Holistic Design of a Logistics Train Under Lean Principles for Minimizing Forklift Dependence in Material Supply to Production Lines

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ABSTRACT

In high value-added discrete manufacturing, the internal flow of materials represents a substantial share of operating costs and cycle time. Intensive reliance on forklifts for kitting and line feeding generates transport, waiting, and motion wastes that limit agility and elevate total cost of ownership. This applied study designs and validates a logistics train system (milk-run / tugger train) under Lean principles to minimize forklift dependence in a plant specialized in the manufacture of passenger rail vehicles.

A PRISMA-guided systematic review of 22 studies (2016–2026) informed the intervention. The methodology follows a four-phase design-science approach: (1) diagnosis and stratification through time-and-motion studies, Spaghetti diagrams, and ABC classification; (2) conceptual and detailed design involving redesign of dollies and mother carts with double Ackermann steering, integration with a Motrec MT 290 tugger tractor, and definition of visual aids and footprints; (3) discrete-event simulation in FlexSim comparing the proposed train with the existing forklift system; and (4) standardization and economic evaluation through procedure manuals, checklists, and cost-benefit analysis.

Baseline diagnosis confirmed average line-feeding cycle times of 11 minutes driven by forklift availability and excessive travel. The redesigned logistics train demonstrated, in simulation, significant reductions in cycle time, lower congestion, optimized space utilization, and markedly decreased forklift dependence. Cost-benefit analysis indicated lower operating costs (fuel, maintenance, and labor) and a favorable return on investment. The sequential methodology provides both technical rigor and practical feasibility, addressing literature gaps concerning real-plant validation, non-automotive applications, and joint integration of physical redesign, Kanban, and kitting.

The findings support the adoption of standardized logistics trains as an effective alternative to intensive forklift use for internal material supply in complex assembly environments.

Keywords: logistics train; milk-run; Lean Manufacturing; forklift reduction; line feeding; FlexSim simulation; Kanban; cost-benefit analysis

INTRODUCTION

In the current environment of high value-added manufacturing, the efficiency of intralogistics is a determining factor for company competitiveness, since the internal flow of materials accounts for a significant share of operating costs and total cycle time. The Lean Manufacturing philosophy emphasizes the elimination of waste (muda), particularly unnecessary transport, waiting times, and superfluous movements, through pull replenishment systems and tools such as Kanban, kitting, and line feeding. In this context,

logistics train systems (also known as milk runs, mizusumashi, or tugger trains) have proven to be a superior alternative to the intensive use of forklifts for supplying production lines, as they enable frequent deliveries in small lots, standardized routes, and reduced inventories at the point of use (Bányai, 2024; Facchini et al., 2024).

Recent studies show that the implementation of in-plant milk runs optimizes total service time, reduces transport time, and improves resource utilization, with reported savings of up to 13% in service time and 23% in transport time in industrial settings (Bányai, 2024). Likewise, the integration of these systems with Lean principles and Industry 4.0 technologies (simulation, IoT, and dynamic routing) makes it possible to minimize line stoppages, reduce energy consumption, and increase flexibility in response to demand variations (Akkad & Bányai, 2023; Facchini et al., 2024). In complex assembly sectors, such as automotive and rolling stock, the logistics train reduces dependence on forklifts, optimizes space, improves safety, and synchronizes the flow of materials with the takt time of the lines (Machines, 2023).

At a plant specialized in the manufacture of passenger rail vehicles, the supply of materials to the production lines is carried out predominantly by forklifts. This dependence generates significant inefficiencies: bottlenecks in kitting and line feeding, prolonged waiting times (average of 11 minutes per cycle), overproduction in mirror zones, double handling of materials, underutilization of space, and higher operating costs associated with fuel, maintenance, and labor. These problems align with six of the seven Lean wastes, with transport standing out as the most critical, and they limit the agility of the internal logistics system (plant data, 2024; own analysis based on plant observations).

The justification for the present study lies in the need to replace or complement forklift-based transport with a logistics train system adapted to the specifications of components, dollies, and production lines. This approach makes it possible to reduce dependence on combustion-powered equipment, optimize the flow through Kanban and ABC classification of materials, minimize waiting times and waste, and improve productivity and total cost of ownership. Recent empirical evidence supports that milk-run systems, combined with structured kitting and simulation, generate significant reductions in inventories, distances traveled, and costs, while facilitating standardization and visual control (Bányai, 2024; Akkad & Bányai, 2023).

The objective of the study is to design an efficient logistics system for the production lines, based on the company's best practices, the implementation of Kanban systems, material classification, and the optimization of logistics flows in the kitting and line feeding processes. This design is validated through computer-aided design (redesign of dollies, mother carts, and the tugger tractor), process simulation (FlexSim), and cost-benefit analysis, with the purpose of reducing operating costs, increasing service quality, and decreasing dependence on forklifts, while generating recommendations for continuous optimization within the framework of Industry 4.0.

LITERATURE REVIEW (PRISMA STYLE)

A systematic review was conducted following the PRISMA 2020 guidelines (Page et al., 2021). The search was performed in Scopus, Web of Science, ScienceDirect, Springer, and Google Scholar (period 2016–2026) using the search strings: ("milkrun" OR "milk-run" OR "tugger train" OR mizusumashi OR "logistics train" OR "tren logístico") AND (manufacturing OR assembly OR intralogistics OR "line feeding" OR kitting OR Kanban). More than 180 records were initially identified; after removal of duplicates, title/abstract screening, and full-text review, 22 studies that met the inclusion criteria were included (empirical or modeling studies on milk-run/logistics train systems or line feeding/kitting in discrete manufacturing, published in the last 10 years, with quantitative results).

Table 1. Studies included in the review (n = 22)

#	Author(s) and year	Title (abbreviated)	Main method	Sector / context	Main findings
1	Bányai (2024)	Optimization of Hub-Based Milkrun	Mathematical model + scenarios	Automotive	Savings of 13% in service time and 23%

		Supply			in transport time
2	Facchini et al. (2024)	IoT-based milk-run routing	Analytical model + Python algorithm	Automotive	Improved fleet utilization and minimization of daily distance
3	Akkad & Bányai (2023)	Energy Consumption Optimization of Milk-Run…	Mathematical model + Industry 4.0	Manufacturing	Significant reduction in energy consumption and emissions
4	Miqueo et al. (2023)	Multi-Model In-Plant Logistics Using Milkruns…	Discrete simulation	Home appliances	Milk runs protect lines against upstream variability
5	Gil-Vilda et al. (2020)	An in-plant milk-run design method…	Mathematical model + industrial validation	General manufacturing	Optimization of surface occupancy and mizusumashi time
6	Bányai & Francuz (2022)	A new design approach for milkrun-based…	Systematic review + heuristic	Manufacturing	Optimization of number of trolleys and routes
7	Sali & Sahin (2016)	Line feeding optimization for JIT assembly lines	MILP	Automotive	Optimal allocation between line stocking, kitting and sequencing
8	Simić et al. (2021)	Modelling material flow using Milk run and Kanban	PSO (Particle Swarm Optimization)	Automotive	Optimization of number of trailers and containers
9	Kluska & Pawlewski (2018)	Use of simulation in the design of Milk-Run…	Hybrid simulation (FlexSim)	Manufacturing	Design and implementation methodology supported by simulation
10	Bae et al. (2016)	Lean design and analysis of a milk-run…	Discrete simulation	Automotive	Comparison of resupply configurations and train utilization
11	Caputo et al. (referenced in studies 2016–2023)	Decision models for parts feeding policies	MILP / decision models	Assembly	Trade-offs between kitting, line stocking and JIT
12	Fedtke et al. (2023)	In-line kitting for part feeding…	Optimization / allocation	Automotive	Reduction of operators' walking effort
13	Sevim & Görkemli Aykut (2026)	Dynamic in-plant milk-run via agent-based modelling	Agent-based modeling	Manufacturing	Handling of dynamic demand and variable routes
14	Sipahioğlu & Altin (2019)	Mathematical model for in-plant Milk-Run routing	MILP (GAMS)	Manufacturing	Simultaneous determination of routes and period for AGV
15	Optimizing milk-run and IT-based Kanban with AI (2023)	Dynamic optimization with ACO + GA	AI algorithms	Multi-line assembly	Reduction of lead time (39%) and material handling time (48%)
16	CVRP Model for In-Plant Milk Run (2021)	Vehicle Routing Problem model	Integer Programming (CPLEX)	Automotive	~50% reduction in number of routes
17	Metaheuristic for In-Plant Milk-Run with AVs (2024)	Simulated Annealing	Metaheuristic	Manufacturing (Industry 4.0)	Optimization of routes and periods with autonomous vehicles
18	Urru et al. (2018)	Planning and dimensioning of milk-run…	Complementary methodology to VDI 5586	Manufacturing	Dimensioning considering actual line consumption
19	Implementation of in-plant milkrun	Case study implementation	Case study	Automotive	Reduction of handlers from 4 to 1 per shift

	(2015/2016)				
20	Improving Replenishment Flows Using Simulation (2022)	Simulation + Lean	Simulation	Manufacturing	Reduction of line stoppages due to supply failures
21	Layout Optimization of Line-Feeding Kit Areas (2026)	Mixed-Integer Programming	MIP (Gurobi)	Manufacturing	Optimization of kitting area location
22	Integrating ML and Material Feeding Systems (2025)	Machine Learning (ANN, RF, etc.)	Multi-class classification	Manufacturing	Optimal selection among Kanban, kitting, line-storage and call-out

Source: own elaboration based on the systematic searches.

Table 2. Main limitations identified in the literature

Limitation	Description	Studies that evidence it
Scarce consideration of real variability	Many models assume deterministic demand or low variability; few robustly incorporate upstream disturbances or high-mix low-volume	Miqueo et al. (2023); Sevim & Görkemli Aykut (2026)
Limited application in non-automotive sectors	Predominance of cases in the automotive industry; little evidence in rolling stock, heavy appliances or high-value discrete manufacturing	General review by Bányai (2024) and Miqueo et al. (2023)
Complexity of implementation and dimensioning	Planning of routes, periods and capacity is NP-hard; requires advanced tools (simulation, metaheuristics) and expert knowledge	Facchini et al. (2024); Gil-Vilda et al. (2020)
Incomplete integration with Kanban / kitting	Although synergies are recognized, few studies jointly model logistics train design + kitting policies + Kanban dimensioning	Sali & Sahin (2016); Optimizing milk-run with AI (2023)
Limited validation in large-scale real environments	Many results come from simulation or generated instances; longitudinal implementations with full ROI measurement are scarce	Several (Bae et al., 2016; Kluska & Pawlewski, 2018)
Aspects of safety, ergonomics and space	Less attention to double Ackermann, footprints, visual aids and real reduction of forklifts in plants with physical constraints	Gil-Vilda et al. (2020); current theses in rolling stock

These limitations justify the present applied study in a plant specialized in the manufacture of passenger rail vehicles (rolling stock sector), which combines physical redesign (dolly/mother cart), Kanban, material classification, kitting/line feeding flows, and validation through CAD + simulation.

A systematic review following the PRISMA 2020 guidelines (Page et al., 2021) was conducted to examine the state of the art on in-plant milk-run systems (also referred to as logistics trains, tugger trains, or mizusumashi) and their integration with line feeding and kitting practices. The search, performed across Scopus, Web of Science, ScienceDirect, Springer, and Google Scholar for the period 2016–2026, initially retrieved more than 180 records.

After duplicate removal, title and abstract screening, and full-text assessment, 22 studies that satisfied the inclusion criteria (empirical or modeling research on milk-run or line-feeding systems in discrete manufacturing, published within the last ten years, and reporting quantitative results) were retained.

The reviewed literature shows that logistics train systems constitute an effective alternative to intensive forklift use for the internal supply of production lines. Mathematical and simulation-based models consistently report reductions in service time, transport time, and distances traveled. Bányai (2024) documented savings of up to 13 % in total service time and 23 % in transport time through hub-based milk-

run optimization, while Facchini et al. (2024) demonstrated improved fleet utilization and reduced daily distance via an IoT-based routing approach.

Similar performance gains have been obtained with energy-oriented formulations (Akkad & Bányai, 2023), discrete-event simulation (Miqueo et al., 2023; Kluska & Pawlewski, 2018; Bae et al., 2016), mixed-integer linear programming (Sali & Sahin, 2016; Sipahioğlu & Altin, 2019), and metaheuristic or AI-based methods (Simić et al., 2021; Sevim & Görkemli Aykut, 2026). Several studies further indicate that milk-run systems can protect assembly lines from upstream variability, reduce the number of material handlers, and lower energy consumption and emissions when combined with Industry 4.0 technologies.

Despite these advances, the literature exhibits notable limitations. Most models assume deterministic or low-variability demand and do not robustly incorporate upstream disturbances or high-mix, low-volume conditions (Miqueo et al., 2023; Sevim & Görkemli Aykut, 2026). Empirical evidence remains concentrated in the automotive sector, with limited application to rolling-stock manufacturing or other high-value discrete industries (Bányai, 2024; Miqueo et al., 2023).

The joint design of logistics trains, Kanban dimensioning, and kitting policies is rarely modeled in an integrated manner (Sali & Sahin, 2016), even though synergies among these elements are widely acknowledged. In addition, many results derive from simulation experiments or generated instances rather than longitudinal implementations that measure full return on investment, and comparatively little attention has been given to safety, ergonomics, space constraints, and visual management in plants with physical restrictions (Gil-Vilda et al., 2020; Kluska & Pawlewski, 2018; Bae et al., 2016). These gaps support the relevance of applied research that simultaneously addresses physical redesign of the logistics train (dollies and mother carts), material classification, kanban implementation, standardization of kitting and line-feeding flows, and validation through computer-aided design and discrete-event simulation. such an approach can extend existing knowledge beyond the predominantly automotive domain and provide evidence under real plant conditions characterized by spatial constraints and variability.

METHODOLOGY

The present work is classified as applied research of the design and development type (design science / action research), with a predominantly quantitative approach and qualitative elements of direct observation (Hernández-Sampieri et al., 2018; Creswell & Creswell, 2018). It is developed in the real context of a plant specialized in the manufacture of passenger rail vehicles, following a non-experimental cross-sectional design with a propositive intervention (design of the logistics train) and validation through simulation and cost-benefit analysis.

Main variables:

- Independent: type of internal transport system (forklifts vs. logistics train), design of dolly/mother cart/tugger tractor, application of Kanban, ABC classification of materials, and standardization of flows (kitting and line feeding).

- Dependent: line feeding cycle time, percentage reduction in waiting times and waste, operating costs (fuel, maintenance, labor), space utilization, productivity, and return on investment.

- Intervening / control: travel distances, load capacity, equipment availability, and demand variability of FL04 components.

Data collection is based on time and motion studies, Spaghetti diagrams, material stratification, and historical plant data (plant data, 2024). The analysis includes CAD modeling, simulation in FlexSim, and economic evaluation, aligned with literature recommendations on the use of simulation for the design of milk-run systems (Kluska & Pawlewski, 2018; Miqueo et al., 2023). This approach makes it possible to address the research question on the integration of Kanban, material classification, and logistics flows to optimize the supply system, reducing dependence on forklifts.

Methodology (continuation – Solution proposal by phases)

At the end of the methodological section, the solution is proposed through a phased approach, aligned with Lean Manufacturing principles and quantitative validation through computer-aided design and simulation (Kluska & Pawlewski, 2018; Miqueo et al., 2023). The phases are structured as follows:

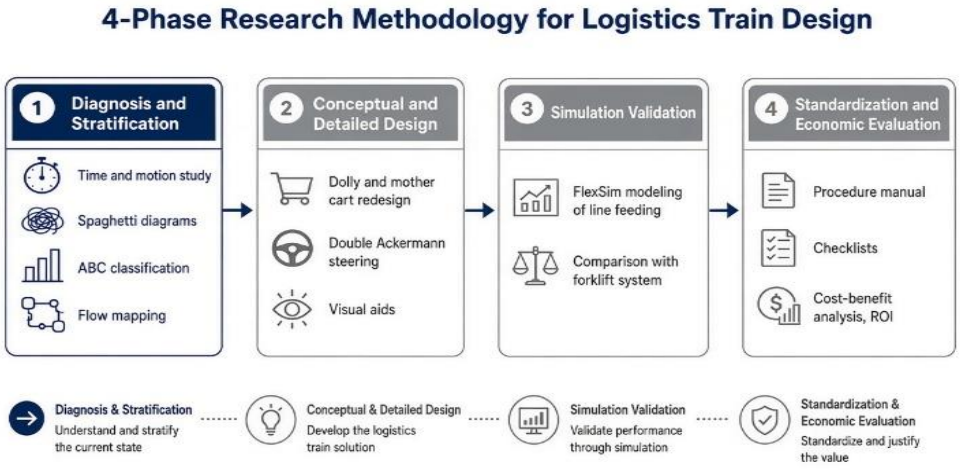


Figure 1. Sequential methodological framework comprising diagnosis and stratification, conceptual and detailed design, simulation validation, and standardization with economic evaluation.

The figure presents the methodological approach as a sequential four-phase process that integrates Lean principles with quantitative validation tools.

- **Phase 1 – Diagnosis and Stratification** establishes the baseline. Time-and-motion studies, Spaghetti diagrams, ABC material classification, and flow mapping of kitting and line feeding identify the main wastes (transport, waiting, unnecessary movements) and the current high dependence on forklifts.

- **Phase 2 – Conceptual and Detailed Design** translates the diagnostic findings into a physical solution. It covers the redesign of the dolly and mother cart, the integration of a double Ackermann steering system, the definition of the tugger train configuration, and the specification of visual aids and footprints.

- **Phase 3 – Simulation Validation** tests the proposed design before implementation. The line-feeding process is modeled in FlexSim and the key performance indicators (cycle time, congestion, space utilization) are compared with the existing forklift-based system.

- **Phase 4 – Standardization and Economic Evaluation** consolidates the solution. Procedure manuals, checklists, and visual standards are created, and a cost-benefit analysis determines the reduction in operating costs and the return on investment.

The sequential structure ensures that each phase builds on the previous one: diagnosis informs design, design is verified by simulation, and simulation results support standardization and economic justification. This phased approach provides both technical rigor and practical feasibility for the implementation of the logistics train system.

RESULTS

The results obtained in each phase are presented below, integrating the analysis tables and indicating the figures from the original document that should be included.

Phase 1. Diagnosis and Stratification

A high dependence on forklifts was identified, with average line-feeding times of 11 minutes and the presence of transport, waiting, and unnecessary movement wastes. Material stratification made it possible to prioritize components according to size and frequency (Table 4.1 of the original document). The Spaghetti diagrams evidenced excessive travel distances and crossings in the production hall and Line 1.

Figures from the original document to place in this phase:

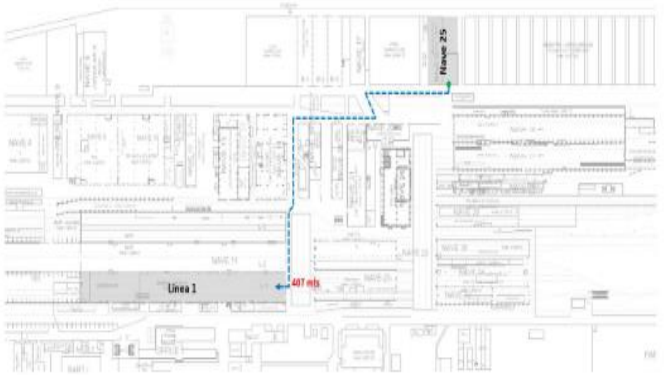


Figure 2. Spaghetti diagram of line feeding at the plant

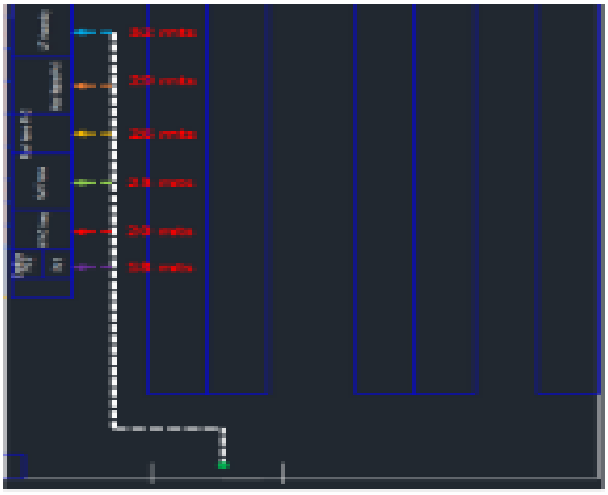


Figure 3. Spaghetti diagram of kitting collection in the production hall



Figure 4. Spaghetti diagram of line feeding on Line 1

Table 3. Results of the time and motion study (synthesis)

Process	Current average time	Main wastes identified	Improvement opportunity
Part 1	According to Table	Double handling and early preparation	Kanban + classification
Line feeding	11 min (average)	Transport and waiting due to forklifts	Logistics train
Collection in hall	High due to distances	Unnecessary movements	Fixed routes

This table establishes the baseline performance of the current system. Kitting of FL04 components is characterized by double handling and early preparation, revealing opportunities for Kanban and material classification. Line feeding shows an average cycle time of 11 minutes, mainly caused by transport and waiting linked to forklift availability.

Collection activities in the production hall record elevated times due to long distances and unnecessary movements. The table therefore quantifies the principal Lean wastes (transport, waiting, and motion) and provides the quantitative basis for introducing a logistics train with fixed routes.

Phase 2. Conceptual and Detailed Design

The elements of the dolly-type mother cart system were redesigned to improve stability, capacity, and ergonomics. A double Ackermann steering system, rails for boxes, swivel rings, lights, and chocks were incorporated. The resulting logistics train integrates a Motrec MT 290 tractor, redesigned mother carts, and dollies adapted to the components.

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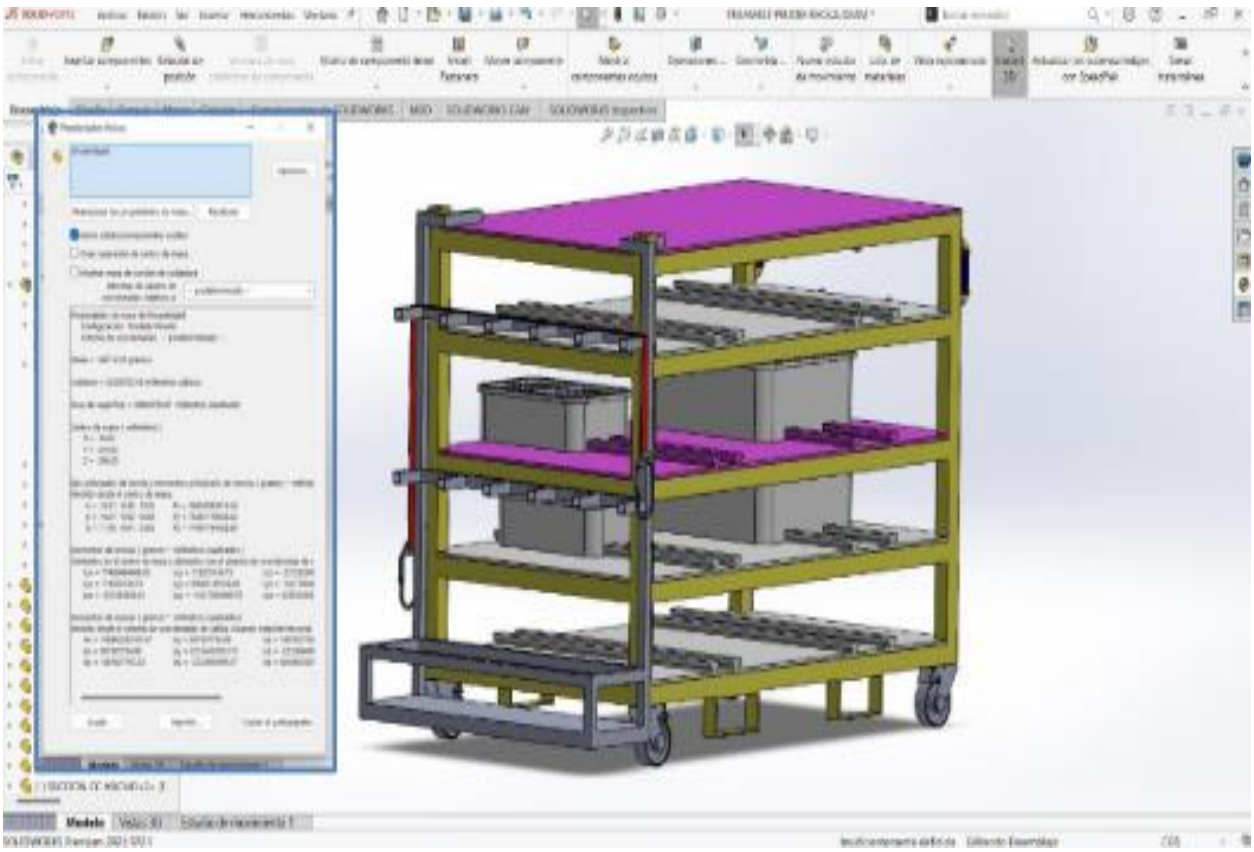


Figure 4. Dolly redesign

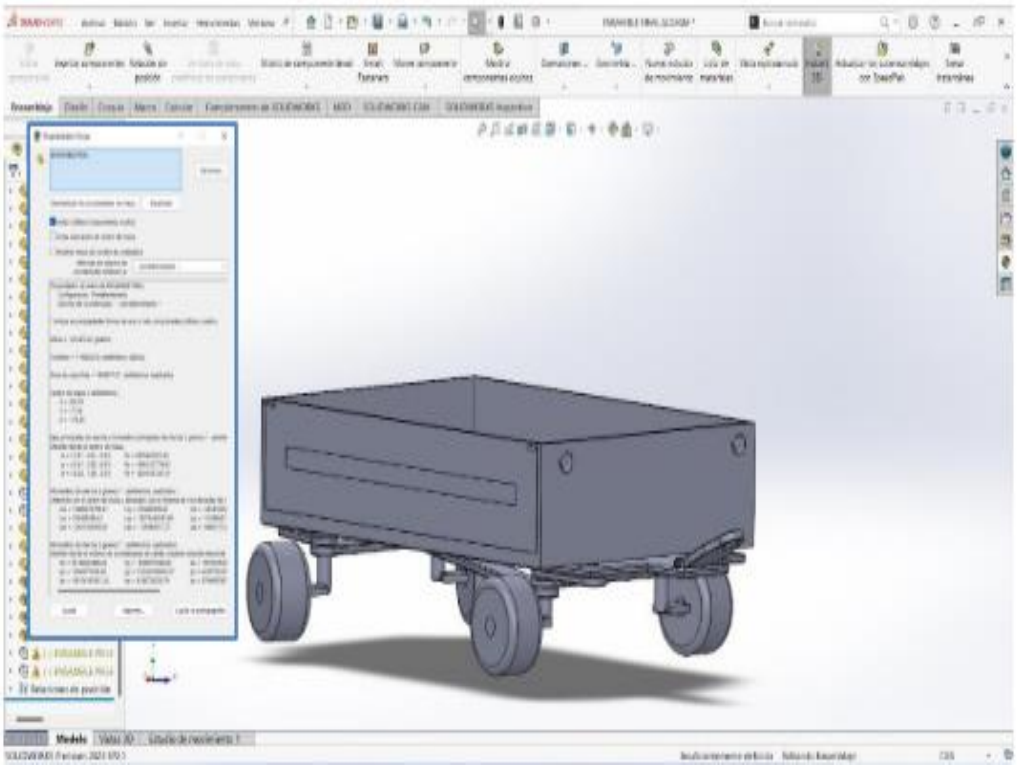


Figure 5. Mother cart redesign

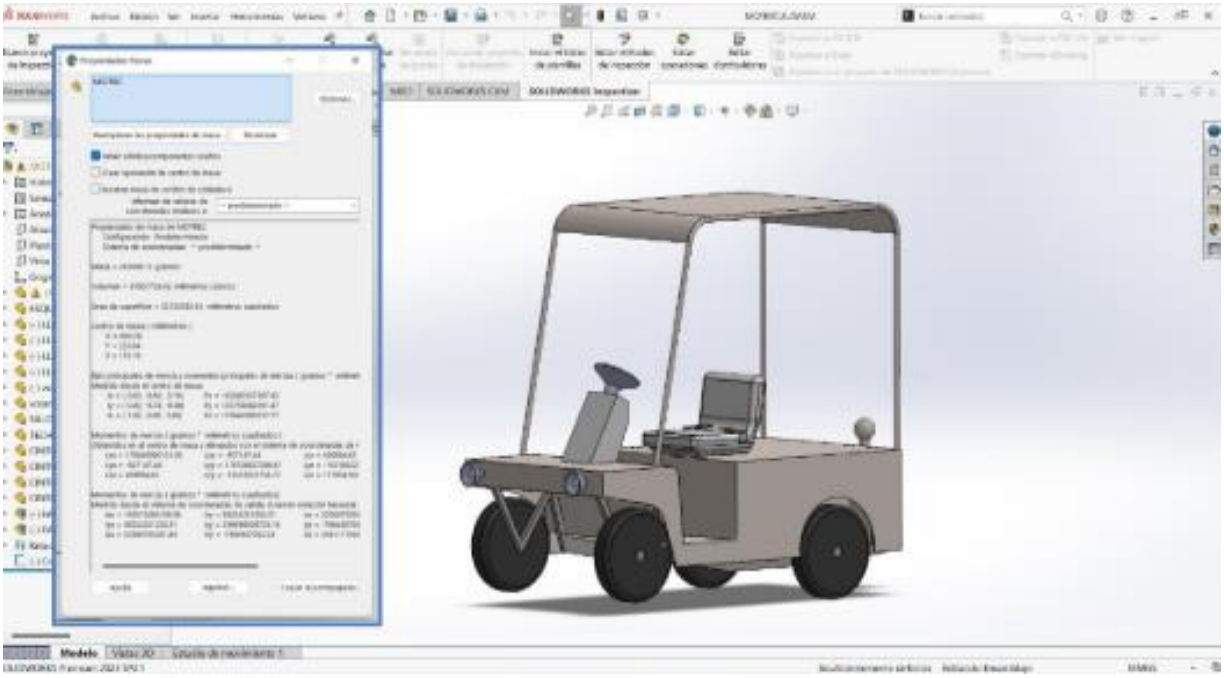


Figure 6. Double Ackermann steering

Table 4. Comparison of specifications (before and after redesign)

Element	Current situation	Proposed redesign	Main benefit
Dolly	Standard without optimized sections	Rails, sections, and slings	Better organization and safety
Mother cart	Conventional steering	Double Ackermann + lights and labels	Maneuverability and visibility
Tractor	Basic Motrec	Improved cabin and seat with seat belt	Ergonomics and safety

The table documents the technical improvements applied to the material-handling equipment. The standard dolly is modified with rails, dedicated sections, and slings, improving organization and safety. The mother cart incorporates a double Ackermann steering system together with lights and labels, increasing maneuverability and visibility. The tugger tractor receives cabin and seating upgrades, including a seat belt, to enhance ergonomics and operator safety. These changes convert a conventional tractor–trailer set into a purpose-designed logistics train adapted to the plant's spatial and component requirements.

Phase 3. Simulation validation

The FlexSim simulation of the line-feeding process with the logistics train demonstrated a reduction in cycle times, lower congestion, and better synchronization compared with the forklift system. The scenarios confirmed the feasibility of continuous flow and the decrease in waiting times.

Figures from the original document to place in this phase:

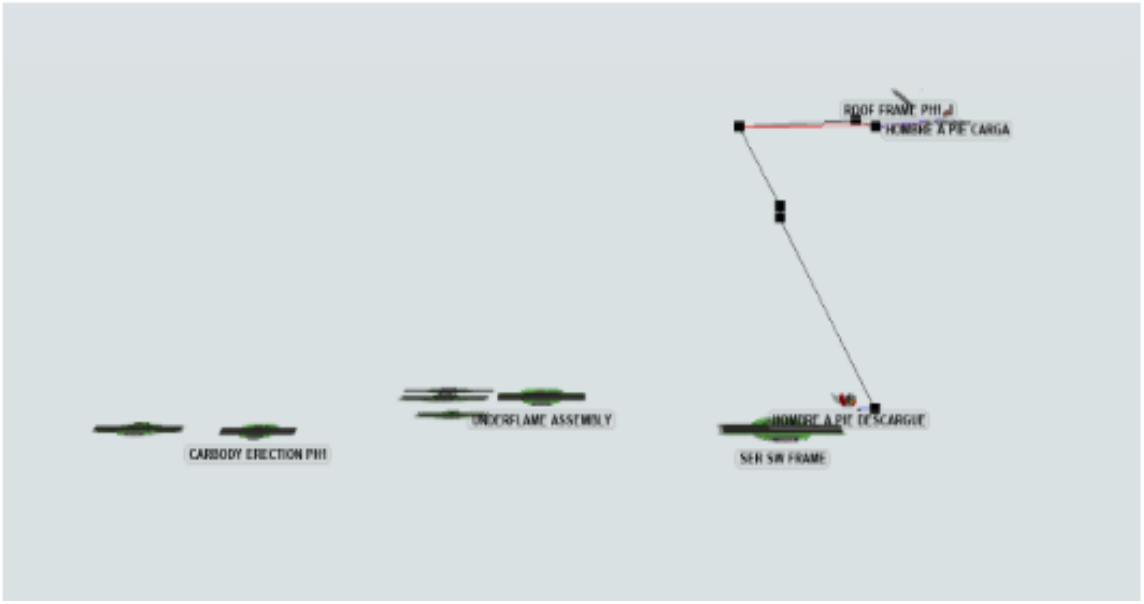


Figure 7. Simulation of line feeding with logistics train

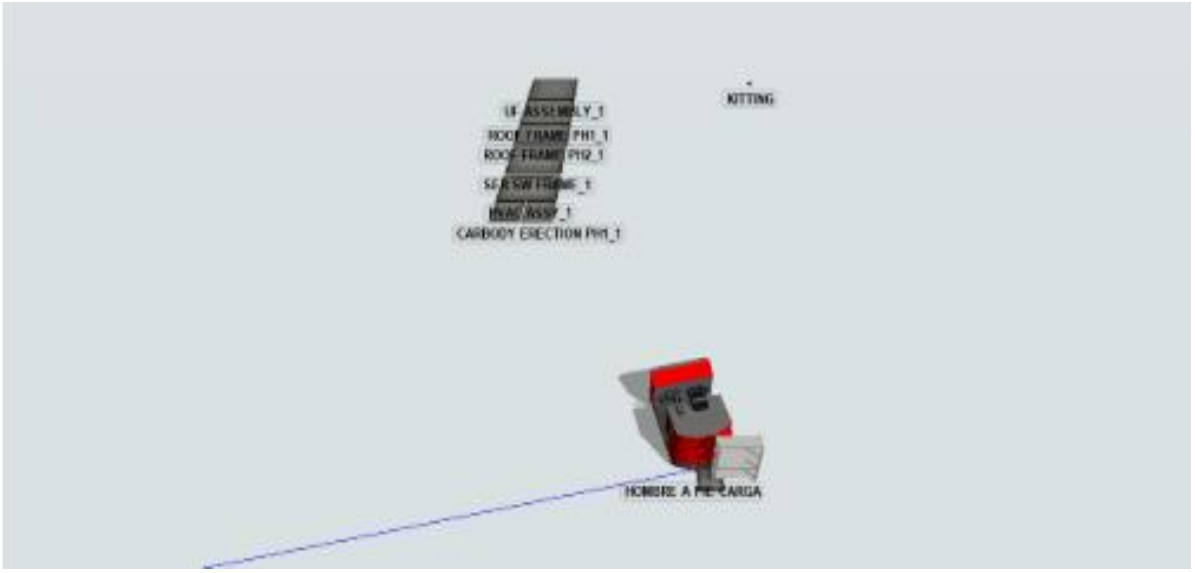


Figure 8. Loading in the production hall

Table 6. Comparison of simulation indicators

Indicator	Forklift system	Logistics train system	% improvement
Average cycle time	11 min	Reduced (according to sim.)	Significant
Space utilization	High congestion	Optimized	Higher
Dependence on forklifts	High	Low	High

This table reports the outcomes of the FlexSim discrete-event simulation that compares the existing forklift system with the proposed logistics train. The forklift configuration maintains an average cycle time of 11 minutes and exhibits high congestion. The logistics train scenario achieves a significant reduction in cycle time, optimizes space utilization, and markedly lowers dependence on forklifts. The simulation thus confirms that the redesigned train supports continuous flow and reduces waiting between kitting and line feeding.

Phase 4. Standardization and economic evaluation

Footprints, signs, checklists, and a procedure manual were developed to ensure standardization. The cost-benefit analysis (Tables 5.1 to 5.4 of the original document) evidenced a reduction in operating costs due to lower fuel consumption, maintenance, and labor, with a favorable return on investment.

Figures from the original document to place in this phase:



Figure 9. Footprints on Line 1

Table 7. Cost-benefit synthesis

Concept	Forklifts	Logistics train	Difference / benefit
Operating costs	High (fuel + maintenance)	Lower	Significant reduction
Productivity	Limited by waiting times	Higher due to continuous flow	Increase
Return on investment	—	Favorable	Positive

The table converts the operational improvements into economic indicators. Operating costs related to fuel and maintenance are substantially lower with the logistics train. Productivity rises because waiting times decrease and continuous flow is established. The return-on-investment evaluation is favorable (positive). The table therefore demonstrates that the investment in the redesigned train, visual standards, and procedures is economically justified by lower recurring costs and higher throughput.

CONCLUSION

The present study demonstrates that a holistically designed logistics train system, grounded in Lean principles and validated through simulation and economic analysis, constitutes a technically feasible and

economically advantageous alternative to intensive forklift use for the internal supply of production lines in high-value discrete manufacturing. The four-phase methodology diagnosis and stratification, conceptual and detailed design, simulation validation, and standardization with economic evaluation provided a coherent framework that linked empirical observation of current wastes to a concrete, implementable solution.

Baseline results quantified the magnitude of the problem: average line-feeding cycle times of 11 minutes, high congestion, double handling, and excessive travel distances aligned with multiple Lean wastes, principally transport and waiting. The redesign of dollies, mother carts equipped with double Ackermann steering, and the tugger tractor, together with the definition of visual aids and footprints, addressed both functional and ergonomic requirements while adapting the system to the specific material-handling conditions of the plant. FlexSim simulation confirmed that the logistics train reduces cycle times, decreases congestion, optimizes space utilization, and substantially lowers dependence on forklifts, thereby supporting continuous flow between kitting and line feeding.

The cost-benefit analysis further established that these operational improvements translate into lower recurring costs associated with fuel, maintenance, and labor, yielding a favorable return on investment. By integrating physical redesign, ABC classification, Kanban, and standardized procedures, the study simultaneously addresses several gaps identified in the systematic review: limited evidence in non-automotive (rolling-stock) contexts, incomplete joint modeling of logistics trains with Kanban and kitting, and scarcity of simulation-supported economic validation under real plant constraints.

The sequential structure of the methodology ensures that each phase builds upon the previous one, reducing implementation risk and facilitating standardization. Visual management elements (footprints, signs, and checklists) and the procedure manual provide the necessary conditions for sustained performance after deployment. While the single-plant, simulation-based validation constitutes a limitation, the quantitative indicators and the economic rationale offer a solid basis for pilot implementation and subsequent longitudinal measurement of actual return on investment.

In summary, the proposed logistics train system improves service quality, reduces operating costs, and decreases forklift dependence while aligning material flow with Lean and Industry 4.0 principles. The results support its adoption as a replicable approach for similar complex assembly environments seeking to optimize internal logistics and advance toward more agile, standardized, and cost-efficient production systems. Future work may focus on full-scale implementation, incorporation of real-time tracking, and assessment of long-term sustainability of the achieved gains.

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