and structural dependencies within the data. These models have demonstrated significant success in tasks like node classification, link prediction, and graph classification, making them a powerful tool for analyzing complex interconnected data sets. In this regard, GNN can be leveraged to improve the computational efficiency of rebar design, which involves a lot of rebar groups interacting with each other.

The workflow of GNN-based design proposal and MA-based design optimization are presented in Figure 3. To unlock the potential of GNN, the first step is to represent the rebar design problem in the format of graph. For elongated RC components like beams and columns, each rebar group in Section 2.1.1 can be treated as a node in the graph representation, while the edge can be established according to the interrelationship between rebar groups, as shown in Figure 4(a). Each node has attributes containing geometrical, positional and design information for the corresponding rebar group, while each edge indicates that the connected rebar groups will affect each other in term of rebar number. GNN can then aggregate information on the graph and provide predictions for each node, which will be the initial design for each rebar group. For flat RC components like slabs and walls, the graph representation can be established based on the finite element mesh, as shown in Figure. 4(b). Each node refers to a vertex of the finite element, containing three attributes: x-coordinate, y-coordinate and required steel area. The edges are established using full connection among the vertexes of each finite element, showing that they together determine the distribution of required steel area in the element. GNN is then leveraged to conduct graph-level prediction, providing the positions of strip segmentations and supporting rebar design in each strip.

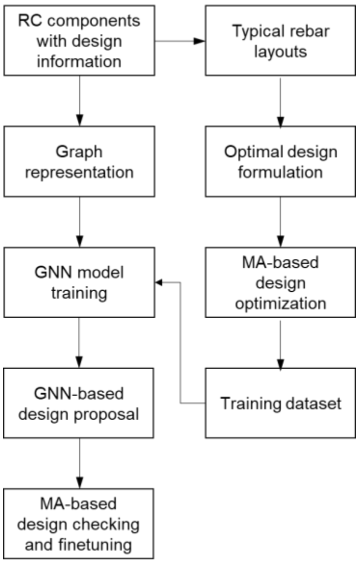
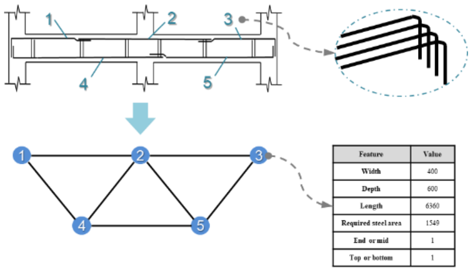


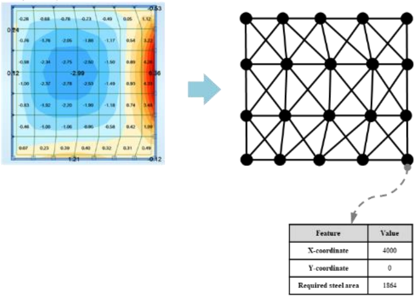
Figure 3. GNN-based design proposal

Several MAs including genetic algorithm (GA), particle swarm optimization (PSO), artificial bee colony (ABC) and ant colony optimization (ACO) are adopted to generate optimal design for thousand of collected design cases based on the optimal formulation in Section 2.1.1. The best design among the optimized results from different MAs are selected as the optimal solution to the design case. In this way, these design cases with optimal designs are used to train GNN. Since GNN aims to uncover patterns and relationships within data, it may not guarantee the generated design is optimal. Therefore, MA is used to further optimize the initial design from GNN and conduct code-compliance checking. This hybrid mechanism not only makes use of the advantage of GNN to accumulate design experience to accelerate the design process, but also exerts the searching ability of MA to ensure the optimality of final design.



| Feature | Value |
|---|---|
| Width | 400 |
| Depth | 600 |
| Length | 6360 |
| Required steel area | 1549 |
| End or mid | 1 |
| Top or bottom | 1 |

(a) Elongated components (RC beam)



| Feature | Value |
|---|---|
| X-coordinate | 4000 |
| Y-coordinate | 0 |
| Required steel area | 1864 |

(b) Flat components (RC slabs)

Figure 4. Graph representations for elongated and flat RC components

### 2.1.3 GNN-based Clash Avoidance

The framework for clash avoidance is presented in Figure 5. Rebar clashes are classified as solvable or unsolvable clashes, depending on whether the rebar clash can be resolved without changing the rebar design. Unsolvable clashes can be found in areas with large amount of rebars, where there are few spaces for repositioning or reshaping rebar to avoid clash. When an unsolvable clash is identified, rebar design adjustment is necessary, and the revised rebar layout will go through the classification again until a clash-free layout or a solvable clash is achieved. On the other hand, a solvable clash can be resolved by only repositioning or/and reshaping some rebars.

To identify and classify rebar clash, we developed the vector representation of rebar clash and formulate the clash avoidance as an optimization problem [8]. Graph representation was further proposed to enable the adoption of GNN to realize efficient clash diagnosis [10]. Thousands of rebar clash cases were collected and presented using the vector representation, and MAs were leveraged to determine the class of each clash case. These clash cases with labels are then used to train the GNN for clash diagnosis.

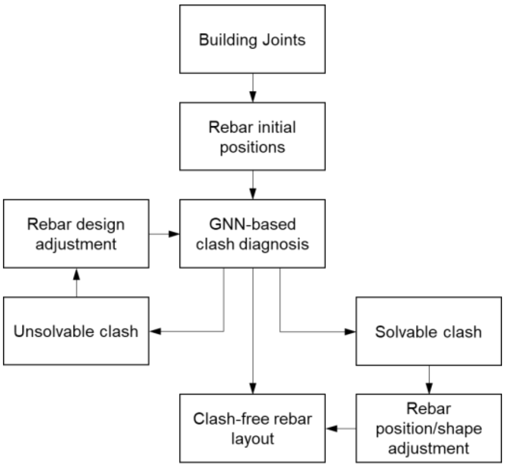


Figure 5. GNN-based clash avoidance framework

## 2.2 Automatic Rebar Prefabrication

As the construction industry embraces digitalization and industrialization, the significance of BIM and IFC is increasing as collaborative approaches to support data interoperability and off-site prefabrication. BVBS is a type of machine code for rebar fabrication, containing rebar geometrical information for fabrication machine to conduct automatic rebar processing [11]. To realize automatic rebar prefabrication, an openBIM-based framework for BIM-BVBS integration is proposed with extended IFC data model, as shown in Figure 6.

### 2.2.1 Information Requirements based on IDM

IDM provides detailed guidance on how information should be exchanged and delivered throughout the lifecycle of a construction project, particularly in the context of BIM. The IDM process includes identifying the information requirements for prefabrication of rebars, and creating the process map to display the information flow and data exchanged among engaging stakeholders. The former is realized following BVBS specification and rebar shape code BS8666:2005, while the latter is developed by linking the product (prefabricated steel reinforcement), resources (material and labor) and control (schedule) in different phases of building lifecycle. The detailed information flow in the off-site manufacturing and prefabrication of rebars should be emphasized and integrated in the process map to support rebar prefabrication.

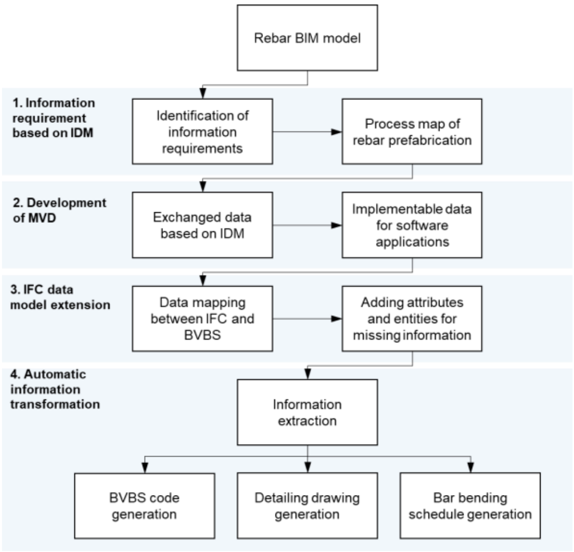


Figure 6. Proposed methodology for BIM-BVBS integration and BIM-based applications

### 2.2.2 Development of MVD

MVD refers to predefined subsets of information and views within a BIM model, which helps standardize and streamline information exchange in the BIM process, ensuring that stakeholders receive the relevant data they need for their specific roles or tasks. These definitions specify how information should be structured, exchanged, and displayed for a particular purpose or stage of the building lifecycle. Following the IDM process, MVD is leveraged to display the necessary information for automatic prefabrication, which also indicates the needful extension of existing IFC data model. New attributes related to rebar prefabrication are added to different aspects of existing MVD structure:

- “Reinforcing bar attributes”: mark number, rebar length, rebar quantity, rebar diameter;
- “Owner and status information”: project number, drawing number, revision index;
- “Steel material association”: steel grade;
- “Rebar bending attributes”: segment angle.

### 2.2.3 Extension of IFC Data Model

The conversion of IFC data to BVBS needs to be precise enough to guarantee that all attributes needed for cutting and bending are covered, which highlights the necessity to extend the existing IFC schema.

The first step is the decomposition and relations of *IfcProcess*. Based on the proposed process map and

MVD, the process of rebar prefabrication can be classified using *IfcTask*, which is the sub-entity of *IfcProcess*. Four main tasks are included, including planning, manufacturing, delivery and assembly. Next, the process information model of steel reinforcement fabrication is established by connecting the IFC entities with relationships among the specific tasks. The entities are located through the entity inheritance of those abstract entities according to the nature of the product, resource or control. Taking the manufacturing process for illustration, it operates on the material resource “metal”, which can be found in the predefined type of the *IfcConstructionMaterialResource*, and the product related to this process is indicated as *IfcReinforcingBar* connected by *IfcRelAssignsToProcess*. Linked to the sub-entities of *IfcControl*, all the related products, resources, and the manufacturing process are under its supervision. The product and the process are included in the work plan on the manufacturing arrangement, while the related progress of the resource “metal” is recorded in the work calendar through *IfcRelAssignsToControl*.

In order to support seamless data conversion, the IFC data model needs to be further extended. IFC data model extension includes the data mapping between IFC and BVBS, and the addition of new IFC entities with reference to information requirements in IDM. Figure 7 shows the framework for data mapping between IFC and BVBS, in which the information requirements for generating the BVBS machine codes is clarified. At the data collection level, the list of attributes required by BVBS is extracted. IDM can be utilized as well to provide reference for the information requirements needed for the development of the rebar prefabrication and offers a universal and standardized method for information exchange.

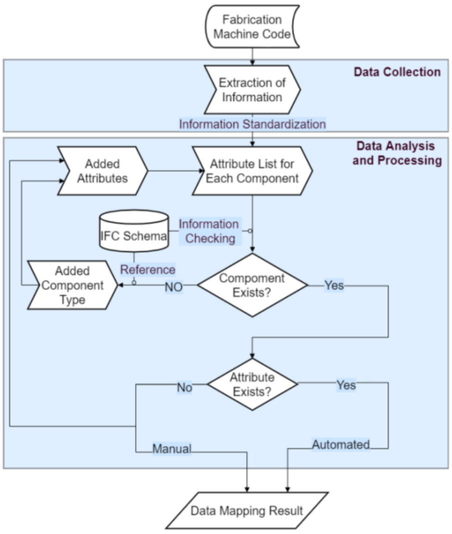


Figure 7. Framework for data mapping between IFC and BVBS

### 2.2.4 Automatic Information Transformation

Based on the extended IFC schema, automatic algorithms and customized programs can further be developed to extract necessary information including identity, geometrical, material and sematic information, to support the automatic generation of BVBS code, detailing drawing and bending schedule to enable automatic rebar prefabrication.

## 2.3 Rebar Installation Progress Monitoring

The onsite installation of rebars is a time-consuming and error-prone step of the RC structure construction, which includes rebar placing and tying. Therefore, it is necessary to develop a monitoring approach for project manager to grasp the installation progress of rebars timely. To be specific, the progress monitoring for rebar installation should provide the project manager with detailed information for the following aspects.

1. What is the progress of rebar installation for each RC component?
2. Are the installed rebars in the correct position?
3. Are the diameters of rebars installed correctly?

Since the rebars will be embedded in RC structures, the acquisition of rebar installation progress should be minutely integrated with the construction schedule. For example, the data of rebars of horizontal RC components (like slabs and beams) should be obtained before concrete pouring, while those of vertical components (like columns and walls) should be obtained before the installation of their formworks. This may involve the adjustment and integration of existing construction procedures, which means realizing progress monitoring of rebar installation not only relies on the development of technical solution, but also emphasize the improvement of project management level.

As the construction industry promotes prefabrication of RC components, the onsite rebar installation work will be reduced and gradually moved to factories. Progress monitoring and indoor prefabrication with computer numerical control (CNC) machines are a natural fit, since the indoor environment provides a stable environment for the layout and parameter setting of reality capturing devices. As the use of precast components has not been fully popularized yet, and partial cast-in-situ is necessary to improve the integrity of structures, the progress monitoring approach proposed in the study is mainly aimed at the onsite construction, and can be adapted to indoor scenario with necessary technical adjustments.

### 2.3.1 Onsite Reality Capturing

3D sensing is a type of techniques that has been widely used to capture and represent 3D information about the objects or environments. These techniques include ultrasonic tomography (UT), photogrammetry, laser scanning, etc. Ultrasonic tomography is a non-destructive testing method, which allows for the inspection of materials and structures without causing any damage. However, when moving to onsite rebar installation, UT can be leveraged to inspect the rebars embedded in solidified concrete, but may not directly adopted to track the installation progress of rebars that has not been covered by concrete. Photogrammetry is a technique used to extract geometric information from photographs. It involves the process of capturing multiple images of an object or a scene from different angles and then using computational methods to analyse and reconstruct the 3D structure of the photographed subject. However, the accuracy of photogrammetry is limited and may not satisfy Aspect 2 and 3. Laser scanning turns out to be a better solution because of its high precision and versatility for various applications, especially with the rapid development of deep learning techniques based on point cloud [12]. Laser scanning techniques can be classified into two categories according to the movability of the scanning platform: terrestrial laser scanning (TLS) and mobile laser scanning (MLS). TLS involves stationary laser scanners that are placed on tripods or fixed mounts, and has limited coverage, which means for complex environments like construction sites, a large number of scanning stations are required to cover all the concerned areas. In addition, the setting up of scanners on construction site when installing rebars could be challenging. On the other hand, MLS relying on mobile platforms such as drones and cars, can be an alternative solution to rapidly capture onsite information. Current RC buildings are built storey by storey, which means that there are generally no buildings above when installing rebars, making the use of drones for laser scanning promising. For low-profile RC buildings, the delta style steel truss or gantry may also be used to carry the laser scanner. In recent years, handheld laser scanning (HLS) appears to be a more portable and flexible approach for rebar installation sites.

#### 2.3.2 Vision-assisted BIM Reconstruction using 3D Point Cloud

To improve the efficiency and accuracy of BIM reconstruction based on point cloud, and make full use of the rich information provided by images, a vision-assisted BIM reconstruction method is proposed [13]. (1) RGB images of onsite rebar installation scenarios can be collected to train a deep learning model for sematic segmentation. Visual foundation models (VFM) can be leveraged to accelerate the development process [14]. (2) The segmented images and corresponding depth images can be used to generate a sematic-rich 3D map. To track rebar installation, the pixels referring to rebar should be identified. (3) The sematic-rich 3D map is then used to guide the 3D point cloud segmentation. Specially, extracting the rebars from the 3D point cloud obtained by laser scanner. (4) Central lines of rebars are then extracted from the point cloud for BIM reconstruction and progress monitoring, while diameter or rebars are estimated and matched with market-supplied diameters. (5) Customized program based on Dynamo can be developed to establish rebars in Revit BIM model.

#### 2.3.3 Progress Determination

The central lines and diameters of rebars in the as-design BIM model are extracted and compare to those extracted in Section 2.3.2 to track the progress of installation. The central lines and diameters from as-design and as-built model can be matched and verified with a given tolerance. Each rebar that has correct diameter and is located at the correct position will be counted as successful installation. Equation (3) shows the formulate the determine the rebar installation progress.

$$P = N_{ab}/N_{ad} \tag{3}$$

where $P$ is the installation progress, $N_{\mathrm{ab}}$ refers to the number of rebars that have been successfully installed according to the as-built model, while $N_{\mathrm{ad}}$ refers to the number of rebars in the as-design model.

### 2.4 BIM-supported Maintenance, Renewal and Demolition

A BIM model with rebar information could unlock a range of applications throughout lifecycle of buildings, including maintenance, renewal and demolition.

***Predictive maintenance***: With the rebar information, when damage on waterproof layer or concrete cover layer is identified, rebar corrosion simulation can be conducted to analyze possible disasters, and help schedule maintenance activities proactively.

***Optimized renewal and maintenance planning***: Building maintenance and renewal, which can include modifications to the building's structure, such as adding new components, reinforcing existing components, or altering the layout, sometimes require excavating RC components. Knowing the specific positional and geometrical information of each rebar in the building allows architects and engineers to visualize the existing rebar layout and plan maintenances or renovations more efficiently, while minimizing the clashes with rebars and avoiding unnecessary rebar cutting.

***Reliable structural assessment***: A BIM with rebars could provide detailed information about the structural components of the building. This information is crucial for conducting structural assessments before renewal or demolition. Engineers can analyze the integrity of the existing structure and determine whether it can be safely renovated or if demolition is necessary.

***Efficient demolition planning***: The rebar BIM model can provide insights into the structure's composition, allowing demolition teams to strategize the removal of materials in a safe and efficient manner. For building demolition with explosive, the BIM with rebars could provide accurate information for demolition simulation to optimize the layout of explosive.

***Accurate construction waste management*:** A rebar BIM can not only assist in evaluating the construction waste and environmental impact of building renewal or demolition projects, but also help identify the quantities and positions of salvageable materials. The steel is usually the most valuable material for recycling, and a rebar BIM model could definitely support the estimation of steel bars that can be recycled. This can reduce waste and contribute to sustainable construction practices.

## 3 Conclusion

This study proposes an openBIM-based framework for lifecycle management of rebars. An automatic clash-free rebar design optimization approach is proposed integrating MAs and GNNs, with detailed optimal formulation. Besides, an integrated digital workflow is invented based on IDM, MVD, and IFC to support BIM-BVBS integration to support automatic rebar prefabrication. In addition, we propose to adopt laser scanning and vision-assisted BIM reconstruction for onsite rebar installation progress monitoring. The applications of the as-built rebar BIM model in building maintenance, renewal and demolition are discussed. Future directions of this work include: (1) validation of the proposed method on more real-life projects, and (2) software development for rebar lifecycle management.

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