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Original Article

Reducing Truck Dwell Time in an Andean Wholesale Market through Lean-Green Six Sigma, Discrete-Event Simulation, and Energy-Environmental Assessment

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Abstract - *Congestion in Andean wholesale food markets is primarily due to a concentration of truck arrivals in specific time periods, combined with inadequate unloading infrastructure and a lack of control during peak periods. This study analyzes the impact of unloading capacity on truck dwell time in an Andean wholesale market, bringing together Lean-Green Six Sigma, DMAIC, and discrete-event simulation coupled with an energy-environmental assessment. The receiving and unloading process was modeled as a discrete-event system characterized by stochastic truck arrivals, FIFO service, and three unloading capacity scenarios with 10, 15, and 20 unloading bays. The primary measure of truck dwell time was supported in the analysis by the indicators of maximum truck dwell time, process variability, and energy consumption. From the results, the baseline scenario with 10 unloading bays presented an average truck dwell time of 101.342 minutes. With the unloading capacity expanded to the 15 and 20-bay scenarios, average truck dwell time was reduced to 70.007 minutes (30.9% improvement) and 54.644 minutes (46.1% improvement). The concurrent reduction of both maximum truck dwell time and its variability confirmed that the lack of unloading capacity was the primary operational bottleneck. The integration of LGSS with discrete-event simulation provides, integrates a rigorous methodology for diagnosing congestion in Andean wholesale markets. The methodology was also useful for evaluating unloading capacity and operational improvements.*

Keywords - *Lean-Green Six Sigma, Energy-environmental, Discrete-event, Truck dwell time, Wholesale food market.*

1. Introduction

The consolidation of bulk shipments, unloading, and redistribution of agricultural products from diverse production areas makes wholesale food markets critical for urban logistics in intermediate cities [1, 2]. Supply activities in Andean intermediate cities are often confined to limited urban spaces. These operations are commonly carried out in constrained urban spaces with limited unloading support, yet are affected by high concentrations of supply vehicles during critical operating periods. However, truck flow management, unloading space, and peak demand coordination also present problems for many supply activities [3, 4].

One of the most evident manifestations of this problem is the prolonged time that trucks remain inside the market. The inadequate service capacity of the market leads to blocked entrances and an overall inefficient reception and unloading process [5, 6]. The concept of truck dwell time is particularly useful for this situation, as it combines the time trucks spend waiting, the time associated with resource use and service, and the time trucks spend being serviced, and offers an overall assessment of system performance.

Continuous improvement philosophies have been beneficial for this type of problem. The core concepts of Lean and Six Sigma have been used to define and describe the main variables as well as quantify variables related to the improvement of waiting and crowding, and the effective use of resources and space [7]. Lean-Green Six Sigma (LGSS) has expanded the focus to include environmental impacts and overall resource efficiency [8]. However, its application in this context (wholesale markets) has been limited. Where LGSS has been implemented, it has not been integrated with the possible modeling systems that would be able to accurately forecast the consequences of making specific alterations to system capacity prior to those alterations being implemented [9].

Discrete event simulation has become a popular tool for modeling systems with stochastic elements and minimizing the interference caused by the analysis of existing operations [10-12]. Its popularity has been seen in modeling port facilities, health care systems, and distribution networks; however, there has been a notable lack of published research focusing on the application of this tool in the simulation of

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urban wholesale markets, particularly in the Andean and intermediate cities. The lack of research focused on this area is unfortunate because of the added challenges of limited infrastructure, physical resource constraints, and a high degree of variability in the operating systems of these markets.

The existing body of research is limited in a number of ways. Previous studies have investigated the individual components of operational logistics and the sustainability of wholesale food markets, yet they tend to be more structured than the wholesale food markets. This has limited the understanding on the resource constraints and the impact of truck arrival concentration, and truck dwell time on the operational sustainability of food wholesale markets with limited infrastructure [13]. This has resulted in a lack of research combining logistics, green supply chain systems, and energy and environmental assessments to develop and assess operational models for real wholesale markets using DMAIC and discrete event simulations to identify the key operational constraints of that market and to assess alternative scenarios of that market based on a key operational performance variable. Most notably, there has been a lack of research focused on Andean wholesale markets to explore the adverse impact of high truck arrival concentration on the operational congestion of the market and the limited unloading services of that market.

Based on this gap, the present study aimed to evaluate the effect of unloading capacity on truck dwell time in an Andean wholesale market through the integration of Lean-Green Six Sigma, the DMAIC cycle, discrete-event simulation, and a complementary assessment of energy-environmental performance. To this end, the process of truck entry, waiting, bay assignment, unloading, and exit was analyzed, and different capacity scenarios were compared in order to identify the main bottleneck of the system.

The main contribution of the article lies in showing, in a scarcely explored context, that unloading capacity constitutes a structural variable of system performance and that its evaluation through simulation can be coherently integrated within a formal continuous improvement logic. Unlike previous approaches that usually examine continuous improvement, simulation, or environmental performance as separate analytical components, this study links them within a single methodological framework focused on truck dwell time reduction.

Complementarily, the study incorporates an energy-environmental dimension linked to the Green component of LGSS, without displacing the main industrial engineering focus. Thus, the contribution is not limited to estimating time reduction, but also to demonstrating how capacity-based operational improvements can be evaluated before implementation and interpreted together with complementary energy-use indicators.

2. Literature Review

2.1. Wholesale Markets and Operational Congestion

Despite functioning as vital logistical nodes for the urban supply, wholesale food markets are limited by the entire system's capacity to manage vehicles' access, unloading, and departures in actual space and time [14]. When there are high levels of incoming arrivals combined with limited service and poorly implemented control measures, congestion becomes a structural operational fact and no longer an isolated event [14, 15]. In this situation, congestion accumulates internally and externally as access points become saturated and movement becomes more and more difficult, causing pressure on local traffic.

In this instance, truck dwell time is especially important as it summarizes the combination of waiting time, the availability of unloading bays, the time spent unloading, and the flow of trucks after unloading. Unlike other measures that only capture the waiting time, truck dwell time can illustrate the consequences that operational decisions and capacity constraints have on the functioning of the entire system. Even though the logistics literature has identified the importance of this type of measure, using it as a primary measure in wholesale food markets has still been documented to be very limited [14, 15]. Therefore, it is recognized that congestion aggravates poor facility performance, but the more challenging issue is what type of structural limitation explains this aggravation and how it can be evaluated comparatively.

2.2. Continuous Improvement in Logistics Systems: From Lean and Six Sigma to LGSS

More recent continuous improvement methods show a better understanding of how process systems that waste resources, demonstrate variability, and lack operational control can be improved. Lean wastes time, movement, and resources. Six Sigma builds on Lean's structural rigor to pinpoint process variables and the root cause of the analysis. When operational problems extend beyond disorder, the combination of both methodologies is most appropriate to logistical systems. Capacity problems, variability that is not uniform, and time pressure that influences irrational behavior are some of the challenges.

Where these methods are used, they tend to describe broad patterns and are mostly not aimed at in-depth analysis of framework performance [16]. The Green element is frequently apparent, but almost always as an "add-on" with no empirical evidence that explains how it relates to the system's operational functions [17, 18].

Consequently, one key concern related to the potential use of LGSS in logistics is how much it is able to concentrate on real improvements to performance and, most importantly, offer a solid framework of resource costs on a transactional basis without losing the focus of the analysis.

2.3. DMAIC as an Analytical Intervention Structure

One of the more process-oriented and stable methodological contributions of Six Sigma is the DMAIC cycle, as it is used to break down complex operational situations that must be treated as manageable in a rational and analytical manner, and its merit goes beyond the organization of steps. It establishes that the logic of an intervention should be based on problem definition, the establishment of the problem parameters (baseline), the quantitative description of the problem (measurement), cause analysis (causal analysis), improvement evaluation (post-intervention), and control evaluation (post-intervention) [19]. Within such complex logistical systems, this methodology is capable of creating the necessary mental separation between merely symptomatic (visible) phenomena such as queues, delays, and so on, and the more fundamental structural phenomena and constraints of the system [16, 19].

However, not all applications of this methodology achieve the same level of rigor. Part of the literature treats it as an autocratic framework and does not make clear what evidence supports each phase of such frameworks, or whether the improvement phase has the appropriate tools to weigh alternatives robustly rather than merely through qualitative contrasts [19]. There appears to be an emerging consensus among scholars that, when only qualitative descriptions of the proposed changes arising from the analysis are provided, without dynamic evaluation of scenarios, causal analysis becomes stagnant. It is evident that DMAIC provides greater value when combined with methodologies that empirically support the measurement, analysis, and intervention phases.

2.4. Discrete-Event Simulation in Systems with Queues

For systems with stochastic customer arrival and service times and pooled resources, Discrete-Event Simulation (DES) is particularly appropriate [20, 21]. One important advantage is that multiple system configurations can be assessed without physically changing the system that is the object of interest, which is especially advantageous when actual modifications are expensive or dangerous [21].

Port, terminal, hospital, and logistics center studies have shown the value of this simulation tool for assessing system performance. In these cases, simulation helps identify system bottlenecks, provides approximate values for system average service times, and shows the impact of enlarging system service capability or changing service policies. Although studies assessing urban wholesale markets are limited, these markets would certainly benefit from this type of simulation.

Urban wholesale markets contain systems with stochastic customer arrivals, congestion, and service bays that are used in sequence [14, 20]. However, the absence of application stems from the little structuring of the system, as opposed to the absence of valid tools and systems to analyze.

2.5. Energy-Environmental Performance Assessment

The inclusion of sustainability, resource efficiency, and environmental performance metrics has transformed the analysis of logistics systems. This is a welcome change since, traditionally, operational performance metrics have been limited to the trade-off between speed and productivity. In logistics and commercial facilities, systems include lighting and auxiliary equipment as well as the effective use and varying intensity and duration of the systems, which ultimately impacts the consumption of resources [22, 23].

Contrarily, existing studies have shown that the dimension is somewhat unevenly integrated. In some instances, analysis of the environment is integrated only tangentially, while in other instances, it redefines study areas to focus on problems that are unrelated to industrial systems [17, 18]. Therefore, it is recommended to separately identify a complementary energy-environmental analysis related to the operational behavior of the system and a specialized analysis of electrical engineering or safety of the facilities. For studies primarily focused on the flow, the capacity, and the dwell time of vehicles, the former is more methodologically sound, as it allows for an enhancement of the Green component of the analysis without rupturing the holistic approach to the study [17, 22, 23].

2.6. Comparative Analysis of Truck Dwell-Time Reduction Strategies

Previous strategies for reducing truck dwell time and congestion in logistics systems can be grouped into four main approaches. The first approach focuses on operational and capacity-based measures, including the improvement of vehicle access, unloading organization, service-resource allocation, and congestion management in wholesale or urban logistics environments [14-16]. These measures can reduce waiting time and improve flow continuity, although their effect depends on the physical layout, available unloading resources, and the degree of operational control in the facility. The second approach is based on continuous-improvement methods, particularly Lean, Six Sigma, and LGSS, which help identify waste, variability, process constraints, and resource-use inefficiencies in logistics and supply chain systems [17-20]. Unfortunately, most of the methods described do not take a dynamic assessment of alternative capacity scenarios before implementation.

While the third approach utilizes simulation-based methods, especially with DES to model queues, stochastic arrivals, service times, and common resources [21, 22], the fourth approach is based on sustainability-oriented assessment and includes energy efficiency and environmental performance measurement to link operational processes and resource consumption [18, 19, 23, 24]. Nevertheless, the environmental component is often treated separately from the operational model, limiting its usefulness for explaining how process changes affect energy-related indicators.

In this context, the present study differs from previous approaches by combining capacity-based scenario evaluation, DMAIC-based problem structuring, discrete-event simulation, and complementary energy-environmental indicators within the same analytical framework. Emerging digital technologies, including IoT-based monitoring and machine-learning prediction, may strengthen future applications through real-time data collection, arrival forecasting, and automated bay assignment. However, their implementation requires a continuous data infrastructure that is not always available in Andean wholesale markets. Therefore, the proposed approach prioritizes a simulation-based and operationally feasible framework for contexts with limited digitalization and constrained infrastructure.

2.7. Research Gap

Overall, the literature has demonstrated four issues: that congestion deteriorates the performance of logistics systems, that Lean and Six Sigma offer useful improvement structures, that DES makes it possible to evaluate scenarios under capacity constraints, and that sustainability has expanded analysis toward the rational use of resources [14-23]. However, these advances have occurred mostly in parallel. In particular, studies integrating these components in food wholesale markets remain scarce, especially in Andean and intermediate cities, where limited infrastructure and operational heterogeneity intensify the problem.

The gap does not, therefore, lie in the absence of tools, but in the lack of integrated evidence on how unloading capacity conditions truck dwell time in this type of system, and how this problem can be analyzed through a coherent articulation among Lean-Green Six Sigma, DMAIC, discrete-event simulation, and a complementary energy-environmental assessment [16]. Compared with previous studies that address these components separately or in more structured contexts, the present work provides a different approach by applying them within the same analytical framework to a real wholesale market, in order to identify its main bottleneck and compare improvement alternatives from a predominantly industrial perspective.

3. Methodology

3.1. Research Design

The research was developed as an applied single-case study, with a predominantly quantitative approach, aimed at evaluating and improving the operational performance of the truck receiving and unloading system in an Andean wholesale market. The methodological design was aligned with the LGSS framework and applied DES to model the current system in order to identify and measure potential improvement scenarios in operational performance.

The design integrated three complementary components. The first corresponded to the operational-industrial diagnosis, focused on times, truck flow, unloading capacity, and functional system constraints. The second consisted of the modeling and comparison of scenarios through discrete-event simulation. The third incorporated a complementary energy-environmental assessment, integrated within the Green component of LGSS, with the purpose of broadening the interpretation of performance without shifting the main focus of the study toward a specialized electrical engineering evaluation.

From a methodological point of view, the simulation was not treated as an independent exercise, but as an analytical resource integrated into the Measure, Analyze, and Improve phases of the DMAIC cycle. In this way, the research was not limited to describing the system, but combined diagnosis, modeling, scenario comparison, and complementary assessment of resource use within the same improvement architecture. The general scheme of this methodological integration is presented in Figure 1.

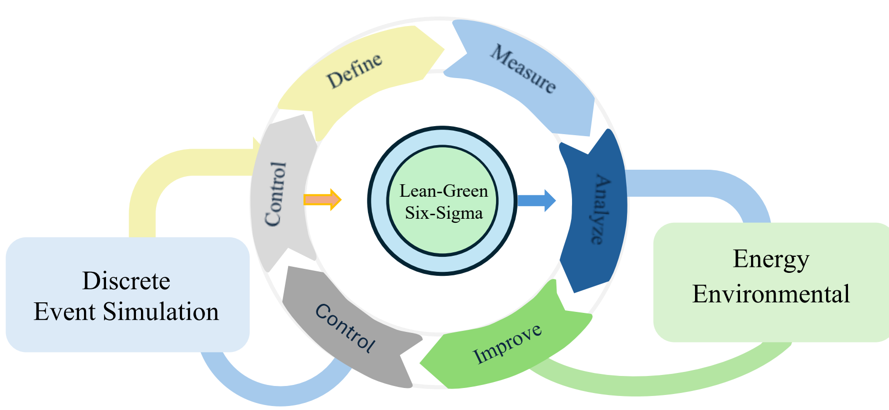

Fig. 1 Methodological framework of the study based on LGSS

3.2. Case Study and System Boundaries

The case study corresponds to an Andean wholesale market linked to the arrival, unloading, and redistribution of food products to merchants, buyers, and other participants in the urban supply system. The problem under study was most intensely manifested during the 02:00 to 05:00 a.m. time interval, during which a high concentration of trucks was observed without a formal entry schedule, based on order of arrival, along with the progressive filling of the unloading bays. The study was limited to the internal truck service processes, including arrival, waiting, bay assignment, unloading, and departure.

3.3. Integrated LGSS-DMAIC-DES Framework for Energy-Environmental Assessment

The methodological framework was structured to integrate LGSS, DMAIC, discrete-event simulation, and the energy-environmental assessment within the same improvement logic. Lean was used to identify operational waste associated with waiting, congestion, unnecessary truck permanence, and inefficient use of unloading space. Six Sigma provided the analytical structure to define the critical-to-quality variables, quantify the baseline condition, and compare improvement scenarios. The Green component expanded the assessment to include energy and resource efficiency, but did not shift the focus from operational performance to specialized electrical analysis.

Within this framework, DMAIC served as the basic structure of the intervention. The operational issue and the boundaries of the system were set in the Define phase. The Measure phase sets the baseline and input parameters. The main constraint in the system was identified in the Analyze phase. The Improve phase examined the impact of different capacity scenarios using discrete-event simulation, and the Control phase set parameters for explaining the system in the post-improvement situation. In this context, DES was embedded in the structure and was not used as an independent modeling approach. DES was the main quantification approach of the Measure, Analyze, and Improve phases. The energy-environmental assessment was connected to the simulated scenarios by distinguishing fixed loads from process-related variable loads, whose operating time could change according to the reduction in truck dwell time.

3.4. Application of the DMAIC Cycle

3.4.1. Define Phase

In the Define phase, the research problem was formulated, the system of interest was delimited, and the critical study variables were established. The problem was defined as the presence of high delays and operational congestion in the truck entry and unloading process, especially during the 02:00 to 05:00 a.m. time slot, due to the high temporal concentration of arrivals, first-come, first-served service, and limited bay capacity.

As part of this phase, the main CTQ was defined as the total truck dwell time in the system, and the secondary CTQ as the waiting time before accessing a bay. Likewise, a SIPOC scheme was prepared to identify suppliers, inputs, processes, outputs, and customers of the system. The functional delimitation of the process is summarized in Figure 2, which presents the SIPOC structure of the truck receiving and unloading system analyzed in the study.

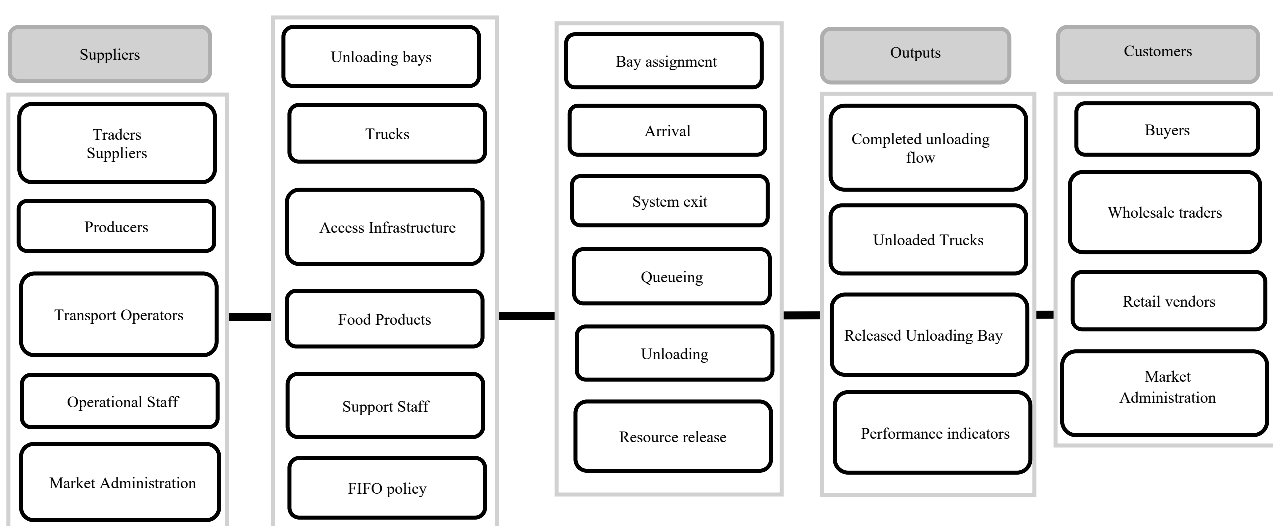

Fig. 2 SIPOC framework of the truck receiving and unloading process

3.4.2. Measure Phase

The measure phase aimed to establish the system baseline and quantify its initial performance. For this purpose, observation of the actual functioning of the market, parameterization of the AS-IS scenario, and measurement of the critical variable through simulation were used. The baseline indicators considered were: number of trucks served, average time in system, maximum time, process variability, and installed capacity corresponding to the current scenario of 10 bays. In this same phase, the preliminary survey of the energy-environmental block was incorporated through load inventory, recording of usage times, and characterization of the main consumption components associated with lighting, refrigeration, ventilation, extraction, weighing, and power outlets at stalls.

3.4.3. Analyze Phase

In this phase, the analysis of the factors causing the problem was developed, and the dominant systemic constraint was determined. The root cause hypothesis was developed around the following six factors: temporal concentration of arrivals, lack of entry scheduling, First In, First Out (FIFO) policy without prioritization, bay capacity, external obstruction at the entrance, and lack of operational control by time intervals.To support this analysis, an Ishikawa diagram shown in Figure 3 was used. This analysis helped differentiate between the apparent symptoms of congestion and the underlying structural constraints of the system, and it was used to define the improvement alternatives to be evaluated.

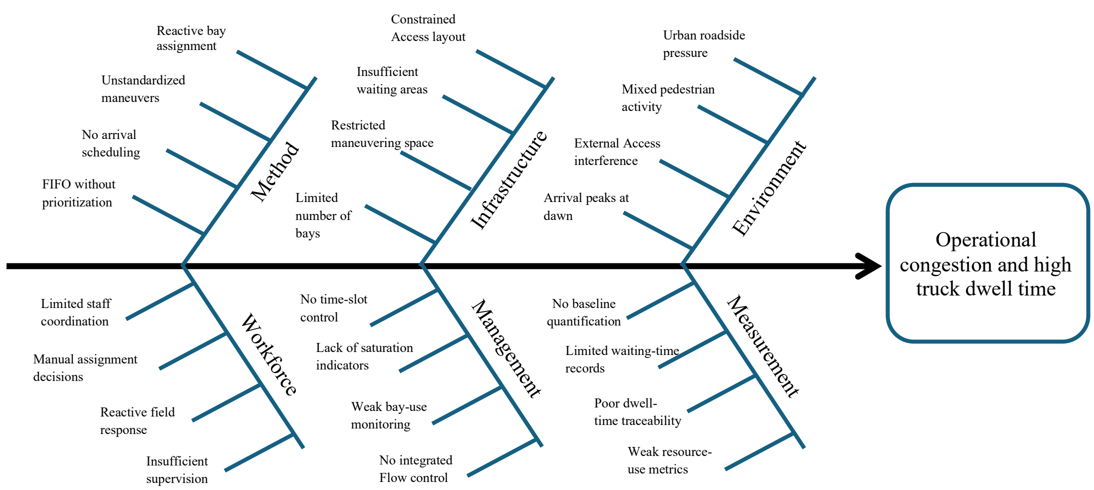

Fig. 3 Ishikawa diagram of the operational congestion problem in the unloading system

3.4.4. Improve Phase

The Improve phase focused on the evaluation of improvement alternatives through scenario simulation. Three capacity configurations were analyzed:

- AS-IS: 10 bays
- TO-BE 1: 15 bays
- TO-BE 2: 20 bays

Beyond bay-capacity expansion, the improvement proposal also included operational measures such as entry time-window scheduling, arrival-flow control, predefined bay assignment, truck-type classification, and maneuver sequencing. These measures were not simulated individually; however, they were included as support actions to improve flow control under the proposed operating scenario.

The unloading capacity for each scenario considered is summarized in Table 1. During this phase, a criterion was established to compare the energy-environmental impacts between the baseline scenario and the improved scenario by separating fixed loads, whose consumption remains relatively unchanged, from process-related variable loads, whose operating time could be reduced due to the shorter system duration.

Table 1. Evaluated scenarios and unloading capacity considered in the Improve phase

Scenario	Bay	Configuration type	Hypothesis evaluated
AS-IS	10	Baseline configuration	The current system presents capacity constraints that increase truck dwell time.
TO-BE 1	15	Intermediate improvement	A moderate increase in bays appreciably reduces the time in the system
TO-BE 2	20	Expanded improvement	A greater increase in bays further reduces time in the system and variability.

3.4.5. Control Phase

The Control phase proposed measures to sustain the improvement, considering that the modifications were evaluated through simulation and were not physically implemented in the market. Here, key indicators were defined as average time in system/truck, average waiting time before unloading, number of trucks in a time period, occupancy of unloading bays, and maximum dwell time.

In these situations, a few control measures consist of recording the time of entry and exit, observing bay utilization on a daily basis, performing periodic saturation checks, and imposing restricted entry, especially during the peak congestion period of 02:00 a.m. to 05:00 a.m.

3.5. Discrete Event Simulation Model

A DES was constructed to model a truck's stay in the wholesale market. Arriving trucks wait for an unloading bay, unload cargo, free resources, and then exit the market. As a typical single-resource queuing system, its focus was on discovering capacity blockades in the unloading system. Simulation resource parameters were an average interarrival time of 3 minutes with a maximum batch of 60 trucks. Each truck had a cargo unloading service time of 15-30 minutes, and the model followed a First-In-First-Out (FIFO) service order. Based on the scenario being analyzed, resource capacity for the unloading bay was modified. To ensure that resource conditions remained constant across multiple model scenarios, a run was considered valid when all generated entities had been completely processed, and the model ended with no remaining unserved entities in the system. The primary output of the simulation was the total time that trucks spent in the system, while the time spent in the service queue was regarded as a secondary output.

3.6. Data Sources and Preprocessing

Data for this study were gained through firsthand field observation, process characterization of unloading in order to determine the operation, and an energy-load inventory of the market facilities. Field observation determined the critical operating period, helped differentiate between the process stages, supported the verification of the FIFO service logic, and assisted in the characterization of unloading bay usage. The operational parameters were aligned with the simulation and framed the inputs related to demand, service time, resource constraints, and outputs.

In order to preserve consistency between the scenarios, demand and service time assumptions of the simulations were retained, while unloading capacity was adapted to the set configurations. This Preprocessing made it possible to isolate the effect of unloading bay capacity on truck dwell time. With consideration of the energy-environmental aspect, a load survey was conducted, and the data were disaggregated by components, rated power, quantity, and time, and were classified as either fixed or process-related variable loads.

3.7. Study Variables and Indicators

Indicators were split into operational indicators and energy-environmental indicators. Operational indicators provided an analytical foundation and were quantifiable by the total number of trucks serviced, average time spent in the facility, maximum time spent in the system, process time variability, time spent in a queue, and bay occupancy. These indicators provided an analysis of the unloading system, identified the bottlenecks, and measured the impacts of changes in the system's installed capacity.

The electricity consumption for the lighting, exhaust fans, ventilators, electronic scales, refrigeration chambers, power outlets at the stalls, total electricity consumption, and consumption per truck served, along with the lighting operating time and the process energy intensity, were used to analyze the energy-environmental indicators. The variables and indicators presented in this study were classified and tabulated in Table 2 according to their respective dimensions.

Table 2. Study variables and indicators

Variable/indicator	Dimension	Type	Unit	Source	Use in the analysis
Number of trucks served	Operational	Outcome	trucks	Simulation	Assess processing capacity
Average time in system	Operational	Main CTQ	min	Simulation	Compare process performance
Waiting time before unloading	Operational	Secondary CTQ	min	Simulation	Assess pre-assignment congestion
Maximum time in the system	Operational	Outcome	min	Simulation	Assess dwell-time extremes and congestion
Standard deviation of time in the system	Operational	Outcome	min	Simulation	Assess truck-level variability
Bay occupancy	Operational	Outcome	% or number of occupied bays	Simulation	Detect unloading saturation

Unloading capacity	Operational	Intervention variable	number of bays	Scenario design	Compare AS-IS and TO-BE
Total electricity consumption	Energy-environmental	Outcome	kWh/day	Load inventory and estimation	Compare energy performance
Specific consumption per truck served	Energy-environmental	Outcome	kWh/truck	Estimate unit consumption	Assess relative energy efficiency
Operating time associated with lighting	Energy-environmental	Outcome	h/day	Field survey and scenario adjustment	Link operating time and lighting use
Process energy intensity	Energy-environmental	Outcome	kWh/h of operation	Calculation from variable loads	Assess process energy performance
Installed power by component	Energy-environmental	Baseline variable	W	Field survey	Estimate component consumption
Usage time by component	Energy-environmental	Baseline variable	h/day	Field survey - operational assumption	Calculate the energy consumed by the component
Estimated consumption by component	Energy-environmental	Outcome	kWh/day	Calculation (E = P*t)	Determine load contribution

3.8. Energy-Environmental Assessment Procedure

The energy-environmental assessment was developed to estimate electricity consumption, specific consumption per truck, lighting operating time, and process energy intensity from the load inventory and the operational performance obtained through simulation. First, a load inventory was prepared based on direct observation of the market and the recording of the main electrical and energy components of the facility. For each component, quantity, unit power, total installed power, and daily usage time were estimated. Daily electricity consumption was estimated based on the relationship given in Equation (1):

$$E = P \cdot t \quad (1)$$

Where E represents the energy consumed, P the installed power, and t the operating time. Based on this criterion, the estimated consumption by component and the total consumption of the facility were calculated. For the comparison between scenarios, the loads were classified into two groups:

- Fixed loads, whose consumption does not change substantially with operational improvement.
- Variable loads associated with the process, whose operating time may be reduced by decreasing the effective duration of the unloading system.

Using the simulation outputs, a temporal reduction factor was obtained as the ratio between the average time in the improved scenario and the average time in the baseline scenario. This factor was applied only to process-related variable loads, assuming that their operating time decreases proportionally with the reduction in system operating time. With this adjustment, total electricity consumption, specific consumption per truck served, lighting operating time, and process energy intensity were estimated. Figure 4 summarizes the energy-environmental procedure and the comparison between the baseline and improved scenarios.

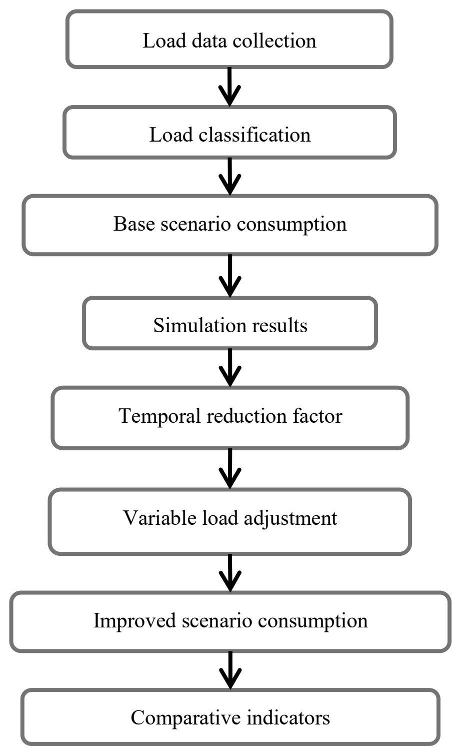

Fig. 4 Load classification framework and energy-environmental assessment procedure

3.9. Model Validation and Sensitivity Analysis

Model validation combined logical verification, conceptual correspondence with the observed process, and scenario-based sensitivity analysis. Logical verification confirmed that each simulated truck completed the full-service cycle and that each run ended without unprocessed entities in the system. This step supported the internal consistency of the simulation model and avoided incomplete comparisons among scenarios.

Conceptual validation examined the correspondence between the modeled system and the operating conditions observed in the market. The model reproduced the main characteristics of the real process, including FIFO service discipline, concentrated truck arrivals during the critical operating period, limited unloading capacity, and sequential use of unloading bays. This made the model suitable for evaluating the internal receiving and unloading process without extending its scope to the external urban traffic network.

Sensitivity analysis varied only the unloading capacity while keeping the main operating assumptions constant. The AS-IS scenario included 10 bays, whereas the TO-BE scenarios included 15 and 20 bays. This controlled comparison isolated the effect of unloading capacity on truck dwell time, maximum dwell time, standard deviation, and the energy-environmental indicators derived from the temporal reduction factor.

4. Results

4.1. Diagnosis of the Current State (AS-IS scenario)

Under a stochastic arrival pattern and FIFO service, for 60 processed trucks, a baseline scenario was established with the current configuration of 10 unloading bays to derive the reference line of the system. Under these conditions, the system completed service for the entire lot but showed operationally stressed performance, with an average dwell time of 101.342 min, a maximum time of 188.398 min, and a standard deviation of 48.854 min.

The minimum observed value was 21.237 min, which evidences wide dispersion among the served vehicles. The main indicators of the AS-IS scenario are summarized in Table 3, where it is observed that the system manages to process all the simulated demand, although with high delays and considerable variability.

Table 3. Results of the AS-IS scenario (10 bays)

Indicator	Value
Processed trucks	60
Average time in system (min)	101.342
Minimum time (min)	21.237
Maximum time (min)	188.398
Standard deviation (min)	48.854

The operational configuration of the baseline scenario and the output of the simulation model are shown in Figure 5, where the flow of the truck service process and the main statistics of total time in the system for the AS-IS condition with 10 unloading bays are observed.

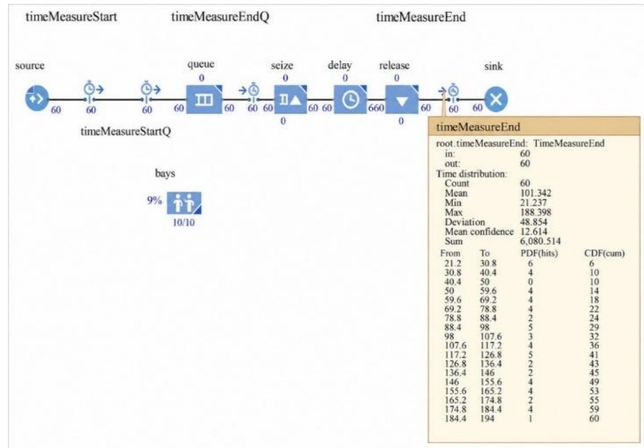

Fig. 5 Model output for the AS-IS scenario with 10 bays

The distribution of total time in the system for the AS-IS scenario is shown in Figure 6, where the frequencies are grouped by time intervals obtained from the simulation output.

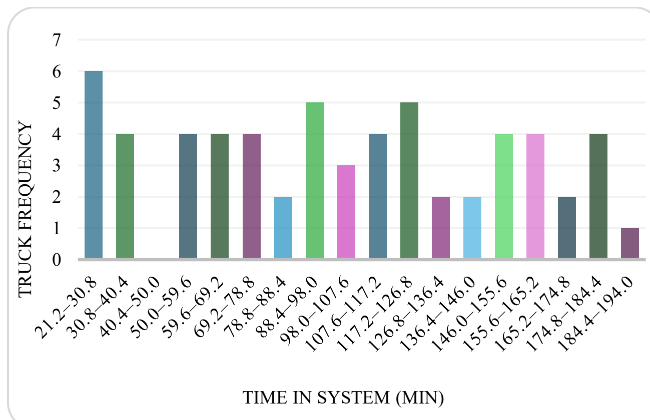

Fig. 6 Distribution of total time in the system in the AS-IS scenario

4.2. Comparison of Unloading Capacity Scenarios

The comparison among scenarios made it possible to evaluate the effect of increasing the number of bays on truck dwell time. For this purpose, three configurations were analyzed: 10 bays (AS-IS), 15 bays (TO-BE 1), and 20 bays (TO-BE 2), keeping the total number of processed trucks constant.

In the scenario with 15 bays, the average time in the system decreased to 70.007 min, while in the scenario with 20 bays, it was reduced to 54.644 min. In parallel, the maximum time decreased from 188.398 min in the baseline scenario to 125.126 min and 94.746 min, respectively.

Increasing unloading capacity reduced the average truck dwell time and also decreased the severity of the most congested operating conditions. Table 4 provides a detailed comparison of the major simulation outputs for each capacity scenario.

Table 4. Comparison of results among capacity scenarios

Bays	Processed trucks	Average time in system (min)	Minimum time (min)	Maximum time (min)
10	60	101.342	21.237	188.398
15	60	70.007	21.151	125.126
20	60	54.644	21.104	94.746

Figure 7 provides a clearer visualization of the average time in the system across the different scenarios.

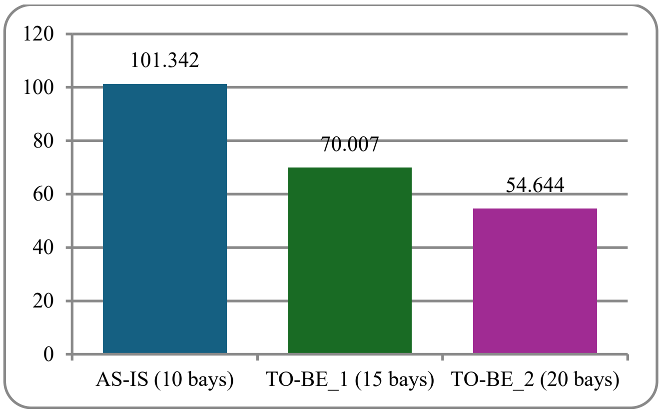

Fig. 7 Comparison of average time

Figure 8 compares the maximum time in the system and the corresponding standard deviation for each scenario.

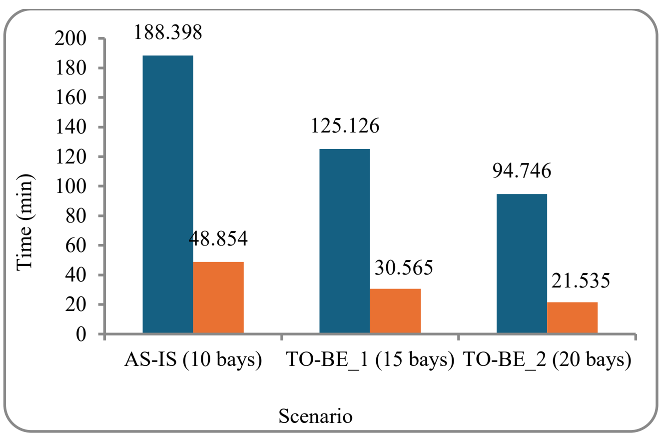

Fig. 8 Comparison of maximum time and standard deviation among scenarios

The percentage improvements are summarized in Figure 5. The average dwell time decreased by 30.9% when unloading capacity increased from 10 to 15 bays and by 46.1% when capacity increased from 10 to 20 bays.

The additional improvement from 15 to 20 bays was 21.9%, indicating that the largest performance gain was obtained when the baseline scenario was compared with the expanded-capacity configuration.

Table 5. Percentage improvement in the average time in the system

Comparison	Percentage improvement
10 → 15 bays	30.9 %
10 → 20 bays	46.1 %
15 → 20 bays	21.9 %

4.3. Quantitative Identification of the Bottleneck

The combined behavior of the indicators corroborates the claim that unloading capacity was the predominant systemic bottleneck. This claim is evidenced through three converging patterns: unloading capacity limitations were operationally reflected through the uninterrupted decline in average system time, the reduction in maximum time, and the incremental decrease in standard deviation as the number of bays increased. Therefore, the bottleneck was not identified only from the presence of queues in the baseline scenario, but from the quantitative response of the system when unloading capacity was modified under equivalent demand and service-time assumptions. The visual evidence of resource saturation in the baseline scenario is presented in Figure 9, while the relationship between the number of unloading bays and average dwell time is presented in Figure 10, where a decreasing trend in the system time is observed as the capacity of the unloading resource increases.

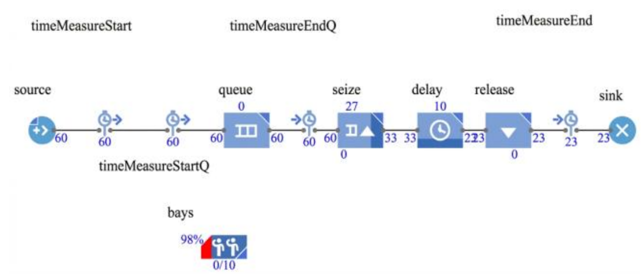

Fig. 9 Queue accumulation and saturation of the unloading resource in the AS-IS scenario

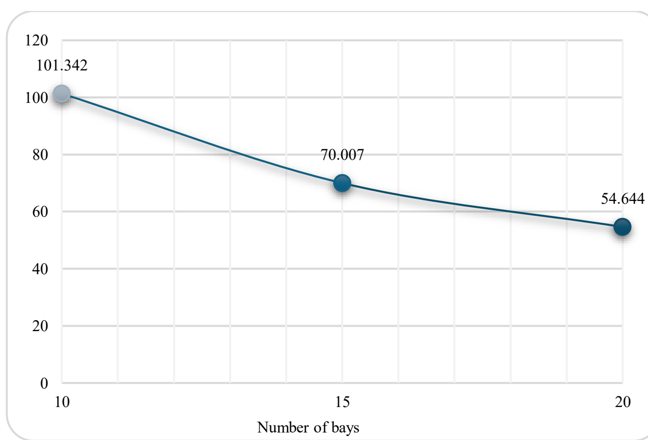

Fig. 10 Relationship between the number of bays and the mean time in the system

Overall, the results indicate that the increase in capacity not only reduced the average time in the system but also decreased the observed maximum values and process variability.

4.4. Relationship between Internal Performance and the Immediate Surroundings

The model focused on the internal process of truck receiving and unloading. However, Figure 11 shows the location of the main access points and the areas adjacent to the market with greater operational interference, making it possible to spatially contextualize the analyzed system.

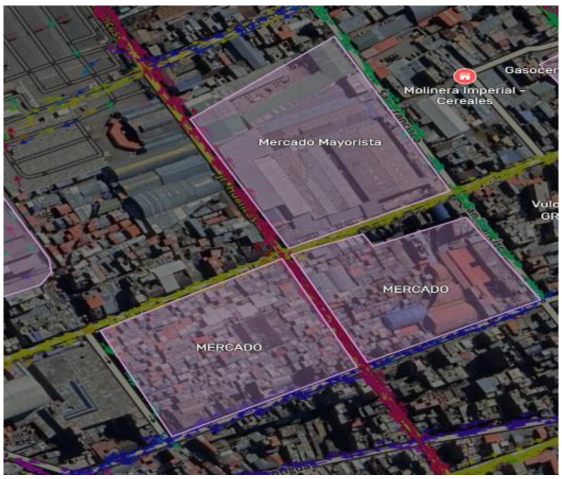

Fig. 11 Sketch of the immediate surroundings of the market and affected roads

In this context, the results of the internal system can be interpreted in relation to the immediate access areas of the market. However, this reference must be interpreted within the scope of the study, since the model did not include an explicit representation of the urban road network or external traffic.

Thus, the surrounding-area information was used only to contextualize the operational problem, not to establish a direct causal effect on urban traffic conditions.

4.5. Results of the Energy-Environmental Component

The energy-environmental component has been integrated as an additional dimension in the analysis to describe the energy consumed by lighting and auxiliary equipment, as well as other elements supporting the market's operational activities. The results were categorized into two levels: load inventory and estimated facility consumption, and the comparative energy-environmental indicators corresponding to the baseline case and the improved case.

First, a temporal load inventory was developed based on market observation and real data for luminaires, light bulbs, auxiliary devices, plugs, refrigeration units, and similar equipment. The market was described as a small- to medium-sized facility, with an approximate area of 1000 to 3000 m², and it was verified that it has LED and fluorescent luminaires, support lamps at the stalls, light bulbs in the operational area, and ventilation, exhaust, weighing, and refrigeration equipment.

The load characterization is presented in Table 6, which illustrates an installed capacity of approximately 20.8 kW and an estimated daily consumption of 143.6 kWh/day. Refrigeration chambers were shown to have the highest energy consumption, at 48.0 kWh/day.

This was followed by general lighting at 30.0 kWh/day and extractors at 25.6 kWh/day. Fans showed the smallest contribution to the total energy consumption. Electronic scales showed a lower but still significant share of the energy balance.

Table 6. Inventory of electrical loads and estimated market consumption

Component	Quantity	Unit power (W)	Total power (W)	Usage time (h/day)	Estimated consumption (kWh/day)
General lighting	30	100	3000	10	30.0
Spot lighting/floodlights	4	300	1200	10	12.0
Extractors	8	800	6400	4	25.6
Fans	5	60	300	4	1.2
Electronic scales	30	30	900	12	10.8
Refrigeration chambers	8	1000	8000	6	48.0
Power outlets / LED bulbs	20	50	1000	16	16.0
Estimated total	-	-	20 800	-	143.6

Figure 12 depicts the percentage distribution of electricity consumption. The largest share of electricity consumption was represented by refrigeration chambers at 33.4%. General lighting accounted for 20.9%, and extractors accounted for 17.8%.

The other components accounted for lower relative contributions. These include power outlets, LED stall bulbs, spot lighting, electronic scales, and fans. In general, these components represented minimum electricity consumption.

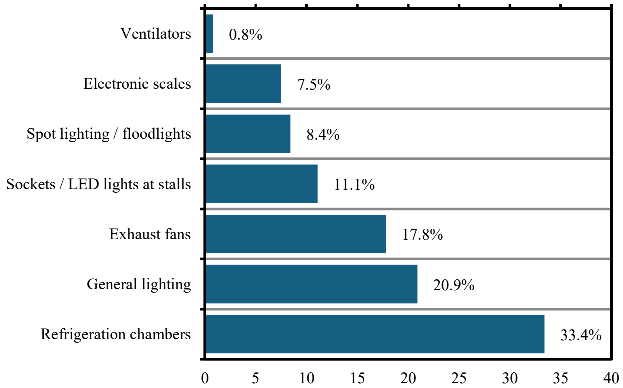

Fig. 12 Percentage distribution of electricity consumption by component

Second, a comparison was made between the baseline scenario of 10 bays and the improved scenario of 20 bays. For this purpose, two categories of loads were identified: fixed loads, whose consumption does not vary significantly with operational improvement, and process-related loads, for which operating time could be reduced with a decrease in the effective duration of the system. Based on the simulation results, the average time in the system decreased from 101.342 min to 54.644 min, which is equivalent to a temporal reduction factor of 0.539. Under this criterion, the usage time of the variable operational loads was proportionally adjusted in the improved scenario. This criterion linked the operational improvement estimated through simulation with the energy-environmental comparison, without assuming that all facility loads changed as a result of the reduction in truck dwell time. The comparative indicators are presented in Table 7. The estimated total electricity consumption decreased from 143.6 kWh/day to 106.9 kWh/day, while the specific consumption per truck served decreased from 2.39 kWh/truck to 1.78 kWh/truck. Likewise, the operating time associated with lighting decreased from 10.00 h/day to 5.39 h/day. The process energy intensity remained at 7.96 kWh/h of operation, since it was calculated considering only the variable operational loads associated with the unloading system.

Table 7. Energy-environmental indicators of the system

Indicator	Unit	10 bays	20 bays
Total electricity consumption	kWh/day	143.6	106.9
Specific consumption per truck served	kWh/truck	2.39	1.78
Operating time associated with lighting	h/day	10.00	5.39
Process energy intensity*	kWh/h of operation	7.96	7.96

** The process energy intensity was calculated considering only the variable operational loads associated with the unloading system.*

The field survey supporting the energy-environmental characterization is presented in Figure 13, where the main lighting conditions and operational support elements identified in the market are documented.

Fig. 13 Photographic record of the energy-environmental survey: (a) Interior lighting, (b) Commercial corridor lighting, (c) Refrigeration/display equipment, and (d) Sales area lighting.

Overall, the results show that the current system operated with a significant constraint in the unloading stage and that increasing the number of bays consistently reduced truck dwell time. The scenario with 20 bays presented the best overall performance, with a reduction of 46.1% compared with the baseline scenario, while the scenario with 15 bays already showed an improvement of 30.9%. Likewise, the increase in capacity reduced the observed maximum values and process variability, and the energy-environmental analysis showed a decrease in estimated total electricity consumption and specific consumption per truck served in the improved scenario.

5. Discussion

5.1. Main Findings

The exposed constraints around unloading capacity were the primary operational restrictions of the systems in question. When different scenarios were analyzed, the increases in the number of unloading bays were the primary factors for improvements in process stability and reduction of the truck waiting times. In particular, the change from 10 bays to 15 bays resulted in a 30.9% reduction in the average time in the system, and moving from 10 to 20 bays resulted in a 46.1% reduction. In addition, the average time, maximum time, and standard deviation decreased simultaneously, and both operational speed and stability improved.

The results indicate that the problems in the market cannot be attributed solely to the time-based clustering of arrivals during the early morning hours. The congestion that was observed is the result of the combination of a demand pattern and a service infrastructure that is too small to handle. Thus, truck dwell time served as a suitable CTQ variable for assessing the receiving and unloading process, because it captures the combined effect of waiting, resource availability, and service duration [16]. DES converted the observed congestion problem into quantifiable scenario results, supporting the identification of unloading capacity as the main bottleneck.

5.2. Comparison with Other Studies

The results align with previous logistics process improvement studies, where reducing waiting and non-value-added time, identifying constraints, and structuring the diagnosis of process problems are common intervention targets. This finding also agrees with prior Lean Six Sigma studies showing that variability, waiting, and inefficient resource use reduce logistics process performance [17].

Likewise, the usefulness of DES observed in this research is consistent with recent and classical reviews that have highlighted its value for representing systems with stochastic arrivals, queues, shared resources, and evaluation of alternative scenarios without physically intervening in the real operation [21, 22]. The main similarity is that simulation allows a comparison of different capacity configurations and their impact on certain operational indicators, especially the receiving and unloading processes.

The current paper, however, presents two significant differences. The first is the context of application. Most of the referenced works on the optimization of unloading rely on the traditional industrial context, logistics centers, or more structured supply chains, whereas this paper refers to an Andean wholesale market, that is, to an urban-commercial context with spatial restrictions and a heterogeneous typology and organization with operational dynamics that are intensive in particular time slots. The other difference refers to the integration of the different methodologies. In some of the referenced works, Lean and/or Six Sigma and/or simulation are applied, but in this case, simulation is integrated into DMAIC, which not only improves the internal coherence of the design but also extends the range of the analysis that goes beyond the studies that are oriented to time, queues, and capacity.

For the above reasons, the proposed method achieved significant results, as the intervention was based on the specific and quantitative identification of the unloading capacity constraint, and not on a general operational change. The simulation, in this case, was used to examine the structural resources of the bays on truck dwell time, and to set the demand and service-time constraints. It also provided the basis for pre-implementation improvement scenarios, which helped focus the analysis on the resource and, as a result, helped avoid reliance on qualitative assessments.

5.3. Interpretation of the Findings

The data indicate that system improvements should focus on unloading capacity. The change in unloading wait times suggests that service infrastructure impacts operational performance. The layout of bays and strategic flow control are tactical components of operational performance that facilitate operational stability. A concurrent reduction in average, maximum, and variance of wait times indicates the system of unloading is now faster and more reliable. This facilitates the control and predictability of operations [16].

The model did not incorporate urban roadway systems or define specific cause-and-effect interdependencies with outside congestion. Thus, the analysis of the surrounding area should be seen as interpreted only as contextual evidence. In the absence of an urban traffic model, reduced truck permanency in the market may lessen congestion at the access points, but this effect would require a specific urban traffic model for direct verification. Similarly, outside congestion would be caused by urban traffic and other smaller markets near the wholesale market of this study.

The energy-environmental analysis should be interpreted as a complementary analytical layer rather than as the central modeling component of the study. Its contribution lies in linking the operational reduction in truck dwell time with electricity consumption indicators associated with market operation. However, the results depend on the load inventory, installed-power estimates, usage-time assumptions, and the criterion used to adjust process-related variable loads. Therefore, this component should be interpreted as an approximate energy-environmental assessment rather than as a comprehensive energy model [24].

5.4. Managerial and Policy Implications

There are several implications for the management of Andean wholesale markets and similar urban logistics facilities. First, market administrators should consider unloading capacity as a structural control variable and not only as an infrastructure condition. The diminishing average and maximum dwell times and the diminishing variability of the process suggest that service and operational stability are affected by the availability of the bays. Thus, the market management must include the expansion, relocation, or temporary mobilization of the bays during the high-demand periods as part of the operational plans.

The results, however, have a second implication in that they support the establishment of basic control mechanisms during key operational periods, especially those occurring from 02:00 to 05:00 a.m. These mechanisms may include entry-time registration, time-window assignment, monitoring of bay occupancy, and periodic saturation checks. Such measures are especially relevant in markets where advanced digital infrastructure is limited, since they can improve flow control without requiring immediate deployment of complex technologies.

Third, the energy-environmental results suggest that operational improvements should not be evaluated only through time-based indicators. The reduction in truck dwell time may also modify the duration of process-related loads, which affects electricity consumption and specific consumption per truck. For this reason, managers should integrate operational and resource-use indicators when assessing improvement alternatives.

5.5. Strengths and Limitations

One of the strengths of the study is that it presents all components as a single study that demonstrates the integrity and coherence of a specific methodology. The problem was theoretically framed with LGSS, methodologically organized using the DMAIC approach, and subjected to quantitative analysis through discrete-event simulation. Here, the integration ensured that simulation was not viewed as an independent method and that the other tools contributed to the evidence-based function of the research process framework [18]. The use of a critically defined variable in the study is also noteworthy, and in this case, truck waiting time exemplified this, since it allowed direct evaluation of system performance with ease, particularly in the context of multi-scenario assessment.

In addition, the applied and contextualized nature of the case study is another strength of this research. Operational improvement and simulation are two areas in which the Andean wholesale market provides evidence from a scarcely researched region. However, there are limitations of the study that must be clearly delineated. The first and most important of these limitations is that the model is confined to the internal reception and unloading processes, which means that it neither considers nor explicitly models the urban road network or the complete external traffic system. For that reason, any claims about the external boundaries of the model should be treated with caution and should not be interpreted as a direct result of urban mobility modeling. The second limitation is that the energy-environmental component has a complementary scope. Although its incorporation strengthens the Green approach of the study, it does not constitute a modeling block equivalent to the operational component. In addition, its results depend on the level of detail of the load survey, the quality of the power and usage time estimates, and the methodological assumption used to adjust the operating time of variable loads among scenarios [19, 24].

The third limitation refers to the fact that the enhancements were assessed ex ante by means of a simulation, which did not require the actual implementation of the improvements in the marketplace. Thus, the results build a strong justification for the improvements, but the tangible benefits would be confirmed in a later phase of actual implementation and real-world observation. Lastly, given that the study was mostly concerned with bay capacity as the intervention variable, future research could be more comprehensive and include in more detail policies for the scheduling of arrivals, prioritization of vehicles, load segmentation, time slot controls, and digital tracking systems.

6. Conclusion

Insufficient unloading capacity was confirmed to be the main operational constraint to the operation of the truck receiving and unloading system of the surveyed wholesale market. The scenarios developed show that the number of unloading bays directly impacts the reduction of truck dwell time, confirming that this variable constitutes the central Critical-to-Quality (CTQ) factor for the process. The results show that the baseline scenario with ten bays had an average dwell time of 101.342 minutes. The scenarios with fifteen and twenty bays had an average dwell time of 70.007 minutes and 54.644 minutes, respectively. Consequently, the expanded-capacity scenario achieved the highest improvement, with a 46.1% reduction compared with the baseline condition.

Methodologically, this study demonstrates the ability to integrate Lean-Green Six Sigma to evaluate energy and environmental issues as part of a system from the Green perspective, within industrial engineering. The results can be a starting point for improving the unloading capacity, the service flow, and the operational control of the market. The main limitation is that the results are restricted by the scope of the model, considering the internal unloading process, and not the entire urban road network.

Conflicts of Interest

The authors declare no conflict of interest.

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