Spektrum Industri
Vol. 24, No. 2, 2026, pp. 421–440
ISSN (print) 1693-6590 | ISSN (online) 2442-2630
https://journal3.uad.ac.id/index.php/spektrum/index

Optimizing LPG Distribution Resilience: A Fuzzy-Heuristic Approach and Monte Carlo Simulation for Single-Manifold Bottleneck Mitigation in Refinery Facilities

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ARTICLE INFO

Article history
Received May 8, 2026
Revised August 13, 2026
Accepted September 14, 2026

Keywords
LPG Distribution;
Monte Carlo simulation;
Heuristic priority rule;
Fuzzy logic;
Single-manifold bottleneck;

ABSTRACT

Operational bottlenecks in LPG refinery distribution can arise from single-manifold constraints, creating a critical trade-off between throughput maximization and product quality assurance. Existing scheduling approaches often address vessel evacuation and blending separately, leaving a gap in integrated decision models that simultaneously consider infrastructure constraints, production fluctuations, and quality specifications. This study aims to develops an integrated simheuristic decision-support framework combining a five-tier Lexicographic Heuristic Priority Rule, Fuzzy Logic membership functions, and a Zero-Sealing mechanism to prevent off-specification products from entering distribution. The framework enables refinery managers to determine achievable throughput through a single manifold while maintaining product quality. A discrete-event simulation with hourly time steps was developed over a 31-day operational horizon using historical vessel arrival, distribution, and production data from a refinery case. Model performance was evaluated through Monte Carlo simulation under four uncertainty dimensions: maritime arrival variability, batch-size variation, pipeline degradation, and upstream feed-quality fluctuations. Sensitivity analysis was conducted to identify critical operational thresholds. Across the tested scenarios, the framework recorded no overfill incidents or quality specification violations and achieved a mean domestic gas supply of approximately 1,355 MT/day, evacuating nearly all available upstream production. Pipeline rate degradation was identified as the most sensitive parameter, affecting both throughput evacuation and quality control when capacity declined below a critical level. The findings demonstrate that evacuation capacity and quality management are structurally interdependent in single-manifold systems. The proposed framework contributes provides a quantitative decision-support tool for reducing off-specification risks and informing refinery infrastructure investment decisions.

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1. Introduction

The stability of the energy supply chain, particularly Liquefied Petroleum Gas (LPG), relies heavily on the reliability of logistics infrastructure and refinery distribution facilities. The fundamental research problem addresses the severe operational bottlenecks inherent in single-line manifold infrastructures, which persistently trigger mutually exclusive scheduling conflicts, facility queues, time allocation inefficiencies, critical tank overfill risks, and massive financial penalties due to maritime demurrage (Fernando & Sigera, 2021; Nakpalad et al., 2025; Nicknezhad & Zegordi, 2024; Wang & Hao, 2025; Wibowo & Arvitrida, 2026; Yao et al., 2026). This singular physical constraint dictates that maritime supply intake and domestic downstream distribution cannot occur simultaneously. Such operational vulnerabilities are highly susceptible to disrupting the entire continuity of market demand fulfilment and forcing a critical halt to refinery profitability if not managed with precise and robust computational optimization (Mechal et al., 2024).

The state of the art in petrochemical supply chain management is currently shifting towards intelligent automation to solve the complexities of severely limited resource allocation. A comprehensive literature review indicates that pipeline network and logistics scheduling optimization has been extensively explored through various exact mathematical approaches, such as Mixed-Integer Linear Programming (MILP) and multi-objective optimization algorithms (Ardekani, 2022; Hua et al., 2023; Junior, 2022; Pervukhin et al., 2025; Sharma & Khare, 2024). These exact approaches typically resolve a scheduling problem into a single deterministic solution and are frequently hindered by excessively long computational times, often categorized as NP-Hard problems when applied to large-scale discrete-continuous hybrid models on the dynamic refinery operation floor (Bakon et al., 2022; Laisupannawong et al., 2021). Discrete-event simulation and metaheuristic methods have been proposed as more agile alternatives, offering shorter execution duration and reduced logistical risk without neglecting existing physical infrastructure constraints (Eldawody et al., 2025; Éles & Heckl, 2025; Mahmoudi et al., 2021). However, similar to their exact-method counterparts, these agile approaches have predominantly targeted a single deterministic schedule, separate from the product-quality dimension discussed next.

Furthermore, compliance with upstream product quality controls, specifically the maximum limit regulation for heavy hydrocarbon (C5+), demands strict quality blending scheduling interventions, which prior work has largely approached through dedicated blend-scheduling models (Ahmednooh & Menezes, 2024; Fang et al., 2025; Karimova & Özdağoğlu, 2025). Fuzzy logic integration has also been effectively adopted to model uncertain operational parameters in such distribution networks, but as a standalone modelling layer rather than one embedded within a combined evacuation-and-quality scheduling architecture (Khalili et al., 2021). Concurrently, supply chain risk evaluations must adapt to global demands regarding the integration of Environmental, Social, and Governance (ESG) sustainability practices (Agbaji et al., 2023; Hasan et al., 2024; Reda et al., 2023).

Taken together, the literature reviewed above reveals a research gap: throughput/evacuation scheduling (addressed through MILP, DES, or metaheuristics) and product-quality/blending scheduling (addressed through dedicated blend-scheduling or fuzzy-uncertainty models) have been developed as separate streams of research, each solved with its own dedicated model that produces a single deterministic schedule. None of the reviewed studies jointly enforces, within one decision framework, the mutually exclusive pipeline constraint of a single manifold, continuous upstream production fluctuations, and blending quality specifications at the same time. This separation leaves a gap for infrastructures where evacuation capacity and quality management physically compete for the same pipeline window, such that a scheduling decision favouring throughput can directly foreclose the time available for quality correction, and vice versa, an interdependency that a model solving either problem in isolation cannot capture. Table 1 makes this positioning explicit by systematically comparing the proposed framework with representative prior studies across the capabilities that jointly define the identified gap: joint treatment of evacuation throughput and product quality on one shared manifold, stochastic resilience validation, and structural rather than penalized off-spec prevention.

Table 1. Systematic comparison between the proposed framework and representative prior scheduling studies

Study	Core approach	Problem scope	Joint throughput–quality on one manifold	Stochastic resilience validation	Structural off-spec block
(Khalili et al., 2021)	Interactive fuzzy multi-objective programming	Multi-product oil pipeline scheduling	No	No (fuzzy parameters only)	No
(Laisupannawong et al., 2021)	MILP with heuristic decomposition	Short-term industrial process scheduling	No	No (deterministic)	No
(Junior, 2022)	Robust optimization (C&CG, GRASP)	Flow-shop and energy scheduling in oil and gas	No	Partial (budgeted uncertainty)	No
(Chen et al., 2023)	Lexicographic bi-objective optimization	Parallel-machine production scheduling	No	No (deterministic)	Quality loss as prioritized objective, not a block
(Ahmednooh & Menezes, 2024)	MILP/MINLP blend scheduling	Refinery blend-shop scheduling	No (blending only)	No (deterministic)	Penalized quality deviation
(Fang et al., 2025)	Preference-prediction evolutionary optimization	Gasoline blending scheduling	No (blending only)	Partial (preference uncertainty)	No
(Éles & Heckl, 2025)	Simulation with heuristic local optimization	Multiproduct pipeline networks	No (throughput only)	No	No
(Awan et al., 2025)	Monte Carlo disruption simulation	Downstream oil supply chain resilience	No	Yes (Monte Carlo)	No
This study	Fuzzy-heuristic lexicographic DSS with Monte Carlo discrete-event simulation	LPG single-manifold evacuation and blending	Yes (mutually exclusive manifold constraint)	Yes (four-dimension Monte Carlo stress test)	Yes (Zero-Sealing mechanism)

To bridge this gap, the proposed solution is the design of an automated Decision Support System (DSS) based on a multi-tiered lexicographic Heuristic Priority Rule algorithm, mathematically integrated with Fuzzy Logic, and rigorously tested using stochastic Monte Carlo discrete-event simulation (Ahmednooh & Menezes, 2024; Éles & Heckl, 2025; Hua et al., 2023; Khalili et al., 2021; Laisupannawong et al., 2021; Vermeire & Vanhoucke, 2025). While hierarchical prioritization via lexicographic optimization has itself been established in production scheduling contexts Chen et al., (2023), and Monte Carlo simulation is a recognized tool for quantifying disruption uncertainty in downstream oil supply chains Awan et al. (2025), prior studies have not integrated these methods within a single decision-support framework that enforces a structural off-spec blocking mechanism for LPG single-manifold distribution.

Building on this identified gap, the novelty of this research lies not in any single method in isolation, but in their integration for a domain and mechanism not previously addressed. The proposed framework rigidly enforces mutually exclusive operation constraints on a single pipeline through a rigid, sequentially evaluated lexicographic priority structure, in which maritime unloading, emergency evacuation, and quality management are resolved in strict order rather than through a soft trade-off, and is equipped with a mathematical Zero-Sealing mechanism that structurally blocks any off-spec product from entering the distribution pipeline, rather than treating quality violations as a penalized but permissible outcome. To the best of our knowledge, this is the first study to integrate (i) a rigid lexicographic priority rule, (ii) real-time fuzzy membership gates evaluated at each simulation step, and (iii) a structural Zero-Sealing mechanism, within a single stochastic discrete-event decision-support framework for LPG single-manifold distribution, where evacuation throughput and product quality compete for the same infrastructure window, and where framework resilience is validated across four uncertainty dimensions via Monte Carlo simulation. The contribution of the research is providing a robust quantitative framework for refinery managers to balance pipeline utilization equilibrium, mitigate off-spec risks through proactive blending innovations, and measurably eliminate demurrage incidents. The manuscript structure is Introduction, Method, Result and Discussion, and Conclusions.

2. Method

2.1. Research Design and Data Collection

This research employs a quantitative approach through discrete-event simulation (DES) model development (Eldawody et al., 2025). The model is designed to represent and optimize the LPG distribution system on single-line manifold infrastructure (Sharma & Khare, 2024; Yao et al., 2026). Historical operational data were collected from the processing facility of PT Pertamina Patra Niaga Refinery Unit IV Cilacap during November to December 2025. The data encompass vessel arrival schedules (Discharge Order Lists), actual distribution to Domestic Gas (hereinafter Gasdom) records (Gas Distribution Orders), tank level fluctuations, and production specifications from the Residue Fluid Catalytic Cracking (RFCC) and Fuel Oil Complex II (FOC-II) production units.

All input distributions and operating parameters of the model were fitted from these historical records using Arena Input Analyzer and cross-checked through practitioner interviews with facility operations advisors, so that the simulation is driven by an expert-calibrated parameterization rather than by raw confidential records. A fully anonymized synthetic dataset generated from this parameterization, which exactly reproduces the results reported in this paper, is provided in the Supplementary Materials. The storage infrastructure represented in the model consists of six tanks with a total design capacity of 18.300 Metric Tons (MT), classified into two operational groups based on upstream production unit characteristics, as detailed in Table 2.

Table 2. LPG storage tank classification and characteristics

Tank Code	Characteristics		
	Group	Unit of Measurement	Origin
47T103	Group A	3.300	FOC-II
47T104	Group A	3.300	FOC-II
47T105	Group A	3.300	FOC-II
47T501A	Group B	2.800	FOC-II & RFCC
47T501B	Group B	2.800	FOC-II & RFCC
47T501C	Group B	2.800	FOC-II & RFCC

2.2. Mathematical Formulation and Fuzzy Logic Constraints

The operational characteristics of the system are distilled into mathematical equations to facilitate the scheduling algorithm in validating operational feasibility. Parameter constraints are reformulated through fuzzy logic sets and absolute (crisp) constraints, following the interactive fuzzy programming approach proven effective for modeling uncertain parameters (such as demand fluctuation and

processing times) in the oil industry (Khalili et al., 2021). This formulation yields high-precision membership degree parameters (μ) that lock the algorithm's solution space against violation of physical refinery constraints. The model is structured around four primary constraint functions, whose variables are summarized in Table 3 for reference throughout this section.

Table 3. Variable definitions used in Eq. (1)–(9)

Symbol	Legend Details	
	Definition	**Unit/Domain**
x	Current tank volume	MT
C	Total design capacity of a tank	MT
c	Measured heavy hydrocarbon (C5+) content of tank content	% Vol
s	Inflow status of a tank	binary
t	Elapsed time since the last discharge operation on a tank	hours
t_lock	Mandatory isolation duration after ship discharge	hours
V_batch	Accumulated transferable volume in a tank at the time of evaluation	MT
μ_overfill	Overfill-risk membership degree	[0, 1]
μ_onspec	On-specification membership degree	[0, 1]

The formulation rests on the following modeling assumptions: (1) the simulation advances in discrete hourly time steps over a 31-day operational horizon, with all flow rates treated as constant within each step; (2) continuous upstream production from the RFCC and FOC-II units enters at nominal rates of 44.875 MT/hour and 4.17 MT/hour respectively, except where a stress scenario explicitly perturbs them; (3) vessel arrivals follow the nominal schedule perturbed by Gaussian noise hard-clipped to ±6 hours, with wider arrival dispersions explored separately in the maritime uncertainty scenario; (4) the single-manifold pipeline serves at most one transfer operation in any given hour, and a blended tank is locked for a 6-hour post-mix settling period before it can be released for distribution; (5) C5+ concentration is treated as homogeneous within each tank, and blending volumes follow a linear mass-balance rule; (6) internal refinery fuel consumption is constant at 127 MT/day and is drawn exclusively from FOC-group tanks; and (7) no unplanned equipment outages occur beyond those imposed in the infrastructure degradation scenario. All stochastic sampling uses a fixed random seed, ensuring full reproducibility of the reported results.

The overfill risk evaluation is formulated using a piecewise linear membership function rather than a simple binary constraint. The membership value ($\mu_{overfill}$) is forced to zero until tank volume (x) reaches a warning threshold at 75% of total design capacity (C), rising linearly to an absolute value of 1.0 at the critical threshold of 85% as formulated in Eq. (1). The selection of these thresholds is grounded in petroleum storage safety standards and intended to give the scheduling algorithm an early, graduated signal instead of a single trigger point. The 85% upper boundary corresponds to the High-High Level alarm setpoint recommended by API Standard 2350 (Overfill Protection for Storage Tanks in Petroleum Facilities), which defines this level as the critical intervention point activating shutdown procedures (Marcano, 2018). The 75% threshold constitutes the pre-alarm (High Level) boundary consistent with the graduated safety layer architecture prescribed by IEC 61511 (Safety Instrumented Systems). The linear ramp between the two thresholds is chosen so that the priority vector computed in Section 2.3 receives a continuously increasing evacuation urgency signal as the tank approaches the critical level, rather than an abrupt binary switch that would produce discontinuous scheduling decisions.

$$\mu_{overfill}(x) = \begin{cases} 0, & \text{if } x \leq 0.75C \\ \dfrac{x - 0.75C}{0.85C - 0.75C}, & if\ 0.75C < x < 0.85C \\ 1, & if\ x \geq 0.85C \end{cases} \quad (1)$$

Product quality regulations demand strict crisp constraints to prevent the distribution of off-spec products. According to the Indonesian national specifications mandated by the Directorate General of Oil and Gas Decree No. 116.K/10/DJM/2020 (Direktorat Jenderal Minyak dan Gas Bumi, 2020), the absolute maximum allowable limit for heavy hydrocarbon (C5+) is 2.0% to prevent dangerous liquid-

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phase condensation. However, the operational quality threshold is established at ≤ 1.49% C5+ as an internal company standard. This 0.51 percentage-point safety margin ensures that process variability and measurement uncertainty do not inadvertently cause regulatory non-compliance, a practice consistent with safety margin engineering principles. Following these rigorous margins, the on-spec function exclusively equals 1 if the C5+ level (c) is ≤ 1.49%, while the off-spec function triggers emergency blending interventions if contamination reaches 1.50% or higher, as shown in Eq. (2) and Eq. (3) (Ahmednooh & Menezes, 2024; Fang et al., 2025; Karimova & Özdağoğlu, 2025).

$$\mu_{onspec}(c) = \begin{cases} 1, if\ c \leq 1.49 \\ 0, if\ c > 1.49 \end{cases} \quad (2)$$

$$\mu_{offspec}(c) = \begin{cases} 1, if\ c \geq 1.50 \\ 0, if\ c < 1.50 \end{cases} \quad (3)$$

A physical prohibition against Simultaneous Operations (SIMOPS) is enforced to prevent cross-flow phenomena. A tank may not simultaneously receive inflow from production units and be pumped out toward downstream facilities within the same hour. If inflow status is active ($s = 1$), pipeline availability is forced to zero as defined in Eq. (4).

$$\mu_{\text{simops}}(\text{s}) = \begin{cases} 0, \text{if s} = 1 \\ 1, \text{if s} = 0 \end{cases} \quad (4)$$

Finally, a mandatory isolation period, encompassing settling and laboratory analysis, is imposed following each discharge operation. This ensures product quality confirmation before redistribution as described in Eq. (5).

$$\mu_{available}(t) = \begin{cases} 0, \text{jika } t < t_{lock} \\ 1, \text{jika } t \geq t_{lock} \end{cases} \quad (5)$$

2.3. Lexicographic Heuristic Priority Rule Algorithm

Priority rule-based heuristics are adopted to simulate human expert intuition through a tiered decision-making structure (Hu et al., 2025; Vermeire & Vanhoucke, 2025). The proposed algorithm applies lexicographic optimization, where the system rigidly satisfies the highest-priority constraint (preventing demurrage) Nakpalad et al. (2025) before advancing to secondary (domestic distribution) and tertiary (product quality) optimization. This approach guarantees feasible schedules with near-instantaneous computation, a fundamental characteristic for DSS applications in capital-intensive industries (Éles & Heckl, 2025). Exact mathematical approaches such as MILP are regularly outpaced by the NP-Hard complexity of large-scale refinery scheduling (Bakon et al., 2022; Junior, 2022; Laisupannawong et al., 2021), the lexicographic heuristic overcomes this by mapping operational decisions onto a sequentially evaluated priority vector, Z = (Z1, Z2, Z3, Z4, Z5).

2.3.1. Five-Tier Lexicographic Vector Optimization

Each element of the priority vector is computed through aggregation of Fuzzy membership values. The Zero-Sealing mechanism locks all calculations: if the membership degree product at any priority level equals absolute zero, the algorithm rigidly returns an empty vector (0, 0, 0, 0, 0), architecturally guaranteeing that no off-specification product passes through the distribution pipeline. The five tiers are evaluated strictly in order, a lower-numbered tier is always resolved before a higher-numbered tier is considered.

- Z_1 (Primary Priority: Maritime Unloading): This index acts as a macro-override. When the maritime fleet arrival schedule is met, Z_1 is forced to an absolute value, instantly suspending all domestic distribution activities to facilitate cargo unloading and prevent demurrage.
- Z_2 (Secondary Priority: Emergency Domestic Evacuation): Designed as a capacity defense mechanism, this value forces the system to evacuate volume-critical tanks, provided the product meets quality standards in Eq. (6).

$$Z_2 = \mu_{overfill} \times \mu_{onspec} \times \mu_{simops} \times \mu_{available} \quad (6)$$

- Z_3 (Tertiary Priority: Emergency Blending): Activated when a critical tank violates quality standards. It instructs the system to find a clean donor tank and execute inter-tank blending to save the inventory from overfill in Eq. (7).

$$Z_3 = \mu_{overfill} \times \mu_{offspec} \times \mu_{simops} \times \mu_{available} \quad (7)$$

- Z_4 (Quaternary Priority: Operational Homeostasis): Under safe capacity conditions, this index takes over pipeline control. It implements a Push-System mechanism where normal distribution is only executed when a minimum hydraulic efficiency threshold (V_{batch}) is accumulated.

$$Z_4 = \mu_{onspec} \times V_{batch} \times \mu_{simops} \times \mu_{available} \quad (8)$$

- Z_5 (Quinary Priority: Proactive Blending): Represents continuous quality management. When the pipeline is idle, the algorithm exploits this gap to proactively blend off-spec products in Eq. (9).

$$Z_5 = \mu_{offspec} \times \mu_{simops} \times \mu_{available} \quad (9)$$

At every simulation hour, the algorithm evaluates Z1 through Z5 in strict numerical order and executes the action associated with the first non-zero tier encountered; all lower-priority tiers are not evaluated for action in that hour once a higher tier fires in Eq. (8). This sequential, non-negotiable evaluation order is what distinguishes the proposed heuristic from a soft multi-objective trade-off: a lower-priority objective can never be executed at the expense of a higher-priority one, regardless of its numerical magnitude. To prevent excessive valve wear and tear caused by continuously alternating inflow tank destinations, the DSS incorporates a Sticky Logic heuristic. FOC-II production flow is exclusively routed to the Group A (T100 series tank group). RFCC flow prioritizes the Group B (T500 series), with a fallback capability to Group A (T100 series) when full. The system persistently retains the active destination parameters (active_foc_dest, active_rfcc_dest) on the same tank until it reaches maximum capacity saturation or is subject to SIMOPS limitation.

2.3.2. Algorithmic Workflow

The complete simulation procedure, illustrated in Fig. 1, follows four sequential phases.

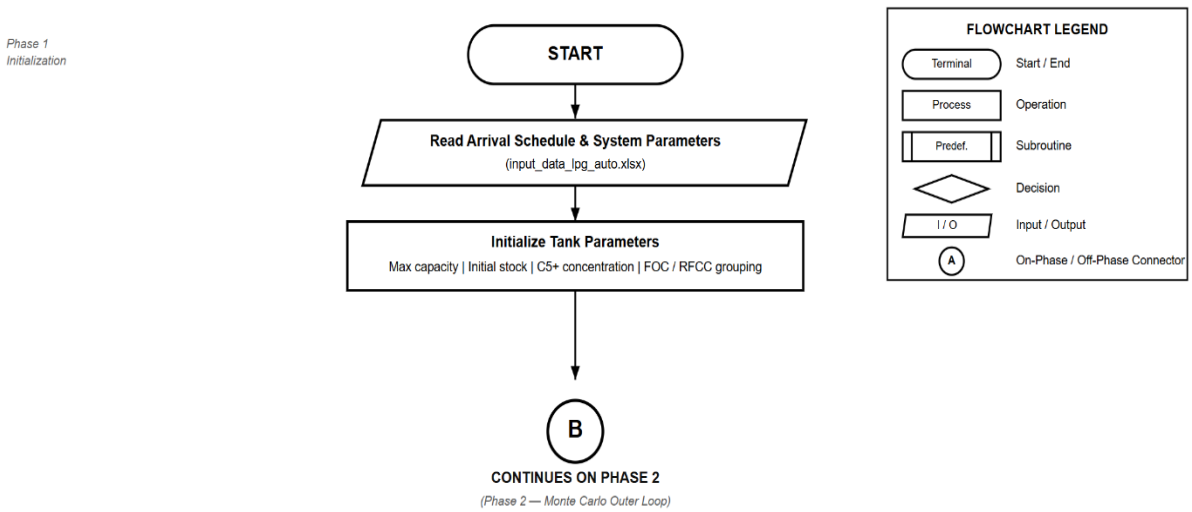


Fig. 1. Flowchart of Priority-Based Decision-Making Phase Initialization

Initialization. Read the vessel arrival schedule and system parameters from Table 4; initialize all six tanks to their starting conditions.

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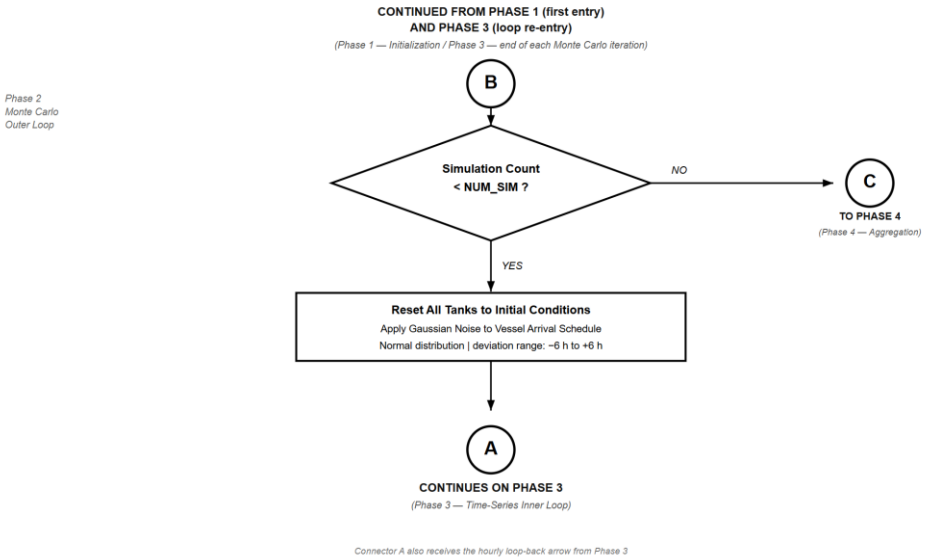


Fig. 2. Flowchart of Priority-Based Decision-Making Phase Monte Carlo Outer Loop

Monte Carlo outer loop. For each simulation run (1 to NUM_SIM), reset all tanks to initial conditions before proceeding to the inner loop in Fig. 2.

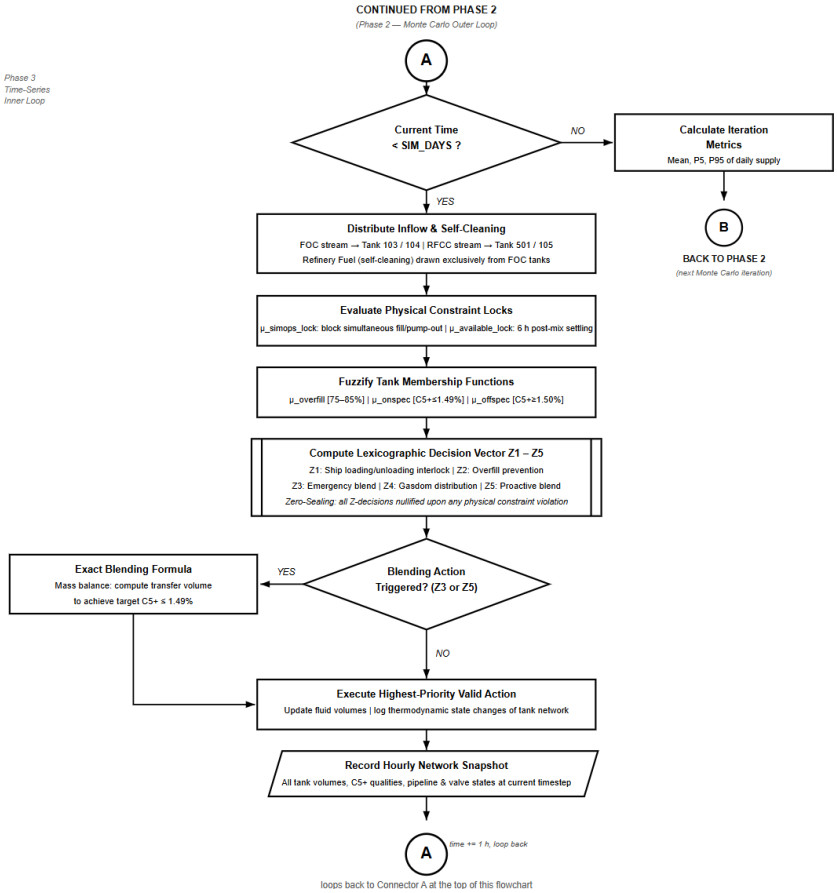


Fig. 3. Flowchart of Priority-Based Decision-Making Phase Time Series Inner Loop

Time-series inner loop in Fig. 3. For each hour of the operational horizon: (a) distribute upstream inflow and apply self-cleaning fuel consumption; (b) evaluate the physical constraint locks (Eqs. 4–5); (c) compute the fuzzy tank membership functions (Eqs. 1–3); (d) compute the five-tier

lexicographic decision vector Z1–Z5 (Eqs. 6–9); (e) if a blending action is triggered, execute the blending formula, otherwise execute the highest-priority valid action; (f) record the hourly network snapshot.

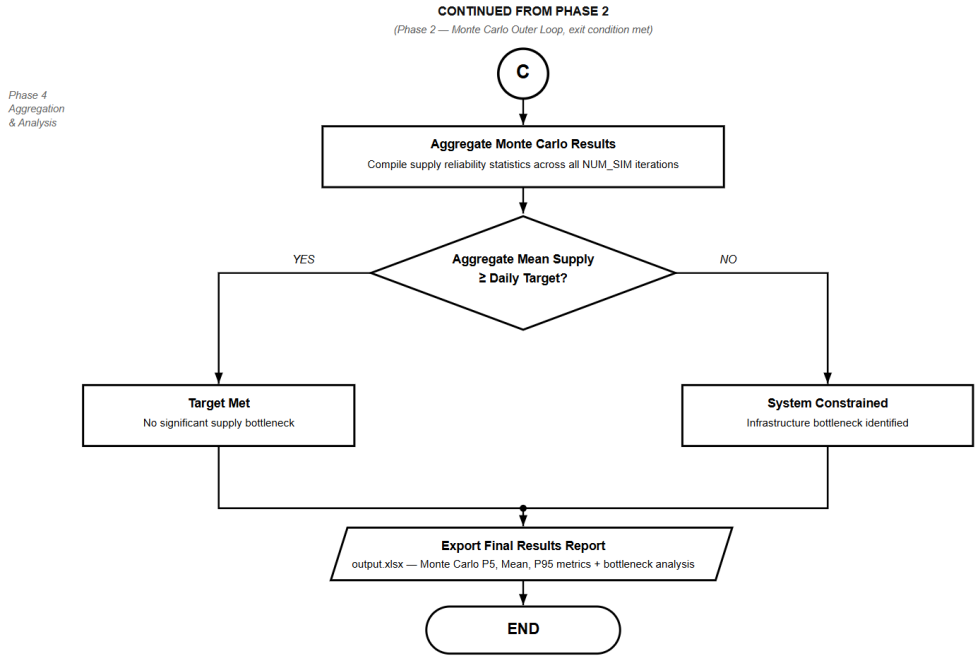


Fig. 4. Flowchart of Priority-Based Decision-Making Phase Aggregation & Analysis

Aggregation and analysis in Fig. 4. After all Monte Carlo run complete, aggregate results across iterations, compare the mean aggregate supply against the daily target, and export the final results report.

2.4. Monte Carlo Simulation Setup and Data Analysis

The reliability of the proposed Decision Support System (DSS) is evaluated using a stochastic Monte Carlo simulation running on an hourly time step over a 31-day operational horizon (representing January 2026). The simulation executes 100 iterations to conduct stress tests across four specific dimensions of operational uncertainty: maritime arrival jitter (up to 24 hours standard deviation), push-system batch sizing equilibrium, mechanical infrastructure degradation (varying pipe rates), and upstream quality stress represented by FOC-II C5+ fluctuations (Nicknezhad & Zegordi, 2024; Wibowo & Arvitrida, 2026). Monte Carlo convergence was assessed at 50, 100, and 200 iterations under the final-run configuration and fixed random seed. The lower-tail estimate (P5) of daily supply was identical across all three sample sizes at 1,332.9 MT, the upper-tail estimate (P95) did not shift materially between N=50 and N=200 (1.372.0 versus 1.371.8 MT), and the mean was stable to within 1.1 MT between N=100 and N=200 (1.354.7 versus 1.355.8 MT), against an intrinsic stochastic spread (P95−P5) of approximately 39–43 MT. Accordingly, 100 iterations were adopted: this sample size captures stable lower- and upper-tail estimates without the redundant computation of N=200.

Initialization parameters strictly established within the simulation model to represent the actual physical limitations of the facility are detailed in Table 4. The theoretical net maximum throughput from combined upstream production (RFCC at 44.875 MT/Hour and FOC-II at 4.17 MT/Hour) yields approximately 1.177 MT/Day of gross upstream generation before deductions. After accounting for internal refinery fuel consumption (127 MT/Day) and self-cleaning fuel routing, the physical mass-balance ceiling for domestic gas supply corresponds closely to the simulated mean throughput reported in the Result and Discussion section. This authentic production constraint serves as the primary benchmark against which scheduling algorithm performance is measured. Following the

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experimental runs, output metrics are statistically evaluated to comprehensively analyse pipeline time utilization, supply fulfilment stability, overfill incident counts, and C5+ specification compliance rates in Table 4.

Table 4. System initialization parameters

Operational Parameter	Parameters	
	Set Value	Unit of Measurement
Pipeline Capacity Rate (Pipe Rate)	120	MT/Hour
FOC-II Inflow Rate	4.17	MT/Hour
RFCC Inflow Rate	44.875	MT/Hour
FOC-II Inflow C5+ Level	3.5	% Vol
RFCC Inflow C5+ Level	0.5	% Vol
Internal Fuel Consumption	127	MT/Day
Mandatory Isolation Time	6	Hours
Monte Carlo Iterations	100	Iterations
Simulation Horizon	31	Days

The simulation was implemented in Python 3.11, with stochastic sampling controlled by a fixed random seed (seed = 42) to ensure reproducibility of the reported results across runs.

3. Results and Discussion

3.1. Pipeline Infrastructure Utilization and Inventory Dynamics

The core analysis of the single-line manifold bottleneck necessitates a rigorous evaluation of pipeline utilization dynamics under the proposed scheduling heuristic (Wang & Hao, 2025). The simulation results, aggregated from 100 iterations of the Monte Carlo model over the 31-day operational horizon, provide quantitative evidence of the infrastructure's operational status. A critical metric in mitigating wear and tear of physical valves and pumps is the proportion of pipeline idle time achieved without compromising continuous evacuation of upstream production units. The stochastic simulation output reveals a structural shift in pipeline time allocation. Gasdom transfer consumed 36.51% of manifold time, maritime discharge occupied 11.73%, proactive blending utilized 3.10%, and idle time represented a dominant 48.66%. By strictly implementing the quaternary priority tier with a push-system mechanism that demands a minimum hydraulic efficiency threshold of 1.000 MT before pump actuation, the algorithm consolidates distribution activity into fewer, larger transfers instead of frequent small ones. This consolidation is what generates the 48.66% idle-time share, and that idle time functions as an operational buffer against arrival and demand jitter rather than as wasted manifold capacity. This finding corroborates the assertion by and that discrete-event simulation integrated with heuristic rules provides superior agility in generating operational buffers compared to rigid mathematical models. The idle time is not merely a passive by-product of consolidation, however; it is deliberately reserved and later allocated to quality-correction actions, a causal chain examined quantitatively in the batch-equilibrium analysis below.

Through this mechanism, the mutually exclusive scheduling conflict described by is empirically resolved: the single physical manifold is made to serve both maritime intake and domestic evacuation not by expanding its capacity, but by scheduling the two demands into complementary time windows (Fernando & Sigera, 2021; Mahmoudi et al., 2021; Nakpalad et al., 2025). The monitoring of inventory fluctuations provides further validation for the emergency evacuation and emergency blending priority tiers. The fuzzy overfill membership function actively governed tank evacuation scheduling, and across all 100 iterations of the 31-day horizon the system recorded zero tank overflow incidents (Wibowo & Arvitrida, 2026). This result confirms that the designated 120 MT/hour pipeline capacity, when governed by the priority heuristic, is sufficient to absorb the combined continuous inflows from the RFCC and FOC-II units together with periodic maritime cargo intake. Inventory levels remained below the 85% critical safety threshold at every hourly step across every iteration, which translates the theoretical fuzzy-overfill formulation into a practical, empirically verified safeguard for the dynamic refinery operation floor (Bakon et al., 2022).

3.2. Domestic Gas Distribution Performance

Monte Carlo stochastic simulation with 100 iterations records a mean daily supply rate of 1.354.7 MT/day, with a standard deviation of 13.4 MT/day, a 95% confidence interval of 1.352.0 to 1.357.3 MT/day, and a resilience range spanning a fifth-percentile value of 1.332.9 MT/day to a ninety-fifth-percentile value of 1.375.5 MT/day. The stochastic analysis further confirms that the push-system mechanism executes dynamic transfers with a mean batch size of 1.302.7 MT, ranging from a minimum of 1.000.1 MT to a maximum of 2.742.0 MT under critical conditions. Because the algorithm withholds pump actuation until the minimum transfer threshold is met, pump chattering, the hydraulic anomaly of continuous starting and stopping at low volumes, is eliminated entirely. This scheduling behavior secures both the distribution quantity and the service life of mechanical infrastructure assets, a conclusion consistent with pump asset-management literature demonstrating that reducing uncontrolled actuation cycling extends centrifugal-pump service life and lowers maintenance exposure (Chen et al., 2023; Éles & Heckl, 2025).

It is important to clarify what this throughput figure is composed of, since it exceeds the refinery's own production capacity when that capacity is considered in isolation. The combined continuous production inflow from RFCC at 44.875 MT/hour and FOC-II at 4.17 MT/hour, net of internal refinery fuel consumption of 127 MT/day, yields a refinery-origin domestic supply base of approximately 1.050 MT/day. The remaining volume needed to reach the observed mean of 1.354.7 MT/day is supplied by periodic maritime cargo discharge, which the same single-line manifold receives on a scheduled basis and subsequently redistributes downstream once the mandatory isolation and quality-confirmation period has elapsed.

The lexicographic algorithm therefore does not generate throughput beyond the physical capacity of the system; the observed mean instead represents the successful, non-conflicting evacuation of both continuous refinery production and discrete maritime replenishment through a manifold that can only serve one of these two intake-and-output streams in any given hour. This is consistent with refinery-wide planning models in which achievable throughput is fundamentally bounded by the simultaneous supply, production, and demand envelope rather than by the scheduling logic itself. Resolving that competing demand is precisely the function of the highest two priority tiers described in the method, and the near-total absence of unevaluated backlog reported above indicates that the heuristic captures nearly all of this combined supply envelope without accumulating idle inventory in the tanks (Zhang et al., 2021).

To quantify the relative improvement offered by the proposed lexicographic-fuzzy framework, two comparison configurations were implemented and simulated under identical stochastic conditions, each run for 100 iterations. The first is a purely reactive scheduling policy, in which tanks are evacuated only after a quality or overfill threshold has already been breached, representing the conventional inspect-then-correct approach criticized in the discussion below. The second is an ablation of the proposed model in which the full lexicographic priority structure remains active but the Zero-Sealing hard-block mechanism is deliberately disabled, isolating the specific contribution of that single mechanism. Table 5 summarizes the comparison against the proposed model.

A Welch's t-test was conducted to statistically validate these differences given the unequal variances between the groups. The proposed model significantly outperforms the reactive baseline by 297.31 MT/day, with a t-statistic of 125.79 and a standard error of 2.36. This gap arises because the reactive policy only clears a tank once it has already breached a threshold, which forces intermittent forced-idle periods while corrective action is organized, whereas the proposed model's evacuation and blending tiers act before the constraint binds, avoiding that lost time entirely. The superiority of proactive scheduling that intervenes ahead of the binding constraint over reactive inspect-then-correct policies is corroborated by dynamic optimization studies that embed maintenance and production decisions under uncertainty and show that anticipatory action avoids the idle and corrective losses inherent to reactive control (Wu & Zhang, 2022).

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Table 5. Comparative performance of the proposed model, the reactive baseline, and the Zero-Sealing-disabled ablation (100 iterations each)

Model	Performance Matrix				
	Mean Daily Supply (MT/day)	Standard Deviation	95% Confidence Interval (MT/day)	Overfill Incidents	Quality Violations (of 100 iterations)
Proposed model	1.354.7	13.4	1.352.0 to 1.357.3	0	0
Reactive baseline	1.057.39	19.50	1.053.57 to 1.061.22	0	0
Zero-Sealing-disabled ablation	1.426.08	10.52	1.424.02 to 1.428.14	0	100

The comparison against the ablation configuration is more nuanced and speaks directly to the practical cost of the Zero-Sealing mechanism. The ablated configuration achieves a marginally higher mean throughput than the proposed model, a difference of 71.38 MT/day that is also statistically significant, with a t-statistic of negative 42.01 and a standard error of 1.70. This occurs because removing the hard quality block allows the scheduler to evacuate volume that the proposed model would otherwise withhold pending blending. That apparent throughput gain is illusory from a compliance standpoint, however, because without the structural block, off-spec product with a C5+ concentration above 1.50% reaches the distribution pipeline in all 100 of 100 iterations, a complete breach of the regulatory ceiling set by the Directorate General of Oil and Gas (Direktorat Jenderal Minyak dan Gas Bumi, 2020). The proposed model sacrifices 71.38 MT/day, equivalent to 5.0% of the ablated configuration's throughput, in exchange for eliminating regulatory violation entirely. In a regulated fuel-quality environment this trade-off is not negotiable in economic terms: a single off-spec delivery event carries reputational, contractual, and regulatory exposure that far exceeds the value of the marginal throughput gained by disabling the seal. This comparison provides direct empirical evidence, rather than a purely theoretical justification, for encoding the quality block as a rigid structural constraint instead of a soft, penalized objective term, an approach aligned with lexicographic optimization formulations in which product-quality loss is minimized as the highest-priority objective ahead of all secondary performance goals (Chen et al., 2023).

For contextual benchmarking, the facility's nominal planning reference of 2.000 MT/day represents the downstream Gasdom pipeline system's designed receiving capacity, reflecting the corporate supply commitment to downstream market demand. The gap between the algorithm's throughput and this planning reference is a manifestation of the combined refinery-and-maritime supply envelope described above, not a consequence of scheduling inefficiency: the algorithm orchestrates fluid flow logistics, but it cannot generate throughput beyond what the tank network physically receives (Junior, 2022). Closing this gap requires capital expenditure on debottlenecking upstream production or expanding manifold capacity, a strategic asset management decision that lies outside the scope of a scheduling algorithm (Sharma & Khare, 2024).

3.3. Hydrocarbon Quality Validation and Proactive Contaminant Mitigation

Heavy hydrocarbon quality parameters were rigorously evaluated to validate the Zero-Sealing mechanism. Stochastic simulation records zero Gasdom specification violations above the 1.49% internal threshold across all 100 Monte Carlo iterations of the proposed model, in direct contrast to the complete violation rate observed once the mechanism is disabled, as reported in Table 5. The absence of off-specification product reaching the domestic distribution pipeline empirically validates the effectiveness of the lexicographic architecture, and the ablation result demonstrates that this outcome is not an incidental property of the scheduling logic but is causally attributable to the structural block itself. Conventional approaches in prior literature have generally relied on post-distribution inspection, which carries an inherent risk of allowing defective product to pass before detection; the proposed model instead eliminates that risk at the point of scheduling decision rather than after the fact (Karimova & Özdağoğlu, 2025).

This quality stability is achieved through successful proactive blending operations at the fifth priority tier. The algorithm exploits pipeline idle time to initiate 23.1 blending operations on average with a total injection volume of 2.768.4 MT. These operations consistently dilute C5+ concentration in the FOC-II receiving tank group before contamination levels approach the critical release threshold, converting the idle-time reserve discussed above into a concrete quality-management resource. This finding supports the broader argument developed in the discussion below, that product-quality management on single-manifold facilities should not depend on reactive corrective action but on the systematic pre-allocation of infrastructure idle time (Ahmednooh & Menezes, 2024; Fang et al., 2025).

As an additional quality safety layer, the self-cleaning heuristic proves complementary to this mitigation structure. The algorithm systematically selects 1.550 MT of inventory with the highest weighted-average C5+ concentration of 2.17% for exclusive diversion as upstream refinery utility fuel rather than for distribution. Combining proactive blending with fuel substitution ensures that heavy contaminant is localized and internally consumed rather than flared or distributed, a strategy consistent with the circular material management principles aligned with SDG 12, Responsible Consumption and Production (Agbaji et al., 2023; Hasan et al., 2024).

3.4. Stochastic Resilience Testing and Sensitivity Analysis

The reliability of the DSS architecture was evaluated across four operational uncertainty dimensions to identify the infrastructure's breaking points. Critical point identification of this kind is essential in multi-product pipeline network design, where optimization frameworks integrating technical and commercial parameters provide superior decision-making capability for system designers (Sharma & Khare, 2024).

3.4.1. Scenario 1: Maritime Uncertainty

The first scenario tests the robustness of the maritime priority tier against fluctuations in estimated time of arrival, varying ship arrival standard deviation from 0 to 24 hours. Simulation results show zero overfill incidents even when arrival standard deviation reaches 24 hours, and manifold idle time percentage remains stable, ranging only from 48.39% to 49.61% across the entire tested range in Fig. 5. This stability is a direct consequence of the buffer capacity built into the priority structure: because the maritime tier only suspends domestic distribution rather than halting production intake, any delay in vessel arrival is absorbed by the existing idle-time reserve rather than propagating into a scheduling conflict. This finding challenges the conventional diagnostic premise that vessel delays are a primary trigger of supply chain failure (Nakpalad et al., 2025). As long as ground evacuation infrastructure is maintained at rated efficiency, maritime schedule turbulence is isolated from refinery-side stability rather than merely correlated with it, and this resilience does not depend on precise vessel scheduling in Table 6; it is a property of the buffer architecture itself.

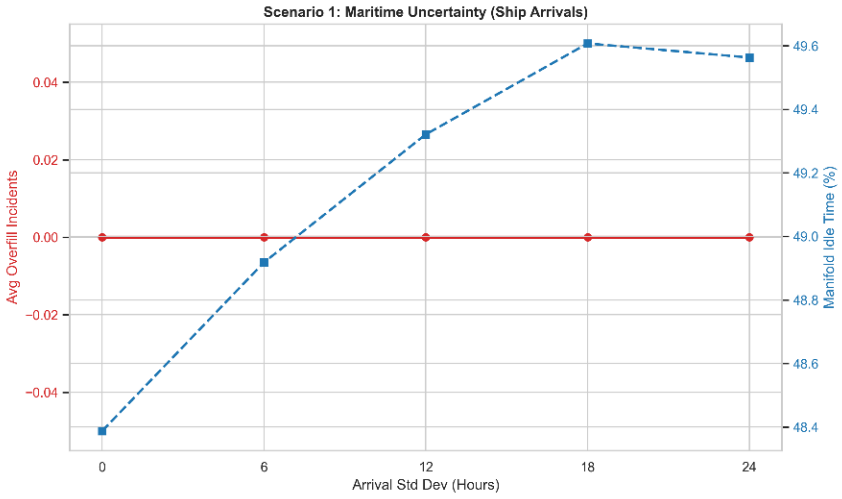


Fig. 5. Sensitivity analysis results for maritime arrival uncertainty

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Table 6. Maritime uncertainty sensitivity analysis results

Std Dev (Hours)	Sensitivity Value	
	Average Overfill Incidents	Manifold Idle Time (%)
0	0.0	48.39
6	0.0	48.92
12	0.0	49.32
18	0.0	49.61
24	0.0	49.56

3.4.2. Scenario 2: Push-System Equilibrium (Batch Size Optimization)

The second scenario evaluates the push-system's dynamic equilibrium by varying the minimum Gasdom transfer threshold from 250 to 2.000 MT. Increasing the minimum batch threshold improves single-pumping efficiency but locks the manifold for longer continuous periods, which creates a direct trade-off between hydraulic efficiency and quality-management opportunity. The data identify a computational sweet spot between 1.000 and 1.500 MT, within which the pipeline obtains adequate rest periods and proactive blending volume stabilizes at 1.440 MT in Fig. 6. Setting the minimum batch too low, at 250 MT, produces a counter-intuitive result: total proactive blending volume rises sharply to 5.880 MT, not because more blending is structurally required, but because the pipe enters fragmented, short idle windows too frequently, and each fragment is treated as a separate blending opportunity in Table 7. This increases valve actuation cycling considerably without a proportional gain in quality outcomes. These results establish minimum batch size as the primary lever for shaping quality-management idle time in Table 7: it determines not only how efficiently the pipeline is used, but how that idle time is structurally partitioned for later use in blending, enabling proactive C5+ control without requiring investment in a dedicated blending pipeline.

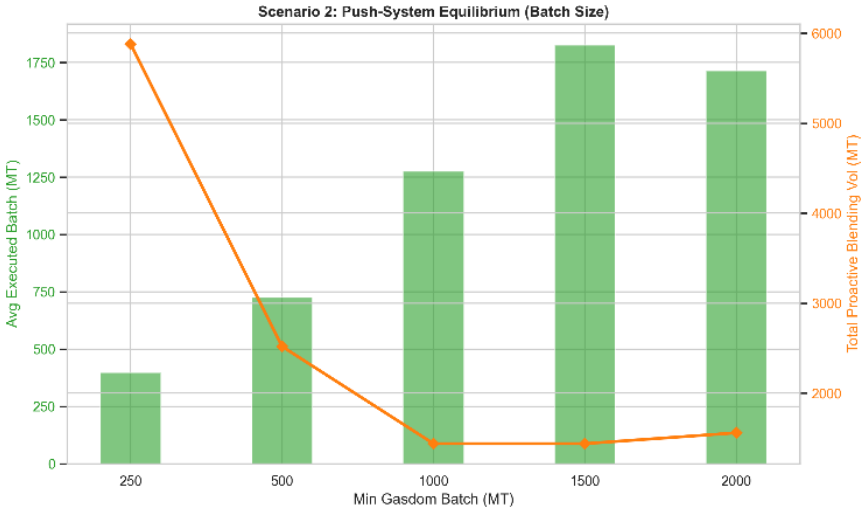


Fig. 6. Sensitivity analysis results for batch size equilibrium

Table 7. Batch size equilibrium sensitivity analysis results

Min Batch (MT)	Sensitivity Value	
	Average Executed Batch (MT)	Proactive Blending Vol (MT)
250	397.00	5.880.0
500	724.81	2.520.0
1.000	1.275.30	1.440.0
1.500	1.826.17	1.440.0
2.000	1.713.64	1.560.0

3.4.3. Scenario 3: Infrastructure Degradation (Pipe Rate)

The third scenario simulates mechanical infrastructure aging by reducing hydraulic pump evacuation capacity across a range from 80 to 140 MT/hour. Reduced evacuation capacity is identified as the system's dominant paralysis risk. When pipe rate degrades to 80 MT/hour, the manifold is occupied almost entirely by Gasdom physical evacuation, which structurally starves proactive blending time and forces the system to fall back on 16 sporadic emergency blending operations rather than the steady 12 observed at the nominal rate in Fig. 7. This is the direct operational consequence of the interdependency established earlier in this section: when hydraulic evacuation time expands to consume nearly all available manifold hours, the idle-time reserve that proactive blending depends upon contracts correspondingly, and quality management is forced from a proactive into a reactive posture. This exposes a specific reliability boundary of the Zero-Sealing mechanism. Because emergency blending and proactive blending both depend on manifold time that evacuation must first vacate, a pipe rate degradation below approximately 100 MT/hour risks a compounding effect in which insufficient time remains for either evacuation or quality correction, elevating the probability of inventory accumulation even though the structural block itself continues to guarantee zero off-spec release in Table 8. This scenario identifies pipe rate as the single most sensitive parameter for refinery operational continuity among the four uncertainty dimensions tested, and it directly informs the infrastructure investment priority discussed below in Table 8.

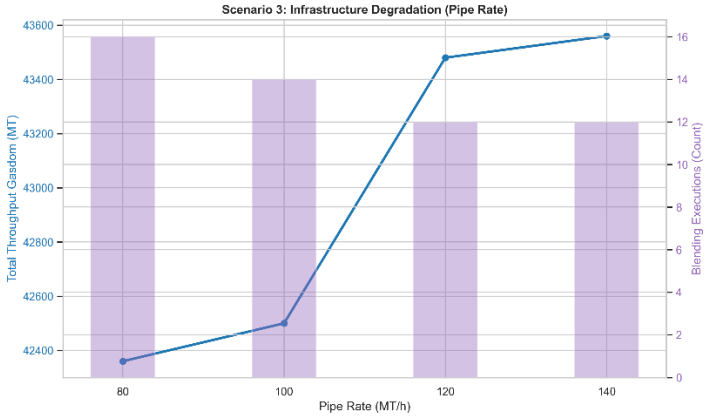


Fig. 7. Sensitivity analysis results for pipe rate degradation

Table 8. Pipe rate degradation sensitivity analysis results

Pipe Rate (MT/h)	Sensitivity Value	
	Total Throughput (MT)	Blending Operations
80	42.360.0	16
100	42.500.0	14
120	43.480.0	12
140	42.560.0	12

3.4.4. Scenario 4: Upstream Quality Stress (C5+ Contamination)

The fourth scenario tests the resilience of the blending formulation against escalating upstream heavy hydrocarbon contamination from FOC-II, ranging from the baseline operating value of 3.5% to 5.5% C5+ inflow in Fig. 8. Increasing C5+ contamination forces the algorithm to continuously revise donor-volume calculations for each blending event, since a higher inflow concentration requires proportionally more on-spec donor volume to achieve the same dilution target. Contamination pressure at 5.5% elevates the resulting mean system quality to 1.371% C5+ in Table 9, approaching but not breaching the 1.49% internal hard limit while remaining far inside the 2.0% regulatory ceiling (Akintayo et al., 2026; Karimova & Özdağoğlu, 2025).

The 0.51 percentage point internal safety margin above the regulatory limit therefore remains structurally intact across the entire tested contamination range, confirming that the margin was sized with sufficient headroom for realistic upstream variability. Fluctuations above 5.0%, however, begin to expose a resource-availability limitation rather than a mechanism failure: as contamination rises, the pool of clean, on-spec donor fluid available for blending shrinks relative to the volume requiring dilution, which would be expected to require increased internal fuel-diversion volumes to sustain distribution feasibility if contamination were to rise further beyond the tested range.

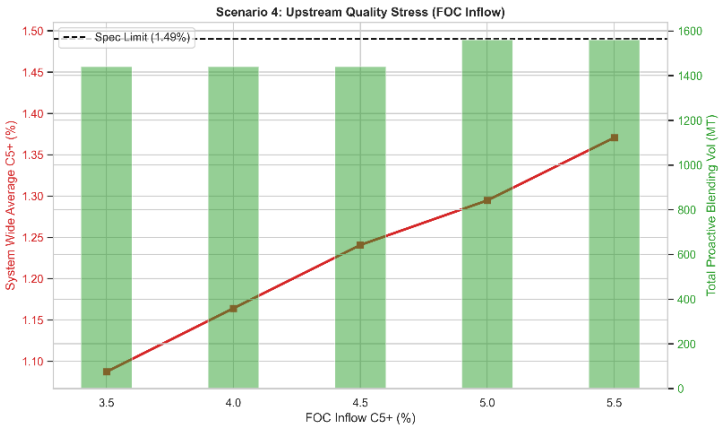


Fig. 8. Sensitivity analysis results of upstream quality stress

Table 9. Upstream quality stress sensitivity analysis results

Min Batch (MT)	Sensitivity Value	
	Average Executed Batch (MT)	Proactive Blending Vol (MT)
3.5	1.087	1.440.0
4.0	1.164	1.440.0
4.5	1.241	1.440.0
5.0	1.295	1.560.0
5.5	1.371	1.560.0

3.4.5. Comparative Sensitivity and Cross-Scenario Discussion

The comparative analysis across the four uncertainty dimensions reveals a clear hierarchy of parametric sensitivity. Pipe rate is the single most sensitive and deterministic parameter for refinery operational continuity. Maritime arrival fluctuations and batch size variation are computationally absorbed by tank buffer elasticity and by the pipeline idle-time reserve respectively, while evacuation rate degradation directly compresses the shared time budget on which both product distribution and quality management depend. This ranking is not an assumption carried over from prior literature but an outcome directly measurable from the sensitivity tables above: only the pipe rate scenario shows a monotonic reduction in both throughput headroom and blending operation stability at the same time, whereas the maritime and batch size scenarios each affect only one side of that trade-off. This operationally validates the framework's ability to identify asset-specific investment priorities directly from simulated behavior rather than from a priori theoretical ranking.

Prior literature has generally addressed scheduling quantity optimization separately from chemical specification management, treating the two as independently solvable problems. The results presented above demonstrate that on single-manifold infrastructure these domains are not independent but mechanistically coupled: the rate at which fluid can be hydraulically evacuated directly governs the manifold time available for quality correction maneuvers, as evidenced quantitatively by the inverse relationship between pipe rate and blending operation count in the pipe rate degradation scenario. This coupling is structurally invisible to models, including Mixed-Integer Linear Programming formulations, that decompose throughput scheduling and blend scheduling into separate

solved problems, and it is this specific mechanism, rather than a general claim of superiority, that constitutes the primary empirical contribution of the integrated lexicographic-fuzzy architecture.

In the context of product quality management, the comparative baseline analysis presented earlier provides direct quantitative support for the argument that a purely reactive blending strategy is structurally disadvantaged on congested single-manifold infrastructure. The reactive baseline was significantly outperformed by the proposed model, by 297.31 MT/day according to the Welch's t-test reported above, and the ablation of the Zero-Sealing mechanism showed that removing the structural quality block, while nominally increasing throughput, produced a complete violation rate. Together these results indicate that the automated blend-scheduling approach of Ahmednooh & Menezes (2024) and the predictive, evolutionary optimization approach of Fang et al. (2025) remain valuable at the level of the blending decision itself, but that on single-manifold infrastructure specifically, the timing of when blending is permitted to occur is at least as consequential as how the blend recipe itself is optimized. This is a scheduling-level constraint that sits upstream of, and is complementary to, both of those blend-optimization approaches, and it positions predictive, machine-learning-based donor-selection methods as a natural extension of the present framework rather than a competing approach, particularly at the upper contamination range above 5.0% C5+ discussed above.

Converting this logistics-level intervention into a macro-sustainability narrative, the DSS design carries measurable implications for corporate Environmental, Social, and Governance parameters. The scheduling structure that prioritizes maritime fleet arrival reduces vessel queuing idle time and thereby contributes to bunker fuel Scope 3 emission reduction. The empirically observed zero-overfill outcome prevents emergency gas flaring, avoiding the associated methane and carbon dioxide release, consistent with the risk-reduction framing of (Mahmoudi et al., 2021). In terms of Sustainable Development Goal alignment, the system supports Goal 7, Affordable and Clean Energy, by sustaining LPG supply continuity; Goal 9, Industry, Innovation, and Infrastructure, by demonstrating that scheduling intelligence can defer capital expenditure on manifold duplication; and Goal 12, Responsible Consumption and Production, through the systematic diversion of off-quality inventory to internal utility fuel rather than to flaring (Agbaji et al., 2023; Hasan et al., 2024; Wang & Hao, 2025).

3.5. Research Limitations

This research carries several limitations that warrant attention in future studies. First, the infrastructure evaluation in the pipe rate degradation scenario identifies the critical degradation threshold operationally but does not compute a techno-economic comparison between additional physical infrastructure capital expenditure and the long-term demurrage penalty avoidance it would enable; such an analysis is needed to justify debottlenecking urgency in monetary terms. Second, as shown in the batch equilibrium analysis, proactive blending is structurally dependent on idle time generated by batch equilibrium, and this dependency has not been tested beyond the 5.5% C5+ contamination ceiling examined in the upstream quality stress scenario, so the model's behavior under more extreme upstream quality excursions remains an open question, for which integration of predictive quality scheduling models based on supervised machine learning, such as the framework proposed by Karimova & Özdağoğlu (2025), offers a plausible direction. Third, the comparative baseline analysis isolates the contribution of the Zero-Sealing mechanism and of proactive versus reactive scheduling, but it was conducted against internally constructed comparison configurations rather than against a published exact or metaheuristic implementation applied to the same facility dataset; a direct comparison against, for example, a Mixed-Integer Linear Programming or discrete-event-simulation metaheuristic reimplementation of this specific case would further strengthen the external validity of the throughput and compliance claims. Finally, the proposed lexicographic heuristic is validated as a tactical scheduling instrument for this single-manifold configuration, but its reliability ceiling will ultimately remain bounded by the combined thermodynamic capacity of upstream production and maritime intake, a physical constraint that scheduling logic alone cannot relax.

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4. Conclusion

This study demonstrates that a Decision Support System built on five-tier lexicographic heuristic optimization, integrated with Fuzzy Logic and validated through 100-iteration Monte Carlo simulation, offers an effective way to manage resource allocation conflicts on single-manifold LPG distribution infrastructure. Within the tested scenarios, the algorithm avoided physical overfill incidents and demurrage penalties across all iterations, indicating strong potential for operational risk mitigation under the conditions modeled in this study. Rather than being constrained by scheduling inefficiency, aggregate distribution output was found to track upstream refinery production capacity closely, suggesting that the proposed scheduling logic does not itself introduce a meaningful throughput bottleneck.

Beyond confirming these simulation outcomes, the results carry several practical implications for refinery operations. The Push-System mechanism, combined with equilibrium batch thresholds, shows that hydraulic pumping efficiency and proactive quality management can be pursued simultaneously rather than treated as competing objectives, an insight refinery planners can apply when designing batch-release policies for similarly constrained facilities. The identification of pipe rate degradation below 100 MT/h as a singular critical failure point offers a concrete, actionable threshold that operators can monitor and use to prioritize infrastructure maintenance or investment decisions. Similarly, the zero quality-violation record achieved through lexicographic exploitation of idle time suggests that facilities facing comparable blending constraints could adopt this scheduling logic to reduce off-spec risk without necessarily requiring major infrastructure expansion.

From a broader perspective, the proposed architecture aligns with ESG-related objectives and supports SDG 7, 9, and 12 through improved asset utilization and reduced emissions associated with demurrage and off-spec reprocessing. It should be noted that these findings are derived from a single refinery case with specific infrastructure and demand characteristics; further validation across different manifold configurations, production scales, and demand patterns would help establish the generalizability of the proposed framework. Future research is therefore recommended to focus on: (1) testing and adapting the proposed framework across different refinery configurations, including multi-manifold and dual-pipeline layouts, to assess its applicability and robustness beyond the single-manifold case examined here; (2) techno-economic feasibility analysis comparing dual-pipeline debottlenecking investment against continued reliance on operational risk mitigation; and (3) integration of predictive quality scheduling via supervised machine learning to extend system resilience at upstream contamination levels exceeding 5.0% C5+.

Supplementary Materials: The algorithm pseudocode and a fully anonymized synthetic dataset that exactly reproduces the reported results are available online at https://drive.google.com/drive/folders/1NUAky5V8_9o-j1tS40e8kOyzCp47XVKC. The raw operational data cannot be made publicly available due to a strict Non-Disclosure Agreement (NDA) with the facility.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Funding: This research received no external funding

Acknowledgment: The authors gratefully acknowledge the management and operational staff of PT Pertamina Patra Niaga Refinery Unit IV Cilacap for their administrative and technical support, specifically in providing the historical operational context essential for the simulation model in this study.

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

Declaration of AI-Tool Usage: AI-assisted tools were used to support manuscript proofreading, verify the consistency of variables and mathematical notation, and check reference formatting. All outputs were reviewed and verified by the authors, who take full responsibility for the accuracy and integrity of the final manuscript.

References

Agbaji, A. L., Morrison, R., & Lakshmanan, S. (2023, June 5). ESG, Sustainability and Decarbonization: An Analysis of Strategies and Solutions for the Energy Industry. *SPE EuropEC - Europe Energy Conference Featured at the 84th EAGE Annual Conference & Exhibition*. https://doi.org/10.2118/214346-MS

Ahmednooh, M., & Menezes, B. (2024). Blend Scheduling Solutions in Petroleum Refineries towards Automated Decision-Making in Industrial-like Blend-Shops. *Processes*, *12*(3), 561. https://doi.org/10.3390/pr12030561

Akintayo, V. O., Jian-tang, X., Han, L., Zepeng, A., & Pingping, F. (2026). mHTMapping and identifying candidate genes enabling lead (Pb) accumulation and tolerance in Dark Jute (Corchorus olitorius L.) as revealed by BSA-seq and RNA-seq. In *Industrial Crops and Products*. https://doi.org/10.1016/j.indcrop.2025.122558

Ardekani, M. A. (2022). A Multi-Objective Supply Chain Configuration for the Oil Industry under Uncertainty. *Advances in Industrial Engineering*. https://doi.org/10.1051/ro/2021158

Awan, M. A. H., Naseem, A., Ahsan, A., Shahzad, A., Ullah, M., & Sadiq, A. S. (2025). Evaluating disruption scenarios for improving downstream oil supply chain resilience and cost minimization using Monte Carlo simulation. *Scientific Reports*, *15*(1), 38910. https://doi.org/10.1038/s41598-025-22678-9

Bakon, K., Holczinger, T., Sule, Z., Jasko, S., & Abonyi, J. (2022). Scheduling Under Uncertainty for Industry 4.0 and 5.0. *IEEE Access*, *10*, 74977–75017. https://doi.org/10.1109/ACCESS.2022.3191426

Chen, L., Yang, W., Qiu, K., & Dauzere-Peres, S. (2023). A lexicographic optimization approach for a bi-objective parallel-machine scheduling problem minimizing total quality loss and total tardiness. *Computers & Operations Research*, *155*, 106245. https://doi.org/10.1016/j.cor.2023.106245

Eldawody, S., Nassar, K., & Essawy, Y. A. S. (2025). Activity Sequencing Optimization in Petroleum Projects Using Simulation Modeling. *Modular and Offsite Construction (MOC) Summit Proceedings*, 34–41. https://doi.org/10.29173/mocs311

Eles, A., & Heckl, I. (2025). Efficient Simulation Algorithm and Heuristic Local Optimization Approach for Multiproduct Pipeline Networks. *Logistics*, *9*(3), 114. https://doi.org/10.3390/logistics9030114

Fang, W., Du, W., Yu, G., He, R., Tang, Y., & Jin, Y. (2025). Preference Prediction-Based Evolutionary Multiobjective Optimization for Gasoline Blending Scheduling. *IEEE Transactions on Artificial Intelligence*, *6*(1), 79–92. https://doi.org/10.1109/TAI.2024.3444736

Fernando, M., & Sigera, I. (2021). Assessing the Oil Supply Chain Risk in Sri Lankan Petroleum Industry. *2021 Moratuwa Engineering Research Conference (MERCon)*, 374–379. https://doi.org/10.1109/MERCon52712.2021.9525691

Hasan, J., Thomas, A., & Tomos, O. (2024). Sustainable Supply Chain Practices in the Oil and Gas Industry: A Case Study. *Sustainability*, *16*(5), 1720. https://doi.org/10.3390/su16051720

Hu, X., Li, J., Li, F., Wang, J., & Wang, Y. (2025). Priority rule-based heuristics for distributed multi-project scheduling considering global resource failures. *Journal of the Operational Research Society*, *76*(10), 2112–2131. https://doi.org/10.1080/01605682.2025.2457655

Hua, J., Chen, Q., Liu, W., He, R., Li, Q., & Zhu, Z. (2023). Optimization and Application of Gasoline Blending Multi-period Scheduling Considering Blending Effect. *2023 2nd International Conference on Advanced Sensing, Intelligent Manufacturing (ASIM)*, 66–70. https://doi.org/10.1109/ASIM62342.2023.00020

Junior, M. C. L. (2022). *Scheduling optimization applied to the electricity, oil and gas industries*. theses.hal.science. https://theses.hal.science/tel-04048648/

Karimova, A., & Ozdagoglu, G. (2025). Optimal Control of Specification in LPG Blend: A Deep Learning and PSO-Driven Framework for Minimizing Off-Spec Production. *ACS Omega*, *10*(15), 14908–14923. https://doi.org/10.1021/acsomega.4c10068

Khalili, G. F., Maleki, H. R., & Niroomand, S. (2021). *An interactive fuzzy programming approach for a new multi-objective multi-product oil pipeline scheduling problem*. Iranian Journal of Fuzzy Systems. https://doi.org/10.22111/IJFS.2021.5989

Laisupannawong, T., Intiyot, B., & Jeenanunta, C. (2021). Mixed-Integer Linear Programming Model and Heuristic for Short-Term Scheduling of Pressing Process in Multi-Layer Printed Circuit Board Manufacturing. *Mathematics*, *9*(6), 653. https://doi.org/10.3390/math9060653

Mahmoudi, H., Bazrafshan, M., & Ahmadipour, M. (2021). Sustainable multi-objective optimization for the supply chain of petroleum products. *Journal of Applied Research on Industrial Engineering*. https://doi.org/10.22105/jarie.2022.318695.1407

Marcano, J. M. (2018). *Design and Development of a UAV System for Multispectral Imaging and Remote Sensing Applications*. *Theses and Dissertations*. https://doi.org/10.7939/R3JW8731J

Mechal, A., Fekadu, D., & Abadi, B. (2024). Multivariate and water quality index approaches for spatial water quality assessment in Lake Ziway, Ethiopian Rift. *Water, Air, &Soil Pollution*. https://doi.org/10.1007/s11270-023-06882-9

Nakpalad, E., Kodjampa, J., & Prasongsuk, S. (2025). Heuristic Berth Scheduling for Dual-Service Petrochemical Tank Terminals: A Field-Driven Approach to Managing ETA Uncertainty. *Asian Journal of Logistics and Intermodal Transport Management*, *1*, 13–18. https://doi.org/10.66149/ajlitm.2025.01.02

Nicknezhad, J., & Zegordi, S. H. (2024). Petroleum supply chain dynamic risk assessment using Bayesian network. *Computers & Chemical Engineering*, *189*, 108771. https://doi.org/10.1016/j.compchemeng.2024.108771

Pervukhin, D. A., Davardoost, H., Gasimov, E., & Hawezy, A. L. J. (2025). Optimizing Multimodal Logistics in Petroleum Supply Chains Using Linear Goal Programming: A Case Study on South Pars Gas Field Development. *International Journal of Engineering*, *38*(8), 1909–1921. https://doi.org/10.5829/ije.2025.38.08b.15

Reda, R. M., Helmy, R. M. A., Osman, A., Ahmed, F. A. G., & El-Fattah, A. H. A. (2023). The potential effect of Moringa oleifera ethanolic leaf extract against oxidative stress, immune response disruption induced by abamectin exposure in Oreochromis niloticus In *Environmental Science and Pollution Research International*. https://doi.org/10.1007/s11356-023-26517-0

Sharma, B., & Khare, S. K. (2024). Optimizing Multi-Product Pipeline Network Configuration Design: A Comprehensive Framework With Objective Function Sensitivity Analysis. *IEEE Access*, *12*, 18804–18820. https://doi.org/10.1109/ACCESS.2024.3360193

Vermeire, G., & Vanhoucke, M. (2025). A priority rule heuristic for the multi-skilled resource-constrained project scheduling problem. *Applied Soft Computing*, *171*, 112776. https://doi.org/10.1016/j.asoc.2025.112776

Wang, B., & Hao, H. (2025). Process Integration in Optimising the Oil and Gas Supply Chain. *Journal of Sustainable Development of Natural Resources Management*, *1*(1), 1–20. https://doi.org/10.13044/j.sdnarema.d1.0556

Wibowo, S. H., & Arvitrida, N. I. (2026). *Balancing Stockout and Demurrage Risks in Fuel Supply Chains through Monte Carlo Simulation* (pp. 102–116). https://doi.org/10.2991/978-94-6463-990-2_9

Wu, X., & Zhang, K. (2022). Chance constrained dynamic optimization approach for single machine scheduling involving flexible maintenance, production, and uncertainty. *Engineering Applications of Artificial Intelligence*, *114*, 105024. https://doi.org/10.1016/j.engappai.2022.105024

Yao, J., Liu, X., Pan, Z., Hao, C., Xu, X., & Jia, W. (2026). Short-Term Scheduling Optimization of a Single-Pipeline Refining System With High Melting Point Crude Oil. *Asia-Pacific Journal of Chemical Engineering*, *21*(3). https://doi.org/10.1002/apj.70211

Zhang, L., Yuan, Z., & Chen, B. (2021). Refinery-wide planning operations under uncertainty via robust optimization approach coupled with global optimization. *Computers & Chemical Engineering*, *146*, 107205. https://doi.org/10.1016/j.compchemeng.2020.107205