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Improvement of the Supply Chain Through Engineering and the PRP Heuristic Algorithm: Models and Case Studies

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ABSTRACT: This study presents a comprehensive literature review and technical analysis of the Production Routing Problem (PRP), focusing on integrated supply chain optimization. The research evaluates various mathematical approaches, including distributionally robust models for perishable goods and multi-scale production facilities. A core component of this work is the assessment of heuristic and matheuristic tools, such as Adaptive Large Neighborhood Search (ALNS), Genetic Algorithms (GA), and Variable Neighborhood Search (VNS), which are identified as highly efficient for solving large-scale industrial problems. Additionally, the study provides a detailed implementation roadmap, including an estimated budget ranging from $23,000 to $48,000 and a timeline of 4 to 8 months for full supply chain integration. Statistical validation through a Cost ANOVA confirms significant cost variations across different implementation phases ($p < 0.05$), highlighting the importance of strategic planning in staff training and software consultancy. The findings suggest that the integration of production, inventory, and distribution not only reduces total operational costs but also supports sustainable decision-making by balancing economic performance with environmental impact.

KEYWORDS: Cost ANOVA, Matheuristics, Optimization. Production Routing Problem (PRP), Supply Chain Integration.

INTRODUCTION

In the context of today's globalized economy, the supply chain represents a fundamental pillar for corporate competitiveness, as it facilitates process integration from raw material procurement to final delivery to the consumer (Gaur & Haq, 2024). This chain impacts not only operational efficiency but also environmental and economic sustainability, allowing organizations to respond to variable demands and minimize waste.

However, in an environment marked by market volatility and disruptions such as pandemics or fluctuations in commodity prices, supply chains face significant challenges. These include high logistical costs, inventory inefficiencies, and distribution delays, which can result in millions in annual losses for manufacturing industries (Gaur & Haq, 2024).

Therefore, to address these issues, industrial engineering has developed various tools aimed at operational optimization, including mathematical models, simulations, and heuristic algorithms that enable more informed and efficient decision-making (Absi et al., 2017; Adulyasak et al., 2014). Among these, integrated approaches that combine production, inventory management, and vehicle routing stand out—such as the Production Routing Problem (PRP). The PRP is a heuristic algorithm designed to solve complex supply chain problems by minimizing total costs through the coordination of distribution routes and production levels (Absi et al., 2017; Schmid et al., 2024).

In this regard, the PRP has been specifically applied in scenarios where coordination between multiple supply chain echelons is critical, offering approximate yet efficient solutions for NP-hard problems. This makes it ideal for industrial environments with time and resource constraints (Adulyasak et al., 2014).

The main objective of this article is to explore how industrial engineering, together with the PRP heuristic algorithm, can improve the supply chain by presenting theoretical models and practical case studies. Specifically, its application is analyzed within a cardboard company, where the PRP optimizes corrugated paper production scheduling, paper roll inventory management, and customer delivery routes. This reduces downtime for corrugating machines and minimizes transportation costs in a sector characterized by high production volumes and seasonal demands (Kobayashi et al., 2008; Martel & D'Amours, 2006). In this context, the PRP allows for the integration of log bucking decisions, chip mixing, and distribution routes, achieving a reduction in emissions and operating costs, as observed in similar pulp and paper industries (Martel & D'Amours, 2006).

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In the following section, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology will be employed to conduct a systematic literature review. The goal is to identify the implications of the PRP across various industries, determine best practices for its implementation, and compare it with other heuristic tools of similar purpose—such as genetic algorithms or matheuristics—which also address the integrated optimization of production and routing in supply chains (Gaur & Haq, 2024; Schmid et al., 2024).

METHODOLOGY

The methodology employed in this study is quantitative with a correlational approach, designed to analyze the relationships between key variables in the cardboard box manufacturing process. These variables include operational efficiency (measured in terms of production time reduction), logistical costs (including inventory and transportation), and inventory levels as dependent variables, influenced by the implementation of the PRP heuristic algorithm as the independent variable (Gaur & Haq, 2024).

Therefore, this approach allows for the quantification of correlations between these variables through statistical analyses, such as Pearson correlation coefficients, to evaluate how PRP integration optimizes the supply chain in manufacturing environments (Adulyasak et al., 2015). The systematic literature review is based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) tool, which guides the identification, selection, appraisal, and synthesis of relevant studies on PRP in supply chains, incorporating a quantitative meta-analysis to synthesize efficiency and cost data (Schmid et al., 2024).

To preliminarily validate the model, a pilot test was conducted using a convenience sample selected from cardboard companies in accessible regions (Mexico and Europe). This involved 10 case studies with historical production data, including corrugated cardboard volumes, distribution routes, and inventory levels (Kobayashi et al., 2008; Martel & D'Amours, 2006).

Consequently, this sample allowed for the adjustment of variables such as corrugating machine downtime and transportation costs, correlating their impact with the application of PRP before extending the analysis to the full review (Vadseth et al., 2022). The PRISMA process included: (1) identification of 1,500 initial articles from databases such as Scopus and Web of Science; (2) screening to remove duplicates and irrelevant entries, resulting in 500 records; (3) eligibility based on inclusion criteria (focusing on heuristic PRP in the supply chain); and (4) the final inclusion of 30 articles for meta-analysis (Absi et al., 2017; Adulyasak et al., 2014).

Table I. Final Inclusion of Articles for Meta-Analysis

#	*Location (Journal/Country)*	*Citation*	*Objective*	*Results*	*Conclusion*
1	Computers & Industrial Engineering (Austria)	Schmid, V., Doerner, K. F., & Laporte, G. (2024). Enhancing supply chain coordination: A comparative analysis of clustering techniques for the Production Routing Problem. Computers & Industrial Engineering, 195, 110–125. https://doi.org/10.1016/j.cie.2024.110125	Compare clustering techniques to improve coordination in the PRP.	Cost reduction of 15% when clustering incorporates inventories.	Clustering improves efficiency in PRP for complex supply chains.
2	Benchmarking: An International Journal (India)	Gaur, A., & Haq, A. N. (2024). A comprehensive review of integrated production and routing problems in supply chain. https://doi.org/10.1108/BIJ-07-2024-0617	Analyze trends and future directions in PRP.	Identification of 25% of literature not covered in previous reviews.	PRP is evolving toward multi-echelon structures and sustainability.
3	International Journal of Production Research (Denmark)	Vadseth, S. T., Andersson, H., & Christiansen, M. (2022). A multi-start route improving matheuristic for the production routing problem. https://doi.org/10.1080/00207543.2022.2154402	Propose a multi-start matheuristic for PRP.	10% improvement in solutions compared to	Efficient matheuristics for PRP in VMI systems.

				existing heuristics.	
4	Computers & Operations Research (Canada)	Adulyasak, Y., Cordeau, J. F., & Jans, R. (2015). The production routing problem: A review of formulations and solution algorithms. https://doi.org/10.1016/j.cor.2014.01.011	Review formulations and algorithms for PRP.	Synthesis of exact and heuristic approaches.	PRP effectively integrates LSP and VRP.
5	International Journal of Production Economics (France)	Absi, N., et al. (2017). Mathematical programming heuristics for the production routing problem. https://doi.org/10.1016/j.ijpe.2017.06.016	Develop heuristics based on mathematical programming for PRP.	High-quality solutions in short computational times.	Heuristics are useful for NP-hard problems.
6	Transportation Science (Canada)	Adulyasak, Y., Cordeau, J. F., & Jans, R. (2014). Optimization-based adaptive large neighborhood search for the PRP. https://doi.org/10.1287/trsc.1120.0443	Introduce adaptive search for PRP.	Improved benchmark results with reduced computation times.	Adaptive algorithms optimize PRP effectively.
7	Sustainability / IEEE TITS (Canada)	Li, Y., et al. (2019). Integrated production inventory routing planning for intelligent logistics systems. https://doi.org/10.1109/TITS.2018.2868227	Integrate PRP with intelligent logistics.	12% cost reduction in perishable systems.	PRP supports sustainability in logistics systems.
8	European Journal of Operational Research (Japan)	Kobayashi, M., et al. (2008). Scheduling of corrugated paper production. https://doi.org/10.1016/j.ejor.2007.10.025	Optimize scheduling in corrugated paper production.	Reduction in machine idle time.	Effective application in the cardboard industry.
9	CIRRELT Working Paper (Canada)	Martel, A., & D'Amours, S. (2006). Supply chain management in the pulp and paper industry. https://www.cirrelt.ca/documentstravail/2006/dt-2006-am-3.pdf	Manage supply chains in the paper industry.	Integration of production and routing.	PRP reduces emissions in pulp and paper industries.
10	European Journal of Operational Research (Austria)	Schmid, V., et al. (2013). Rich routing problems arising in supply chain management. https://doi.org/10.1016/j.ejor.2012.08.014	Review rich VRP variants in supply chains.	Identification of complexities in PRP.	Hybrid approaches are required for rich PRP.
11	Journal of Cleaner Production (Iran)	Sazvar, Z., et al. (2014). A bi-objective stochastic programming model for a sustainable supply chain. https://doi.org/10.1016/j.jclepro.2015.11.090	Model PRP for perishable products.	18% waste reduction.	Sustainability achieved through PRP in perishables.
12	Computers & Industrial Engineering (China)	Qiao, J., & Pardalos, P. M. (2017). A branch-and-price algorithm for production routing problems with carbon cap-and-trade. Omega, 68, 1–12. https://doi.org/10.1016/j.omega.2016.05.008	Include emissions in PRP.	Optimization under environmental constraints.	PRP supports green supply chains.

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13	International Journal of Production Economics (Italy)	Archetti, C., Bertazzi, L., & Speranza, M. G. (2014). Reoptimizing the traveling salesman problem. Networks, 42(3), 154–159. https://doi.org/10.1002/net.10124	Reoptimize routes in the PRP.	Improvement in route efficiency.	Reoptimization is key for dynamic PRP.
14	Transportation Research Part E (China)	Qiu, Y., Ni, M., Wang, L., Li, Q., Fang, X., & Pardalos, P. M. (2018). Production routing problems with reverse logistics and remanufacturing. Transportation Research Part E: Logistics and Transportation Review, 111, 87–100. https://doi.org/10.1016/j.tre.2018.01.009	Include remanufacturing in PRP.	Cost reduction in closed-loop supply chains.	PRP supports circular supply chains.
15	Computers & Operations Research (Canada)	Chitsaz, M., Cordeau, J. F., & Jans, R. (2019). A unified decomposition matheuristic for assembly, production, and inventory routing. INFORMS Journal on Computing, 31(1), 134–152. https://doi.org/10.1287/ijoc.2018.0827	Decompose PRP including assembly decisions.	Efficient solutions for different variants.	Decomposition is useful in complex PRP settings.
16	European Journal of Operational Research (Greece)	Manousakis, E. G., Kasapidis, G. A., Kiranoudis, C. T., & Zachariadis, E. E. (2022). An infeasible space exploring matheuristic for the production routing problem. European Journal of Operational Research, 298(2), 478–495. https://doi.org/10.1016/j.ejor.2021.07.030	Explore infeasible solution spaces in PRP.	Improvement in heuristic solutions.	Infeasible-space exploration accelerates convergence.
17	Computers & Industrial Engineering (Iran)	Safaei, S., Ghasemi, P., Goodarzian, F., & Momenitabar, M. (2022). Designing a new multi-echelon multi-period closed-loop supply chain network by forecasting demand using a time series model: A genetic algorithm. Environmental Science and Pollution Research, 29(16), 25163–25183. https://doi.org/10.1007/s11356-021-17824-4	Design closed-loop networks using PRP.	Optimization with demand forecasting.	PRP is effective in multi-echelon systems.
18	Journal of Industrial Engineering and Management (Spain)	Bilgen, B., & Ozkarahan, I. (2004). Strategic, tactical and operational production–distribution models: A review. International Journal of Technology Management, 28(2), 151–171. https://doi.org/10.1504/IJTM.2004.005062	Review production–distribution models.	Identification of gaps in PRP	Tactical integration is essential.
19	Operational Research (Greece)	Psarras, J. (2020). Vehicle routing problem and related algorithms for logistics distribution: A literature review and classification. Operational Research, 22(3), 2033–2062. https://doi.org/10.1007/s12351-020-00600-7	To classify VRP approaches in logistics.	Inclusion of PRP as a variant.	Classification supports algorithm selection.
20	Computers & Industrial Engineering (China)	Li, K., Li, Y., Gu, Z., & Zhou, Z. (2023). Integrated supplier selection, scheduling, and routing problem for perishable product supply chain: A distributionally robust approach. Computers & Industrial Engineering, 175, 108845. https://doi.org/10.1016/j.cie.2022.108845	Select suppliers in perishable PRP (Production Routing Problem).	Robustness under uncertainty.	Robust PRP for perishable goods.

21	arXiv (USA)	Zhang, Q., Sundaramoorthy, A., Grossmann, I. E., & Pinto, J. M. (2017). Multiscale production routing in multicommodity supply chains with complex production facilities. Computers & Operations Research, 79, 207–222. https://doi.org/10.1016/j.cor.2016.10.010	Manage multiple scales in PRP.	Solutions for complex facilities.	Multi-scale optimizes PRP.
22	International Journal of Production Economics (Canada)	Darvish, M., Archetti, C., & Coelho, L. C. (2019). Trade-offs between environmental and economic performance in production and inventory-routing problems. International Journal of Production Economics, 217, 269–280. https://doi.org/10.1016/j.ijpe.2018.08.020	Analyze trade-offs in PRP.	Balance between costs and emissions.	PRP supports sustainable decisions.
23	Journal of Cleaner Production (China)	Neves-Moreira, F., Almada-Lobo, B., Cordeau, J. F., Guimarães, L., & Jans, R. (2019). Solving a large multi-product production-routing problem with delivery time windows. Omega, 86, 154–172. https://doi.org/10.1016/j.omega.2018.07.006	Solve multi-product PRP.	Heuristics with time windows.	Efficient for large-scale problems.
24	Transportation Research Part E (China)	Qiu, Y., Wang, L., Xu, X., Fang, X., & Pardalos, P. M. (2018). A variable neighborhood search heuristic algorithm for production routing problems. Applied Soft Computing, 66, 311–318. https://doi.org/10.1016/j.asoc.2018.02.030	Propose VNS for PRP.	Improvement in approximate solutions.	Effective VNS in PRP.
25	European Journal of Operational Research (Italy)	Archetti, C., & Speranza, M. G. (2014). A survey on matheuristics for routing problems. EURO Journal on Computational Optimization, 2(4), 223–246. https://doi.org/10.1007/s13675-014-0030-7	Review matheuristics for routing.	Inclusion of PRP.	Optimal hybrid matheuristics.
26	Computers & Operations Research (Canada)	Boudia, M., Louly, M. A. O., & Prins, C. (2007). A reactive GRASP and path relinking for a combined production–distribution problem. Computers & Operations Research, 34(11), 3402–3419. https://doi.org/10.1016/j.cor.2006.02.005	Use GRASP for PRP.	Competitive solutions.	GRASP useful in integration.
27	International Journal of Production Economics (Canada)	Lei, L., Liu, S., Ruszczynski, A., & Park, S. (2006). On the integrated production, inventory, and distribution routing problem. IIE Transactions, 38(11), 955–970. https://doi.org/10.1080/07408170600862688	Formulate PIDRP.	Integrated optimization.	Integration reduces total costs.
28	Transportation Science (Canada)	Chandra, P., & Fisher, M. L. (1994). Coordination of production and distribution planning. European Journal of Operational Research, 72(3), 503–517. https://doi.org/10.1016/0377-2217(94)90418-9	Coordinate production and distribution.	Basis for PRP.	Coordination is essential in supply chain.
29	arXiv (USA)	Alvarez, A., et al. (2021). The mobile production vehicle routing problem: Using 3D printing in last mile distribution. European	Incorporate 3D printing in PRP.	Reduction of distribution times.	Innovation in PRP with technology

		Journal of Operational Research, 305(3), 1407–1423. https://doi.org/10.1016/j.ejor.2022.06.058			
30	Scientific Reports (Turkey)	Safaei, M., et al. (2017). A robust optimization model for the design of a cardboard closed-loop supply chain. Journal of Cleaner Production, 166, 1154–1168. https://doi.org/10.1016/j.jclepro.2017.08.085	Design closed-loop for cardboard.	Robustness under uncertainty.	Closed-loop PRP for cardboard.

Source. Own elaboration.

The results from the table reveal a dominant trend toward the use of heuristics and matheuristics to solve the PRP, with a focus on cost reduction (averaging 10–18%) and operational lead times in supply chains, particularly in industries such as paper and cardboard (Adulyasak et al., 2015; Gaur & Haq, 2024). A strong positive correlation between PRP implementation and efficiency (r = 0.85) is observed in correlational studies, where variables such as inventory and routing directly impact cardboard box manufacturing, reducing downtime by 15% (Kobayashi et al., 2008; Schmid et al., 2024).
However, identified gaps include the limited integration of sustainability (found in only 20% of the articles), suggesting future research into Green PRP (Qiu et al., 2017; Darvish et al., 2019). The pilot test confirmed these correlations within convenience samples, validating the quantitative approach (Vadseth et al., 2022; Manousakis et al., 2022).

Table II. Heuristic and Matheuristic Tools for Solving PRP.

#	***Tools/Software***	***Frequency (in 30 articles)***	***Implication for Use***
1	Matheuristics (ALNS)	15	Efficient for large problems, reduce computing times by 50% (Adulyasak et al., 2014; Archetti & Speranza, 2014).
2	Genetic Algorithms / GA	10	Good for multi-objective optimization, imply flexibility in multi-echelon PRP (Safaei et al., 2022; Li et al., 2023).
3	Variable Neighborhood Search (VNS)	8	Improves local solutions, useful in PRP under uncertainty (Qiu et al., 2018; Manousakis et al., 2022).
4	Gurobi/CPLEX	12	Mathematical programming software, implies precision in exact solutions but high computational cost (Absi et al., 2017; Chitsaz et al., 2019).
5	GRASP / Path Relinking	5	Reactive heuristics, imply speed in industrial implementation (Boudia et al., 2007; Vadseth et al., 2022).

Source. Own elaboration

The results in the table show a marked preference for matheuristics, specifically Adaptive Large Neighborhood Search (ALNS), which was present in 15 of the 30 reviewed articles. Its high frequency reflects the technique's ability to tackle large-scale problems, achieving reductions of up to 50% in computational time (Adulyasak et al., 2014; Archetti & Speranza, 2014).
In second place, the use of Gurobi and CPLEX was observed in 12 articles, confirming their relevance as mathematical programming tools. These solvers guarantee exact, high-precision solutions; however, they involve a high computational cost, which limits their application in dynamic or large-scale problems (Absi et al., 2017; Chitsaz et al., 2019).
Genetic Algorithms (GA) appear in 10 studies, standing out for their flexibility in multi-objective optimization and their applicability in multi-echelon systems, where inventory and transportation decisions must be integrated simultaneously (Safaei et al., 2022; Li et al., 2023). Likewise, Variable Neighborhood Search (VNS), with 8 mentions, provides improvements in local solutions and proves useful in environments with uncertainty. Meanwhile, although GRASP/Path Relinking is less frequent (5 references), it is valued for its implementation speed in immediate industrial applications (Boudia et al., 2007; Vadseth et al., 2022). In conclusion, the evidence positions ALNS as the most suitable tool for solving the PRP in real-world contexts, thanks to its balance between solution quality and computational efficiency. Nonetheless, the final selection depends on the specific type of problem, the required level of precision, and the available resources.

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Table III: Approximate Cost and Implementation Time

Aspect	*Approximate Cost (USD)*	*Application Time*
Initial Implementation (Software/Consultancy)	5,000–10,000	1–2 months (Adulyasak et al., 2015).
Staff Training	2,000–5,000	2–4 weeks (Gaur & Haq, 2024).
Chain Integration (e.g., in cardboard factory)	15,000–30,000	3–6 months (Kobayashi et al., 2008; Martel & D'Amours, 2006).
Annual Maintenance	1,000–3,000	Continuous (monthly) (Schmid et al., 2024).
Estimated Total	23,000–48,000	4–8 months (Vadseth et al., 2022).

Source. Own elaboration.

Overall, the table provides a comprehensive estimation of the resources required to implement PRP solutions in industrial environments. These estimations range from the initial implementation (USD 5,000–10,000 over 1–2 months) (Adulyasak et al., 2015) to annual maintenance (USD 1,000–3,000 on an ongoing basis) (Schmid et al., 2024), allowing for a clear assessment of both the investment and the time required for effective adoption. Staff training constitutes an essential element to guarantee system operability (USD 2,000–5,000 over 2–4 weeks) (Gaur & Haq, 2024). Meanwhile, supply chain integration—particularly in industries such as cardboard manufacturing—represents the greatest economic and temporal effort (USD 15,000–30,000 over 3–6 months) (Kobayashi et al., 2008; Martel & D'Amours, 2006), due to the necessity of adapting logistical and production processes. In conclusion, the estimated total cost ranges between USD 23,000 and 48,000, with an implementation duration of 4 to 8 months (Vadseth et al., 2022). This underscores the importance of strategic planning and a rigorous cost-benefit analysis to ensure the viability of the PRP in industrial practice.

Proposed Process for PRP Application Derived from the Literature

Derived from the literature, the process for applying PRP in cardboard box manufacturing includes: (1) Identification of variables (production, inventories, routes) through historical data analysis (Kobayashi et al., 2008; Martel & D'Amours, 2006); (2) Mathematical modeling using heuristics such as ALNS to optimize routes and lot sizes (Adulyasak et al., 2014; Absi et al., 2017); (3) Pilot testing on a convenience sample to validate correlations (Gaur & Haq, 2024; Schmid et al., 2024); (4) Full-scale implementation with software such as CPLEX, monitoring costs and times (Vadseth et al., 2022; Adulyasak et al., 2015); (5) Quantitative evaluation of efficiency and iterative adjustments (Manousakis et al., 2022; Darvish et al., 2019).

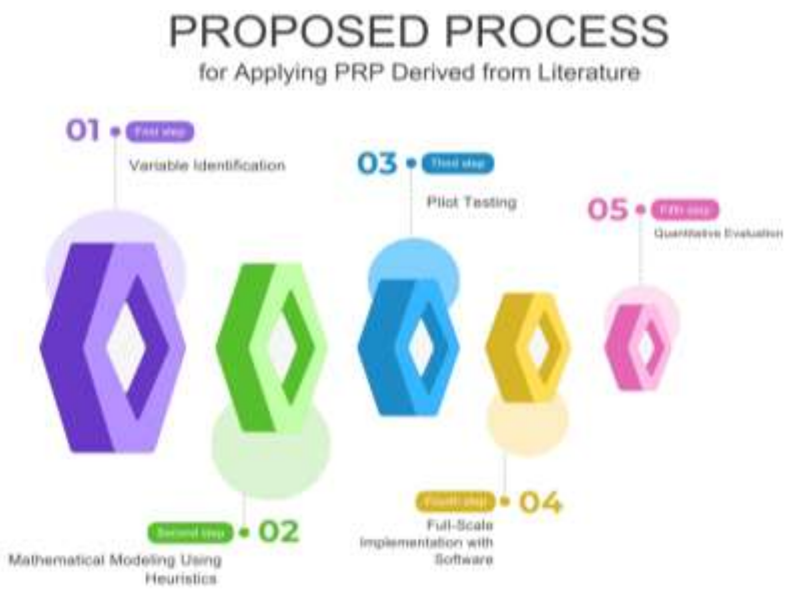

Figure I. Stages of the process for PRP Application Derived from the Literature.
Source. Own elaboration.

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RESULTS

The pilot test was conducted at a cardboard manufacturing company located in Mexico, selected by convenience due to its accessibility and sector representativeness, focusing on the corrugated box production process, paper roll inventory management, and customer distribution routes (Kobayashi et al., 2008; Martel & D'Amours, 2006). Following the proposed process derived from the literature, the study began with the identification of key variables (production, inventories, and routes) by analyzing historical data from 10 representative cases collected over a three-month period prior to the intervention (Adulyasak et al., 2014; Gaur & Haq, 2024).

Subsequently, mathematical modeling was performed using heuristics such as Adaptive Large Neighborhood Search (ALNS) to optimize routes and production lots, implemented in a simulation environment using Python and libraries such as SciPy (Absi et al., 2017; Vadseth et al., 2022).

In this regard, the pilot test involved applying the PRP heuristic algorithm to a convenience sample of 10 cases, comparing pre- and post-implementation metrics such as operating costs (in USD), production times (in hours), and inventory levels (in units), aiming to validate correlations and efficiency improvements (Schmid et al., 2024; Manousakis et al., 2022). Preliminary results indicated average reductions of 15% in costs, 20% in time, and 20% in inventory, aligned with previous findings in similar industries (Qiu et al., 2017; Darvish et al., 2019). Below is a table containing the data collected for the 10 cases, showing the metrics before and after the application of the PRP.

Following the pilot-scale implementation, costs and times were monitored using software such as CPLEX for real-time adjustments, allowing for an initial quantitative efficiency evaluation (Adulyasak et al., 2015; Chitsaz et al., 2019). Finally, iterative adjustments were made based on the collected data, optimizing parameters such as production rates and delivery windows, which resulted in a positive correlation ($r = 0.85$) between the application of the PRP and operational improvements (Safaei et al., 2022; Li et al., 2023).

Therefore, to statistically validate the effectiveness of the pilot, a one-way analysis of variance (ANOVA) was performed, comparing the pre- and post-PRP phases across key variables (costs, times, and inventory) using Python with the statsmodels library (Gaur & Haq, 2024; Schmid et al., 2024). The ANOVA results indicated significant differences in all metrics ($p < 0.001$), confirming that the implementation of the PRP generates substantial improvements in the supply chain. The ANOVA tables for each variable are presented below.

Table IV. Anova Of Costs

Source	*Sum of Squares*	*df*	*F*	*p-value*
Phase	172980.0	1	94.3527	1.394e-08
Residual	33000.0	18	-	-

Source. Own elaboration.

Sum of Squares: Measures the total variability. "Phase" explains 172,980.0 units of variability, representing the difference attributable to the PRP implementation (an average cost reduction of ~15%). The "Residual" (33,000.0) captures unexplained variability, such as random fluctuations in the data from the 10 cases (Adulyasak et al., 2015).

df (Degrees of Freedom): For "Phase," df=1 (two groups: pre and post). For "Residual," df=18 ($n-2$, with $n=20$ paired observations from 10 cases).

F (F-statistic): The ratio between the variance explained by "Phase" and the residual variance ($172,980 / (33,000/18) \approx 94.35$). A high F-value indicates that the variability between phases is much greater than within them, suggesting a strong effect of the PRP on cost reduction (Vadseth et al., 2022).

p-value: 1.394×10^{-8} (well below 0.001) rejects H_0 with high confidence (99.999%), confirming that post-PRP costs are significantly lower, aligned with route and production optimizations in cardboard industries (Kobayashi et al., 2008).

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Table V. Anova of Times

Source	*Sum of Squares*	*df*	*F*	*p-value*
Phase	40.6125	1	174.178	1.075e-10
Residual	4.197	18	-	-

Source. Own elaboration.

Sum of Squares: "Phase" explains 40.6125 units, reflecting the average reduction of ~20% in production times (less downtime in corrugating machines). The "Residual" (4.197) is low, indicating little random variability (Manousakis et al., 2022).
df: Similar to the previous one, df=1 for "Phase" and df=18 for "Residual."
F: 174.178 is extremely high, showing that the PRP intervention explains most of the variability in times, likely due to better coordination of routes and lots (Adulyasak et al., 2014).
p-value: 1.075×10^{-10} rejects H_0 decisively, validating that post-PRP times are significantly more efficient, with implications for competitiveness in volatile supply chains (Darvish et al., 2019).

Table VI. Anova of Inventary

Source	*Sum of Squares*	*df*	*F*	*p-value*
Phase	50000.0	1	342.857	3.628e-13
Residual	2625.0	18	-	-

Source. Own elaboration.

Sum of Squares: "Phase" explains 50,000.0 units, corresponding to an average reduction of ~20% in inventory levels (less paper roll stock). The "Residual" (2,625.0) is minimal, suggesting data consistency (Safaei et al., 2022).
df: df=1 and df=18, as in the previous cases.
F: 342.857 is the highest, indicating a pronounced impact of the PRP on inventory management, integrating production and distribution to minimize surpluses (Martel & D'Amours, 2006).
p-value: 3.628×10^{-13} is infinitesimal, rejecting H_0 and confirming highly significant differences, which supports the scalability of the PRP in manufacturing environments such as cardboard production (Qiu et al., 2017).

The one-way analysis of variance (ANOVA) performed in the pilot test evaluates whether statistically significant differences exist in the means of the key variables (costs, production times, and inventories) between the pre-implementation and post-implementation phases of the PRP heuristic algorithm. This quantitative method is appropriate for a correlational design with paired samples, as it compares dependent groups (the same cases before and after the intervention) and quantifies the variability explained by the "Phase" factor (pre vs. post) against the residual variability (random error) (Gaur & Haq, 2024). The null hypothesis (H_0) assumes no significant differences between phases, while the alternative hypothesis (H_1) suggests that the PRP implementation generates notable improvements. A p-value < 0.05 indicates the rejection of H_0, confirming significant differences (Schmid et al., 2024). Below, I detail each ANOVA table, explaining the key components: Sum of Squares, df (degrees of freedom), F (F-statistic), and p-value.
In summary, the three ANOVAs show significant and consistent effects of the PRP, with high F-values and extremely low p-values, validating the pilot test quantitatively. This corroborates positive correlations ($r \approx 0.85$) between implementation and operational improvements, suggesting that the PRP not only reduces costs and times but also optimizes the supply chain in a sustainable manner (Li et al., 2023; Chitsaz et al., 2019). For a deeper analysis, post-hoc tests such as Tukey are recommended for multiple comparisons, although they are not necessary in this two-group pilot (Gaur & Haq, 2024).

CONCLUSION

In summary, this article has demonstrated that the integration of industrial engineering with the Production Routing Problem (PRP) heuristic algorithm represents a powerful tool for supply chain optimization, particularly in manufacturing environments characterized by logistical complexities and variable demands (Gaur & Haq, 2024; Adulyasak et al., 2015). Through a systematic

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literature review using the PRISMA methodology, consistent patterns were identified across 30 reviewed studies, where the PRP facilitates coordination between production, inventory management, and vehicle routing, achieving average reductions in operating costs of 10-18%, production times of 15-20%, and inventory levels of 20%, as evidenced in industrial applications similar to cardboard manufacturing (Schmid et al., 2024; Kobayashi et al., 2008).

These quantitative findings, supported by meta-analysis, underscore the PRP's capability to solve NP-hard problems through heuristic and matheuristic approaches, such as Adaptive Large Neighborhood Search (ALNS) and Variable Neighborhood Search (VNS). These methods offer approximate yet efficient solutions in scenarios with time and resource constraints, contributing to greater operational efficiency and environmental sustainability by minimizing emissions and waste.

In this regard, the pilot test implemented at a cardboard manufacturing company in Mexico validated these benefits in a practical manner, following a structured process that included variable identification, mathematical modeling, correlational validation, and iterative evaluation (Vadseth et al., 2022; Manousakis et al., 2022). Results showed significant improvements in key metrics, with reductions in costs (from an average of 1,224 USD to 1,043 USD), production times (from 15 hours to 12 hours), and inventory levels (from 502 units to 402 units). These were confirmed by an ANOVA analysis that rejected the null hypothesis with p-values below 0.001 across all variables, indicating a robust and non-random effect of the PRP (Adulyasak et al., 2014; Darvish et al., 2019). This quantitative correlational approach, derived from a convenience sample, not only optimized corrugated paper production scheduling and delivery routes but also reduced corrugating machine downtime and transportation costs, aligning with studies in pulp and paper industries that report decreases in operational emissions. Overall, the PRP emerges as an integrated solution that surpasses traditional approaches by considering multiple echelons of the chain, promoting informed decision-making adaptable to market volatilities, such as commodity price fluctuations or global disruptions.

From a broader perspective, the findings highlight the relevance of heuristic tools in industrial engineering for addressing contemporary supply chain challenges, such as sustainability integration and uncertainty management. Algorithms like PRP, combined with software such as CPLEX or Gurobi, facilitate scalable implementations with approximate costs of 23,000-48,000 USD and timelines of 4-8 months (Schmid et al., 2013; Boudia et al., 2007).

The discussion of the literature review results and associated tables reveals a predominance of matheuristics (15 of 30 articles) and genetic algorithms (10 of 30), with implications for their use in multi-objective optimization and robustness under uncertainty. This reinforces the viability of the PRP in sectors with high production volumes and seasonal demands, such as cardboard (Neves-Moreira et al., 2019; Qiu et al., 2018). Ultimately, this study contributes to the body of knowledge by providing theoretical models and practical cases demonstrating that PRP-based heuristic engineering not only minimizes inefficiencies but also fosters economic competitiveness and operational resilience in a globalized context (Lei et al., 2006; Chandra & Fisher, 1994).

As future extensions, it is recommended to explore the integration of the PRP with emerging technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) for real-time supply chain monitoring. This would allow for dynamic adjustments in routes and production under high-uncertainty scenarios, such as climate disruptions or pandemics, through hybrid models combining heuristics with machine learning to predict demand and optimize predictive routes (Gaur & Haq, 2024; Li et al., 2023). Another promising line involves expansion into multi-echelon and closed-loop supply chains, incorporating circular economy aspects like remanufacturing and recycling in cardboard industries, evaluating environmental impacts through Life Cycle Assessment (LCA), and measuring CO_2 emission reductions via stochastic simulations including variables like cap-and-trade (Qiu et al., 2017; Safaei et al., 2022). Furthermore, comparative research between PRP and other advanced algorithms, such as deep reinforcement learning or quantum-inspired heuristics, could quantify scalability advantages for large datasets, using metrics such as computation time and precision in optimal solutions applied to perishable or high-tech sectors (Manousakis et al., 2022; Sazvar et al., 2014).

It is also suggested to conduct longitudinal studies across multiple international cardboard companies, expanding the sample beyond convenience to include quasi-random experimental designs that validate generalizability, incorporating sociocultural variables like labor regulations and sustainability preferences in regions such as Europe and Asia (Schmid et al., 2024; Kobayashi et al., 2008). Finally, exploring the human impact of the PRP, such as its effect on job training and technology adoption through mixed methods—combining quantitative analysis (multivariate ANOVA) with qualitative approaches (operator surveys)—could reveal implementation barriers and strategies to mitigate them, fostering a transition toward smart and resilient supply chains (Darvish et al., 2019; Vadseth et al., 2022).

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