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Optimizing Rebar Consumption and Cutting Waste in Column Reinforcement: Integrated Mechanical Couplers and a Special-Length-Priority Minimization Algorithm

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Abstract: The construction of reinforced concrete (RC) structures inevitably consumes an excessive number of rebars, leading to significant cutting waste and carbon emissions. Extensive research has been conducted to minimize this issue and its consequences; however, these methods consistently consume a substantial number of rebars. This includes a previous study that utilizes the lap splice position optimization and special-length rebar concept without considering the lapping zone regulation. Moreover, conventional lap splices pose inherent drawbacks that could jeopardize the structural integrity of RC members. In contrast, mechanical couplers eliminate the need for rebar lapping, effectively reducing rebar consumption. This research aims to evaluate the impact of an integrated mechanical coupler and special-length-priority minimization algorithm on the reduction in rebar consumption and cutting waste in RC columns, achieving near-zero cutting waste. To validate the effectiveness of the proposed algorithm, it was applied to the column rebars of an RC building. The results revealed a significant reduction in the ordered rebar consumption by 18.25%, accompanied by substantial reductions in the cutting waste (8.93%), carbon emissions (12.99%), and total costs (9.94%) compared with a previous study. The outcomes provide the industry with insights into further reducing rebar consumption and its related consequences. Applying the proposed algorithm to various construction projects will further amplify the corresponding benefits.

Keywords: rebar consumption; cutting waste; column; coupler; special length; minimization; carbon dioxide emissions; resource conservation

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1. Introduction

The construction of reinforced concrete (RC) structures inevitably consumes an excessive number of rebars and generates rebar cutting waste, with a projected range of 3–5% during the planning phase and an actual range of 5–8% during on-site realization [1]. Furthermore, the manufacture of rebars requires a tremendous amount of energy, which contributes to carbon emissions, thus posing a threat to the environment. In 2020, the global construction industry consumed 14 billion m^3 of concrete [2], generating 53.9 million tons of cutting waste and emitting 188.92 million tons of CO_2, resulting in a loss of USD 55.12 billion.

Conventional lap splicing with confining reinforcement, commonly used to connect adjacent rebars for decades [3,4], is one of the major contributors to waste and carbon emission issues in the industry. Lap splices necessitate longer lapping lengths, especially for larger-diameter rebars in high-rise buildings, and they have to be positioned following building codes, which augment rebar consumption and waste. Lap splice efficacy is dependent on the bonding strength between the concrete and rebars, which is reflected in the lap splice length. Moreover, investigations assert that adequate concrete cover, tensile strength, and transverse reinforcement ensure the performance of lap splices [5,6]. Building code regulations mandate specific positions or zones for lap splices, yet construction sites often find it difficult to follow these regulations and therefore disregard them [6]. Disregarding the regulation does not necessarily lead to structural failure. Although diverse optimization methods have been investigated, including cutting pattern and lap splice position optimization [7,8], their efforts have been limited to the adoption of stock-length rebars and building code regulations regarding lap splice position. As a result, it is difficult to reduce rebar cutting waste to below 5%, even with great effort.

In response to the disadvantage of stock-length rebars, researchers have introduced the use of special-length rebars to reduce cutting waste. The utilization of special-length rebar has been demonstrated to effectively minimize rebar cutting waste for beam elements, achieving waste reductions of less than 3% [9]. Despite the benefits of utilizing lap splice position flexibility and special-length rebar, column elements fabricated with this approach still exhibit substantial rebar consumption, even when zone regulations are not considered.

In addition, the application of conventional lap splicing has several drawbacks, including rebar congestion, increased rebar waste, higher costs, and impaired structural integrity [4,10–15]. The emergence of mechanical splices or couplers sheds light on this issue. Couplers can connect adjacent rebars with significantly shorter lengths. They achieve greater strength than the rebar, efficiently transferring rebar tensile forces and maintaining structural integrity and stability compared to lap splices. Thus, couplers consume significantly less rebars and less waste, eventually reducing cost and carbon emissions.

1.1. Rebar Consumption and Cutting Waste

The global concrete volume reached 14 billion m^3 in 2020 [2]. The extensive usage of concrete and rebars accounts for 65% of the CO_2 emissions from the construction sector, with rebars alone responsible for 60% of this [16]. Research has established a rebar-to-concrete consumption ratio of 0.077 tons/m^3 [1], indicating that the global concrete volume above corresponds to 1.078 billion tons of rebars. Considering a 5% cutting waste rate, this equates to 53.9 million tons of rebar cutting waste and 188.92 million tons of carbon emissions. Integrating these findings with a rebar price of USD 900/ton [17], a unit of rebar–carbon emissions of 3.505-ton-CO_2/ton [18], and a carbon price of USD 75/ton-CO_2 [19] implies a potential loss of USD 62.68 billion.

Traditionally, material cutting waste has been viewed as a 1D-cutting stock problem. Researchers later expanded this focus to a 1D assortment problem, utilizing multiple stock lengths to minimize waste [20,21]. In the context of rebars, previous research focused on identifying the most optimal combination of stock-length rebars that generates the least amount of cutting waste. Nonetheless, this approach still generates a significant amount of cutting waste (>1%). Table 1 summarizes numerous studies that have attempted to optimize rebar cutting waste utilizing stock-length rebars. Additionally, investigations [7,8] have also combined stock-length rebars with lap splice position optimization per the related regulation provided by building codes and failed to reduce the cutting waste to below 5%.

Table 1. The impact of stock-length rebar usage on cutting waste.

Author(s)	Structural Member(s)	Rebar Cutting Waste
Khalifa et al. [22]	N/A	5.15%
Khondoker [23]	RC frames	2.69%
Zheng et al. [24]	RC slab	14.49%
Zheng et al. [25]	RC slab	1.8%
Chen and Yang [7]	RC beam section	8.4%
Nadoushani et al. [8]	RC columns	7.2%
	RC shear walls	10.6%

Faced with the challenge posed by stock-length rebars and their consequential high cutting waste, researchers and the industry have actively explored alternative solutions, including special-length rebars. The use of special-length rebar enables the rebar lengths to be adjusted to fit the specific circumstances of a construction project, as they are supplied in

0.1 m increments. Previous research, as summarized in Table 2, confirms the effectiveness of special-length rebars in minimizing cutting waste, enabling the achievement of near-zero cutting waste. Nevertheless, their utilization remains limited to medium- and large-scale construction projects.

Table 2. The impact of special-length rebar usage on cutting waste.

Author(s)	Structural Member(s)	Rebar Cutting Waste
Porwal and Hewage [26]	RC frames	0.93%
Lee et al. [27]	RC frames	0.58%
Widjaja and Kim [28]	RC beams	0.93%

1.2. Rebar Splicing Methods

The need for lap joints on reinforced concrete (hereinafter, RC) structures arises due to various factors, including the limited length of the supplied rebar, variations in rebar diameter, and challenges related to transportation [13]. Although conventional lap splicing has long been considered a reliable and effective method for rebar splicing, it has several drawbacks that limit its applicability. These drawbacks include increased rebar consumption and waste, rebar congestion, a higher cost, and unsuitable use in the plastic hinge region [4,10,11,15]. Moreover, several studies [12,15,29] have highlighted that the adoption of lap splices may lead to the over-reinforcement of the section, reduced ductility, and ultimately a change in the structure's deformation capacity. Ductility plays a vital role in averting sudden collapse due to brittle failure during seismic events [30]. Additionally, an increase in the diameter of the rebar corresponds to an extended development or anchorage length. As building codes define the lap splice length as a multiplication of factors (ranging from 1.0 to 1.3) by the development length, an extended lap splice length will ultimately increase rebar consumption and rebar waste.

Such drawbacks of conventional lap splices urge researchers and experts to devise a novel splicing method, including mechanical splices or couplers. In RC structures, a mechanical coupler serves as a device to connect two rebars, establishing a mechanical bond and eradicating the need for lap splicing. Couplers are primarily used to shorten splice length and alleviate bar congestion in the connections of RC structural members [31]. Initially, related building and seismic codes prohibited the application of couplers within the plastic hinge region, especially in areas prone to high seismic activities. However, recent investigations have shown that couplers may be used in the plastic hinge region of precast concrete columns. In terms of seismic application, the coupler length should be less than $15d_b$ [32]. This discovery provides valuable knowledge regarding the behavior and applicability of couplers in RC structures. Furthermore, previous studies have reported several benefits of mechanical couplers [4,11,15]: (1) alleviating rebar congestion problems; (2) significantly reducing rebar waste and consumption; (3) allowing for the effective control of concrete crack propagation; (4) improving the structural continuity between rebars, ensuring better integrity; (5) reducing the required labor, resulting in construction cost reduction; and (6) providing feasibility to connect rebars of varying lengths and diameters.

A variety of couplers are commercially accessible and available on the market, namely, (1) shear screw couplers [31,32], (2) grouted sleeve couplers [31,32], (3) parallel threaded couplers [4,31,32], (4) swaged couplers [4,31,32], and (5) rib-thread couplers [4,31,32], as illustrated in Figure 1. Threaded couplers are the most prevalent type of coupler, characterized by their short length and ease of installation [14,33]. Threaded couplers can be categorized as parallel threaded couplers (PTCs), taper threaded couplers (TTCs), upset-headed couplers (UHCs), and rib-thread couplers (RTCs) [34].

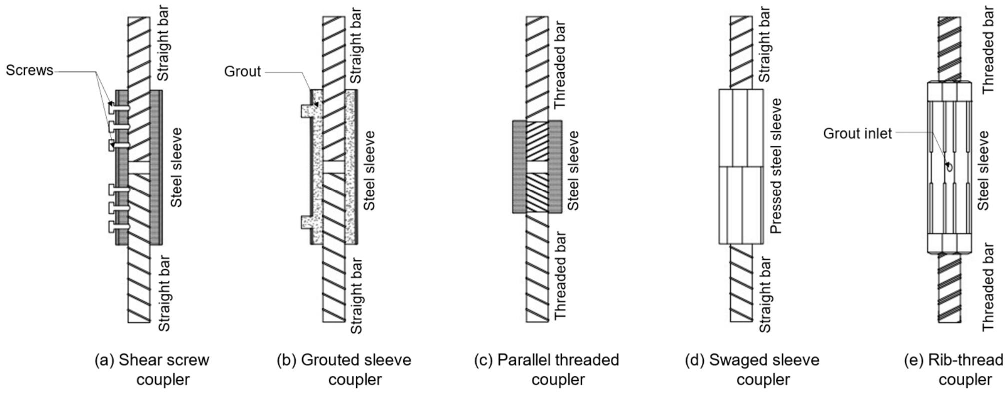


Figure 1. Market-ready mechanical couplers.

1.3. Research Feasibility and Research Objective

Mechanical couplers have not been prevalently used due to three challenges: pre-planning requirements, cost and installation time concerns, and constructability issues if rebar prefabrication and assembly are not well organized. Building information modeling (BIM)-based integrated project delivery can mitigate the challenges of pre-planning and constructability. Progress in technology combined with a concurrent rise in material and labor costs have positioned couplers as competitive substitutes for lap splices, notably for rebar diameters exceeding 19 mm.

Conventional lap splices have inherent disadvantages related to rebar consumption, waste, and structural integrity. Conversely, couplers offer many advantages as potential substitutes for splicing, as described above. Surprisingly, despite their potential to reduce rebar usage and cutting waste, couplers have been notably absent from previous studies addressing this issue. To the best of the authors' knowledge, there is a dearth of research on the combined use of mechanical couplers, special length rebars, and flexible coupler placement to minimize rebar consumption and waste in concrete structures. Existing studies primarily focus on individual strategies, with limited exploration of their synergistic impacts. Furthermore, the crucial role of each structural member's characteristics in optimizing the algorithm process has been largely overlooked.

Hence, this research aims to evaluate the impact of an integrated mechanical coupler and a special-length-priority minimization algorithm on the reduction in rebar consumption and cutting waste in RC columns, achieving near-zero cutting waste. This research restricts the proposed algorithm to the main rebars of the columns. RC columns are chosen due to their crucial role in transferring entire building loads from beams and slabs to the foundation below. In earthquake-resistant structures, their high ductility and energy absorption capacity are essential for maintaining structural integrity under seismic loads. This research serves as a pioneer investigation into this integrated approach.

The effectiveness of the proposed approach is assessed by undertaking the following steps: (1) the establishment of the proposed algorithm; (2) validation through a case study; (3) the calculation of cutting waste, rebar consumption, carbon emissions, and associated costs, and a comprehensive comparison with the original design and conventional lap splice method; and (4) an in-depth analysis and discussion of the obtained results. With the present limited attention toward rebar consumption optimization, this initiative carries significant importance for both researchers and the construction industry, delving into this critical concern. In addition, this research also provides insights into the possibility of reducing the number of required rebars without compromising the structural integrity of RC structures.

2. Column Characteristics

Columns, vertical load-bearing components responsible for carrying axial compressive loads [35], transfer the entire load from the beams and slabs above to the foundation while ensuring the stability of the structure. They are designed to withstand axial and bending loads. Columns can also experience bending, torsion, and shear forces, particularly when subjected to eccentric or lateral loads. Excessive transverse loads can induce buckling, resulting in sudden bending deformations and buckling failure. Column longitudinal reinforcement resists axial and bending loads; torsional reinforcement resists torsion; and transverse reinforcement resists shear forces and buckling, as well as enhancing lateral load resistance by providing confinement. Moreover, the shear stress in a column may not be uniformly distributed, with the maximum shear stress occurring at the end of the column. These loads can significantly affect the structural integrity of the building, increasing the risk of failure. Nonetheless, this research mainly centers its attention on the main rebars within the columns. Figure 2 illustrates the detailed column rebar arrangement considering couplers.

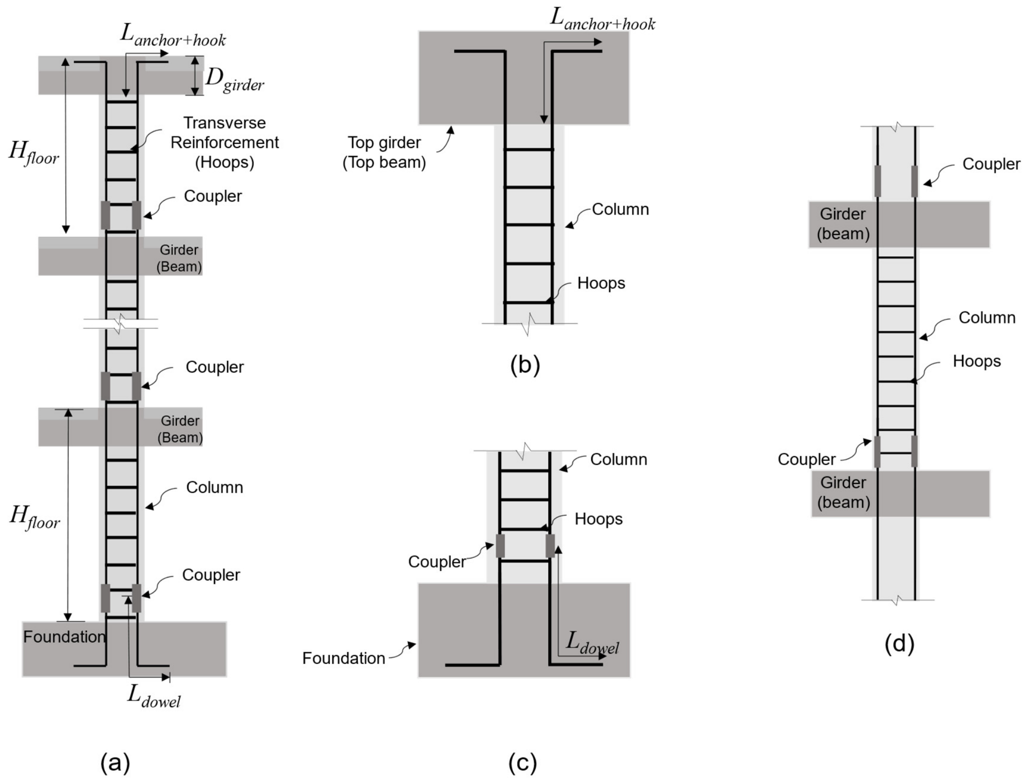


Figure 2. (**a**) Common column rebar arrangement with couplers; (**b**) detail of top-anchored rebar; (**c**) detail of foundation–column connection; (**d**) detail of couplers between floors (modified from [9]).

Continuous columns are reinforced with dowel bars that connect the foundations and columns, longitudinal rebars that are repeatedly connected by couplers on each floor, and rebars that are anchored to the top beam of the building [9]. High-rise buildings are generally reinforced with 20 mm rebars, while skyscrapers require 32 mm or larger rebars [36].

The use of couplers offers the advantage of reducing bar congestion issues, which requires careful attention to rebar spacing. Rebar spacing must be maintained, as certain types of couplers can affect the minimum spacing requirements and reduce the bond between the concrete, rebar, and coupler, decreasing the strength and quality. Building codes define the minimum rebar spacing requirements, and they are summarized in Table 3.

Table 3. Minimum rebar spacing requirements in RC structural members.

Building Code(s)	Description
ACI 318-19 [37]	The minimum spacing between reinforcement for column or vertical structural members should be at least $1.5d_b$ and $\frac{4}{3}d_{agg}$ (maximum size of coarse aggregate).

Table 3. *Cont.*

Building Code(s)	Description
BS 8110-97 [38]	The minimum horizontal spacing or distance between bars should not be less than $h_{agg} + 5$ mm, and vertical spacing should not be less than $\frac{2}{3}h_{agg}$ (maximum size of coarse aggregate).
JGC 15-2007 [39]	The minimum clear distance between bars for columns should not be less than 40 mm, $\frac{4}{3}d_{agg}$, or $1.5d_b$.

3. Methodology

The proposed framework for evaluating the impact of integrated mechanical couplers and the special-length-priority minimization algorithm on the reduction in column rebar consumption and cutting waste while maintaining a near-zero waste strategy is divided into five modules, as depicted in Figure 3: (1) model preparation and data collection; (2) the application of integrated mechanical couplers and a special-length-priority minimization algorithm on main rebars of the column; (3) rebar adjustment considering the identified special-length rebars; (4) special-length-priority minimization for the remaining rebars and quantity confirmation; and (5) the validation of the algorithm in terms of the rebar consumption, rebar cutting waste, CO_2 emissions, and associated cost. In this research, the minimum order quantity for special-length rebar is defined as 50 tons and two months of preorder time [27].

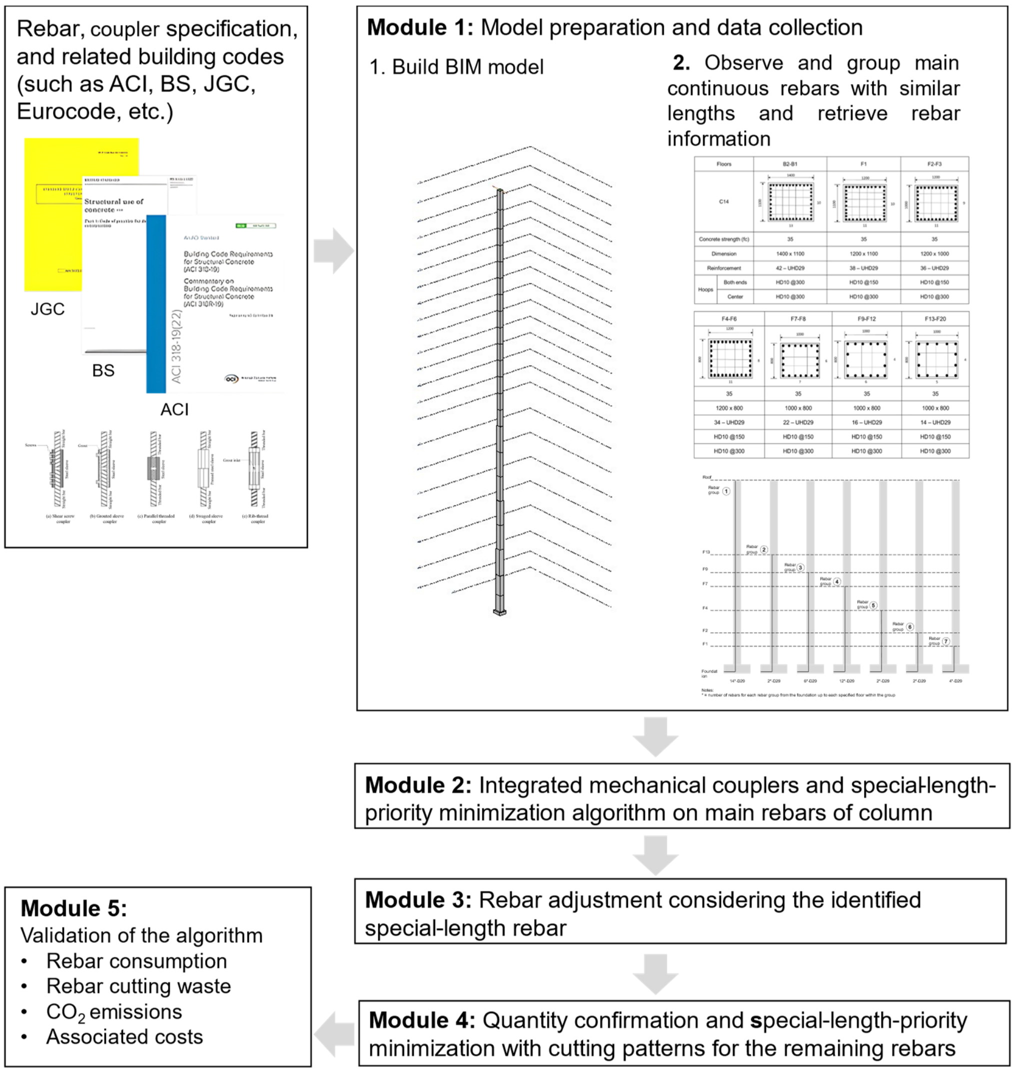


Figure 3. A framework of the proposed algorithm (modified from [9]).

3.1. Module 1: Model Preparation and Data Collection

In this module, the column is initially built as a structural BIM model in Autodesk Revit 2022 based on the structural analysis and design results. BIM adoption in this research was motivated by its documented potential for construction waste reduction, as evidenced by various prior investigations [40–45]. A 3D model of concrete columns from the foundation to the roof floor is built using their length, width, depth, and other information, including concrete grade and reinforcement grade that determine the reinforcement details. Reinforcements and their details are then added to the model in accordance with the relevant building codes, such as the rebar shape code [46] and other building codes. British Standard 8666 [46] governs the requirements for the rebars' dimensioning, scheduling, cutting, and bending, allowing for an exact calculation. The 3D model shows that the column has various rebar layout arrangements from the basement floor to the roof floor, as the column dimensions and the number of rebars decrease on the upper floors. It can be perceived that certain rebars stretch from the foundation to the roof, while others may extend only up to a specific point within the column. Therefore, rebars with similar lengths are grouped into the same group.

3.2. Module 2: The Application of Integrated Mechanical Couplers and Special-Length-Priority Minimization Algorithm on Main Rebars of the Column

The previous module identifies the longest rebar group. In this module, a set of mathematical equations is applied to identify one specific special-length rebar, accommodating the usage of couplers. Rebar details regarding the floors (H_{floor}), the number of rebars, and the lengths of the hook anchorage ($L_{anchorage+hook}$) of the original design must be obtained. Figure 4 describes the steps taken in this module. These steps [9] are developed under the premise that the minimum spacing between the bars meets the regulation.

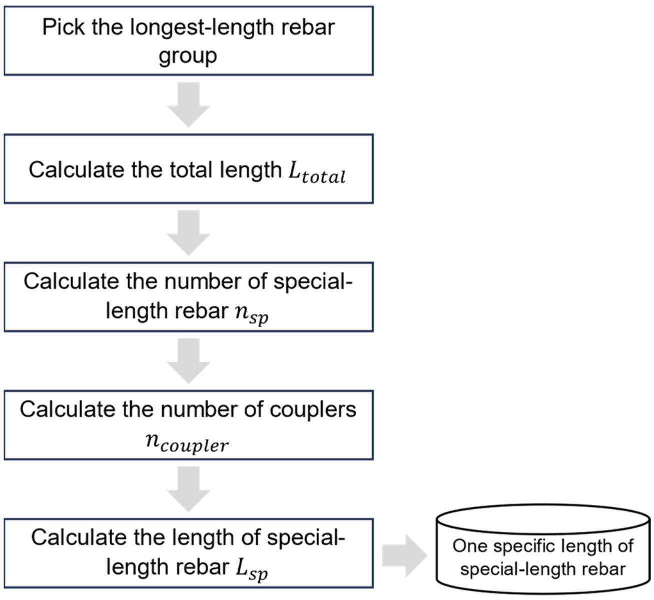


Figure 4. Steps taken in the 2nd module of the algorithm.

First, the total length (L_{total}) of the continuous rebar in the longest rebar group is calculated. The total length equation of the column's main rebar that extends from the foundation to the top girder is expressed in Equation (1). Equation (1) considers the following factors: the height of each floor, the total number of floors, the depth of the girder, the length of the dowel and anchorage, and the bending deduction.

$$L_{total} = \sum H_{floor} + L_{dowel} + L_{anchor+hook} - D_{girder} - \sum B_{deduct} \quad (1)$$

Here, L_{total} is the total length of the continuous main rebar (mm), H_{floor} is the height of the floor (mm), n_{floor} is the number of floors, D_{girder} is the depth of the girder (mm), L_{dowel} is the length of the dowel bar (mm), $L_{anchor+hook}$ is the hook anchorage length (mm), and B_{deduct} is the bending deduction.

Second, the number of special-length rebar (n_{sp}) is calculated by dividing the total length of the rebars (L_{total}) by the reference length or the maximum length of the rebars that can be ordered (L_{ref}). The ceiling function is used to round the result up to the nearest integer, as expressed in Equation (2):

$$n_{sp} = \left\lceil \frac{L_{total}}{L_{ref}} \right\rceil \tag{2}$$

Third, the number of couplers required to connect the rebars ($n_{coupler}$) in the group can be calculated using Equation (3), deducting one from the number of special-length rebar (n_{sp}):

$$n_{coupler} = n_{sp} - 1 \tag{3}$$

Finally, the total length of the special-length rebars is divided by the number of special-length rebars to obtain the calculated length (L_{calc}), as shown in Equations (4) and (5). A coupler may include an inner gap ($s_{coupler}$) between the rebars to facilitate installation in the case of misaligned threads and for grouting purposes. The inner gap of the coupler may vary depending on the type and diameter of the coupler itself. Thus, this gap has to be deducted from the rebars. Half of the gap is deducted from the end bar, whereas the entire gap is deducted from the middle bar, as illustrated in Figure 5. The round-up function is used, as special-length rebars (L_{sp}) can only be ordered in 0.1 m increments, as shown in Equation (6).

$$L_{calc} = roundup\left(\frac{L_{total}}{n_{sp}} - \frac{s_{coupler}}{2}\right) \text{ for end bar} \tag{4}$$

$$L_{calc} = roundup\left(\frac{L_{total}}{n_{sp}} - s_{coupler}\right) \text{ for middle bar} \tag{5}$$

$$L_{sp} = roundup(L_{calc}) \tag{6}$$

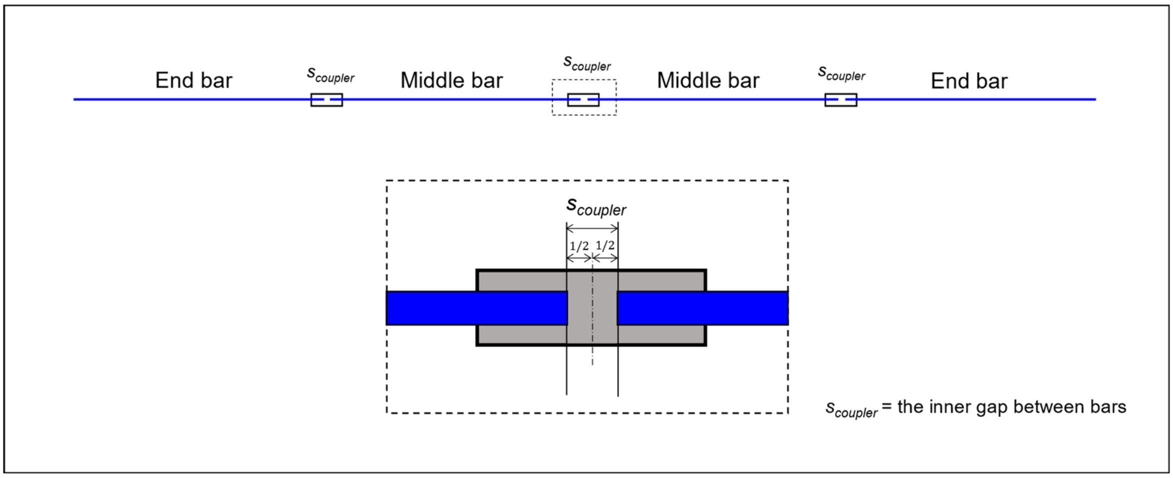


Figure 5. Illustration of coupler's inner gap.

3.3. Module 3: Rebar Adjustment Considering the Identified Special-Length Rebars

This module attempts to accommodate other rebar groups by utilizing the special-length rebar identified in the previous module. Dividing the total length of each rebar group by the identified special length of the rebars may result in a non-integer value, which results in remaining rebars. The steps [9] taken in this module are illustrated in Figure 6.

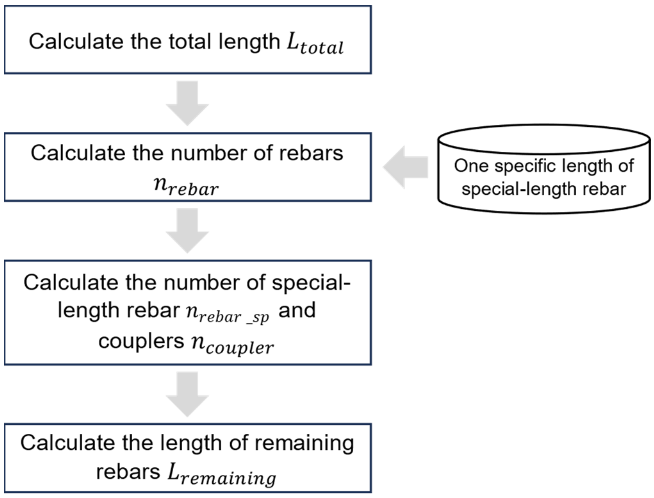


Figure 6. Steps taken in the 3rd module of the algorithm.

First, the total rebar length for each rebar group (L_{total}) can be calculated using Equation (1) described above. Second, prioritizing the special length obtained, the number of rebars within the rebar group (n_{rebar}) can be calculated by dividing the total length (L_{total}) with the identified special length of the rebars (L_{sp}) in the previous module, as expressed in Equation (7). In this equation, the ceiling function is used to generate an integer number. Third, Equation (8) is utilized to identify the number of special-length rebar (n_{rebar_sp}) for each rebar group. Then, the number of couplers required in each rebar group ($n_{coupler}$) can be calculated utilizing Equation (9).

$$n_{rebar} = \left\lceil \frac{L_{total}}{L_{sp}} \right\rceil \quad (7)$$

$$n_{rebar\_sp} = n_{rebar} - 1 \quad (8)$$

$$n_{coupler} = n_{rebar} - 1 \quad (9)$$

Nevertheless, not all the rebars can be accommodated by the identified special length of the rebars, resulting in remaining rebars. The remaining rebar length ($L_{remaining}$) can be calculated by subtracting the total length of the special-length rebars that can be installed within the rebar group and coupler's inner gap from the total rebar length (L_{total}), as shown in Equation (10). The number of remaining rebars should always be one.

$$L_{remaining} = L_{total} - \left(n_{rebar_{sp}} \times L_{sp}\right) - \frac{s_{coupler}}{2} \quad (10)$$

3.4. Module 4: Special-Length-Priority Minimization with Cutting Patterns for the Remaining Rebars and Quantity Confirmation

This module is divided into two processes, special-length-priority minimization for the remaining rebars and rebar quantity confirmation for both the continuous and remaining rebars. The number of special-length rebars is identified utilizing Equations (11)–(16), as proposed by previous investigations [9,27]. Equation (11) plays a role as an objective function, searching for the special-length rebar that generates the lowest ratio of cutting waste.

$$Minimize\ f(X_i) = \sum_{i=1}^{N} \frac{Lsp_i n_i - l_i n_i}{Lsp_i n_i} \quad (11)$$

Here, Lsp_i is the special length i (mm), l_i is the length of the cutting pattern i derived by combining multiple demand lengths (mm), and n_i is the number of rebar combinations with the same cutting pattern.

Equations (12)–(16) play a role as the constraints needed to achieve the objective of minimization. Equation (12) ensures that the total length of the cutting pattern i (l_i) is less than or equal to the special length (Lsp_i). Equation (13) ensures that the number of combinations with the same cutting pattern i (n_i) is greater than zero. Equation (14) requires that the special length (Lsp_i) is within the range of the minimum (L_{min}) and maximum (L_{max}) lengths of the special-length rebar that can be ordered. Equation (15) ensures that the total quantity of rebars (Q_{total}) is greater than or equal to the minimum order quantity required by steel mills (Q_{so}). Equation (16) establishes that the rebar cutting waste (ε) should be equal to or less than the target rebar cutting waste (ε_t).

$$l_i \leq Lsp_i, \; l_i = r_1 + r_2 + \cdots + r_n \tag{12}$$

$$0 < n_i, \quad i = 1, 2, \ldots, N \tag{13}$$

$$L_{min} \leq Lsp_i \leq L_{max} \tag{14}$$

$$Q_{so} \leq Q_{total} \tag{15}$$

$$\varepsilon = \frac{Lsp_i - l_i}{Lsp_i} \leq \varepsilon_t \tag{16}$$

The rebar cutting waste (RCW), required quantity (Q_{req}), and ordered quantity (Q_{ord}) can be obtained at the end of this module, using a set of equations described in previous research [9]. Equation (17) can be used to calculate the rebar cutting waste, which is defined as the difference between the required and ordered quantities divided by the ordered quantity. The required and ordered quantities are the total quantity of rebars required and used on the construction site and the total quantity of rebars ordered from steel mills, respectively. Calculating the required quantity of continuous rebars (Q_{req-c}) involves utilizing the rebar length calculated using Equations (4) and (5), as illustrated in Equation (18). For the remaining rebars, their quantity (Q_{req-r}) can be determined by considering the total length of the cutting pattern i ($\sum l_i$), outlined in Equation (19). To calculate the ordered quantity (Q_{ord}) for both the continuous and remaining rebars, considering the identified special-length rebar, Equation (20) can be utilized.

$$RCW = \frac{Q_{ord} - Q_{req}}{Q_{ord}} \times 100\% \tag{17}$$

$$Q_{req-c} = \sum n_{sp} \times L_{calc} \times w_{rebar} \tag{18}$$

$$Q_{req-r} = \sum n_{sp} \times \sum l_i \times w_{rebar} \tag{19}$$

$$Q_{ord} = \sum n_{sp} \times L_{sp} \times w_{rebar} \tag{20}$$

3.5. Module 5: Validation of the Proposed Algorithm

In this module, the results from the previous modules (required quantity, ordered quantity, and rebar cutting waste) are compiled and compared with the original design and a previous study's finding using conventional lap splices. The required quantity, ordered quantity, and cutting waste are converted into CO_2 emissions and associated costs. This module quantifies the impact of utilizing couplers on rebar consumption, rebar cutting waste, CO_2 emissions, and total costs.

4. Case Study and Validation of the Algorithm

4.1. Case Study Application

A single continuous column that extends from the building's foundation to the roof floor was chosen for the application of the proposed algorithm. This type of column was chosen to demonstrate the whole proposed algorithm's ability. The building comprised 22 floors, that is, 20 floors above ground and 2 basement floors. The column height varied from 3.7 m to 6 m depending on the floor height. For this case, the minimum order quantity of 50 tons was temporarily disregarded to identify the optimal solution.

Regarding the coupler, a rib-thread coupler from Tokyo Tekko Co., Ltd., Tokyo, Japan [47] was selected for this research due to its wide range of diameters; ease of installation; high strength; and ability to resist lateral forces, such as wind and earthquakes. See Appendix A (Figure A1 and Table A1) for the detailed specifications of the coupler. Additionally, this research utilized threaded rebars from the same manufacturer. Table 4 depicts the rebar layout and arrangement of the column. Detailed information on the column and its reinforcement can be seen in Table 5.

Table 4. Rebar layout and arrangement of single continuous column for each floor (adapted from [9]).

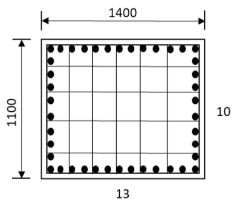
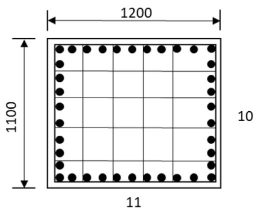
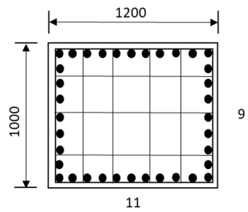
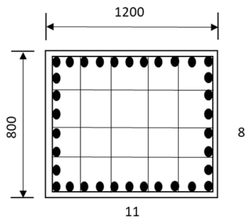
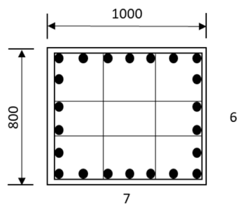
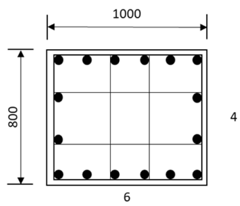
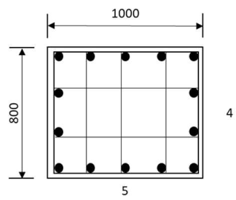
Floors		B2-B1	F1	F2-F3	F4-F6
C14					
Concrete strength, f_c (MPa)		35	35	35	35
Dimension (mm)		1400 × 1100	1200 × 1100	1200 × 1000	1200 × 800
Reinforcement		42—UHD29	38—UHD29	36—UHD29	34—UHD29
Hoops	Both ends	HD10@300	HD10@150	HD10@150	HD10@150
	Center	HD10@300	HD10@300	HD10@300	HD10@300
Floors		F7-F8		F9-F12	F13-F20
C14					
Concrete strength, f_c (MPa)		35		35	35
Dimension (mm)		1000 × 800		1000 × 800	1000 × 800
Reinforcement		22—UHD29		16—UHD29	14—UHD29
Hoops	Both ends	HD10@150		HD10@150	HD10@150
	Center	HD10@300		HD10@300	HD10@300

Table 5. Detailed information on the column case and its reinforcement.

Description	**Content**
Foundation depth (D_f)	600 mm
Foundation concrete cover (C_f)	50 mm
Basement level (B2-B1) height	8300 mm
Upper ground level (F1-Roof) height	87.4 m
Total floor height ($\sum H_{floor}$)	95.7 m
Girder depth (D_{girder})	700 mm
Rebar diameter (d)	UHD600 D29
Concrete strength (f_c)	B2-F20: 35 MPa
Girder depth (D_{girder})	700 mm

Table 5. *Cont.*

Description	Content
Anchorage length (L_{anchor})	1050 mm
90-degree hook length (L_{hook})	350 mm
Dowel bar length (L_{dowel})	850 mm
Bend deduction (B_{deduct})	79 mm
D29 unit weight	5.04 kg/m
Coupler inner gap ($s_{coupler}$)	20 mm

The BIM model revealed that some of the main rebars spanned the entire column height from the foundation to the roof, while others extended to specific points within the column, as illustrated in Figure 7. These main rebars were grouped into seven groups, as presented in Table 6.

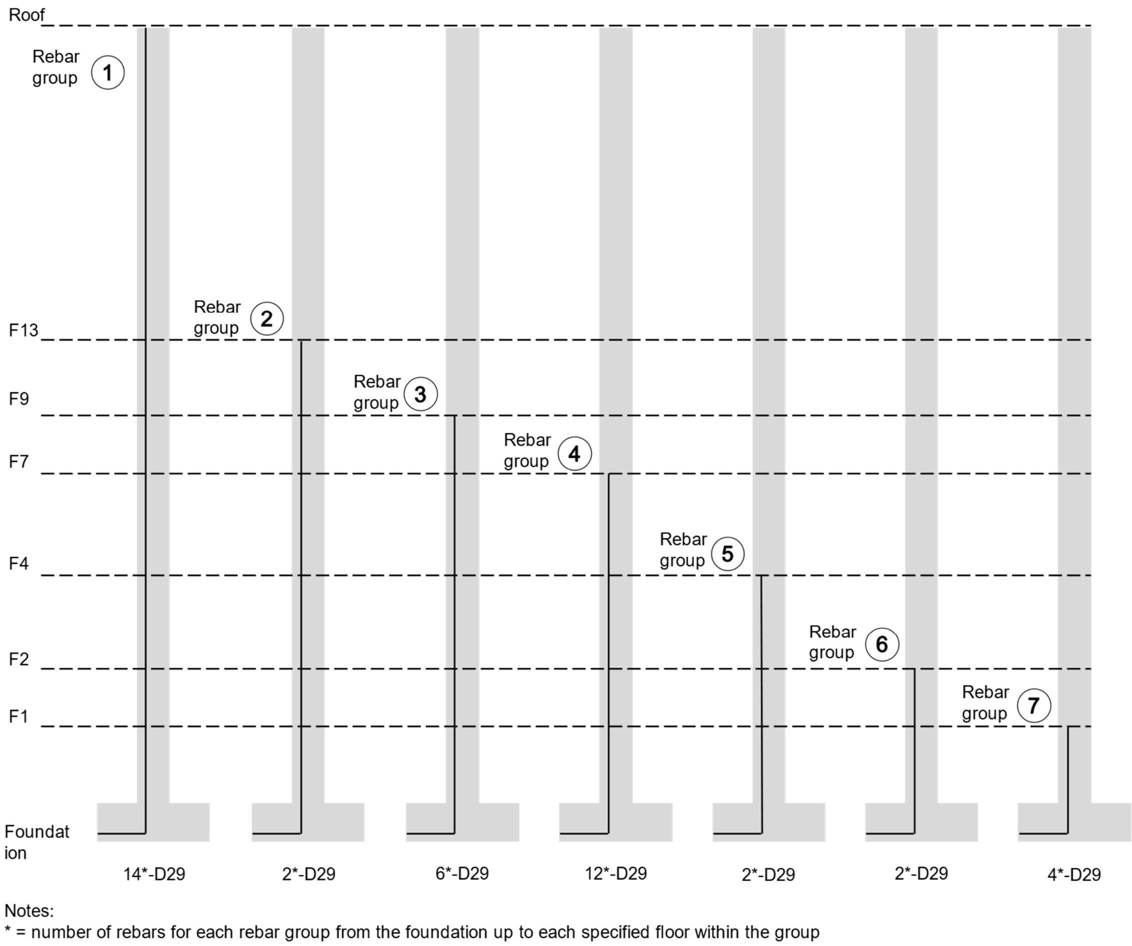


Figure 7. Rebar groups with similar lengths (adapted from [9]).

Table 6. Rebar groups with similar total lengths.

Rebar Group	Floors	No. of Continuous Rebars (pcs)	Total Height of Floor (m)
1st	B2-Roof	14	95.7
2nd	B2-F13	2	64.1
3rd	B2-F9	6	48.9
4th	B2-F7	12	41.3
5th	B2-F4	2	24.1
6th	B2-F2	2	12.9
7th	B2-F1	4	8.3

4.1.1. The Application of Integrated Mechanical Couplers and Special-Length-Priority Minimization Algorithm on Main Rebars of the Column

This stage determined the specific special length of the continuous rebars accommodating the use of couplers. Column and reinforcement information was collected, including the rebar layout and arrangement. The first rebar group, which spanned the entire column, was initially used to determine the special length rebars. Utilizing Equation (1), a total rebar length of 97.09 m was obtained.

Then, the number of special-length rebar was identified using Equation (2), given a maximum stock length that steel mills can provide of 12 m. This maximum stock length may vary depending on the country. The calculation identified that nine special-length rebars were required, which means that there were nine continuous special-length rebars connected with eight couplers (Equation (3)).

Next, the special length of the rebars was calculated utilizing Equations (4)–(6). A minimum of a 20 mm gap is required between the inner threads for coupler sizes above D16; thus, for the end bar, 10 mm was subtracted from the exact special length, resulting in 10.778 m, and, for the middle bar, 20 mm was subtracted from the special length, resulting in 10.768 m. Due to the characteristics of special-length rebar, this was rounded up to 10.8 m. Therefore, nine special-length rebars of 10.8 m were connected with eight couplers for the column's continuous rebar system that extended from the foundation to the roof of the building.

4.1.2. Rebar Adjustment Considering the Identified Special Length Rebar

The special-length rebar identified in the previous module was then utilized for other rebar groups. Consequently, one remaining rebar for each rebar group was generated, since the division of the total length of each group by the special length did not result in an integer value. The second rebar group, which spanned from the foundation to the 13th floor, was used as an example of this process.

The total rebar length for the second rebar group was calculated utilizing Equation (1), and 64.87 m was obtained. Then, the number of rebars within the second rebar group was calculated using Equation (7), resulting in seven rebars that were embedded from the foundation to the 13th floor. This means that six of the seven rebars were installed with a special length of 10.8 m, generating one remaining rebar. These rebars were connected using six couplers (Equation (9)). Equation (10) was utilized to calculate the length of the remaining rebar by subtracting the total length of the special-length rebar required from the total rebar length, resulting in a length of 70 mm (0.07 m). This process was repeated for the rest of the rebar groups, and it is summarized in Table 7.

Table 7. Remaining rebars generated through the process.

Rebar Group	Floors	Total Length (m)	Number of Special-Length Rebars (pcs)	Remaining Rebar (mm)
2nd	B2-F13	64.87	6	70
3rd	B2-F9	49.67	4	6470
4th	B2-F7	42.07	3	9670
5th	B2-F4	24.87	2	3270
6th	B2-F2	13.67	1	2870
7th	B2-F1	9.07	0	9080

4.1.3. Special-Length-Priority Minimization and Quantity Confirmation

The remaining rebars obtained were then combined using the special-length-priority minimization algorithm to identify the most optimum special-length rebar that produces the least amount of waste, as summarized in Table 8. Utilizing Equations (11)–(16), two special-length rebars were obtained: 10.8 m and 10 m. The 10.8 m special-length rebar could maintain one specific length for the entire column. A rebar maintaining one specific length for an entire column is preferable for steel mills. Once the special lengths of the rebars were identified, the required and ordered quantities could be calculated. The ordered quantity was determined by multiplying the length by the total number of special-length rebar and the rebars' unit weight. The required quantity of remaining rebars was determined by the length of each combined rebar, the number of rebars that were to be combined, and the unit weight of the rebars. Nevertheless, a cutting waste of 14.31% was generated, while the 10 m special-length rebar generated 7.50% cutting waste. For reference, since special-length rebars are provided by the steel mills in 0.1 m increments, a stock length of 10 m can be categorized as a special-length rebar. Thus, a 10 m special-length rebar can be used instead of a 10.8 m rebar.

Table 8. Special-length-priority combination with cutting patterns on the remaining rebars.

Length (m)	Number (pcs)	Required Quantity (ton)	Ordered Quantity (ton)	Cutting Waste (%)
10.8	22	1.026	1.198	14.31
10.0	22	1.026	1.109	7.50

The total number of special-length rebar was obtained by multiplying the number of special lengths within a continuous rebar system by the number of rebars in each rebar group. The unit weight of D29 rebars can vary between manufacturers; however, in this case, 5.04 kg/m was used [48]. The required quantity was calculated using the special length before the ceiling function was applied, while the ordered quantity was calculated using the rounded-up length, as shown in Equations (18)–(20). Table 9 provides a summary of the confirmed rebar quantities.

Table 9. Quantity of continuous rebars.

Rebar Group	Floor	No. of Special Lengths per One Continuous Rebar	Total No. of Special-Length Rebars (pcs)	Total No. of Couplers (pcs)	Required Qty. (ton)	Ordered Qty. (ton)	Cutting Waste (ton)
1st	B2-Roof	9	126	112	6.8395	6.8584	0.0140
2nd	B2-F13	6	12	12	0.6513	0.6532	0.0013
3rd	B2-F9	4	24	24	1.3028	1.3064	0.0027
4th	B2-F7	3	36	36	1.9544	1.9596	0.0040
5th	B2-F4	2	4	4	0.2172	0.2177	0.0004
6th	B2-F2	1	2	2	0.1086	0.1089	0.0002
7th	B2-F1	0	0	0	0	0	0
Total				190	11.074	11.104	0.030

4.2. Validation of the Algorithm

4.2.1. Rebar Consumption and Rebar Cutting Waste

After all the required and ordered quantities were obtained, the rebar consumption and rebar cutting waste could be assessed. Equation (17) was utilized to calculate the overall rebar cutting waste. Using a 10.8 m special-length rebar, the continuous rebars had a required quantity of 11.074 tons and an ordered quantity of 11.104 tons, with a 0.27% cutting waste. The same length was also used to combine the remaining rebars, resulting in a required quantity of 1.026 tons and an ordered quantity of 1.198 tons, with a 14.31% cutting waste. Table 10 summarizes the overall quantities and cutting waste generated by the 10.8 m special-length rebar. As shown in the table, using one specific special length of 10.8 m resulted in a required quantity of 12.100 tons; an ordered quantity of 12.302 tons; and a cutting waste of 1.64%, which exceeds 1%. Using only the 10.8 m special-length rebar resulted in a rebar consumption of 12.302 tons for the construction of the column.

Table 10. Overall rebar consumption and cutting waste using 10.8 m special-length rebar.

Description	Special-Length Rebar (m)	Required Qty. (ton)	Ordered Qty. (ton)	Cutting Waste (ton)	Cutting Waste Rate (%)
Continuous rebars	10.8	11.074	11.104	0.030	0.27
Remaining rebars	10.8	1.026	1.198	0.172	14.31
Total		12.100	12.302	0.202	1.64

However, using the 10 m special-length rebar to combine the remaining rebars generated a required quantity of 1.026 tons and an ordered quantity of 1.109 tons, with a 7.50% cutting waste. Utilizing the 10.8 m special-length rebar for continuous rebars and the 10 m special-length rebar for the remaining rebars generated a required quantity of 12.100 tons and an ordered quantity of 12.213 tons, with a 0.93% cutting waste, as shown in Table 11. The use of the 10.8 m and 10 m special length rebars resulted in a rebar consumption of 12.123 tons for the construction of the column. As previously mentioned, a stock-length rebar of 10 m can be regarded as a special-length rebar; thus, the use of the 10.8 and 10 m special-length rebars was preferable. Originally, one specific special length was preferable as long as a cutting waste of less than or equal to 1% was maintained.

Table 11. Overall rebar consumption and cutting waste using 10.8 and 10 m special length rebars.

Description	Special-Length Rebar (m)	Required Qty. (ton)	Ordered Qty. (ton)	Cutting Waste (ton)	Cutting Waste Rate (%)
Continuous rebars	10.8	11.074	11.104	0.030	0.27
Remaining rebars	10	1.026	1.109	0.083	7.50
Total		12.100	12.213	0.113	0.93

4.2.2. CO_2 Emissions and Cost Reduction Analysis

An investigation conducted by Ghayeb et al. [18] found that rebars generate 3.505-ton CO_2-e/ton. The CO_2 emission unit rate of the D29 coupler was interpolated from their findings, resulting in 14.50 kg CO_2-e/pcs (See Appendix B, Table A2). Based on this information, the ordered quantities of the rebars and couplers could be converted into the total CO_2 emissions.

The total cost comprises the rebar material cost, and the rebar connection cost encompasses both the processing and material costs and carbon pricing. The total CO_2 emissions were multiplied by the carbon price of USD 75/ton-CO_2, as defined by the IMF [19]. To reflect the current market conditions, the rebar cost was calculated based on the available rebar price [17] and inflation rate [49], resulting in a value of USD 908 per ton. The installation expense associated with each lap splice or coupler, termed the processing cost, was considered identical for both methods. This cost was determined to reflect the current inflation rate [49], employing data from the study conducted by Kwon et al. [1]. The material costs and processing costs of lap splices and couplers can be seen in Appendix B (Table A3). The total CO_2 emissions and associated costs are tabulated in Table 12. As shown in Table 8, 12.213 tons of rebars were consumed, 45.56 tons of CO_2-e were generated, and USD 16,070 was required to construct a single column.

Table 12. CO_2 and associated costs.

Description	Rebar Quantity (ton)	CO_2 Emission (ton CO_2-e)	Rebar Cost (USD)	Coupler Cost (USD)	Carbon Cost (USD)	Total Cost (USD)
A single column	12.213	45.56	11,090	1562	3418	16,070

4.2.3. Comparison of the Obtained Results

To validate and evaluate the impact of the proposed algorithm, the rebar quantity and its performance were evaluated by comparing the rebar quantity, cutting waste, CO_2 emissions, and total cost of the original design and a previous study's findings [9] to the results generated by the proposed algorithm. The original design quantity was calculated based on 6 m and 8 m stock-length rebars and conventional lap splices (see Appendix B Table A4). The performance of the original design, a previous study, and the proposed algorithm are compared in Figures 8–12. Detailed results are available in Appendix B Table A5.

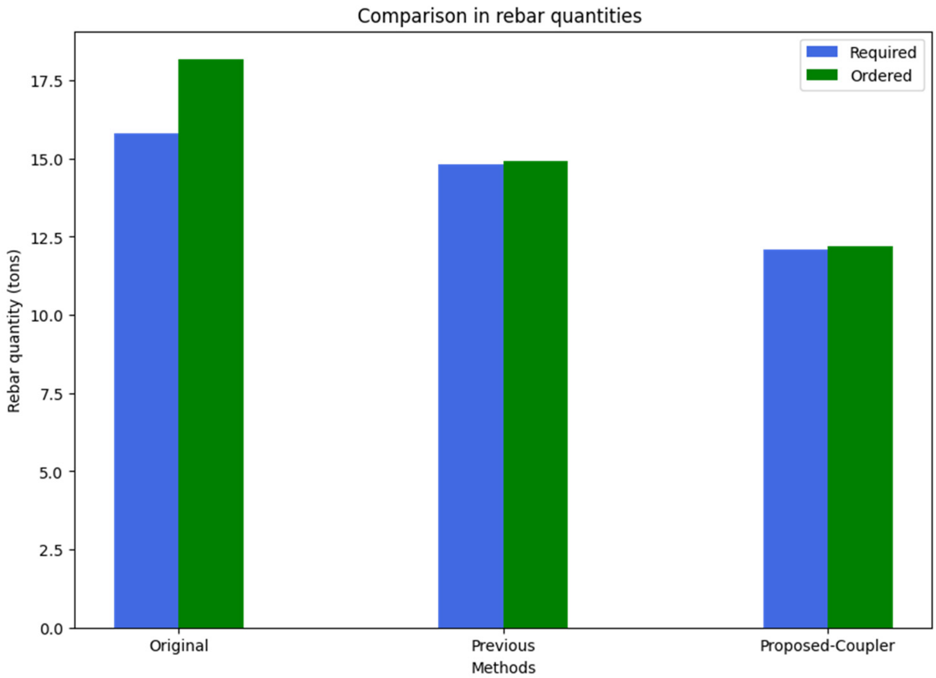


Figure 8. Rebar quantities comparison.

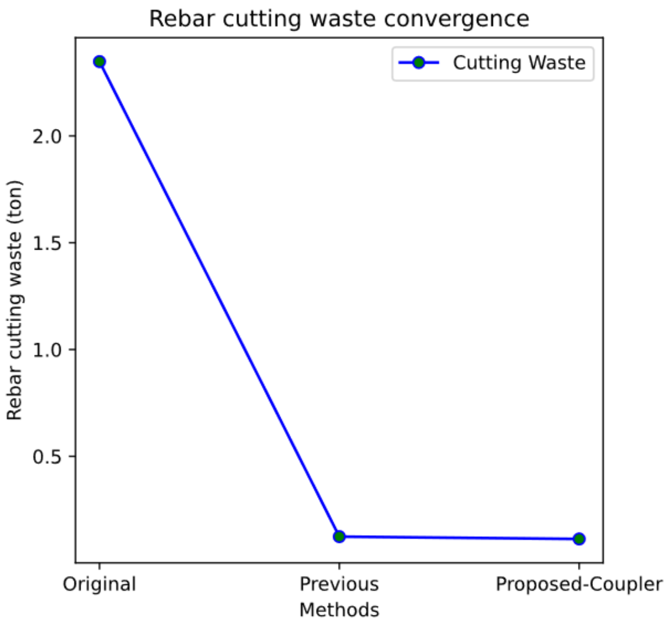


Figure 9. Rebar cutting waste convergence.

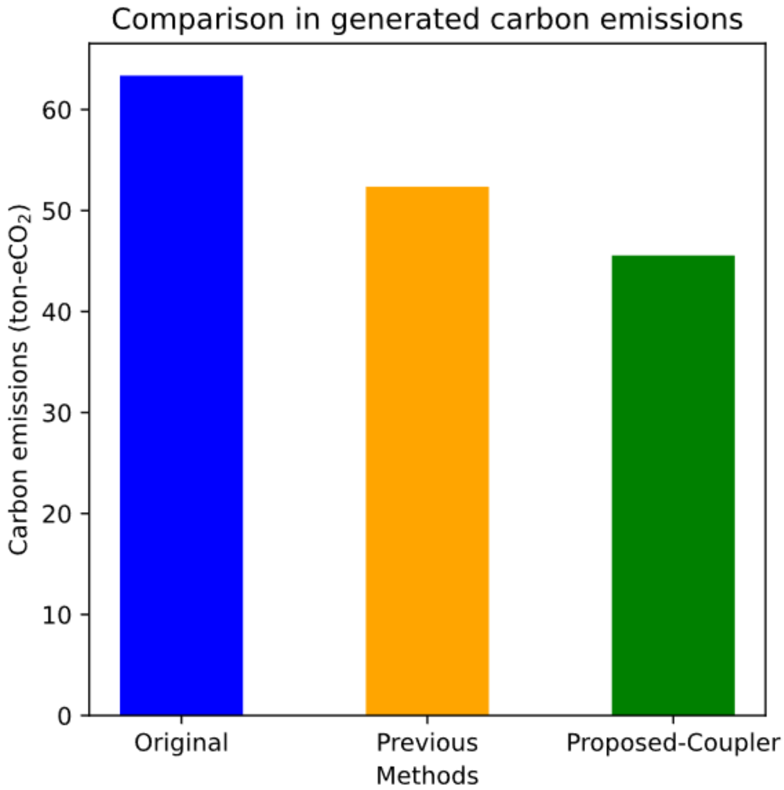


Figure 10. Carbon emissions comparison.

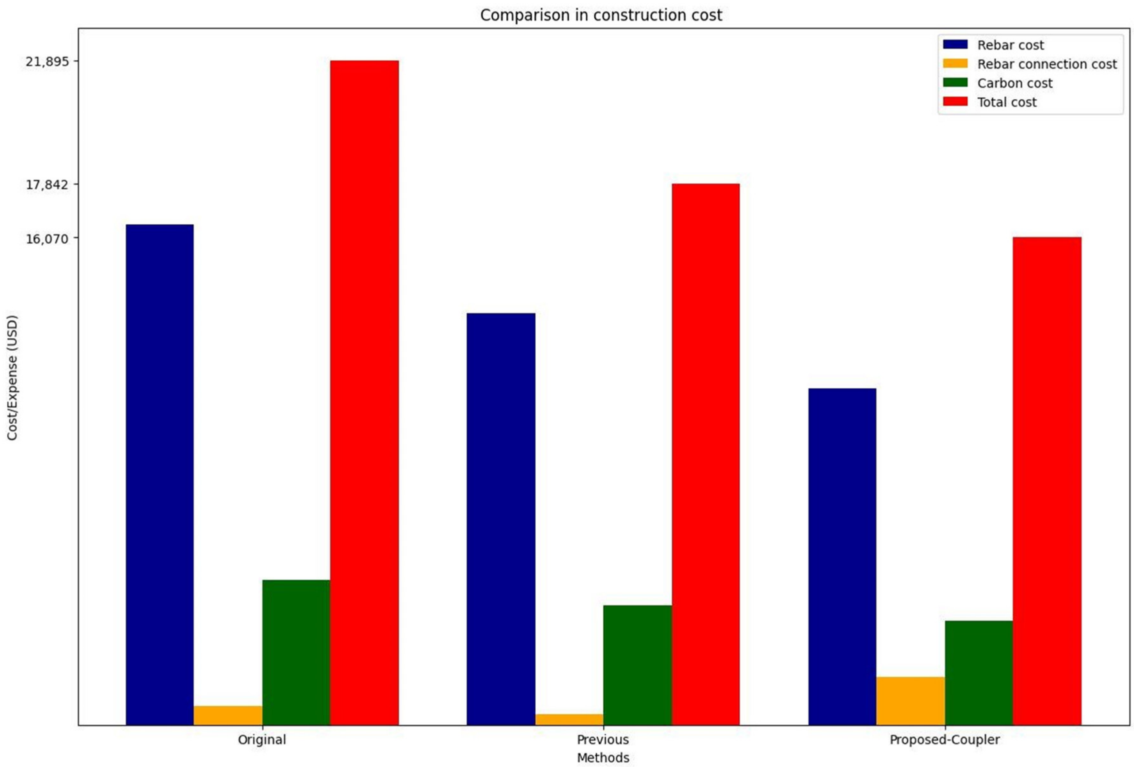


Figure 11. Construction cost comparison.

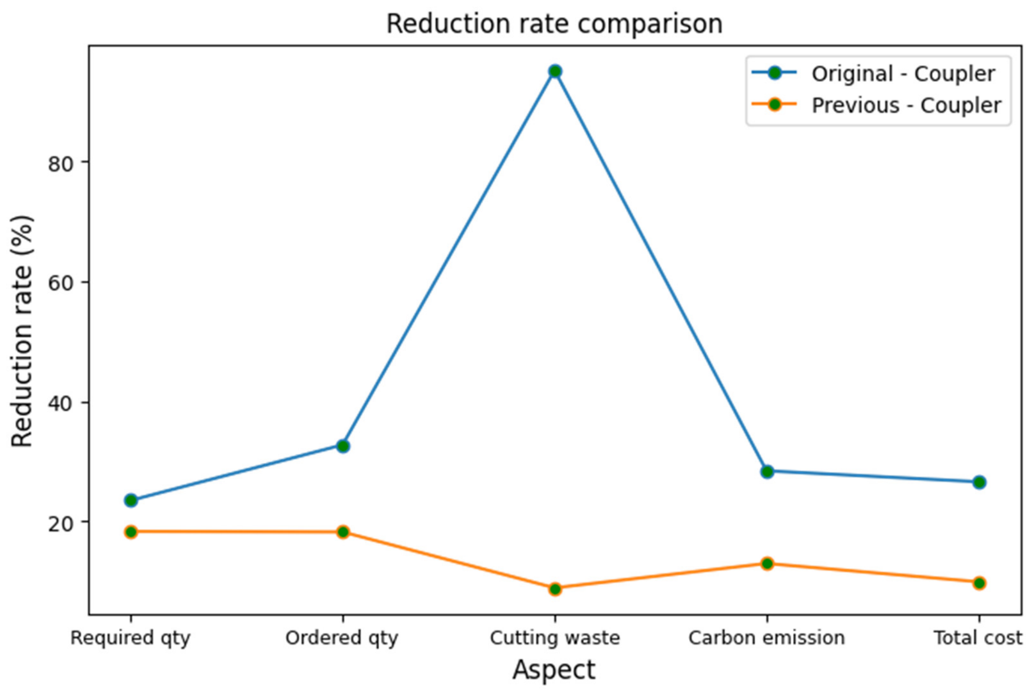


Figure 12. Reduction rate comparison.

The original design had a total required and ordered rebar quantity of 15.817 tons and 18.164 tons, respectively, with 2.348 tons (12.93%) of cutting waste. Meanwhile, the previous study had a total required and ordered rebar quantity of 14.815 tons and 14.939 tons, respectively, with 0.124 tons (0.83%) of cutting waste. Conversely, the proposed algorithm generated a required rebar quantity of 12.100 tons and an ordered rebar quantity of 12.213 tons, with 0.113 tons (0.93%) of cutting waste. Figure 8 depicts the comparison between the original design, the previous study's finding, and the proposed algorithm in terms of rebar quantities. As can be seen from the figure, there is a substantial reduction in the consumed rebars.

As anticipated in the paper's objectives, reducing rebar consumption also led to a decrease in rebar cutting waste. Figure 9 showcases the convergence plot depicting the rebar cutting waste generated by each method. The proposed algorithm demonstrably generates the least waste compared to both the original design and the previous study's findings, with a minimal waste rate of 0.113 tons.

The reduction in rebar consumption and rebar cutting waste corresponds to the reduction in carbon emissions generated. Figure 10 illustrates this relationship, showcasing a comparison of the carbon emissions generated for each method. As depicted, the original design, previous study, and proposed algorithm generated 63.67, 52.36, and 45.56 tons of CO_2-e, respectively.

The multifaceted reductions in rebar consumption, waste, and carbon emissions reflect a substantial decrease in the overall construction cost for the column. The original design's rebar connection cost was based on 474 lap splices, using the processing cost described in the previous subsection and Table A3 due to the material cost being accounted for in the rebar cost. In contrast, the proposed algorithm utilized 190 couplers, with its rebar connection cost determined by the coupler material cost and processing cost, also detailed in Table A3. Prior research aimed to minimize rebar waste and consumption in columns primarily through conventional lap splice position and the number of splice optimization, achieving approximately 260 splices. As described earlier, the associated rebar connection cost encompassed both the material and processing costs. Figure 11 depicts the comparison of the cost incurred by each method. The original design, previous study, and proposed algorithm required a total cost of USD 21,895, 17,842, and 16,070, respectively as illustrated in the figure.

Figures 8–11 provide a comprehensive assessment of the proposed algorithm's reductions in the rebar required and ordered quantity, cutting waste, carbon emissions, and total cost. Figure 12 describes the reduction rate achieved by the proposed algorithm on those aspects compared to the original design and the previous study's findings. As shown in Figure 12, there was a substantial reduction in the ordered rebar consumption of 32.77%, leading to significant decreases in cutting waste (95.19%), CO_2 emissions (28.44%), and total cost (26.61%). Compared to a previous study's findings [9], the proposed algorithm achieved superior outcomes by generating a lower quantity of rebar and cutting waste. Notable reductions of 18.25% (2.726 tons) in the ordered rebar and 8.93% (0.011 tons) in the cutting waste were achieved, leading to a 9.94% decrease in the total cost despite the lap splice cost being significantly lower than the coupler's cost. More detailed results can be found in Appendix B Table A5. These results confirm that the application of couplers effectively reduced the rebar consumption.

5. Discussion

Conventional lap splicing is the most common method for rebar connection due to its simplicity and low cost. However, it has several drawbacks:

1. It requires adherence to the lapping zone as recommended by building codes, which can limit flexibility and lead to more rebar waste.
2. It is vulnerable to errors, such as an inappropriate lapping length or erroneous installation, which can jeopardize its performance.
3. It requires more and longer rebars as the diameter increases, making it impractical for large-diameter rebars. The American Concrete Institute (ACI) [37] specifically prohibits the use of lap splices for rebar joints larger than 36 mm in diameter.
4. It is difficult to inspect and repair.

Therefore, there is a need for alternative rebar connection methods that address these drawbacks. The welded joint technique serves as an alternative option to conventional lap splicing, reducing rebar consumption but requiring higher expenses and skilled labor. However, this method emits flames and smoke, likely endangering nearby construction activities, and the welding gas used is not entirely environmentally friendly. Furthermore, inadequately executed welded joints may be prone to cracking.

Mechanical couplers are a fast and easy way to connect rebars, saving time and costs, as well as reducing rebar usage and cutting waste. Their increasing popularity is driven by decreasing costs and rebar shortages. This study demonstrated that mechanical couplers could reduce the ordered rebar usage by 32.77% and cutting waste by 95.19%, corresponding to a 28.44% reduction in carbon emissions for column structures. Compared to previous findings [9], a significant 18.25% reduction in rebar consumption was observed in addition to a 12.99% carbon emissions reduction, validating the coupler's effectiveness. The coupler selection can impact cutting waste due to the coupler's inner gap. A larger gap may eventually generate more rebar cutting waste. However, coupler selection is challenging due to the wide variety available, including non-seismic and seismic options. Moreover, coupler usage is primarily limited to new construction. Further research is warranted to optimize coupler selection and utilization in seismic regions and retrofitting applications. Additionally, further seismic studies and finite element analysis of the columns based on the proposed approach should be developed in future endeavors. Exploring the use of alternative concrete materials like geopolymers, alongside comprehensive life cycle assessments, presents a potential avenue for achieving further reductions in carbon emissions within the construction sector.

The ease of the installation of couplers enhances construction site productivity. To preserve and boost this productivity, it is essential to have systematic planning and supply chain management (SCM) strategies for couplers throughout the construction process. Future research could focus on the development of an SCM model that prioritizes couplers, including coupler selection, prefabricated rebar processes, and supporting devices.

Nonetheless, the integration of couplers and special length rebars into a wide range of construction projects, including buildings and other large infrastructure projects, represents a significant opportunity to reduce rebar consumption. This not only lowers construction costs but also accelerates the construction process and mitigates the environmental impacts associated with rebar use.

6. Conclusions

This research evaluated the impact of integrated mechanical couplers and a special-length-priority minimization algorithm on rebar consumption and cutting waste reduction by proposing a novel framework that considers the use of special-length rebars. A single column was used as a case study to demonstrate the proposed algorithm's effectiveness. Its impact was evaluated by comparing its results to those of conventional lap splicing. The following key findings were identified:

1. There was a substantial reduction in the ordered rebar consumption, with the proposed algorithm consuming 5.951 tons less rebar (32.77%) compared to the original design that employs conventional lap splicing. A reduction of 2.726 tons (18.25%) was also observed when compared to a previous study's findings.
2. The proposed algorithm reduced cutting waste by 95.19% compared to the original design; a cutting waste rate of 0.93% was obtained, representing the achievement of near-zero cutting waste. In addition, using a single length of special-length rebar for both the continuous and remaining rebars appeared to reduce cutting waste less significantly.
3. The proposed algorithm reduced carbon emissions by 18.11 tons eCO_2 (28.44%) and total costs by USD 5825 (26.61%). Compared to a previous study's finding, a reduction of 6.8 tons of eCO_2 (12.99%) and USD 1772 (9.94%) was observed for both CO_2 emissions and total costs, respectively. This showcases the potential of integrated couplers and the special-length-priority minimization algorithm in significantly reducing rebar consumption and waste, as well as CO_2 emissions and total costs, without harming the members' structural integrity.
4. It should be noted that couplers are generally used in new construction, with some exceptions in retrofitting or renovation projects. The cost of couplers is expected to decrease as their usage becomes more prevalent.

Upcoming research should investigate the feasibility of developing systematic planning and supply chain management (SCM) strategies that consider coupler usage, in addition to coupler selection and supporting devices. As couplers offer speed and ease of installation, construction site productivity should be maintained throughout all phases. This research demonstrates the significant impact of an integrated coupler and the special-length-priority algorithm on rebar consumption and cutting waste, providing the industry with insights into further reducing rebar and related consequences. Applying the proposed algorithm to various construction projects will further amplify the corresponding benefits.

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

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

Appendix A

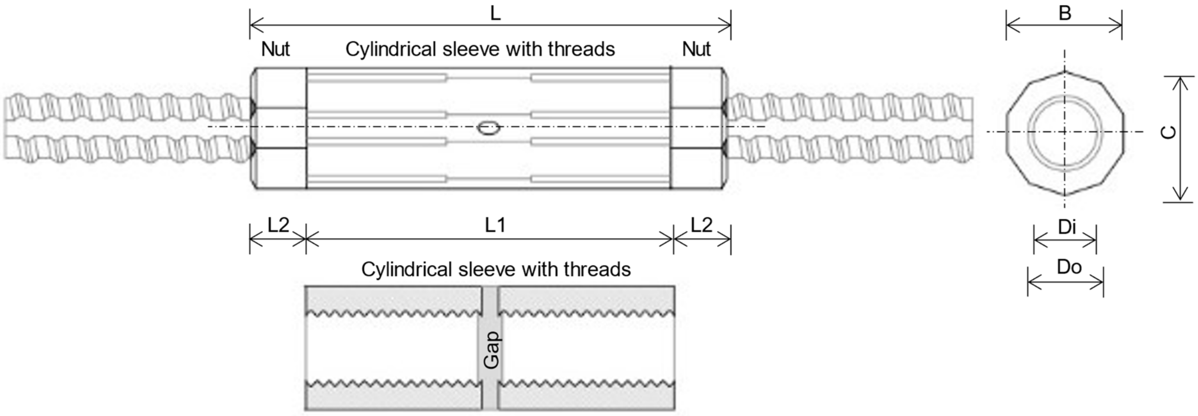

Figure A1. Details of a rib-thread coupler [47].

Table A1. Specifications of the rib-thread coupler available (in mm) [47].

Bar Size	Outside Diameter of the Coupler		Length			Dimension of Thread		
			Coupler	Nut	Total	Pitch	Inside Diameter	Root Diameter
	B	C	L1	L2	L	P	Di	Do
19	29	30	100	20	140	8	18.9	22.3
22	34	35	110	20	150	9	21.8	25.6
25	38	39	120	20	160	10	24.8	29.0
29	43	44	135	20	175	12	28.2	33.0
32	48	49	160	20	200	13	31.4	36.6

Appendix B

Table A2. Carbon emissions unit of couplers [19].

Diameter	CO_2 Emissions (kg-CO_2-e/pcs)
12	1.91
16	3.33
20	4.69
25	8.60
29	14.49
32	23.98

The data for D29 was interpolated using regression.

Table A3. Material and processing costs of rebars and couplers.

Description	Material Cost		Processing Cost	
	Rebar (USD/ton)	Coupler (USD/pcs)	Lap Splice (USD/m)	Coupler (USD/m)
D40	908	12.35	2.09	2.09
D35	908	11.50	1.75	1.75
D32	908	8.44	1.62	1.62

Table A3. *Cont.*

Description	Material Cost		Processing Cost	
	Rebar (USD/ton)	Coupler (USD/pcs)	Lap Splice (USD/m)	Coupler (USD/m)
D29	908	6.90	1.32	1.32
D25	908	6.14	1.05	1.05
D22	908	5.37	0.80	0.80
D19	908	4.22	0.59	0.59

The data of D40 was interpolated using regression. The processing cost for lap splice should be multiplied by the lapping length mandated. The cost was converted from KRW into USD using the current exchange rate [50].

Table A4. Original design quantity calculation [9].

Floor	Floor Height (mm)	Lap Length (mm)	Required Length (mm)	Preferred Stock Length (mm)	Number of Rebar	Total Quantity (ton)	Ordered Quantity (ton)
B2-B1	3700	1500	5200	6000	42	1.101	1.270
B1-F1	4600	1500	6100	8000	42	1.291	1.693
F1-F2	4600	1500	6100	8000	38	1.168	1.532
F2-F3	5600	1500	7100	8000	36	1.288	1.452
F3-F4	5600	1500	7100	8000	36	1.288	1.452
F4-F5	5600	1500	7100	8000	34	1.217	1.371
F5-F6	5600	1500	7100	8000	34	1.217	1.371
F6-F7	6000	1500	7500	8000	34	1.285	1.371
F7-F8	3800	1500	5300	6000	22	0.588	0.665
F8-F9	3800	1500	5300	6000	22	0.588	0.665
F9-F10	3800	1500	5300	6000	16	0.427	0.484
F10-F11	3800	1500	5300	6000	16	0.427	0.484
F11-F12	3800	1500	5300	6000	16	0.427	0.484
F12-F13	3800	1500	5300	6000	16	0.427	0.484
F13-F14	3800	1500	5300	6000	14	0.374	0.423
F14-F15	3800	1500	5300	6000	14	0.374	0.423
F15-F16	3800	1500	5300	6000	14	0.374	0.423
F16-F17	3800	1500	5300	6000	14	0.374	0.423
F17-F18	3800	1500	5300	6000	14	0.374	0.423
F18-F19	3800	1500	5300	6000	14	0.374	0.423
F19-F20	4400	1500	5900	6000	14	0.416	0.423
F20-Roof	4400	1500	5900	6000	14	0.416	0.423
		Total			516	15.817	18.164

Table A5. Reduction rate of the proposed algorithm.

Description	Original (O)	Previous (P)	Coupler (C)	Reduction (O-C)	Reduction Rate (O-C)/O (%)	Reduction (P-C)	Reduction Rate (P-C)/P (%)
Required rebar quantity (ton)	15.82	14.815	12.1	3.717	23.5	2.715	18.33
Ordered rebar quantity (ton)	18.16	14.939	12.21	5.951	32.77	2.726	18.25

Table A5. *Cont.*

Description	Original (O)	Previous (P)	Coupler (C)	Reduction (O-C)	Reduction Rate (O-C)/O (%)	Reduction (P-C)	Reduction Rate (P-C)/P (%)
Cutting waste (ton)	2.348	0.124	0.113	2.235	95.19	0.011	8.93
CO_2 emissions (ton CO_2-e)	63.67	52.36	45.56	18.11	28.44	6.8	12.99
Rebar cost (USD)	16,494	13,565	11,090	5404	32.77	2475	18.25
Rebar connection cost (USD)	626	349	1562	−936	−149.53	−1213	−347.57
Carbon cost (USD)	4775	3928	3418	1357	28.42	510	12.99
Total cost (USD)	21,895	17,842	16,070	5825	26.61	1772	9.94

The cost was converted from KRW into USD using the current exchange rate [50].

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