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Research Paper

Crafting an Automated Algorithm for Estimating the Quantity of Beam Rebar

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ABSTRACT

Precise construction cost estimation is paramount to determining the total construction expense of a project prior to the initiation of the construction phase. Despite this, manual quantification and cost estimation methods, which continue to be widely used, may result in imprecise estimation and subsequent financial loss. Given the fast-paced and efficiency-demanding nature of the construction industry, trustworthy quantity and cost estimation is essential. To mitigate these obstacles, this research is focused on establishing an automated quantity estimation algorithm, particularly designed for the main rebar of beams which are recognized for their complicated reinforcement configurations. The exact quantity derived from the proposed algorithm is compared to the manually approximated quantity, reflecting a variance of 10.27%. As a result, significant errors and impending financial loss can be averted. The implementation of the findings from this research holds the potential to significantly assist construction firms in quickly and accurately estimating rebar quantities while adhering strictly to applicable specifications and regulatory requirements.

Keywords : rebar, lay-out, automatic estimation, mathematical algorithm, beam

1. Introduction

In construction management, construction cost estimation is among the most essential duties to determine the total construction cost of a project before the construction stage sets off[1]. Consequently, project stakeholders need to estimate the construction cost immediately following the completion of the design stage. To estimate the construction cost, a quantity take-off process is conducted after the design stage to prepare a bill of quantity(BOQ) for the bidding and tendering stage of the project. Quantity take-off is the process of analyzing design documents to estimate the quantities of construction materials[2], including rebars. The estimated quantity denotes the quantity approximated through the application of a standardized method of measurement[3]. The measured quantities have diverse applications, such as cost estimation, cost management, procurement, and construction schedule planning activities[4].

The contractor is eager to immediately perform the quantity take-off process for bidding project purposes. In practice, however, the contractors are estimating the rebar quantity manually. Manual quantity take-off is a time-consuming and error-prone process due to it being based on manual-made construction documents and human interpretations[5]. In addition, the manual procedure of estimating rebar quantities can produce diverse outcomes among quantity surveyors, leading to inaccurate estimation. The construction industry's highly competitive nature requires construction firms to perform the task quickly and cost-effectively[6]. Due to the above-mentioned circumstances, establishing an automatic and precise method for rebar estimation then becomes a necessity. Reliable quantity take-offs are integral to the generation of precise estimates, which in turn, ensure project cost control[2].

This research aims to establish an automated quantity estimation algorithm, particularly for the main rebar of beams. Beam elements are rather more complicated to handle than other structural elements due to the many options regarding the reinforcement arrangement[7]. The following steps were taken to demonstrate the efficacy of the proposed algorithm: (1) development of the algorithm, (2) comparison of manually estimated quantity and proposed algorithm generated quantity to verify the outcomes, (3) analysis and discussion of the outcomes. This research is structured as follows: section 2 outlines the study of manual estimation and beam rebar characteristics. Section 3 presents the concept and development of the proposed algorithm. Section 4 verifies the proposed algorithm through a case study. Section 5 concludes this research and discusses potential avenues for future research.

2. Preliminary studies

2.1 Manual quantity estimation

Figure 1 depicts the manual quantity estimation workflow from the early stage to the construction. Structural analysis and design are generally carried out after the architectural design has been completed. Then, the structural design report and drawing are prepared following the completion of the structural analysis and design[8]. Subsequently, the quantity surveyor will estimate the quantities, including rebars based on the architectural drawings, structural drawings, and specifications to determine the cost that will be used for bidding and tendering. After the contract is won, the contractor can commence the project’s construction. The manual estimation process commonly utilizes the guidelines such as the Standard Method for Measurement(SMM), which has transformed into New Rules for Measurement(NRM)[9] and Civil Engineering SMM 4(CESMM4)[10] to measure and take off the quantities of the material. The followings are the general steps involved in this process: 1) identification of the rebar associated with each structural member on the structural drawing, 2) comprehension of the rebar details such as rebar sizes, types, shapes, spacing, lapping lengths, etc., 3) measurement of the rebar lengths based on the aforementioned details, and 4) calculation of the quantities[9,10].

However, manual quantity estimation has inherent drawbacks along the process. Manual quantity take-off is a time-consuming and error-prone process due to it being based on manual-made construction documents and human interpretations of the documents and guidelines[5]. As the construction documents are also manually prepared, mistakes and errors are probable in the preparation and interpretation[11]. In addition, quantity surveyors are likely to make mistakes with rebar, and there can be a discrepancy in the estimation outcomes, depending on their experience and expertise[12]. Therefore, this research proposed to use structural analysis and design information for the automatic rebar quantity estimation, thereby loss of information in the process can be prevented. Efficient and accurate quantity takeoffs and cost estimations are both significantly crucial to contractors, as they use these estimations to assess the most economical manner to approach the project and increase their profit[11].

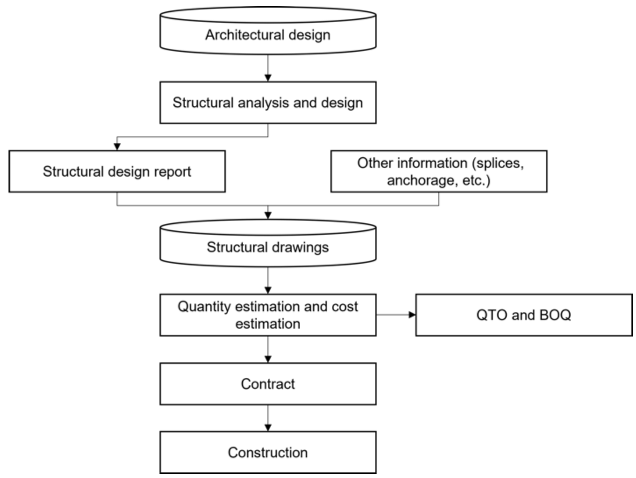


Figure 1. Workflow for manual quantity estimation(Adapted from Kim et al.[3])

2.2 Beam rebar characteristics

Columns and beams are the most fundamental and commonly used structural element types in a typical structural frame, as most of the building's loads are supported by them[13]. All the forces supported by the beams will be transferred to the column system and ultimately transferred to the foundation and adjacent soil. The reinforcement in the beams(girders) can be divided into two groups: continuous rebars and additional rebars. While the continuous rebars span along the beams from the left support to the right support, the additional rebars are only embedded in the left end, middle span, and right end of each beam. Figure 2 depicts the reinforcement details in a beam system.

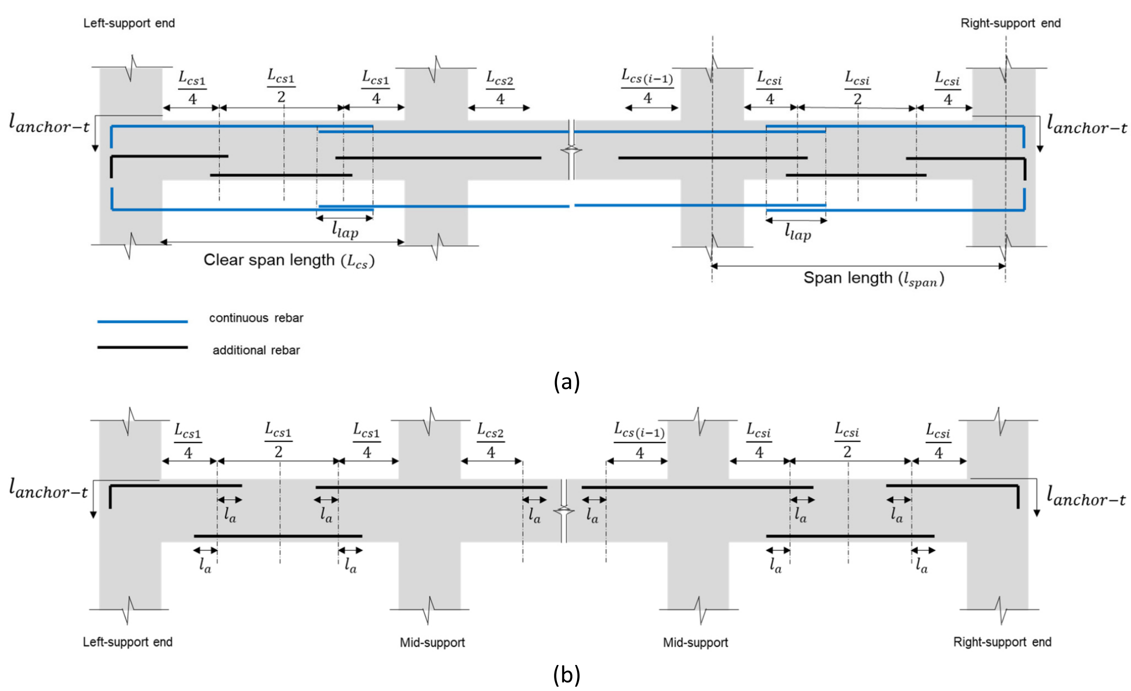


Figure 2. Typical arrangements for beam rebar: (a) continuous rebar; (b) additional rebar

3. Automated quantity estimation algorithm for beam rebar

As mentioned earlier, this research aims to establish an automated quantity estimation algorithm for beam main rebars. The proposed algorithm is utilizing structural analysis and design information combined with specifications and rebar-related building codes to develop the mathematical algorithms. Figure 3 provides an overview of the workflow of the proposed algorithm. The algorithm can be outlined in subsequent steps to achieve the objective:

1. Retrieve the beam and rebar information derived from structural analysis and design, then incorporate the rebar requirements mandated by building codes.
2. Calculate the total length and quantity of continuous reinforcement for the beam.
3. Calculate the length and quantity of additional reinforcement required by the beam.
4. Collect the outcomes and generate a summary sheet containing the total length of continuous reinforcement, length of additional reinforcement, and their respective quantities. These compiled outcomes can be utilized to generate a rebar bill of quantity.

In addition, the development of the proposed algorithm provides several benefits, summarized as follows:

1. The development of the proposed algorithm can prevent mistakes, errors, and loss of information involved in manual estimation.
2. The utilization of the proposed algorithm can estimate the quantity swiftly and precisely while satisfying all the rebar-related codes.
3. Utilizing the proposed algorithm enables the development of an algorithm that can minimize the rebar cutting waste to near zero and reduce the rebar usage.
4. The outcomes of the proposed algorithm can be further used to develop a BIM-based drawing automation system that integrates and manage a series of tasks covering from the rebar cutting and bending to delivery, procurement, installation, and documentation for progress payment.

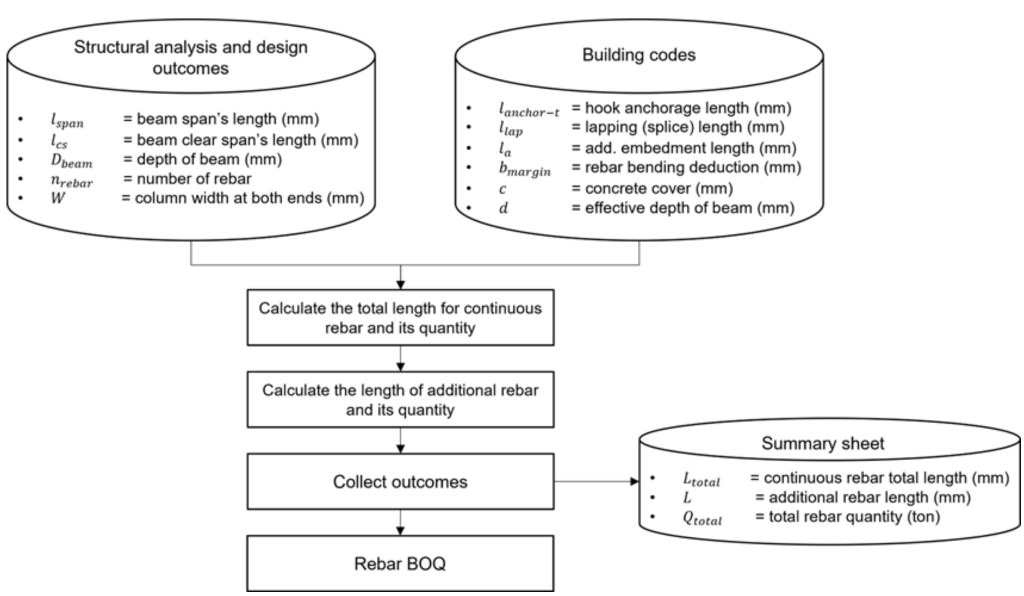


Figure 3. Workflow for automated quantity estimation algorithm for beam rebar

3.1 Continuous beam rebar algorithm

The beams and rebar information are acquired following the completion of the structural analysis and design. The beam span's length, clear span length, depth, and column width at both ends can be acquired. Then, this information is combined with the requirements mandated by the building code and specification, including the hook anchorage length, lapping length, additional embedded length, bending margin, concrete cover, and effective depth of the beam.

Then, the total length of the continuous main rebar can be precisely estimated. Figure 2(a) shows that the beams' continuous main rebar contains the top and bottom rebar. The total length of these rebars(L_{total}) can be calculated through Equation (1) by adding the total length of the beam span(l_{span}) with the total hook anchorage length(l_{anchor_t}) and the total lapping(splicing) length($L_{total-lap}$) and then subtracting the column(support) width(W_l; W_r) at both ends and rebar bending deduction(b_{margin}) from it. British Standard 8666[14] regulates the bending deduction of the rebar. Equation (2) is used to calculate the total lapping length($L_{total-lap}$) by multiplying the number of splices(n_{lap}) with the splice length(l_{lap}).

$$L_{total} = \Sigma l_{span} + 2 \times l_{anchor_t} + L_{total-lap} - \left(\frac{W_l + W_r}{2} \right) - b_{margin} \quad (1)$$

$$L_{total-lap} = \Sigma n_{lap} \times l_{lap} \quad (2)$$

Then, the rebar quantity can be calculated utilizing Equation (3) by multiplying the number of continuous rebars(n_{rebar}) with the rebar's unit weight(w_{rebar}) and the total length(L_{total}).

$$Q = \Sigma n_{rebar} \times w_{rebar} \times L_{total} \quad (3)$$

3.2 Additional beam rebar algorithm

The initial process of estimating the precise additional rebar quantity is similar to the continuous rebar quantity estimation. As previously mentioned, the acquired beams and rebar information from the structural design and analysis are combined with the requirements mandated by the building codes and regulations. Figure 2(b) describes the additional rebar arrangement for a beam or girder, including the top additional rebars and bottom additional rebars. The top additional rebars are divided into two groups, left-support end, and right-support end additional rebar for each beam. Whereas the additional bottom rebar stretches around the middle span of the beam.

Then, the additional top rebar for left-support end length(L) can be calculated using Equation (4) below considering the hook anchorage length(l_{anchor_t}), beam's clear span length(L_{cs_i}), additional embedded length(l_a), column width at the left-support end(W_i), and rebar bending deduction(b_{margin}). The additional embedded length(l_a) itself is regulated to at least equal to or longer than the effective depth of a beam(d) or 12 times the rebar diameter(d_b), whichever is greater[15]. Equation (4) can be used to calculate the additional top rebar for the right-support end at the end of a continuous beam system.

$$L = l_{anchor\_t} + \left(\frac{L_{cs_i}}{4} \right) + l_a - W_i - b_{margin} \quad (4)$$

The additional top rebar for mid-support length(L) can be calculated using Equation (5) below considering the beam's clear span length(L_{csi}), additional embedded length(l_a), column width at the mid-support end($W_{(i+1)}$), as depicted in Figure 2. If there is a discrepancy in the number of rebars needed for the additional top rebar for the mid-support, priority will be given to the smaller number. The remaining rebar will be assigned as additional top rebars for either left-mid or right-mid position. The length of the associated rebar can still be calculated using Equation (5) by assigning the $W_{(i+1)}$ and $L_{cs(i+1)}$ to zero.

$$L=\frac{L_{csi}}{4}+W_{(i+1)}+\frac{L_{cs(i+1)}}{4}+2\times l_a \tag{5}$$

The additional bottom rebar for the middle span can be calculated utilizing Equation (6) below considering the beam's clear span length(L_{cs_i}). Then, the quantity of these additional rebars is calculated using Equation (7) by multiplying the number of additional rebar(n_{add}) with the rebar's unit weight(w_{rebar}) and the length(L).

$$L=\frac{L_{csi}}{2}+2\times l_a \tag{6}$$

$$Q=\sum n_{add}\times w_{rebar}\times L \tag{7}$$

4. Verification of the proposed algorithm

A continuous beam of an RC building project was used as a case study to verify the proposed algorithm. The continuous beam consists of 7 spans, ranging from 8400mm to 10200mm. Table 1 summarizes the information on the beam and rebar. Table 2 presents the length of each beam's span.

Table 1. Information on beams and rebar

Description	Contents
Numbers of span	7 spans
Total length of span($\sum l_{span}$)	62,700mm
Column width at the left-support end(W_l)	800mm
Column width at the right-support end(W_r)	1000mm
Beam depth(D)	700mm
Concrete cover(c)	50mm
Beam effective depth(d)	639mm
Concrete compressive strength(f_{ck})	27MPa
Steel ultimate yield strength(f_y)	600MPa
Main rebar diameter(d_b)	22mm
Lapping/splicing length(l_{lap})	1300mm
Tension hook anchorage length(l_{anchor_t})	1180mm
Rebar unit weight(w_{rebar})	2.984kg/m
Rebar bending deduction(b_{margin})	59.51mm

Table 2. Detailed data on beams

Grid	Beam	Span length(l_{span})	Clear span length(L_{cs})	Column width at the left-support of a beam(W_i)	Column width at the right-support of a beam(W_{i+1})
X3-X4	G11A	9300	8500	800	800
X4-X5	G11	9300	8400	800	1000
X5-X6	G12	8400	7400	1000	1000
X6-X7	G12	8400	7400	1000	1000
X7-X8-1	G13	10200	9200	1000	1000
X8-1-X9-1	G12	8700	7700	1000	1000
X9-1-X11	G12A	8400	7500	1000	800

As shown in Table 2, a continuous beam may consist of several types of beams. Each type of beam may have its rebar arrangement. Table 3 summarizes the rebar arrangement of each beam in a continuous beam system. Considering the rebar arrangement, Figure 4 depicts an example of a beam's rebar arrangement, thereby providing a clear perspective.

Table 3. Arrangement of rebar within the beams

Beam	Top				Bottom			
	Left end	Center	Right end	Continuous	Left end	Center	Right end	Continuous
G11A	8	4	12	4	4	8	4	4
G11	14	4	14	4	5	8	5	4
G12	12	4	12	4	4	8	4	4
G13	15	4	15	4	5	10	5	4
G12A	8	4	12	4	4	8	4	4

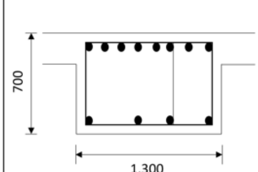
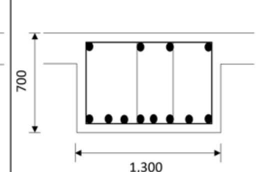
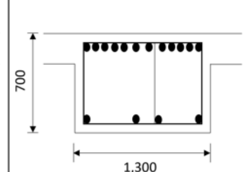
Beam	G12A		
Dimension	1300 X 700		
Section	LEFT-END	CENTER	RIGHT-END
			
Top	8-UHD22	4-UHD22	12-UHD22
Bottom	4-UHD22	8-UHD22	4-UHD22
Stirrups	3-HD10@150	4-HD10@300	3-HD10@150

Figure 4. Sample arrangement for rebar within a beam

After all the required information is collected, the total rebar length of the continuous top and bottom rebars can be calculated utilizing Equation (1). Take the top continuous rebar as an example. Generally, the beams' main rebars are lapped in every span. If there are 7 spans, it means that there are 6 lapping points. Therefore, 71.941m of rebar total length(L_{total}) was acquired. Both top and bottom rebars should be designed in tension to withstand lateral forces, such as wind and earthquake making the total length of both top and bottom continuous rebars identical.

$$L_{total} = \Sigma l_{span} + 2 \times l_{anchor\_t} + L_{total-lap} - \left(\frac{W_l + W_r}{2}\right) - b_{margin}$$

$$L_{total} = 62{,}700 + 2 \times 1180 + (6 \times 1300) - \left(\frac{800+800}{2}\right) - (2 \times 59.51) = 71.941m$$

Then, the quantity of continuous rebar(Q) can be calculated using Equation (2). The proposed algorithm yields 0.8748 tons of continuous rebars. The total quantity of continuous rebars is tabulated in Table 4.

$$Q = \Sigma n_{rebar} \times w_{rebar} \times L_{total}$$

$$Q = 4 \times 2.984 \times 71.940 = 0.8587\ tons$$

Table 4. Calculation summary for continuous rebars

Continuous	No. of rebars	Total length(m)	Quantity(ton)
Top	4	71.941	0.8587
Bottom	4	71.941	0.8587
Total		143.882	1.7174

Regarding the additional rebars, take the G11A beam as an example. Utilizing Equation (4), a 3.084m length of additional top rebar for the left-support end.

$$L = l_{anchor\_t} + \left(\frac{L_{cs_i}}{4}\right) + l_a - W_i - b_{margin}$$

$$L = 1180 + \frac{8500}{4} + 639 - 800 - 59.51 = 3.084m$$

The length of the additional top rebar for the mid-support of the G11A-G11 beams can be calculated using Equation (5). The algorithm generates a 6.303m length of additional rebar.

$$L = \frac{L_{csi}}{4} + W_{(i+1)} + \frac{L_{cs(i+1)}}{4} + 2 \times l_a$$

$$L = \frac{8500}{4} + 800 + \frac{8400}{4} + 2 \times 639 = 6.303m$$

The length of the additional bottom rebar of the G11A beam can be calculated using Equation (6). The algorithm generates a 5.528m length of additional rebar.

$$L = \frac{L_{csi}}{2} + 2 \times l_a$$

$$L = \frac{8500}{2} + 2 \times 639 = 5.528m$$

The quantity of additional rebars can be calculated using Equation (7). Take the additional top rebar for the left-support end of G11A as an example. 0.0368 tons of additional top rebar is generated. Table 5 summarizes all quantities of additional beam rebars, both top and bottom.

$$Q = \sum n_{add} \times w_{rebar} \times L$$

$$Q = 4 \times 2.984 \times 3.084 = 0.0368\ tons$$

Table 5. Quantities of additional beam rebar

Beam	Location	Length(m)	No. of rebars	Quantity(ton)
Top				
G11A	Left end	3.084	4	0.0368
G11A-G11	Mid-support	6.303	8	0.1505
G11	Left	3.378	2	0.0202
G11	Right	3.378	2	0.0202
G11-G12	Mid-support	6.228	8	0.1487
G12-G12	Mid-support	5.978	8	0.1427
G12-G13	Mid-support	6.428	8	0.1534
G13	Left	3.578	3	0.0320
G13	Right	3.578	3	0.0320
G13-G12	Mid-support	6.503	8	0.1552
G12	Right	3.203	4	0.0382
G12-G12A	Mid-support	6.078	4	0.0725
G12	Right end	2.034	8	0.0677
Bottom				
G11A	Midspan	5.528	4	0.0660
G11	Left-midspan	3.378	1	0.0101
G11	Right-midspan	3.378	1	0.0101
G11	Midspan	9.678	1	0.0289
G12	Midspan	4.978	4	0.0594
G12	Midspan	4.978	4	0.0594
G13	Left-midspan	3.578	1	0.0107
G13	Right-midspan	3.578	1	0.0107
G13	Midspan	5.878	6	0.1052
G12	Midspan	5.128	4	0.0612
G12A	Midspan	5.028	4	0.0600
Total				1.5393

The precise quantity acquired from the proposed algorithm above is compared to the manual estimation generated quantity to verify the proposed algorithm. The manual estimation process is conducted based on the NRM[9] and CESMM4[10], which set the guidelines to take off the quantity of rebars. For the D22 rebar, the estimated rebar unit weight is 2.984 kg/m. Table 6 provides the comparison of generated rebar quantity between the manual estimation and the proposed algorithm.

Table 6. Comparison of generated rebar quantities

Description	Manual estimation(ton)	Proposed algorithm(ton)	Difference(%)
	(A)	(B)	$\frac{(B-A)}{(B)} * 100\%$
Continuous	1.5818	1.7174	7.90
Additional	1.3404	1.5393	12.93
Total	2.9221	3.2567	10.27

The precise quantity and manual estimated quantity of beam main rebars are 3.2567 tons and 2.9221 tons, respectively, leading to a difference of 0.3346 tons(10.27%). Results indicate that the rebar quantities are underestimated(A<B). The underestimation of the rebar quantity might force contractors to incur greater expenses as more rebar may be required than originally estimated, resulting in reduced profits or even losses. Conversely, the overestimated condition(A>B) may make the contractors less competitive in bidding due to higher estimated costs, potentially failing to win the project. As previously mentioned, the manual quantity tale-off(QTO) process is prone to human errors resulting in an inaccurate estimated quantity.

The information obtained in this research could be used to establish a 3D-BIM model which can automatically produce the bar bending schedule(BBS), bar cutting list(BCL), and even bill of quantity(BOQ). It can assist the contractor in planning the rebar procurement, installation, and documentation for progress payment.

5. Conclusion

The current method for estimating quantities involves a manual and human effort to carry out the process. The process of manual quantity take-off is known to be both time-consuming and prone to errors, as it depends upon construction documents that are produced manually and subject to human interpretation. Therefore, this research aims to establish an automated quantity estimation algorithm, particularly for the main rebar of beams. The information acquired from the structural design and analysis is integrated with the requirements stipulated by the specifications and building codes. The precise quantity and the estimated quantity of the beam rebar were found to be 3.2567 tons and 2.9221 tons, respectively, resulting in a difference of 0.3346 tons(10.27%).

While the proposed algorithm offers accurate quantity estimations, its practical application may encounter a major challenge. Given the enduring existence of the take-off quantity process, each construction firm may have devised its methodologies and approaches for estimating material quantities. Hence, it becomes essential to exert greater efforts in raising awareness about the benefits and advantages of implementing the proposed algorithm within the industry. Going forward, this research recommends that future research should explore the development of a BIM-based drawing automation system that integrates and manages a series of tasks covering the rebar cutting and bending to delivery, procurement, installation, and documentation for progress payment. In addition, future research could explore the development of an algorithm that minimizes rebar cutting waste to near zero and reducing rebar usage. Upon implementation, the research findings can greatly assist construction firms to swiftly and precisely estimate rebar quantities, while maintaining full compliance with relevant specifications and regulatory requirements.

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