Rizaldi, Y. M., Ashari, A., Permadi, A., Putro, B. A., Thalib, A., & Wirdianto, A. (2026). Digital optimization for green construction – reducing rebar waste and carbon emission. In F. Hamzeh, M. Poshdar, N. P. Garcia-Lopez, & V. Gan (Eds.), *Proceedings of the 34th Annual Conference of the International Group for Lean Construction* (IGLC34) (pp. 461–472). https://doi.org/10.24928/2026/0169

DIGITAL OPTIMIZATION FOR GREEN CONSTRUCTION – REDUCING REBAR WASTE AND CARBON EMISSION

Yura Muhammad Rizaldi[1], Akbar Ashari[2], Adi Permadi[3], Bayu Anggoro Putro[4], Aminullah Thalib[5], & Anang Wirdianto[6]

ABSTRACT

Reinforcing bar (rebar) is a major cost component and contributor to embodied carbon in reinforced concrete construction. In practice, rebar must be cut from standard stock lengths, and inefficient cutting plans often lead to material waste and disruptions in production flow. This study investigates how digital optimization of rebar cutting plans can reduce waste and support planning processes in construction projects. A case study approach was applied using QCDSMPE and quantified Ishikawa analysis to identify root causes, followed by the development and implementation of a digital optimization system across three pilot projects. The results show 2.4% reduction in rebar waste, corresponding to significant cost savings and an estimated reduction of 132,535 kgCO_2e. In addition, preparation time for cutting plans decreased from 3.7 hours to approximately 1s hour per Bar Bending Schedule (BBS). The findings demonstrate that digital optimization of material planning can improve resource efficiency, support workflow reliability, and contribute to both economic and environmental performance in construction.

KEYWORDS

Lean construction, Last Planner System, production flow, rebar cutting plan optimization, embodied carbon.

INTRODUCTION

Material resources play a critical role in determining construction project cost, productivity, and environmental performance. In many projects, material costs account for 40% to 60% of the total budget (Akintoye, 2000; Ashworth et al., 2013), making material management a key focus in Lean Construction (Koskela, 2000).

Reinforcing bar (rebar) is one of the most cost-intensive materials in reinforced concrete structures and is typically supplied in standard stock lengths that require cutting and bending.

[1] Junior Expert, Strategic Project Management Department, PT Wijaya Karya (Persero) Tbk., Jakarta, Indonesia, yura.mr@wikamail.id, orcid.org/0009-0004-8184-2003
[2] Expert 1, Strategic Project Management Department, PT Wijaya Karya (Persero) Tbk., Jakarta, Indonesia, akbar.ashari@wikamail.id, orcid.org/0009-0009-4036-8313
[3] Junior Expert, Strategic Project Management Department, PT Wijaya Karya (Persero) Tbk., Jakarta, Indonesia, adi.permadi@wikamail.id, orcid.org/0009-0009-6921-5046
[4] Junior Expert, Strategic Project Management Department, PT Wijaya Karya (Persero) Tbk., Jakarta, Indonesia, bayu.ap@wikamail.id, orcid.org/0009-0001-7605-0579
[5] Expert 1, Strategic Project Management Department, PT Wijaya Karya (Persero) Tbk., Jakarta, Indonesia, aminullah@wikamail.id, orcid.org/0009-0008-1031-1570
[6] Expert 2, Strategic Project Management Department, PT Wijaya Karya (Persero) Tbk., Jakarta, Indonesia, anang.wirdianto@wikamail.id, orcid.org/0009-0004-9007-4747

Inefficient cutting plans often result in material waste ranging from 4% to 7% (Formoso et al., 2002), indicating persistent inefficiencies in practice.

In addition to cost implications, rebar waste contributes significantly to embodied carbon emissions due to the energy-intensive nature of steel production (Hammond & Jones, 2011; International Energy Agency, 2022). Even small reductions in waste can therefore lead to meaningful environmental benefits.

From a Lean Construction perspective, inefficiencies in rebar cutting planning are not only a material issue but also a production flow problem. In practice, cutting plan preparation is often conducted manually, relying heavily on individual experience and ad hoc calculations. This condition introduces variability in planning outcomes, delays the availability of materials, and contributes to waiting during execution, one of the fundamental forms of waste in Lean thinking (Ohno, 1988).

Within the framework of the Last Planner System (LPS), reliable workflow depends on the effective removal of constraints during the make-ready process (Ballard, 2000). Material availability in the correct quantity and specification is a critical prerequisite for task execution. Inefficient or delayed cutting plans can therefore create unresolved constraints, reduce commitment reliability, and negatively affect workflow stability. Despite this, the relationship between material planning processes (such as rebar cutting optimization) and planning reliability in LPS remains underexplored in existing literature.

In addition, while previous studies have addressed rebar optimization primarily from a cost-efficiency perspective, limited attention has been given to the integration of environmental performance (e.g., embodied carbon) into operational-level planning decisions. Similarly, the use of digital tools for supporting rebar cutting plan optimization has not been widely examined in the context of Lean Construction and production control.

Based on these gaps, this study aims to investigate how digital optimization of rebar cutting plans can reduce material waste and support planning processes in construction projects. The research is guided by the following questions:

1. What are the primary causes of inefficiencies in rebar cutting plan preparation in construction projects?
2. How can digital optimization tools improve rebar utilization and reduce material waste?
3. What operational and environmental benefits can be achieved through the implementation of such a system?

This study contributes to Lean Construction research in several ways. First, it provides empirical evidence linking material planning processes, specifically rebar cutting plan preparation, with production flow reliability in construction projects. By positioning cutting plan optimization as part of the make-ready process, the study extends the understanding of how material-related decisions influence workflow stability within the Last Planner System.

Second, the study integrates environmental performance considerations, particularly embodied carbon reduction, into operational-level planning. This extends existing rebar optimization approaches, which are typically focused on cost efficiency, by demonstrating the dual economic and environmental benefits of waste reduction.

Third, the study translates root cause analysis into a practical digital solution, demonstrating how Lean principles can be operationalized through the development and implementation of a rebar cutting optimization system. This provides a bridge between Lean theory and digital innovation in construction practice.

Finally, the study contributes methodologically by applying a structured combination of QCDSMPE, quantified Ishikawa analysis, and multi-criteria decision-making to support transparent and systematic improvement in construction operations.

METHODOLOGY

RESEARCH DESIGN

This study adopts a case study approach combined with a design-oriented intervention, aiming to both analyze an operational problem and develop a practical solution within a real construction context. The research was conducted within a large Indonesian construction company managing multiple reinforced concrete projects. The study focuses on rebar planning, fabrication, and installation processes, where inefficiencies in cutting plan preparation were observed. The research was structured into four main stages:

4. Problem Identification
5. Identification of inefficiencies in rebar-related processes through field observations and document analysis.
6. Root Cause Analysis
7. This study applies established improvement tools, including QCDSMPE, Ishikawa diagram, and 5W+1H, which are widely used in process improvement and Lean-based problem-solving. The Ishikawa diagram is a well-established method for identifying root causes of operational inefficiencies (Ishikawa, 1986), while structured frameworks such as QCDSMPE and 5W+1H support systematic evaluation and implementation planning in complex project environments (Ohno, 1988; Liker, 2004).
8. Solution Development
9. Development of a digital rebar cutting plan optimization system based on the identified root causes.
10. Implementation and Evaluation
11. Pilot implementation of the developed system across selected projects and evaluation of its impact on material efficiency, planning performance, and environmental outcomes.

This design aligns with improvement-oriented research commonly applied in Lean Construction, where practical interventions are evaluated in real project environments.

RESEARCH CONTEXT AND CASE DESCRIPTION

The study was conducted across three reinforced concrete construction projects executed between 2024 and 2025. The projects represent typical large-scale construction works involving significant rebar usage:

- A toll road project, with a total rebar volume of approximately 25,038,039 kg.
- A dam construction project, with a total rebar volume of approximately 864,660 kg.
- A wastewater infrastructure project, with a total rebar volume of approximately 200,005 kg.

These projects were selected to represent varying levels of scale, complexity, and construction characteristics. The variation in project size from large-scale infrastructure to smaller utility works, supports the transferability of the findings across different construction contexts. The intervention focused on activities related to Bar Bending Schedule (BBS) preparation, rebar cutting plan generation, and rebar fabrication and installation coordination.

The implementation period covered approximately 4 months, including initial deployment, user training, and operational use during project execution.

DATA COLLECTION

Data were collected through document analysis (BBS, procurement records, and BoQ), field observations, and semi-structured interviews with planning engineers, site engineers, and

supervisors. Post-implementation system data were used to evaluate cutting efficiency, waste reduction, and preparation time.

PROBLEM IDENTIFICATION AND PRIORITIZATION

Initial problems in rebar management were identified through observations and document analysis. These problems were then evaluated using the QCDSMPE framework, which considers seven performance dimensions, Quality, Cost, Delivery, Safety, Morale, Productivity, and Environment

Each problem was assessed using a scoring scale from 1 (very low impact) to 5 (very high impact). The evaluation was conducted by a panel consisting of 1 Engineering senior manager, 1 Senior expert, 1 Engineering manager, and1 Expert.

All participants had direct experience in rebar planning and execution.

To emphasize problems affecting multiple dimensions simultaneously, a multiplicative scoring approach was used to calculate total impact scores. Problems with higher scores were prioritized for further analysis.

ROOT CAUSE ANALYSIS

Root cause analysis was performed using a quantified Ishikawa diagram, structured into six categories, Method, Man (People), Machine/Tools, Material, Measurement, and Environment. Each root cause was evaluated based on three criteria:

- Impact (I): severity of effect on performance
- Frequency (F): how often the issue occurs
- Controllability (C): ease of mitigation

Each criterion was scored on a scale of 1 to 5. The Priority Index was calculated using: Priority Index = I × F × C

SOLUTION DEVELOPMENT

Based on the prioritized root causes, alternative solutions were identified and evaluated using a multi-criteria decision approach. The evaluation criteria included quality improvement potential, Implementation time, and Cost. Each alternative was scored and compared to identify the most suitable solution. The selected solution was the development of an in-house digital rebar cutting optimization system, chosen due to its flexibility, alignment with project workflows, and potential for continuous improvement.

IMPLEMENTATION AND EVALUATION

The developed system was implemented in the three pilot projects and evaluated based on material efficiency, planning Performance, and environmental Performance. Carbon emissions were estimated using an emission factor of 1.99 $kgCO_2e$ per kg of rebar, based on established embodied carbon data for steel production (Hammond & Jones, 2011; International Energy Agency, 2022). The reduction in emissions was calculated based on the decrease in rebar waste after implementation, assuming that reduced material consumption directly corresponds to lower embodied carbon associated with steel production and transportation.

RESULTS

PROBLEM IDENTIFICATION

Based on field observations, document analysis, and interviews with project personnel, several recurring problems were identified in rebar management processes, particularly in planning, fabrication, and installation stages. These problems are summarized in Table 1.

Table 1 Common Problems in Rebar Management and Fabrication

No.	Type of Problem	Description
1	Inefficient rebar cutting plan preparation	Increasing waiting, contributing to overproduction, and requiring additional storage space
2	Mock-up fabrication not in accordance with the design	Design discrepancies requiring rework or reconstruction
3	Rebar ordering not in compliance with specifications	Ordered rebars do not meet the required specifications
4	Inaccurate rebar fabrication	Fabrication inaccuracies result in difficulties during installation
5	Improper rebar placement	Errors in installation lead to incorrect reinforcement application

The identified problems indicate that inefficiencies are not limited to a single stage but occur across the entire rebar workflow. Among these, issues related to cutting plan preparation were frequently observed to disrupt coordination between planning and execution, leading to delays and material inefficiencies.

PROBLEM PRIORITIZATION USING QCDSMPE

To determine the most critical problem, the identified issues were evaluated using the QCDSMPE framework. Each problem was assessed across seven performance dimensions, and the results are presented in Table 2.

Table 2: Impact Assessment of Identified Rebar Management Problems

No.	Type of Problem	Quality	Cost	Delivery	Safety	Morale	Productivity	Environment	TOTAL
1	Inefficient rebar cutting plan preparation	3	4	4	3	4	4	3	6912
2	Mock-up fabrication not in accordance with the design	2	3	2	2	3	4	3	864
3	Rebar ordering not in compliance with specifications	3	3	2	2	3	4	3	1296
4	Inaccurate rebar fabrication	4	3	3	3	3	5	3	4860
5	Improper rebar placement	2	4	3	3	3	4	3	2592

The results show that inefficient rebar cutting plan preparation has the highest total impact score among all identified problems. This indicates that it significantly affects multiple performance dimensions simultaneously, including cost, delivery, productivity, and environmental performance.

From an operational perspective, inefficient cutting plan preparation leads to delays in material readiness, increased waiting time during installation, and the tendency to overproduce rebar as a buffer against uncertainty. These conditions contribute to increased material waste and reduced process efficiency. Based on this prioritization, inefficient cutting plan preparation was selected as the primary focus for further analysis.

ROOT CAUSE ANALYSIS

To better understand the underlying causes of inefficient cutting plan preparation, a root cause analysis was conducted using a quantified Ishikawa approach. The results of the analysis are presented in Table 3.

Table 3 Quantified Ishikawa Root Cause Assessment

Ishikawa Category	Root Cause	Impact (I)	Frequency (F)	Controllability (C)	Priority Index (I×F×C)	Lean/LPS Implication
Method	Manual cutting plan preparation	5	5	4	**100**	Low PPC, high waiting
	No standardized optimization method	5	4	4	**80**	Unstable workflow
	Late development of cutting plans	4	4	3	48	Poor make-ready
Man (People)	Reliance on individual experience	4	4	3	48	Planning variability
	Limited lean/LPS understanding	3	4	3	36	Weak commitment
	High planner workload	4	3	2	24	Planning delays
Machine / Tools	No dedicated cutting plan software	5	5	5	**125**	Excess waiting & rework
	Manual data input	4	5	4	**80**	Non–value-added work
	Lack of rebar traceability	4	4	4	64	Excess inventory
Material	Poor reuse of rebar offcuts	5	4	4	**80**	Overproduction & waste
	Standard stock length mismatch	4	4	ππ3	48	Increased cutting loss
	Overproduction as safety buffer	5	3	3	45	Inventory accumulation
Measurement	No cutting efficiency indicators	4	4	4	64	No learning loop
	Waste identified after execution	5	4	3	60	Reactive control
	Weak linkage to PPC metrics	4	3	3	36	Low planning reliability
Environment	Excess on-site inventory	5	4	3	60	Flow disruption
	Fragmented team coordination	4	4	3	48	Planning inconsistency
	Tight project schedules	3	5	2	30	Short-term decision bias

The analysis shows that the highest-priority root causes are concentrated in the Method and Machine/Tools categories. The most critical factors include the absence of optimization tools, reliance on manual calculations, and lack of standardized procedures. These factors contribute to inconsistent cutting plans, increased calculation errors, and delays in preparation.

In addition, issues related to material management, such as poor reuse of offcuts and mismatch between stock lengths and required lengths, further contribute to material waste. Overall, the findings indicate that inefficiencies in cutting plan preparation are primarily driven by limitations in tools, methods, and data management practices.

SOLUTION SELECTION

Based on the identified root causes, several alternative solutions were evaluated using a multi-criteria assessment approach. The evaluation results are presented in Table 4.

Table 4: Determining solutions

Main Couse	Alternative	Quality	Score	Time	Score	Cost	Score	Total Score
Cutting plan preparation is still done manually The impact of rebar bending is still neglected Rebar cutting data is still recorded manually	Using commercially available optimization software	The software is not specifically designed for construction project applications, which results in extensive manual data input. Further improvement or customization is limited.	3	Procurement and implementation process requires approximately 30 days.	5	Approximately IDR 50 million for 50 users (project-based licensing).	4	60
	Developing an in-house software system	The in-house development approach enables closer alignment with project-specific workflows and provides greater potential for iterative refinement based on project feedback.	5	Development, including initial pilot testing at project level, requires approximately 12 months.	4	Approximately IDR 50 million for software development.	4	80
	Using third-party software development services	Documented experience of vendors specifically developing software for rebar cutting plan optimization in construction projects remains limited. This condition may introduce uncertainties related to solution maturity, implementation reliability, and long-term maintainability.	4	Software development and review process requires approximately 12 months.	4	Approximately IDR 250 million.	2	32

The comparison indicates that the development of an in-house software system achieved the highest total score among the evaluated alternatives. This option was selected because it provides:

12. better alignment with project-specific workflows
13. higher flexibility for customization and continuous improvement
14. improved accuracy in cutting plan calculations

In contrast, commercially available software requires significant manual input and lacks integration with construction workflows, while third-party development introduces uncertainties related to domain knowledge and implementation reliability.

IMPLEMENTATION PLANNING

The selected solution was further developed into an implementation plan using the 5W+1H framework to ensure structured execution. The implementation plan is summarized in Table 5.

Table 5: 5W+1H

No.	Why	What	How	Who-Where-When
1	Cutting plan preparation is still done manually	Optimization of rebar cutting plans using a software-based approach	Software was developed to optimize cutting plans and improve the efficiency of rebar cuts, while simultaneously managing cutting operations.	1. Structured brainstorming to identify functional requirements and planning constraints • Who: Subject matter experts • Where: Project and head office coordination sessions • When: Early planning phase 2. Software development based on validated project data and planning requirements • Who: In-house software development team, supported by planning engineers • Where: Head office development environment • When: Following requirement validation 3. System socialization and user training to support consistent application in planning routines • Who: Project planners, site engineers, and supervisors • Where: Project site and planning offices • When: Prior to and during initial Weekly Work Planning cycles 4. Pilot implementation and performance monitoring to evaluate planning reliability and workflow impact. • Who: Project team • Where: Selected pilot project • When: During execution phase
2	Impact of rebar bending is still neglected	Incorporation of BS 8666:2020 standards for bending allowances		
3	Rebar cutting data is still recorded manually	Computerized and systematic recording of rebar cutting and residual materials		

The plan defines key elements of implementation, including objectives of the improvement, development and deployment approach, responsible stakeholders, and timeline of implementation. This structured approach supports systematic deployment and reduces ambiguity during execution.

IMPLEMENTATION RESULTS

The developed rebar cutting plan optimization system was implemented across three pilot projects. The implementation generated measurable improvements in material efficiency, planning performance, and environmental outcomes.

Rebar Waste Reduction

The implementation resulted 2.4% reduction in rebar waste. At the organizational level, this improvement corresponds to estimated annual cost savings of approximately IDR 1.1 billion. At the project level, based on a total rebar volume of 26,102,704 kg, the optimization resulted in cost savings of approximately IDR 1.18 billion.

Planning Performance Improvement

The system also improved planning efficiency, particularly in cutting plan preparation.

- Average preparation time decreased from 3.7 hours to approximately 1 hour per Bar Bending Schedule (BBS)
- Cutting plans were generated more consistently and with fewer revisions
- Material readiness improved, reducing waiting during installation

In addition, the system enabled structured digital recording of rebar usage and residual materials, improving traceability and inventory visibility.

Carbon Emission Reduction

The reduction in rebar waste contributed to a decrease in embodied carbon emissions. Using an emission factor of 1.99 kgCO_2e per kg of rebar, the estimated reduction in carbon emissions is 132,535 kgCO_2e. This reduction includes decreased material production due to reduced waste, and reduced transportation requirements.

Planning Reliability Indicators

Although Percent Plan Complete (PPC) was not directly measured in this study, several indicators suggest improved planning reliability. These indicators are summarized in Table 6.

Table 6: Planning reliability indicators

Metric	Baseline (Manual Cutting Plan)	After Software Implementation	Interpretation
PPC	Not consistently measured / estimated lower reliability	Higher planning reliability observed	Improved material readiness reduced plan failures related to rebar availability
Waiting due to material issues	Frequent	Significantly reduced	Cutting plans available earlier and in correct quantities
Inventory level of rebar	High (buffer-based)	Reduced (demand-driven)	Less overproduction and excess stock
Cutting plan preparation time	~3.7 hours per BBS	~1 hours per BBS	Faster make-ready support

The results indicate reduced waiting due to material availability issues, lower inventory levels, and faster preparation of cutting plans. These improvements suggest better alignment between planning and execution, which is consistent with improved workflow reliability in construction operations.

DISCUSSION

INTERPRETATION OF FINDINGS IN LEAN CONSTRUCTION CONTEXT

The findings of this study demonstrate that inefficiencies in rebar cutting plan preparation represent a significant source of waste and variability in construction operations. The observed reduction in rebar waste indicates improved material utilization, which directly aligns with the Lean Construction principle of waste minimization (Koskela, 2000).

From a production flow perspective, improved cutting plan accuracy reduces the need for overproduction as a buffer against uncertainty. This aligns with inventory waste in Lean thinking (Ohno, 1988), where excess materials compensate for planning unreliability. By reducing this buffering behavior, the system contributes to more stable and predictable material flows.

Furthermore, improved traceability of rebar usage and residual materials supports better inventory control and reduces unnecessary material handling, which is another recognized form of waste in construction processes.

IMPLICATIONS FOR LAST PLANNER SYSTEM (LPS)

This study provides empirical insights into how material planning processes influence production control performance under the Last Planner System (LPS). The results indicate that improved cutting plan preparation contributes to earlier availability of materials in the correct form, reduction of unresolved constraints during the make-ready process, and decreased waiting

time during execution. These conditions are consistent with improved workflow reliability, which is a core objective of LPS (Ballard, 2000).

Although Percent Plan Complete (PPC) was not directly measured, the observed improvements in material readiness and reduced variability in rebar supply suggest that cutting plan optimization plays a supporting role in enhancing commitment reliability. This finding reinforces the idea that material planning is a critical enabler of reliable workflow, rather than a purely logistical function.

COMPARISON WITH PREVIOUS STUDIES

The results of this study are consistent with previous research highlighting the impact of material management on construction performance.

Studies such as Formoso et al. (2002) have reported rebar waste levels ranging between 4% and 7%, which aligns with the baseline conditions observed in this study. The achieved reduction of approximately 2.4% demonstrates that targeted interventions in cutting plan optimization can produce measurable improvements within this range.

In addition, previous research on Lean Construction has emphasized the importance of reducing variability and improving flow reliability (Koskela, 2000; Ballard & Howell, 1998). The findings of this study extend this perspective by showing that digital tools can operationalize these principles at the level of material planning, particularly in rebar-intensive construction processes.

Compared to existing approaches that focus primarily on cost optimization, this study integrates economic and environmental performance, demonstrating that material efficiency improvements can simultaneously reduce embodied carbon emissions.

ROLE OF DIGITALIZATION IN LEAN IMPLEMENTATION

The implementation of a digital rebar cutting optimization system highlights the role of digital technologies in supporting Lean Construction practices. The system enables systematic calculation of cutting patterns, integration of bending allowances, and real-time recording of material usage.

These capabilities reduce reliance on manual calculations and individual judgment, which are sources of variability in planning processes.

From a Lean perspective, the digital system functions as an enabler of standardization and continuous improvement, allowing data-driven identification of recurring waste patterns and supporting learning cycles across projects.

This finding supports the growing body of research emphasizing the integration of digital technologies with Lean principles to enhance construction performance.

ENVIRONMENTAL IMPLICATIONS

The study demonstrates that improvements in material efficiency can lead to meaningful reductions in environmental impact.

The estimated reduction of 132,535 $kgCO_2e$ highlights the significance of addressing material waste as part of sustainable construction practices. This finding is consistent with life cycle assessment studies that identify steel as a major contributor to embodied carbon in construction (Hammond & Jones, 2011).

In addition, the inclusion of transportation-related emissions extends the scope of analysis beyond on-site activities, indicating that improved planning reliability can influence upstream supply chain performance.

This suggests that Lean-based improvements in material planning can contribute not only to operational efficiency but also to broader sustainability objectives.

LIMITATIONS OF THE STUDY

This study has several limitations that should be acknowledged. First, the research adopts a case study approach, and the findings are based on three pilot projects within a single organization. While the results provide valuable insights, their generalizability to other project types or organizational contexts may be limited.

Second, the study does not fully isolate the causal impact of the software intervention from other influencing factors, such as team experience, project complexity, or concurrent process improvements. Therefore, the observed improvements should be interpreted as indicative rather than strictly causal.

Third, Percent Plan Complete (PPC) was not directly measured. Future research could incorporate direct measurement of PPC and other LPS performance metrics to provide stronger empirical evidence of the relationship between material planning and workflow reliability.

IMPLICATIONS FOR PRACTICE AND FUTURE RESEARCH

From a practical perspective, the findings suggest that improving rebar cutting plan preparation can significantly enhance material efficiency and planning performance in construction projects.

The study also highlights the importance of integrating material planning, digital tools, environmental performance metrics into a unified improvement framework.

For future research, several directions can be explored:

- Integration of cutting plan optimization with Building Information Modelling (BIM)
- Application of predictive analytics for material demand forecasting
- Incorporation of formal Lean decision-making methods, such as Choosing by Advantages (CBA), to enhance transparency in solution selection

CONCLUSION

This study demonstrates that inefficiencies in rebar cutting plan preparation represent a significant source of material waste and variability in construction processes. By applying a structured Lean-based approach supported by digital optimization, the study achieved measurable improvements in material utilization, planning efficiency, and environmental performance.

The findings indicate that optimizing cutting plans not only reduces rebar waste but also supports production flow by improving material readiness and reducing variability during execution. This highlights the role of material planning as a critical component of workflow reliability within construction operations. From a practical perspective, the implementation of a digital optimization system provides a scalable solution for improving rebar management, reducing costs, and lowering embodied carbon emissions. From a theoretical perspective, this study contributes by linking material planning processes with Lean Construction principles, particularly in relation to production flow and planning reliability.

Future research is recommended to further investigate the integration of such systems with BIM and to evaluate their impact on formal LPS performance metrics, including PPC.

REFERENCES

Akintoye, A. (2000). Analysis of factors influencing project cost estimating practice. *Construction Management and Economics*, 18(1), 77–89. https://doi.org/10.1080/014461900370979

Ashworth, A., Hogg, K., & Higgs, C. (2013). *Willis's practice and procedure for the quantity surveyor* (13th ed.). Wiley-Blackwell.

Athena Sustainable Materials Institute. (2019). *Life cycle assessment of steel products*. Athena Sustainable Materials Institute.

Ballard, G. (2000). *The Last Planner System of production control*. Doctoral dissertation, University of Birmingham, UK.

Ballard, G., & Howell, G. (1998). Shielding production: Essential step in production control. *Journal of Construction Engineering and Management*, 124(1), 11–17. https://doi.org/10.1061/(ASCE)0733-9364(1998)124:1(11)

Ballard, G., & Howell, G. (2003). Lean project management. *Building Research & Information*, 31(2), 119–133.

Ballard, G., & Tommelein, I. D. (2016). Current process benchmark for the Last Planner System. *Lean Construction Journal*, 2016, 57–89.

Formoso, C. T., Soibelman, L., De Cesare, C., & Isatto, E. L. (2002). Material waste in the building industry: Main causes and prevention. *Journal of Construction Engineering and Management*, 128(4), 316–325. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(316)

Hammond, G. P., & Jones, C. I. (2011). *Inventory of carbon and energy (ICE) version 2.0*. University of Bath.

Hamzeh, F., Ballard, G., & Tommelein, I. D. (2012). Rethinking lookahead planning to optimize construction workflow. *Lean Construction Journal*, 2012, 15–34.

Hopp, W. J., & Spearman, M. L. (2008). *Factory Physics* (3rd ed.). McGraw-Hill.

Horman, M. J., & Kenley, R. (2005). Quantifying levels of wasted time in construction with meta-analysis. *Journal of Construction Engineering and Management*, 131(1), 52–61.

International Energy Agency. (2022). *Global status report for buildings and construction*. International Energy Agency.

Ishikawa, K. (1986). Guide to quality control. Asian Productivity Organization.

Koskela, L. (2000). *An exploration towards a production theory and its application to construction*. VTT Technical Research Centre of Finland.

Love, P. E. D., Edwards, D. J., Irani, Z., & Walker, D. H. T. (2010). Project pathologies: The manifestation of rework in construction. *International Journal of Project Management*, 27(6), 527–536.

Mossman, A. (2009). Why isn't the UK construction industry going lean with gusto? *Lean Construction Journal*, 2009, 24–36.

Navon, R. (2005). Automated project performance control of construction projects. *Automation in Construction*, 14(4), 467–476. https://doi.org/10.1016/j.autcon.2004.09.006

Ohno, T. (1988). *Toyota Production System: Beyond large-scale production*. Productivity Press.

Imai, M. (1986). *Kaizen: The key to Japan's competitive success*. McGraw-Hill.

Liker, J. K. (2004). *The Toyota Way: 14 management principles from the world's greatest manufacturer*. McGraw-Hill.

Womack, J. P., & Jones, D. T. (2003). *Lean thinking: Banish waste and create wealth in your corporation* (2nd ed.). Free Press.

Intergovernmental Panel on Climate Change (IPCC). (2022). *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the IPCC. Cambridge University Press.

World Steel Association. (2021). *Life Cycle Assessment Methodology Report*. World Steel Association.