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A Dynamic Simulation Model for Near-Zero Rebar-Cutting Waste through Special-Length-Priority Optimization

Jinhyuk Oh [1], Sunkuk Kim [2] and Daniel Darma Widjaja [1,*]

[1] Department of Architectural Engineering, Kyung Hee University, Yongin-si 17104, Republic of Korea; jinhyuk94@khu.ac.kr
[2] Department of R&D, Earth Turbine Co., Ltd., Dong-gu, Daegu 41057, Republic of Korea; kimskuk@khu.ac.kr
* Correspondence: danieldarma@khu.ac.kr

Abstract: Global economic fluctuations as exemplified by the recent COVID-19 financial crisis significantly impact the construction industry, particularly steel rebar supply chain and procurement. This impedes engineers' efforts toward achieving near-zero rebar-cutting waste due to dynamic rebar minimum order quantities and maximum lengths imposed by steel mills. This study addresses the challenge of achieving near-zero rebar-cutting waste by proposing a model that simulates the level of optimization in minimizing rebar-cutting waste amidst such dynamics. The model was implemented in a case study involving reinforced concrete columns in a high-rise building. While achieving near-zero waste consistently proved challenging, particularly for greater than 50 tons of minimum quantity, the study identified a maximum 12 m rebar variant that attained this target regardless of minimum order quantity. Nonetheless, this study introduces a real-time decision-support system for rebar procurement, empowering engineers to optimize usage and minimize waste. This system facilitates near-zero rebar-cutting waste levels in response to rebar procurement requirement dynamics.

Keywords: dynamic simulation; near zero; rebar-cutting waste; special length

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1. Introduction

The construction industry (CI) plays a pivotal role in the national economic development of a country [1,2]. Acting as both a foundational element and a connector between other industries, it drives economic growth averaging 5–10% [3] and facilitates inter-industrial connections [4]. The CI contributes 13% of the global Gross Domestic Product (GDP) [5,6]. However, the construction industry is susceptible to market dynamics and fluctuations, including those affecting the construction materials market like steel reinforcement bars.

The construction market is highly susceptible to volatility due to a complex interplay of global economic, geopolitical, and technological factors, as well as unforeseen events such as the pandemic. Economic fluctuations, as evidenced by the 1998 Asian financial turmoil, the 2007/2008 global financial crises, and the recent COVID-19 pandemic economic effect, have significantly impacted and reshaped the industry. In Hong Kong, the combined effect of the Asian financial crisis and the SARS outbreak demonstrably reduced construction volume [4]. Similarly, the 2007/2008 global economic crisis, which started in the United States, triggered a sharp decline in annual world GDP growth from 2% in 2007 to −2.6% in 2009 [7], with cascading negative impacts on the construction sector worldwide. The recent COVID-19 pandemic, deemed the most severe economic threat since the Great Recession [8], further underscores the sector's susceptibility, impacting operations and performance across various industries, including construction. These events highlight the close relationship between the construction industry with the global economic dynamic changes. Furthermore, the pandemic-driven surge in technological development [9–11] coupled with the growing emphasis on the circular economy [12–15], and green and sustainable construction practices [16], is further transforming the industry's landscapes. These dynamic trends pose challenges for engineers seeking near-zero rebar waste, as they influence rebar procurement, particularly special lengths, and necessitate adaptation to dynamic steel mill requirements regarding minimum quantities and maximum lengths that can be provided.

To achieve near-zero rebar-cutting waste under dynamic rebar procurement requirements, real-time analysis of available special-length rebar is crucial. Changes in the economic condition significantly impact the steel and rebar supply chain, necessitating adaptive strategies to minimize waste. Despite the established concept of special-length rebar, a dynamic model for optimizing its use in a volatile construction market appears to be absent in the existing literature. This gap reveals an insufficient focus on the development of frameworks and models that can dynamically adapt to changing construction market conditions, thus failing to fully capitalize on the potential for minimizing waste and rebar costs. The absence of such adaptive models accentuates the critical need for solutions that can effectively integrate real-time situations and adjust procurement strategies accordingly. This study introduces a pioneering model aimed at filling this gap, serving as a pilot investigation into the feasibility of prioritizing special-length rebar optimization in response to dynamic market changes. It seeks to develop a model that simulates the level of optimization in minimizing rebar-cutting waste, targeting near-zero levels considering the changing of minimum requirements in special-length rebar procurement in response to the dynamic construction market and corresponding reductions in carbon emissions and costs. Furthermore, the novelty of this study lies in examining the disruption in the construction market during an economic crisis, particularly concerning special-length rebar. Unlike standard market-length rebar, which is regularly manufactured and less affected due to its consistent availability from steelworks, special-length rebar is produced on a per-request basis and is more susceptible to supply disruptions. Although special-length rebar generates less waste compared to standard-length rebar, its effectiveness depends on meeting minimal purchase requirements to maximize its benefits. Nonetheless, through subsequent simulations, the study will enable engineers to identify optimal cutting patterns (solutions) that satisfy project requirements and achieve near-zero waste under any given rebar availability conditions, providing them with a decision-support system for those who prioritize sustainable and green construction practices.

This study will be presented following this structure: 1. introduction, 2. methodology, 3. preliminary study, 4. causal loop diagram, 5. dynamic simulation model development, 6. case application and verification, 7. discussion, 8. conclusions.

2. Methodology

Figure 1 represents the methodology taken in this study to achieve the mentioned objectives. A comprehensive literature review investigated waste factors in rebar cutting, dynamic changes in the construction market, and the dynamic simulation model concept. Key findings from relevant studies were also incorporated. Based on this review, a causal loop diagram was developed to represent the system dynamics related to rebar-cutting waste. Subsequently, a dynamic simulation model was constructed using system dynamics principles, guided by the developed causal loop diagram. This model allowed engineers and researchers to observe whether near-zero rebar-cutting waste was achieved. If the initial simulation resulted in non-optimal waste levels, the researchers iteratively adjusted the minimum rebar quantity and available rebar length, re-ran the simulation, and analyzed the impact on waste generation. This iterative process ensured that the cutting waste was maintained at near-zero rebar-cutting waste conditions.

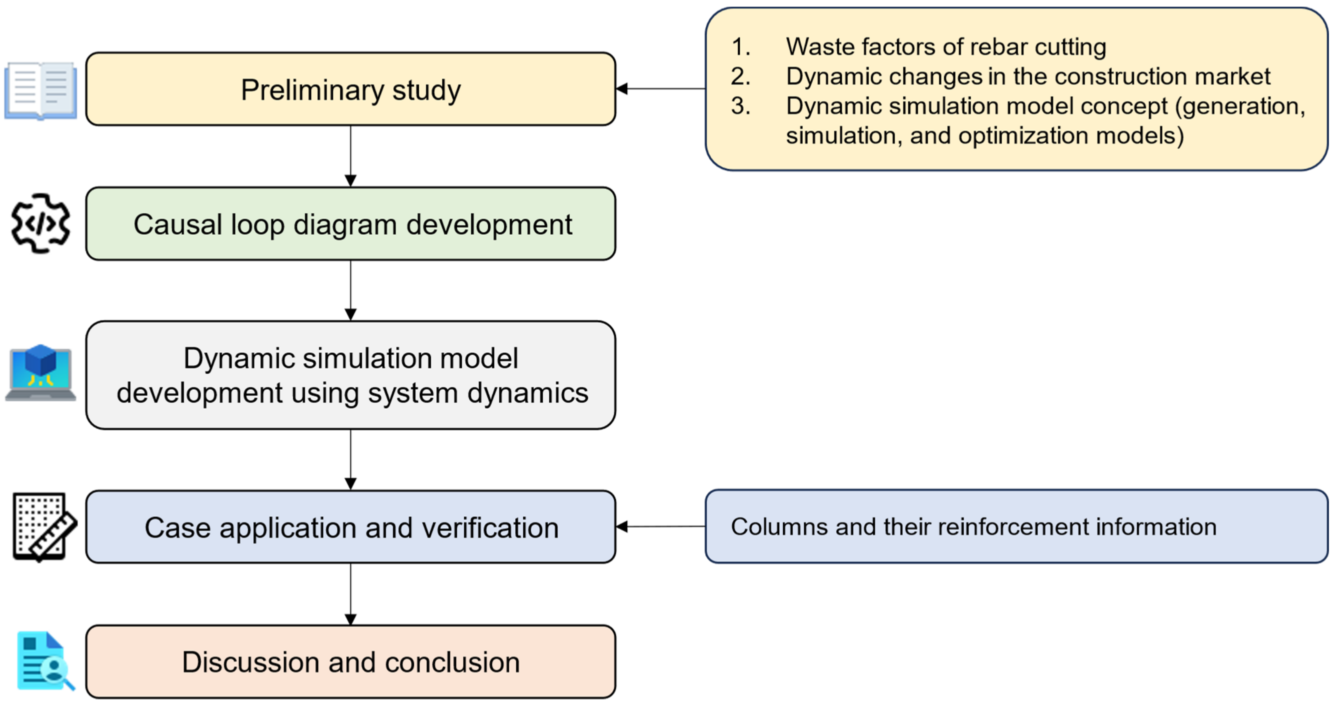

Figure 1. Methodology.

3. Preliminary Study

3.1. Waste Factors in Rebar Cutting

Rebar-cutting waste is an inevitable byproduct, with estimates ranging from 3 to 5% during the planning phase and potentially rising to 8% during the construction phase [17]. Traditionally, rebar-cutting waste has been treated as a one-dimensional cutting stock problem (1D-CSP), assuming rebars are cut from fixed stock lengths to meet specific requirements. Diverse methodologies have been devised to tackle this issue, with some researchers expanding it to a one-dimensional assortment problem involving multiple stock lengths. Salem et al. [18] argued that rebar-cutting waste is influenced by factors such as required length, stock length, and cutting pattern. Zheng et al. [19] supported these considerations and introduced rebar layout as an additional factor. Another study [17] emphasized the impact of stock length, cutting pattern, rebar lengths, and the number of rebars on cutting waste. Li et al. [20] suggested that waste is affected by stock length, rebar lengths, rebar usage, and cutting pattern. These factors remain relevant when utilizing special length rebars, which offer increased flexibility through orders in 0.1 m intervals. This flexibility has been demonstrated to significantly reduce waste in various investigations. Nevertheless, the steel mills' minimum requirements restrict the use of special length rebars, encompassing minimum quantities and available length ranges (minimum and maximum) [21]. A prior study [21] has extensively explored the combined application of the special-length-priority approach and lap splices on continuous and remaining rebars to achieve near-zero rebar-cutting waste. These studies recognize the reduction in lap splice number as a key factor influencing rebar waste generation. Given the adoption of the special-length rebar approach, this study limits the cutting waste factors to the rebar lengths including total continuous rebar length (denoted as total length) and required rebar piece length (denoted as required length), number of rebars, number of lap splices, cutting patterns, and minimum requirements consisting minimum quantity and available length.

3.2. Dynamic Changes in the Construction Market

The effectiveness of the special-length rebar approach is constrained by the steel mills' procurement minimums, which depend on the construction market's conditions. This market is influenced by global economic, geopolitical, and technological factors, as well as unforeseen events like the recent COVID-19 pandemic, which significantly altered the economic landscape. Policies and regulations implemented to control the movement of people and goods have had adverse effects on the economy and critically disrupted the global supply chain [22–27]. This disruption is not a novel occurrence, as the 2007/2008 financial crisis also precipitated similar global supply chain disruption, as observed in Australia [28]. This can lead to material shortages, as evidenced by a report of scarcity in India [29]. The ensuing economic downturn and fragile finances exacerbated the condition, resulting in recessions in several countries [30]. Severe recessions were also observed during the 2007/2008 global financial crisis. Evidence from both Malaysia and Singapore, where project numbers have decreased and owners postponed initiatives due to the pandemic [27,31,32], led to the demand decrease for construction materials. In response to economic challenges and movement restrictions, enterprises, including steel mills, implemented strategies such as reducing production, cost optimization, and adjusting minimum requirements based on the disruption's severity. As the economy recovers, these requirements may change. With advancing technology and growing interest in sustainable construction, the demand for green buildings may lead steel mills to ease their minimum requirements. Therefore, engineers must account for these market changes in real time to achieve near-zero cutting waste effectively.

3.3. Dynamic Simulation Model Concept

A simulation model developed in this study could be used to determine the level of near-zero rebar-cutting waste using multiple cases by considering the dynamic relationship among the waste factors previously identified: rebar lengths, number of rebars, number of lap splices, cutting patterns, and minimum requirements (minimum quantity and available length).

A modeling concept was used to construct the dynamic simulation model [33] encompassing generation, simulation, and optimization models. These were initially established concerning the near-zero rebar-cutting waste minimization. The generation model focused on establishing mathematical equations that captured the relationship between identified factors influencing waste generation. The simulation model incorporated the defined range of rebar-cutting waste factors into the model, and the optimization model iteratively ran the simulation model to obtain the optimal values of rebar-cutting waste within established constraints.

Figure 2 depicts the generation model, which assesses the rebar-cutting waste considering the identified factors. Recognizing that the near-zero rebar-cutting waste strategy consists of two parts (special-length-priority without cutting pattern for continuous reinforcements and special-length-priority with the cutting pattern for remaining reinforcements), the model considers these factors: total rebar length, required rebar length, reference (available) length, number of splices, number of rebar, and unit weight of rebar. These factors denoted as $f_1, f_2, \ldots,$ and f_6, are then incorporated into formulas to calculate rebar-cutting waste. Thus, the model effectively maps the relationship between each factor and the resulting rebar-cutting waste.

Once a generation model is established, a simulation model can be constructed accordingly, as illustrated in Figure 3. This model defines the range of factors, in this case, the reference (available) length of rebar. Subsequently, an optimization model is devised. The optimization model iteratively ran the simulation model under established constraints related to special-length rebar procurement, aiming to obtain the optimal values of rebar-cutting waste, as elaborated in Figure 4.

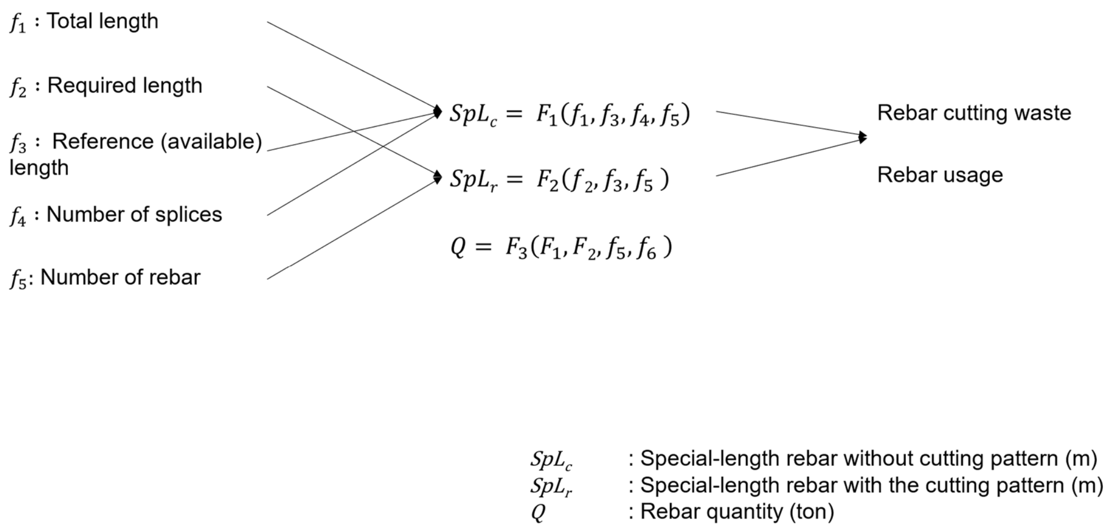

Figure 2. Generation model (adapted and modified from [34]).

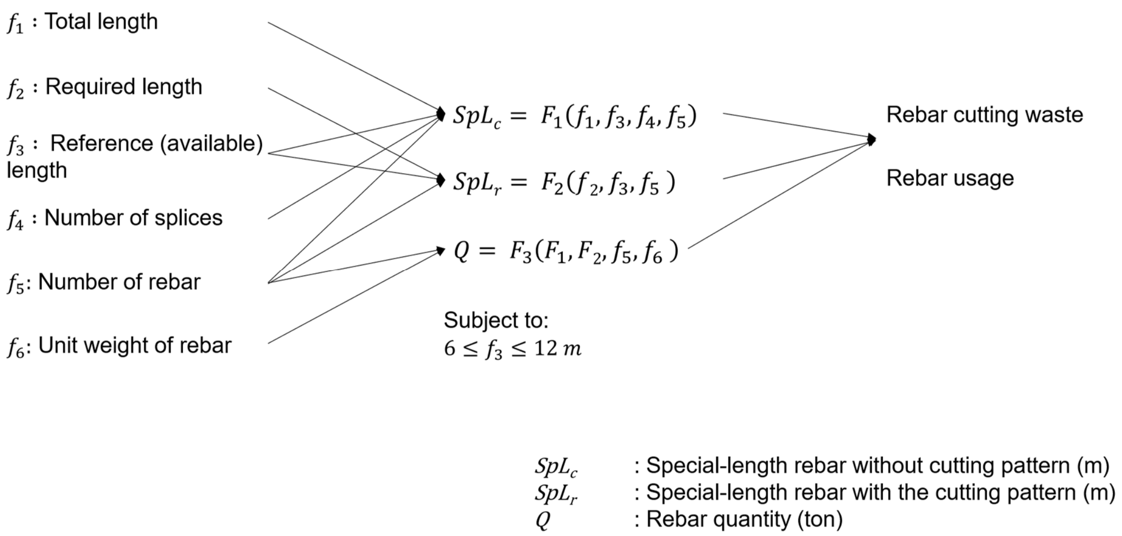

Figure 3. Simulation model (adapted and modified from [34]).

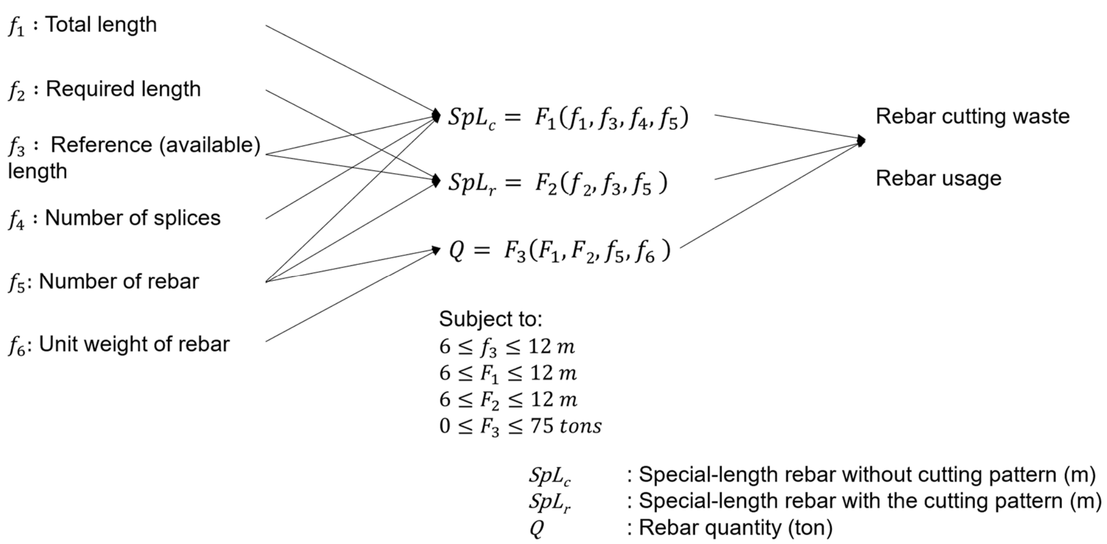

Figure 4. Optimization model (adapted and modified from [34]).

4. Causal Loop Diagram

The adoption of system dynamics allows for the integration of both internal and external factors that impact a certain condition [35]. One key tool employed is the causal loop diagram, which visually depicts the interconnectedness and causal relationship between the key factors [36]. Within this diagram, two types of relationships are employed: mathematical equations for hard relationships and linear regression for soft relationships [35]. Each causal link is assigned a positive or negative polarity to indicate the changes in the dependent variable corresponding to those in the interdependent variable. In addition, the diagram aids in identifying positive feedback loops (reinforcing) or negative loops (balancing) [37,38].

As shown in Figure 5, the near-zero rebar-cutting waste upon the reduction of waste and purchased rebar quantity is shown through a special-length-priority algorithm with and without the cutting pattern. However, its effectiveness is significantly constrained by these minimum requirements applied by the steel mills: (1) reference (available) rebar length and (2) minimum rebar quantity. As noted earlier, these requirements can dynamically change due to construction market volatility, which is closely linked to global economic conditions. A recent example illustrating this dynamic is the global economic crisis induced by the COVID-19 pandemic. Policies and regulations implemented to control movement and goods during the pandemic severely disrupted the global supply chain, negatively affecting the economy [22–27]. In response to these challenges, enterprises, such as steel mills, adopted mitigation strategies including production reduction, cost optimization efforts, and adjustments to minimum order requirements (either tightening or lessening), considering the level of disruption. As the economy recovers, these minimum requirements may be adjusted. The previous Section identified several key factors affecting rebar-cutting waste, including total rebar length, required length, available length, number of splices, number of rebars, and unit weight. This study focuses on employing special-length rebar minimization for continuous (without cutting pattern) and remaining rebars (with cutting pattern) to achieve near-zero cutting waste. Consequently, in Figure 5, both total rebar length and required rebar length are represented by rebar lengths to reflect the application of special-length rebar minimization. Furthermore, most of the links are assigned to positive polarity except for the required rebar quantity and total cost.

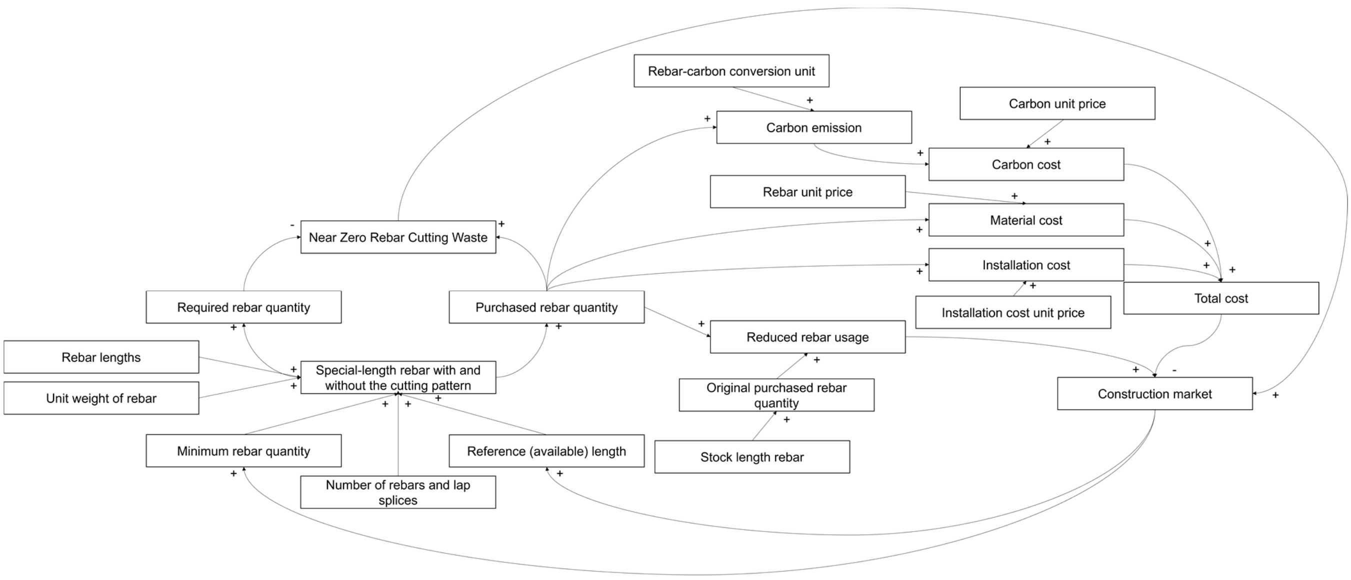

Figure 5. Causal loop diagram ('+' sign indicates a positive relationship while '−' shows a negative relationship).

This study identifies two reinforcing feedback loops within the construction market (Figure 5). The first loop centers on reference (available) bar lengths. When special-length rebars with and without designated cutting patterns are readily available, construction projects can purchase the exact quantity needed, minimizing rebar waste. This minimized waste then feeds back into the market, potentially increasing demand for special-length rebar. The second loop focuses on minimum rebar quantity. Special-length rebar with and without cutting patterns can also help projects meet minimum rebar requirements while purchasing the exact quantity needed, again minimizing waste. This minimized waste can then influence the market towards increased adoption of special-length rebar.

These identified loops will be incorporated into the simulation model for further analysis. Construction waste minimization is rewarding for construction companies within the present cost structure for waste disposal in Malaysia [39]. It is well understood that construction companies aim to maximize profit, as their profitability is at risk due to the complexity of their projects. Therefore, cost savings from waste minimization can be seen as a positive factor impacting the construction market, particularly the near-zero rebar-cutting waste strategy since it facilitates the generation of less than 1% rebar waste. Moreover, this procedure enables companies to increase their profits and simplifies the disposal and handling process of such wastes. The quantity of rebar purchased forms the foundation for calculating carbon emissions, its associated costs, installation costs, and material costs, collectively shaping the total cost. This total cost exerts a negative influence on the construction market, with higher costs potentially dissuading further construction phases as owners seek more favorable economic opportunities.

5. Results

This Section presents the development of the dynamic simulation model to accommodate the intended causal loop diagram above. The proposed model works in several scenarios as shown in Figure 6.

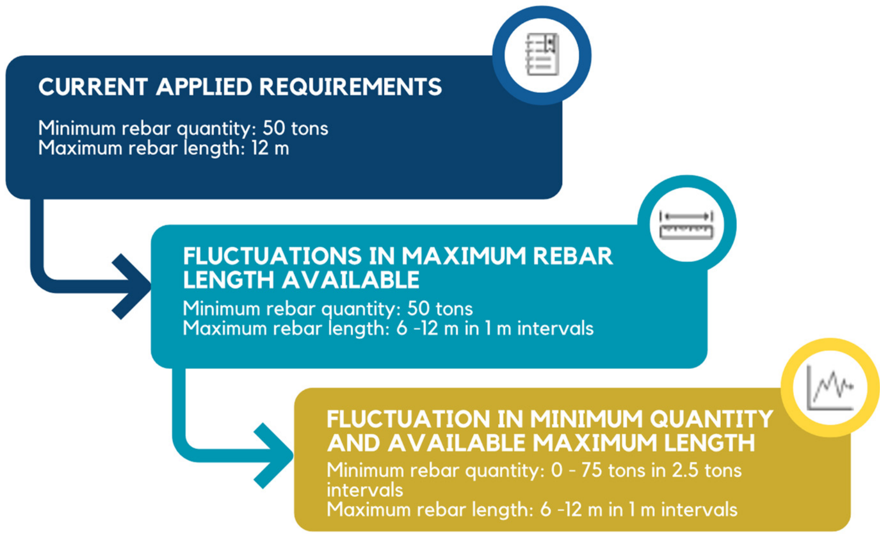

Figure 6. Simulation scenarios regarding the special-length rebar order within the near-zero rebar.

As seen in Figure 6, this simulation model is divided into three scenarios: (1) baseline with current minimum rebar quantity of 50 tons and maximum rebar (reference) length of 12 m, (3) fluctuating maximum rebar (reference) length in 6–12 m, 1 m intervals for special order with a fixed minimum rebar quantity of 50 tons, and (3) combined fluctuations of both minimum quantity and maximum rebar (reference) length for special order in 0–75 tons, 2.5-ton intervals and 6–12 m, 1 m intervals. Global rebar availability varies, with some markets offering lengths exceeding the typical 12 m. The construction market and global economic dynamics could influence the minimum rebar quantity and the maximum rebar (reference) length provided by the steel mills for special orders. Recognizing this interplay, the third scenario will simulate the achievement of near-zero rebar-cutting waste under this premise. The dynamic simulation model under the system dynamics principle is designed to empower researchers and engineers with enhanced decision-making capabilities and planning strategies in the face of complex scenarios. Building upon the identified reinforcing loops in the previous Section, Figure 7 presents the integrated simulation model developed for this study. These loops are explicitly incorporated and reflected within the model's structure. Furthermore, Scenarios 2 and 3 leverage these reinforcing loops as their central framework for the simulation. Besides the cutting waste, this model comprehensively integrates all pertinent factors impacting near-zero rebar-cutting waste and their associated implications, including carbon emissions and total reinforcement cost.

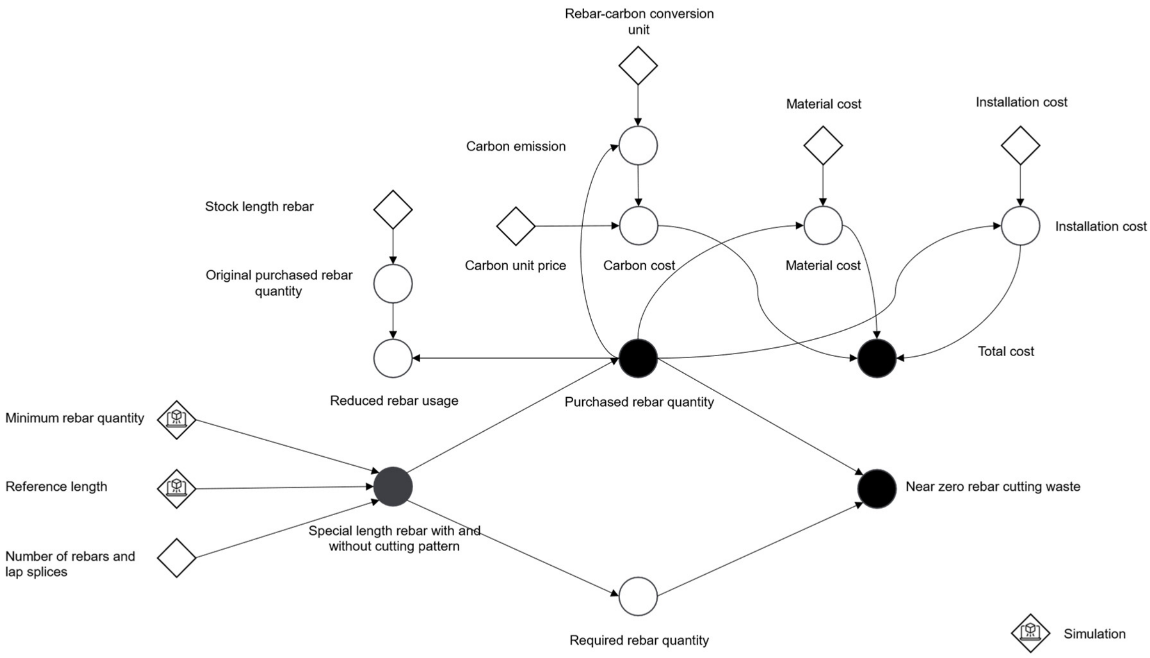

Figure 7. Integrated simulation model.

5.1. Special-Length-Priority Minimization for Continuous Reinforcements Model

As previously mentioned, the near-zero rebar-cutting waste strategy aims to minimize the cutting waste on continuous and remaining reinforcements, specifically the columns. A previously established mathematical algorithm [21], detailed in Equations (1)–(7), addresses this challenge. Prior to the model application, the reinforcements are divided into distinct groups. The initial group encompasses the longest bars, spanning from the foundation to the topmost girder. Subsequent groups comprise shorter segments, each extending from the foundation to a specific point. Essential rebar information regarding splices (n_{splice}), spans (n_{span}), rebars (n_{rebar}), and the length of lapping (L_{lap}) of the original design, is obtained as input for the model. Equation (1) facilitates the calculation of the total length for each rebar group.

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

where L_{total} is the total length of continuous main rebar (mm), H_{floor} is the height of each floor (mm), n_f is the number of floors for each rebar group, 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), L_{splice} is the lap splice length (mm), n_{splice} is the number of splices, and B_{deduct} is the bending deduction.

The number of special-length rebars (n_{rebar_sp}) in the first group can be identified by dividing the total length (L_{total}) by the maximum rebar length available or reference length

(L_{ref}) in the market. This calculation, as shown in Equation (2), utilizes the ceiling function to ensure an integer value representing the number of special-length rebars.

$$n_{rebar\_sp} = ceiling\left(\frac{L_{total}}{L_{ref}}\right) \tag{2}$$

The identified number of special-length rebar may be reduced compared to the original design, corresponding to a reduction in the number of splices. Equation (3) was used to calculate the new number of splices (n_{splice_sp}) by subtracting the number of special-length rebar (n_{rebar_sp}) by one. The resulting reduction in the number of splices (Δ_{splice}) is then quantified as shown in Equation (4). Subsequently, the new total rebar length (L_{total_sp}) due to such reductions can be calculated using Equation (5).

$$n_{splice\_sp} = n_{rebar\_sp} - 1 \tag{3}$$

$$\Delta_{splice} = n_{splice} - n_{splice\_sp} \tag{4}$$

$$L_{total\_sp} = L_{total} - (\Delta_{splice} \times L_{lap}) \tag{5}$$

Following the calculation of the new total rebar length (L_{total_sp}), this value is divided by the number of special-length rebars (n_{rebar_sp}) to determine the calculated length of each special-length rebar (L_{calc}) as described in Equation (6). Due to procurement limitations where special-length rebars can only be ordered in 0.1 m intervals, the calculated length is rounded up using Equation (7) to obtain the final required length for each special-length rebar (L_{sp}).

$$L_{calc} = \frac{L_{total\_sp}}{n_{rebar\_sp}} \tag{6}$$

$$L_{sp} = roundup\ (L_{calc}) \tag{7}$$

The previously determined special-length rebar is then utilized to optimize other rebar groups. However, directly dividing the total length of each group by the obtained special-length rebar value typically results in non-integer numbers, indicating potential remaining rebar after utilizing the special-length bars. Equation (8) facilitates the calculation of the number of rebars (n_{rebar}) by dividing the total rebar length (L_{total}) by the special-length rebar length (L_{sp}). The ceiling function is employed within the equation to guarantee an integer outcome. Subsequently, Equation (9) determines the number of special-length rebar (n_{rebar_sp-j}) that can be effectively installed within each group. Yet not all rebars could be installed with the obtained special-length rebar. Thus, Equation (10) calculates any remaining rebar length by ($L_{remaining}$) subtracting the total installable special-length rebar length from the total rebar length of the group (L_{total}).

$$n_{rebar} = ceiling\left(\frac{L_{total}}{L_{sp}}\right) \tag{8}$$

$$n_{rebar_{sp}-j} = n_{rebar} - 1 \tag{9}$$

$$L_{remaining} = L_{total} - (n_{rebar\_sp-j} \times L_{sp}) \tag{10}$$

5.2. Special-Length-Priority Minimization with the Cutting Pattern for the Remaining Reinforcements Model

The identified remaining rebars are then combined using a special-length-priority minimization with the cutting pattern approach as utilized in a previous study (Equations (11)–(16)) [21]. Equation (11) serves as the objective function, minimizing the cutting waste generated during the special-length rebar cutting process, involving the special length.

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

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

The subsequent constraints (Equations (12)–(16)) ensure the objective function's successful fulfillment. Equation (12) requires that the length of the combined length (l_i) of any cutting pattern i obtained by rebar combinations does not exceed or is equal to the designated special length (Lsp_i). Equation (13) stipulates that each cutting pattern i must be utilized by at least one rebar combination (n_i), with i being a positive integer). Equation (14) enforces the special length (Lsp_i) to remain within the range of minimum (L_{min}) and maximum (L_{max}) of the rebar length that can be ordered. Equation (15) ensures the total combined rebar quantity (Q_{total}) meets or surpasses the minimum rebar requirement set by steel mills (Q_{so}). Finally, Equation (16) establishes the target cutting waste limit, ensuring the generated waste (ε) falls below or equals this threshold (ε_t).

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

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

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

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

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

5.3. Rebar-Cutting Waste (RCW) Model

Prior to estimating rebar-cutting waste, this model necessitates the calculation of both the required and ordered rebar quantities. The required quantity reflects the actual rebar used during construction, while the ordered quantity represents the amount contractors request from steel mills. Both quantities are calculated by multiplying the rebar quantity, length, and unit weight of the rebar (w_{rebar}). For continuous rebars, the required quantity (Q_{req-c}) is determined by using the calculated rebar length (L_{calc}) from Equation (6), as shown in Equation (17), while for the remaining rebars (Q_{req-r}), the quantity is based on the total length of the cutting pattern i ($\sum l_i$), as described in Equation (18). Regardless of being continuous or remaining, the ordered quantity for both types of rebars can be calculated using Equation (19), factoring in the identified special-length rebar (L_{sp}). Finally, the RCW rate is determined by dividing the difference between the ordered and required quantities by the ordered quantity, as described in Equation (20). These equations are all sourced from prior research [21].

$$Q_{req-c} = \sum n_{rebar\_sp} \times L_{calc} \times w_{rebar} \tag{17}$$

$$Q_{req-r} = \sum n_{rebar\_sp} \times \sum l_i \times w_{rebar} \tag{18}$$

$$Q_{ord} = \sum n_{rebar\_sp} \times L_{sp} \times w_{rebar} \tag{19}$$

$$RCW = \frac{Q_{ord} - Q_{req}}{Q_{ord}} \times 100\% \tag{20}$$

5.4. Carbon Emissions and Costs Model

With the rebar quantities and cutting waste determined, Equations (21)–(26) can be employed to calculate the carbon emissions and total reinforcement cost. The obtained rebar quantities can be converted into carbon emissions using the rebar–CO_2 conversion unit. Furthermore, the total cost encompasses the material cost, processing cost, waste disposal charge, and carbon cost. The material cost is obtained by multiplying the rebar quantities with its unit costs. The processing cost, which is referred to as the processing cost of employing the lap splice connection method is obtained by multiplying the lap splice quantities with the processing unit cost. The generation of rebar-cutting waste necessitates the consideration of a construction waste disposal charge (CWDC), which is calculated considering the amount of waste generated. Meanwhile, the carbon cost is calculated using the carbon price and the obtained carbon emissions.

$$CE_{str} = Q_{ord} \times RC_{conv} \tag{21}$$

$$TCost_{str} = \sum MC_{str} + PC_{str} + DC_{str} + CC_{str} \tag{22}$$

$$MC_{str} = Q_{ord} \times UC_{rebar} \tag{23}$$

$$PC_{str} = N_{splice\_sp} \times UC_{pro} \tag{24}$$

$$DC_{str} = RCW_{ton} \times UC_{dis} \tag{25}$$

$$CC_{str} = CE_{str} \times CP \tag{26}$$

where CE_{str} is the carbon emissions (ton CO_2-e), RC_{conv} is the rebar–carbon conversion unit (ton CO_2-e/ton), $TCost_{str}$ is the total reinforcement cost of the column structures (USD), MC_{str} is the material rebar cost (USD), PC_{str} is the rebar processing cost (USD), DC_{str} is the waste disposal charge (USD), CC_{str} is the carbon cost (USD), UC_{rebar} is the unit price of rebar (USD/ton), N_{splice_sp} is the total number of splices, UC_{pro} is the rebar processing unit cost (USD/pcs), RCW_{ton} is the amount of cutting waste generated considering the difference in purchased and required rebar quantities (ton), UC_{dis} is the waste disposal unit cost (USD/ton), and CP is the carbon price (USD/ton CO_2-e).

6. Case Application and Verification

The effectiveness of the simulation model was validated through a case application. The twenty-six continuous columns of a reinforced concrete (RC) high-rise small factory that extended from the foundation to the roof floor were selected from a previous study [21]. Columns are chosen due to their vital role in bearing compressive axial loads and transferring the entire force from overlying beams and slabs to the foundation system. Columns are indispensable for overall structural integrity, significantly contributing to the building's stiffness and strength. Ensuring ductile behavior and effective energy dissipation during seismic events relies on adhering to the "strong column, weak beam" principle, which necessitates reinforcing columns with larger diameter bars compared to beams to prevent premature collapse. The building comprised a total of 22 floors, with 2 basement floors and 20 floors above ground. The floor heights varied, ranging from 3700 mm to 6000 mm (with the standard floor height being 3800 mm). More detailed information regarding the columns is provided in Table 1. The columns' rebar arrangements can be found in the Appendix A. Each column was further divided into distinct rebar groups based on shared rebar lengths as shown in Table 2 and also was illustrated in Figure 8. The optimization model was then applied to these rebar groups.

Table 1. Information on columns and their reinforcements (adapted from [21]).

Description	Contents
Number of columns	26
Foundation depth (D_f)	600 mm
Foundation concrete cover (C_f)	50 mm
Basement level (B2–B1) height	8300 mm

Table 1. *Cont.*

Description	Contents
Upper ground level (F1–roof) height	87,400 mm
Total floor height ($\sum H_{floor}$)	95,700 mm
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
Lap splice length (L_{splice})	1500 mm
Anchorage length (L_{anchor})	1050 mm
$90 -$ degree hook length (L_{hook})	350 mm
Dowel bar length (L_{dowel})	2350 mm
Bend deduction (B_{margin})	79 mm

Table 2. Rebar groups with a similar total length in a continuous column (adapted from [21]).

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

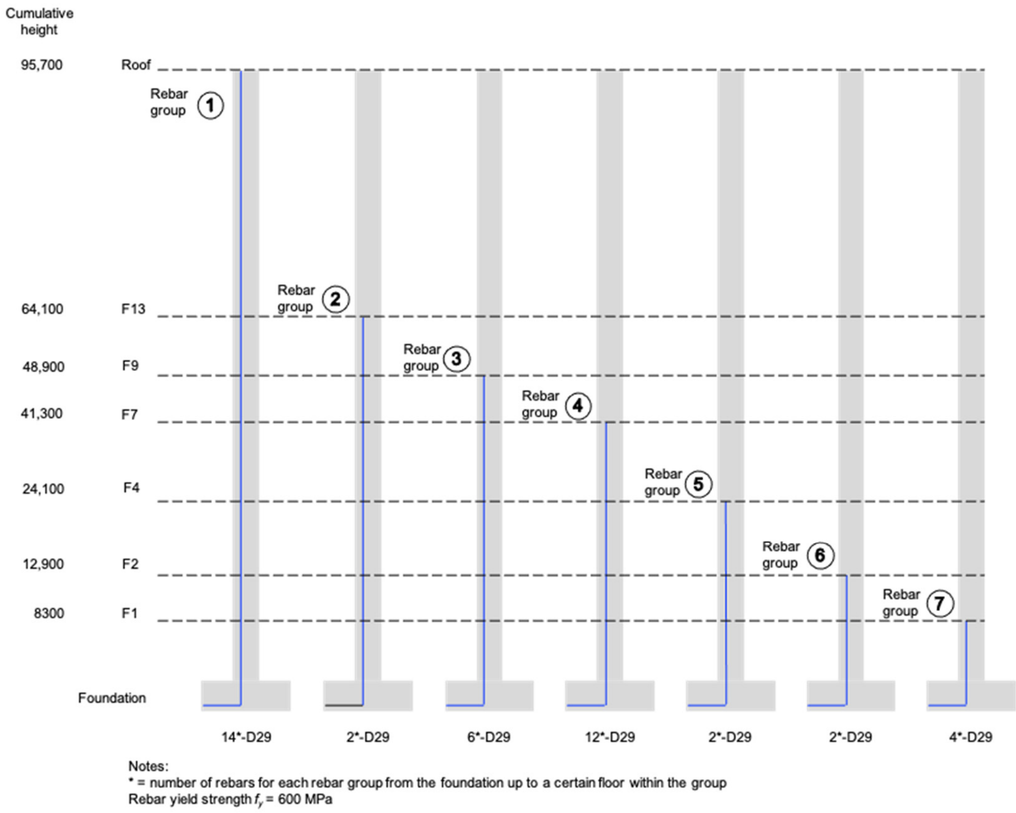

Figure 8. Rebar groups that shared similar lengths (adapted and modified from [21,40]).

The model developed in this study simulates each scenario elaborated in the previous Section. The first scenario serves as the baseline where the current requirements for purchasing special-length rebar are assumed to be applied with a minimum rebar quantity of 50 tons and a maximum available (reference) length of 12 m. In the second scenario, the maximum available rebar length (reference) is assumed to fluctuate between 6 and 12 m in 1 m increments, while the minimum order quantity remains at 50 tons. The third scenario assumes a fluctuation in both minimum quantity and maximum rebar length available for special orders, with the quantity varying from 0 to 75 tons, 2.5-ton intervals, and the length ranging from 6 to 12 m in 1 m intervals. Moreover, the rebar waste rate is targeted under 20% to capture the impact of such fluctuations. The rebar-cutting waste was calculated using Cutting Optimization Pro following Equations (11)–(16). Meanwhile, the simulations are conducted using Microsoft Excel.

6.1. Scenario 1

The first scenario serves as the baseline where the current requirements for purchasing special-length rebar are applied with a minimum rebar quantity of 50 tons and a maximum available (reference) length of 12 m.

Equations (1)–(7) were employed to identify the special rebar length. The analysis prioritized the longest rebar group and assumed each floor utilized a single rebar, resulting in 22 spans with 22 rebars and 21 splices. Employing a lapping length of 1500 mm and Equation (1), the total length of the first group was calculated to be 130.092 m. This calculation resulted in 10.4 m of special-length rebar. Equations (8)–(10) were then applied to utilize this special length for other groups. The remaining rebar for each group resulted from non-integer divisions of the total group length by the special length. These calculations were extended for the remaining 25 columns, with Table 3 summarizing the obtained remaining rebars for all 26 columns.

Table 3. Obtained remaining rebars.

Rebar Group	Floors	Total Length (m)	Total Number of Remaining Rebars (pcs)	Length of Remaining Rebar (mm)
2nd	B2–F13	85.871	52	2680
3rd	B2–F9	64.671	156	2280
4th	B2–F7	54.071	312	2080
5th	B2–F4	32.371	52	1180
6th	B2–F2	18.171	52	7780
7th	B2–F1	12.071	104	1680

Following the initial rebar group allocation, the obtained remaining rebars were consolidated and optimized using a special-length-priority algorithm, detailed in Equations (11)–(16). Due to minimum order quantity constraints, a special length of 10.4 m for continuous rebars was selected for the combination and optimization. This optimization process is presented in Table 4. Utilizing a 10.4 m special length, this approach necessitates an order of 9.1204 tons of rebar and incurs a cutting waste rate of 1.38%.

Table 4. Special-length-priority minimization with the cutting patterns model in the remaining rebars.

Length (m)	Number (pcs)	Required Length (m)	Ordered Length (m)	Cutting Waste (%)
10.4	174	1784.64	1809.6	1.38

The quantity and associated cutting waste rate (RCW) for the columns can be determined using Equations (17)–(20) outlined in the aforementioned RCW model. The rebar quantity calculation involved multiplying the total number of special-length rebars by the unit weight of a D29 rebar, which is 5.04×10^{-6} ton/mm [41]. Table 5 presents a summary of the special-length rebar quantities for continuous reinforcements. As shown, utilizing 10.4 m special length rebars necessitates an order of 378.863 tons, with a rebar requirement of 376.187 tons.

Table 5. Special-length rebar quantities for continuous reinforcements summary.

Rebar Group	Floor	Number of Continuous Rebars (pcs)	No. of SpL Rebars per One Rebar Group (pcs)	Total no. of SpL Rebars (pcs)	Required Quantity (ton)	Ordered Quantity (ton)
1st	B2–roof	14	11	4004	208.391	209.874
2nd	B2–F13	2	8	416	21.651	21.805
3rd	B2–F9	6	6	936	48.715	49.061
4th	B2–F7	12	5	1560	81.191	81.769
5th	B2–F4	2	3	156	8.119	8.177
6th	B2–F2	2	1	52	2.706	2.726
7th	B2–F1	4	1	104	5.413	5.451
Total					376.187	378.863

SpL: special-length rebar.

Following the calculation of rebar quantities, the associated cutting waste rate (RCW) was subsequently determined. Table 6 summarizes the RCW for all elements. As can be seen from the table, continuous rebars exhibit a loss rate of 0.71%. Furthermore, the table details that the column reinforcements necessitate a total rebar requirement of 385.1815 tons, with 387.9832 tons required to be ordered due to the 0.72% RCW.

Table 6. Cutting waste rate of the columns reinforcements.

Description	SpL Rebar (m)	Required Quantity (ton)	Ordered Quantity (ton)	Cutting Waste (ton)	Loss Rate (%)
SpL for continuous reinforcements	10.4	376.1870	378.8628	2.6759	0.71%
SpL for remaining reinforcements	10.4	8.9946	9.1204	0.1258	1.38%
		385.1815	387.9832	2.8017	0.72%

SpL: special-length rebar.

Once the cutting waste was established, the environmental impact and economic cost associated with constructing column reinforcements were evaluated using Equations (21)–(26) from the previously described carbon emissions and cost model. A total of 6864 lap splices were employed. Previous studies by Ghayeb et al. [42] reported that 1 ton of rebar generates 3.505 tons of CO_2 equivalent (CO_2-e) emissions. The rebar price was determined at USD 908/ton [43]. The International Monetary Fund (IMF) employs a carbon price of USD 75/ton of CO_2 [44]. Chen et al. [45] highlight that Hong Kong's construction waste disposal fees depend on the designated destination outlined in the waste management plan. The rebar waste could be directed to sorting facilities for rebar recycling, fetching USD 22.29/ton [43]. Table 7 summarizes the resulting CO_2 emissions and total cost linked to the rebar usage. As indicated in the table, the column reinforcement rebar utilization generates 1359.9 tons of CO_2 emissions and incurs a total cost of USD 436,406.

Table 7. Total CO_2 and costs linked to the rebar usage.

Description	Quantity (Ton)	CO_2 Amount (Ton)	Material Cost (USD)	Carbon Cost (USD)	Processing Cost (USD)	Disposal Charge (USD)	Total Cost (USD)
26 Columns	387.9832	1359.9	352,289	101,993	9061	63	463,406

6.2. Scenario 2

In this scenario, to account for fluctuations in the construction market and global economic situation, the available rebar length (reference) varied between 6 and 12 m in 1 m intervals, while the minimum order quantity remained constant at 50 tons. The developed model was then iterated numerous times to determine optimal solutions for each rebar length variation. Table 8 presents the simulation results, including required and ordered rebar quantities, cutting waste generation, carbon emissions, and total cost. Refer to Table A2 in the Appendix A for detailed results.

Table 8. Scenario 2 results.

SpL (m)		Max Avail. Length (m)	Required qty. (ton)	Ordered qty. (ton)	Cutting Waste (%)	CO_2 Emissions (ton)	Total Cost (USD)
Cont.	Remain.						
6	6	6	414.1451	421.1827	1.67%	1476.3	510,955
6.7	6.7	7	406.1517	414.4009	1.99%	1452.5	500,569
7.3	7.3	8	400.9101	409.4214	2.08%	1435.1	493,101
8	8	9	396.8264	402.5549	1.42%	1411	483,554
8.5	8.5	10	393.3728	397.6409	1.07%	1393.8	477,015
9.6	9.6	11	388.9807	396.2650	1.84%	1389	473,688
10.4	10.4	12	385.1815	387.9832	0.72%	1359.9	463,406

SpL: special-length rebar; Remain.: remaining reinforcements; Cont: continuous reinforcements.

Table 8 illustrates that achieving near-zero cutting waste within the 50-ton minimum order quantity is only possible when the maximum available rebar length is 12 m. All other rebar length variations result in cutting waste exceeding 1%. Due to the limited remaining rebar quantities (less than 50 tons), optimization is based on the identified special-length rebar for continuous reinforcements. Consequently, in this scenario, adopting a maximum rebar length of 12 m minimizes waste generation, carbon emissions, and associated costs.

6.3. Scenario 3

In the third scenario, the impact of dynamic fluctuations in the construction market and global economic situation was investigated by considering variations in both the minimum order quantity and the maximum available rebar length for special orders. The minimum quantity ranged from 0 to 75 tons in increments of 2.5 tons, while the maximum rebar length varied between 6 and 12 m in 1 m increments. The developed model was iterated numerous times to determine optimal solutions for each combination of minimum quantity and maximum rebar length. Figures 9 and 10 present the simulation results, including cutting waste generation and total cost. For detailed results, refer to the attached supplementary data [46].

As illustrated in Figure 9, a significant portion of the simulations yielded cutting waste exceeding 1%. This trend is particularly pronounced for simulations with minimum rebar requirements exceeding 20 tons, regardless of the available rebar length variations. Figure 9 also demonstrates that near-zero cutting waste can be achieved with maximum rebar lengths of 9, 10, and 12 m when the minimum requirement is set below 20 tons. It is crucial to note, as detailed in Table A2, that the limited quantities of remaining rebars necessitate ordering them in the minimum purchasable amount for each solution. For instance, when the maximum available length was set at 9 m with a minimum requirement of 0–15 tons, the remaining rebar was combined into 6.1 m lengths. Similarly, when the minimum requirement was set at 17.5 tons, the remaining rebar was still combined in 6.1 m, but they were ordered in the minimum allowed quantity of 17.5 tons. Thus, it resulted in tremendous amounts of unused rebar. The findings regarding the rebar-cutting waste remain relevant to the total cost of the reinforcements. As shown in Figure 10, solutions achieving near-zero cutting waste exhibit the lowest total reinforcement costs, ranging from USD 463,000 to USD 480,000. In addition, the solutions also exhibit the lowest carbon emissions, ranging from 1360 to 1399 tons of eCO_2. Refer to the attached supplementary data [46] for the detailed results and calculations.

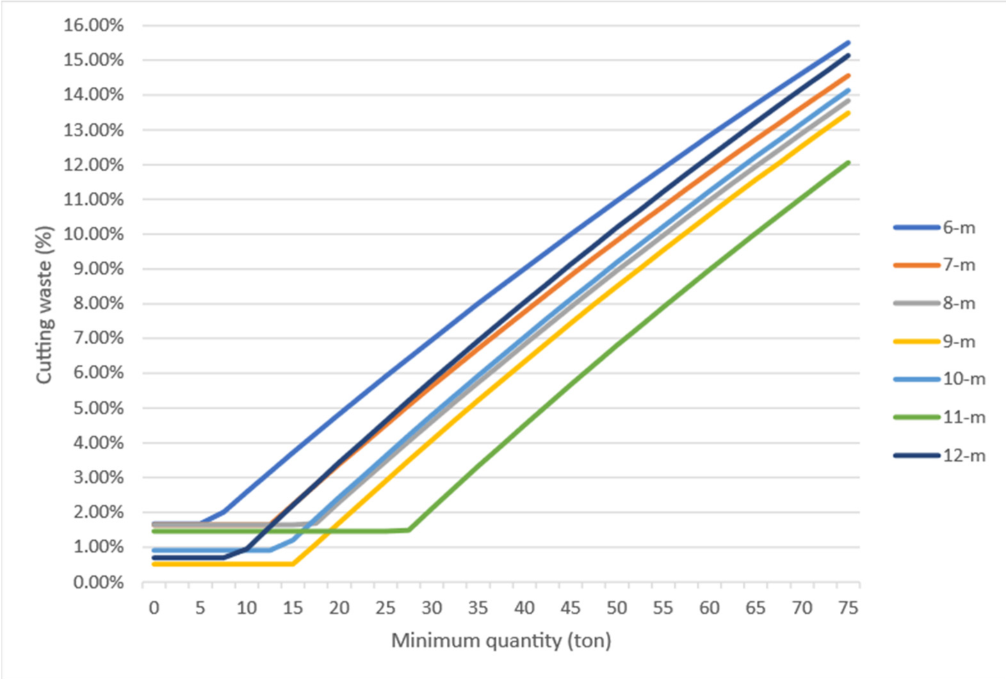

Figure 9. Simulated cutting waste generation.

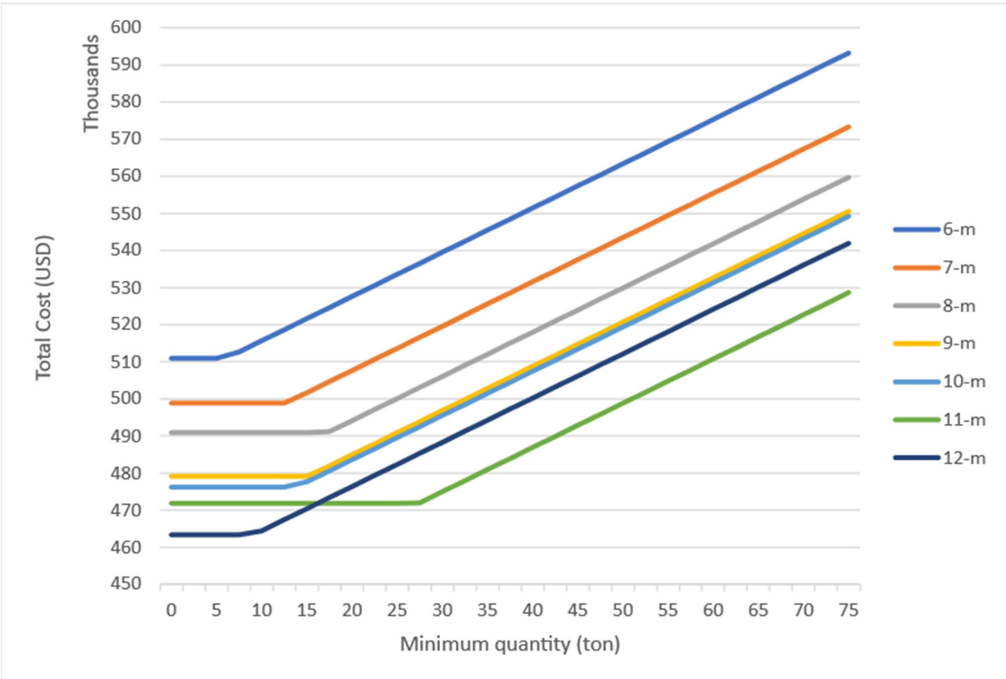

Figure 10. Simulated total reinforcement cost of columns.

A further exploration within scenario three examined cases where the combined quantity of remaining rebars fell below the minimum order requirement. In such instances, these rebars were consolidated based on the established special length for continuous reinforcements. For example, with a maximum available length of 9 m and a minimum order quantity of 0–15 tons, the remaining rebars were combined using 6.1 m lengths. However, when the minimum quantity increased to 17.5 tons or higher, the remaining rebars were consolidated into the 8 m special length for continuous reinforcements instead of 6.1 m. These findings corroborate the previous observation, suggesting that achieving near-zero rebar-cutting waste generally requires a minimum order quantity below 50 tons. A progressively decreasing minimum order quantity corresponds to a reduction in waste generation in general. An exception exists for the 12 m rebar length variation, where near-zero waste can be attained regardless of the minimum quantity, resulting in a minimal waste value of 0.72%. The simulation results are illustrated in Figures 11 and 12. As evident in Figure 11, a significant portion of the simulations yielded cutting waste exceeding 1%, except for the 9, 10, and 12 m rebar length variations. Figure 12 further highlights the strong correlation between minimal cutting waste and reduced costs. Solutions achieving near-zero cutting waste exhibit the lowest total reinforcement costs, ranging from USD 463,000 to USD 480,000. Furthermore, the solutions exhibit the lowest carbon emissions, ranging from 1360 to 1399 tons of eCO_2. For detailed results and calculations, refer to the attached supplementary data [46].

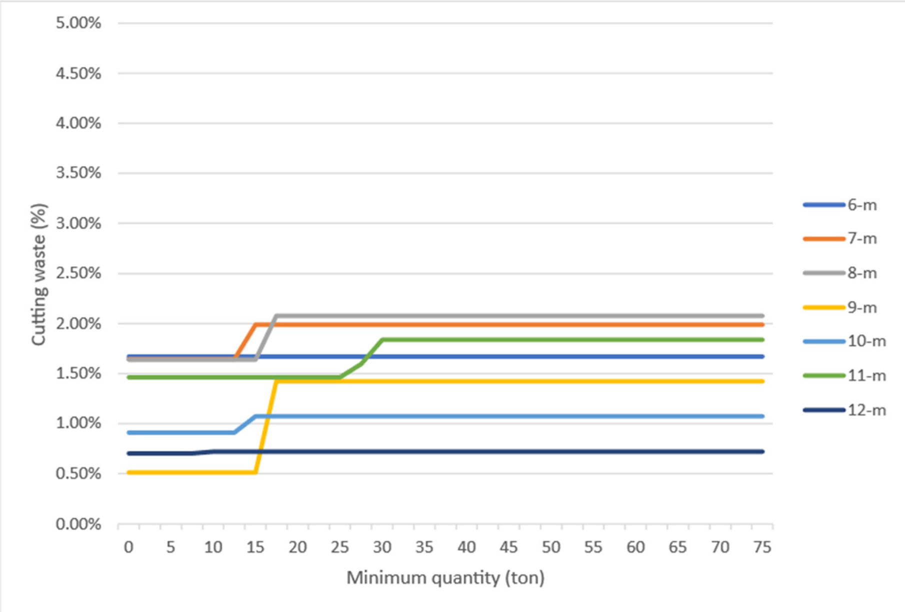

Figure 11. Simulated cutting waste generation following the variation of the third scenario.

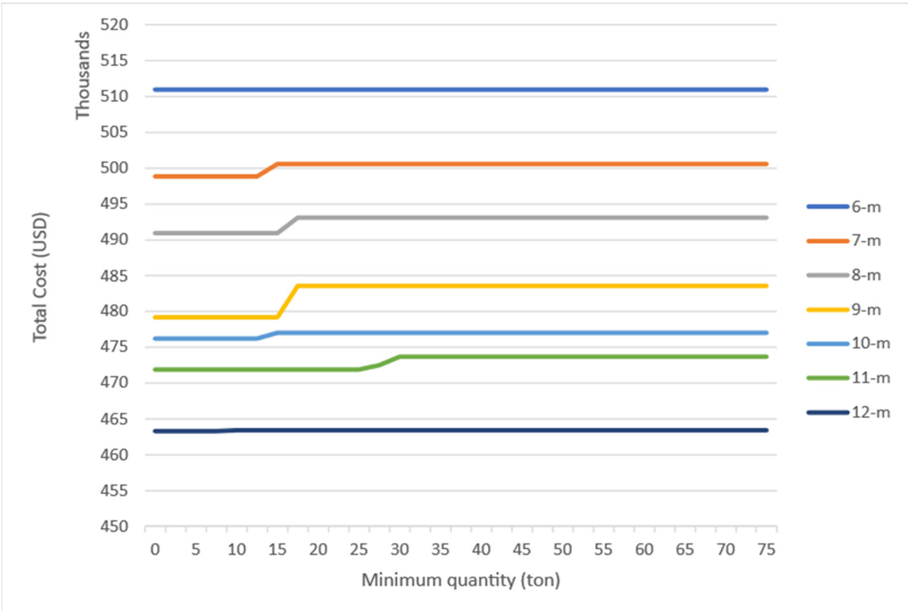

Figure 12. Simulated total reinforcement cost of columns following the variation of the third scenario.

7. Discussions

The construction industry is significantly influenced by the interplay of global economic factors, technological advancements, and sustainability considerations. Notably, the construction market demonstrates a strong correlation with the global economic climate. Fluctuations in the global economy often translate into corresponding fluctuations within the construction sector. In line with this trend, a recent study reports that the average price of construction raw materials in Korea increased by 28.5% in 2022 compared to the fourth quarter of 2021 and surged by over 63% compared to 2020 [44–47], due to the financial crisis induced by the COVID-19 pandemic. These dynamic changes can disrupt the material supply chain, necessitating adjustments to minimum order quantities for essential materials like steel rebar. The severity of these disruptions determines the extent to which minimum requirements are tightened or lessened, considering the production capacities of steel mills. Table 9 provides a summary of the arguments supporting both tightening and relaxing these requirements.

Table 9. Supporting arguments on both tightening and relaxing the requirements.

Tighten	Lessen
A tightened minimum order ensures that steel mills prioritize larger, more efficient production runs due to disruption in production capacity.	Lessened minimum order requirements can make the manufacturer more accessible and accommodating to small customers.
An increase in minimum orders can potentially mitigate revenue losses and facilitate recovery for steel mills experiencing supply disruptions.	Having a larger pool of small projects and a niche market making smaller orders can aid in maintaining cash flow while production is still recovering.
A tightened minimum can help to achieve more efficient inventory management due to the costly and impractical construction material handling.	Construction projects often run on tight schedules. Procuring materials with flexible order sizes can be crucial for meeting the time limit.
A higher minimum can justify the costs associated with transporting rebars that are delivered in bulk in specialized vehicles.	During a disruption, accommodating smaller orders can foster a better relationship with existing customers who might be facing challenges themselves.

The determination of tightening or lessening the minimum order remains a crucial consideration, even during periods of economic stability. Implementing a stricter minimum order offers several advantages, including enhanced production efficiency, improved negotiation leverage for securing better supply costs, and optimized inventory management. Conversely, lessening minimum orders can lead to a broader customer base, potentially expanding market share, fostering stronger customer relationships, and mitigating the risk of excessive production. Therefore, establishing a balanced policy that prioritizes both cost efficiency and customer demand is crucial. Tiered pricing structures, where larger orders receive price discounts, could serve as an alternative strategy.

Nonetheless, the developed dynamic modeling enables it to logically correspond to the dynamic change in special-length rebar procurement requirements regardless of market conditions and steel mill policies in real time. When the baseline values for minimum rebar quantity and maximum rebar length are applied as presented in the first scenario, cutting waste can be minimized to under 1%, as evidenced by Table 6. This scenario may be favorable for construction stakeholders who prioritize sustainable, green, and eco-friendly practices, particularly in a stable economic environment. As previously noted, while not all maximum length variations achieve near-zero rebar-cutting waste level (defined as less than 1% waste), a minimum order quantity below 50 tons proves particularly effective for 9, 10, and 12 m variations, as shown in Figure 9. A demonstrably inverse relationship exists, where a lower minimum order quantity leads to demonstrably reduced waste. An exception was observed for the 12 m rebar length variation, where near-zero waste level can be attained regardless of the minimum quantity, as demonstrated in Figure 11. This finding aligns with a prior study indicating that a maximum rebar length of 12 m generates the least amount of cutting waste, as observed in a previous study simulating cutting waste minimization of RC wall structures [34]. Furthermore, based on the findings provided in the third scenario, the study suggests that when a higher minimum order quantity is imposed or when the remaining rebar's quantity falls below this threshold, it is recommended to combine them using the identified special length for continuous reinforcement. Nonetheless, this approach minimizes cutting waste, consequently reducing environmental and economic burdens, even though the near-zero rebar-cutting waste may not be attainable. Decision-support tools are provided to engineers and stakeholders to prioritize minimal rebar waste amidst fluctuations in rebar procurement requirements due to the dynamic market. It is crucial, however, that they first fully grasp the concept of special-length rebar before utilizing these tools. Since rebar-cutting waste is associated with the use of resources, materials, and processing efficiency, and can be classified as controllable waste [48], its impact is potentially mitigatable. These findings also provide valuable insights for rebar suppliers or steel mills regarding the sustainable implications of their applied requirements, which may affect their future business strategies. Today, it is essential for all construction stakeholders, including rebar suppliers, to collaborate to mitigate the environmental impact of the civil and construction industries.

The findings of this research are currently limited to the scope of the case study. However, it is anticipated that the developed model can be effectively applied to larger construction projects, potentially achieving near-zero rebar-cutting waste with greater ease due to the increased material requirements. This study primarily focused on achieving near-zero waste under two specific scenarios beyond the baseline. Future research could be directed toward exploring a broader range of conditions and factors impacting waste generation. Additionally, this study primarily focuses on the cost implications of reducing waste and rebar usage, particularly concerning the direct costs associated with rebar. Future research should expand on this by including additional rebar-related expenses, such as storage costs, to provide more comprehensive findings. The current study relies on manual simulation techniques and assumptions, which may result in ongoing issues with calculation speed and accuracy. Therefore, future efforts should explore the development of automated model simulations to facilitate faster and more efficient analysis. In addition, future research could investigate the development of risk management models and strategies to address the potential consequences of significant market changes.

8. Conclusions

This study aims to devise a model that simulates the level of optimization in minimizing rebar-cutting waste, targeting near-zero levels considering the dynamic change in special-length rebar procurement requirements regardless of market conditions and steel mill policies in real time. The developed model was applied to a case study consisting of numerous column structures to verify its effectiveness. Numerous essential discoveries are highlighted as follows:

1. The model effectively attains near-zero rebar-cutting waste, ranging from 0.51% to 0.95%. Notably, this minimal waste generation translates to lower carbon emissions and reduced total reinforcement costs.
2. Near-zero rebar-cutting waste is attainable when the maximum available rebar length is limited to 9, 10, or 12 m, with a minimum order quantity requirement of less than 50 tons. Notably, an exception for 12 m variations where it can attain the near-zero level regardless of minimum order quantity.
3. The study recommends combining the remaining rebars using the identified special length for continuous reinforcement when a higher minimum order quantity is imposed or when the remaining rebar's quantity falls below this threshold.

Further research is warranted to investigate a wider range of conditions and factors influencing waste generation. Additionally, the development of automated model simulations for faster and more efficient analysis, alongside risk management models and strategies to mitigate potential consequences of significant market fluctuations, deserves exploration. Nonetheless, this study presents a real-time decision-support system for rebar procurement, enabling engineers to optimize usage and minimize waste generation, thereby facilitating the attainment of near-zero rebar-cutting waste levels in response to construction market-induced rebar procurement requirement dynamics. Furthermore, the study is expected to raise awareness of the special-length rebar approach within the research community and construction industry, potentially leading to wider adoption and continuous advancements in sustainable practices.

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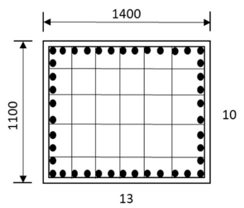
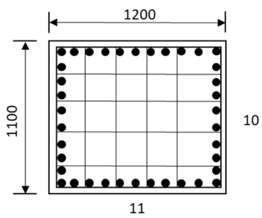
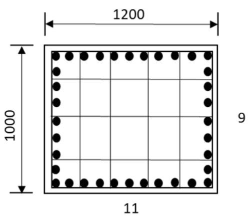
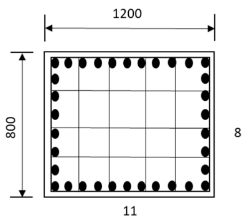
Data Availability Statement: Data sharing is applicable upon reasonable requests.

Conflicts of Interest: Author Sunkuk Kim was employed by the company Department of R&D, Earth Turbine Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Rebar arrangements of the columns (adapted from [21]).

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

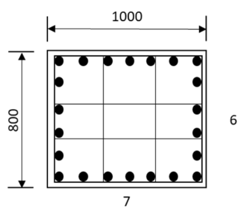
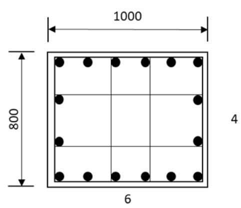
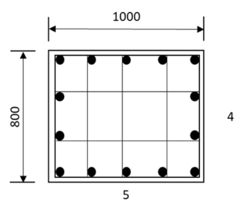
Floors		**F7–F8**	**F9–F12**	**F13–F20**
C14				
Concrete strength, f_c (MPa)		35	35	35
Dimension (mm)		1000 × 800	1000 × 800	1000 × 800
Reinforcement		22–UHD29	16–UHD29	14–UHD29
Hoops	Both ends	HD10@150	HD10@150	HD10@150
	Center	HD10@300	HD10@300	HD10@300

Table A2. Detailed results of the simulation for scenario 2.

SpL (m)		(C)	Continuous		Remaining		(F)	(G)	(H)	(I)	(J)	(K)	(L)	(M)	(N)	(O)	(P)
(A)	(B)		(D)	(E)	(D)	(E)											
6	6	6	409.14	415.14	5.02	6.05	414.15	421.19	7.04	1.67%	13,364	1476.3	382,434	17,641	110,723	157	510,955
6.7	6.7	7	394.99	400.36	11.17	14.05	406.16	414.41	8.25	1.99%	11,492	1452.5	376,277	15,170	108,938	184	500,569
7.3	7.3	8	385.55	390.29	15.37	19.14	400.92	409.43	8.52	2.08%	10,244	1435.1	371,755	13,523	107,633	190	493,101
8	8	9	382.39	383.69	14.45	18.87	396.83	402.56	5.73	1.42%	9152	1411	365,520	12,081	105,825	128	483,554
8.5	8.5	10	380.24	383.17	13.14	14.48	393.38	397.65	4.27	1.07%	8580	1393.8	361,058	11,326	104,535	96	477,015
9.6	9.6	11	366.99	367.34	22.00	28.94	388.99	396.27	7.29	1.84%	7228	1389	359,809	9541	104,175	163	473,688
10.4	10.4	12	376.19	378.87	9.00	9.13	385.19	387.99	2.81	0.72%	6864	1359.9	352,289	9061	101,993	63	463,406

SpL: Special-length rebar (m)
(A): SpL for continuous reinforcements
(B): SpL for remaining reinforcements
(C): Maximum available rebar length (m)
(D): Required rebar quantity (ton)
(E): Ordered rebar quantity (ton)
(F): Total required rebar quantity (ton)
(G): Total ordered rebar quantity (ton)
(H): Cutting waste or loss (ton)
(I): Cutting waste or loss rate (%)
(J): Total number of splices
(K): Carbon emissions (ton eCO2)
(L): Material (rebar) cost (USD)
(M): Rebar processing cost (USD)
(N): Carbon cost (USD)
(O): Disposal charge (USD)
(P): Total reinforcement cost

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