Journal of Applied Data Sciences
Vol. 7, No. 1, January 2026, pp. 1449-1461

Model Integration of Information Technology in Optimizing the Food Supply Chain of the Free Nutritious Meal (MBG) Program to Reduce Food Waste

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(Received: July 1, 2025; Revised: August 25, 2025; Accepted: November 18, 2025; Available online: December 19, 2025)

Abstract

The Free Nutritious Meal Program in Surabaya is a major government initiative designed to improve child nutrition and reduce hunger among schoolchildren from low-income families. Despite its importance, the program faces significant challenges of food loss and waste due to inefficiencies in transportation, storage, and demand matching. This study introduces a Smart MBG Cloud Platform and applies a linear programming model to optimize the program's supply chain under two operational scenarios: a baseline system without Information Technology (IT) support and an IT-enhanced system integrating route optimization and digital inventory monitoring. Simulation results reveal substantial efficiency gains in the IT-integrated model. This study was conducted using a mixed-method approach involving samples from schools as beneficiaries and the Nutrition Fulfillment Service Unit as providers of free nutritious meals. Using simulation data from five kitchens and ten schools and conducting 50 stochastic replications, the IT-enhanced model achieved a 28% reduction in transportation cost and the total objective value declined by 22%, compared to without IT support scenario. These results demonstrate that incorporating digital route planning and inventory monitoring not only reduces operational expenses but also mitigates organic waste, ensuring fresher meal delivery and supporting sustainability targets. These improvements highlight the potential of digital tools to minimize inefficiencies, ensure fresher meal delivery, and strengthen the nutritional impact of the program. Beyond operational savings, the IT-based model contributes to reduced organic waste generation and aligns with broader sustainability goals. The findings provide empirical evidence that digital transformation can significantly enhance the performance of public food programs and offer practical insights for policymakers to replicate these strategies in similar urban initiatives.

Keywords: Food Supply Chain, Linear Programming, Optimization, Information Technology, Public Meal Programs

1. Introduction

The Free Nutritious Meals (MBG) Program is a national initiative launched by the Indonesian government in January 2025 to improve child nutrition and reduce hunger among underprivileged schoolchildren [1]. The program ensures that meals meet the Recommended Dietary Allowance, offering balanced portions of carbohydrates, proteins, fats, vitamins, and minerals. In Surabaya, the program began with 6,159 students across 10 schools, where early monitoring revealed strong acceptance and high meal consumption rates. Beyond improving nutrition, the MBG program aims to alleviate economic pressures on low-income families and support national human capital development [2], [3].

However, effective implementation poses challenges, particularly in food waste management. Globally, more than one billion tons of food are wasted annually, creating significant social, economic, and environmental consequences. The United Nations Sustainable Development Goal (SDG) targets poin 12.3 calls for halving global food loss and waste by 2030 [4]. While this issue has gained international urgency, its local manifestations and solutions vary widely depending on urban infrastructure, consumption patterns, and policy enforcement capacity.

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DOI: https://doi.org/10.47738/jads.v7i1.1039

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Surabaya provides an illustrative case for studying these dynamics. As Indonesia's second-largest city and an early adopter of the MBG program, it combines a dense urban population with a rapidly expanding public food service network. The Surabaya city generates about 1,600 tons of waste. Around 60 percent of waste is organic, largely consisting of food scraps and vegetable residues [5]. This equates to nearly 960 tons of organic waste deposited each day at the Benowo landfill [6]. Preliminary monitoring conducted at five pilot schools participating in the MBG program (January–June 2025) recorded an average of 40–50 kilograms of food waste generated per day per school, depending on student population and meal type. This observation aligns with the findings of [5] who reported comparable daily waste generation levels in urban Surabaya schools. When scaled to multiple schools, this volume significantly adds to the city's organic waste burden, which is already straining landfill capacity and contributing to greenhouse gas emissions. Globally, similar public food programs face difficulties in minimizing waste due to inefficiencies in logistics, limited storage capacity, and inadequate distribution strategies [7]. These realities highlight the gap between the ideal objectives of the MBG program and the inefficiencies that emerge in large-scale food distribution systems.

In Indonesia, including Surabaya, the government is aware of potential food waste generated by the MBG program. Although initial monitoring reports indicate that food waste quantities have not been large, the Surabaya City Government and the Ministry of Environment have initiated proactive interventions to prevent waste accumulation. These include a 2025 pilot project on school-based organic waste segregation under the Kampung Zero Waste initiative, the installation of small-scale composting units in ten pilot schools beginning in April 2025, and coordination with the Nutritional Fulfillment Service Unit (SPPG) to ensure meal residues are collected for composting or biogas conversion. These measures reflect the city's commitment to integrating waste reduction into the operational framework of the MBG Program. The Ministry of Environment coordinates with program implementers and regional offices to ensure waste management standards are followed, including pilot projects focused on waste management for the free meals program. This reflects the broader challenge of managing food waste in large-scale public nutrition programs, where inefficiencies in distribution and consumption can lead to avoidable waste [8]. The Surabaya city's growing population and economic recovery after the COVID-19 pandemic have increased food consumption and waste generation, exacerbating the problem. Globally, food assistance programs face difficulties in rescuing and redistributing surplus food due to logistical and storage challenges. Furthermore, only a small fraction of surplus food is donated, with perishables often being underrepresented because of transportation and storage constraints [9]. Strengthening food rescue efforts requires expanded capacity in storage, transport, and real-time data sharing to reduce waste effectively [10].

While the importance of reducing food loss and waste in public nutrition programs has been widely recognized, there remains limited empirical research on the role of supply chain optimization and the use of information technology to address these challenges in Indonesia [11]. Current interventions have focused largely on waste management after meals are distributed, rather than preventing inefficiencies upstream in forecasting, routing, and storage. Information and Communication Technologies (ICT) enhance the efficiency of logistics operations within food supply chains [12]. By adopting ICT tools, logistics can synchronize the flow of materials and information, which is crucial for the real-time management of perishables, thus significantly reducing food waste associated with mismanagement and inefficiencies in the supply chain [13]. The utilization of smart technologies, such as IoT sensors, has shown promise in tracking and managing inventory, which aids in mitigating waste [11]. For instance, intelligent packaging can monitor the freshness of food items, ensuring that products are consumed before they degrade, which directly addresses prevalent issues in food waste management [14]. Moreover, despite the global evidence that digital tools such as predictive analytics, IoT-based inventory monitoring, and GPS route optimization can reduce inefficiencies in food supply chains, little is known about their measurable impact when applied to government-led school meal programs in urban contexts such as Surabaya. This study addresses this gap by applying a linear programming model to simulate the operations of the MBG program under two scenarios: the baseline without IT integration and an IT-enhanced model. The analysis compares costs, food loss, and system efficiency across the two approaches, with the goal of providing actionable insights for policymakers. By doing so, this research contributes both to academic understanding of supply chain optimization in public food programs and to practical strategies for reducing waste and improving nutritional service delivery.

 ISSN 2723-6471

2. Literature Review

2.1. Food Supply Chain in Public Meal Programs

Public meal programs, particularly those implemented at the municipal or national level, operate within a highly complex supply chain network that spans multiple actors, including procurement agencies, food producers, logistics providers, and distribution centers [4]. In free or subsidized meal initiatives such as Indonesia's MBG program, the supply chain must consistently deliver perishable goods to beneficiaries while maintaining compliance with nutritional standards. These operations are resource-intensive, demanding coordination between central authorities, local suppliers, and school-based service units such as canteens or kitchens [10]. The effectiveness of such programs is heavily influenced by logistical reliability, demand forecasting accuracy, and the capacity to minimize food loss throughout the process, where inefficiencies can exacerbate malnutrition and economic burdens on low-income families.

International experience underscores both the opportunities and contextual limits of supply chain management in public feeding programs. The United States National School Lunch Program, for instance, illustrates how large-scale, federally coordinated systems depend heavily on advanced logistics, dedicated federal funding, and robust cold-chain infrastructure to sustain quality and participation. These institutional and financial capacities differ markedly from Indonesia's MBG program, which operates within more constrained municipal budgets and evolving digital readiness. Thus, the U.S. case serves primarily as an example of the potential role of advanced logistics technologies in mature systems, rather than as a directly comparable benchmark.

In contrast, India's Mid-Day Meal Scheme presents a more contextually relevant parallel due to its decentralized implementation and similar challenges in ensuring consistent quality and reducing waste across diverse regions. However, differences in cultural food preferences, procurement systems, and kitchen-scale infrastructure still limit the direct transferability of lessons. Together, these comparisons highlight how national and local contexts shape the operational dynamics of public meal programs, reinforcing the need for Indonesia-specific strategies such as IT-enabled optimization within the MBG framework. While local sourcing in India improved resilience and reduced spoilage, the program continues to face inconsistencies in quality control and logistics, especially in rural districts [15], these structural challenges differ from Surabaya's primarily urban setting, where issues stem less from geographic dispersion and more from congestion, limited cold storage, and the coordination of multiple vendors under municipal oversight.

In Sub-Saharan Africa and South Asia, food assistance programs operate under conditions of high market volatility, weak logistics infrastructure, and chronic food price inflation. Their increasing adoption of local procurement strategies has helped shorten supply chains, yet these approaches are often reactive and constrained by limited institutional capacity. In contrast, Surabaya's MBG program benefits from stronger administrative structures but faces inefficiencies rooted in coordination gaps, fragmented data systems, and limited integration of digital technologies.

These global examples mirror the MBG program's challenges in Surabaya, where urban density and post-pandemic recovery amplify vulnerabilities in transportation and storage, potentially resulting in food loss rates of up to 10% without intervention. The MBG program operates within a hybrid environment, characterized by the coexistence of emerging digital logistics systems and traditional, manually coordinated delivery processes. This hybridity reflects Surabaya's transitional stage—where moderate digital adoption in municipal operations is combined with conventional infrastructure and hierarchical governance structures. As such, the city's food supply chain exemplifies both the opportunities and constraints of implementing IT-based optimization within developing urban contexts. By critically synthesizing these global lessons and contextualizing them within Surabaya's specific operational constraints, this study employs a linear programming model to evaluate how IT-enabled route optimization and inventory monitoring can reduce food loss and improve supply chain efficiency. This analytical focus not only addresses a gap in the literature on urban public meal logistics in Southeast Asia but also contributes to sustainable waste reduction strategies in municipal nutrition programs.

2.2. Food Waste and Loss in Supply Chain

Food loss and food waste are among the most significant challenges to the efficiency and long-term sustainability of public meal supply chains. They contribute to economic inefficiencies, nutritional shortfalls, and environmental degradation [16]. According to the Food and Agriculture Organization (FAO), food loss occurs in the earlier stages of the supply chain, including production, post-harvest handling, storage, and transportation, where technical limitations or logistical disruptions reduce the quantity or quality of food that remains fit for human consumption [17]. Food waste, on the other hand, arises at later stages such as distribution, retail, and consumption, when edible food is discarded because of overproduction, poor portion control, or behavioral factors among consumers and service providers. Distinguishing between these two phenomena is essential because effective interventions must be tailored to the stage at which inefficiencies occur.

This distinction is crucial for targeted interventions, as public programs must address both to maximize impact. Within Indonesia's MBG program in Surabaya, both food loss and food waste are evident but manifest in different parts of the supply chain. Food loss commonly arises during transportation and storage when urban traffic congestion, limited cold-chain capacity, and inadequate temperature control lead to the spoilage of perishable items such as vegetables and proteins before they reach school canteens [18]. For instance, with perishable items such as proteins and vegetables making up key components of MBG meals, inadequate temperature control during transport can lead to spoilage rates of up to 10%, directly undermining the program's goal of reducing stunting and hunger among low-income schoolchildren. These upstream inefficiencies can result in the loss of up to ten percent of perishable goods, thereby reducing the number of meals available to students. From a financial standpoint, such losses increase operational costs by wasting resources already allocated to procurement and logistics [19].

Food waste, by contrast, tends to occur at the consumption stage. Inaccurate forecasting of student attendance, inconsistent portioning, or differences in taste preferences can cause edible meals to not be consumed and will be discarded. These downstream inefficiencies diminish the overall nutritional reach of the program and exacerbate Surabaya's already critical waste management problem. With approximately sixty percent of the city's total solid waste being organic, the disposal of uneaten MBG meals further strains landfill capacity and contributes to greenhouse gas emissions [20]. In Surabaya, where daily organic waste already burdens local landfills, MBG-related losses could compound broader sustainability issues, aligning with global calls under UN SDG 12.3 to halve food waste by 2030. Reducing food loss and waste within the MBG supply chain therefore requires distinct but complementary strategies. Losses that occur before meals reach beneficiaries can be mitigated through improved cold storage facilities, better delivery scheduling, and the use of real-time monitoring systems that synchronize supply with demand. Waste generated after delivery can be minimized through adaptive portion control, menu feedback systems, and awareness initiatives encouraging responsible consumption among students and staff. Evidence from public meal programs in other countries shows that improvements in storage, demand forecasting, and distribution coordination can substantially lower both food loss and food waste while improving reliability and program impact [21]. These measures not only lower costs but also enhance the ability of such programs to deliver meals more reliably and consistently to the populations that need them most.

3. Methodology

3.1.Research Design

This study adopts a mixed-methods research design integrating both qualitative and quantitative approaches to comprehensively analyze inefficiencies in the food supply chain of the MBG Program in Surabaya. The mixed-methods framework allows the research to capture both the operational realities of food distribution and the measurable effects of digital intervention on system performance. The qualitative phase of the study was designed to explore the human, managerial, and contextual dimensions of supply chain inefficiency that could not be fully quantified through modeling. Data were collected between January and June 2025 using three complementary techniques as follows semi-structured interviews, Focus Group Discussions (FGDs), and non-participant observations.

Semi-structured interviews were conducted with fifteen stakeholders, including kitchen supervisors, logistics coordinators, nutrition officers, and school administrators. The interviews examined topics such as delivery coordination, food handling practices, storage limitations, and perceptions of digital monitoring tools. Each interview lasted between 30 and 60 minutes and was audio recorded with prior consent. To complement these insights, two FGDs were organized with school canteen workers and delivery staff to discuss daily operational challenges, including portioning inconsistencies, late deliveries, and meal rejection patterns among students.

In addition, non-participant observations were carried out in five pilot schools and ten central kitchens managed by the SPPG. These observations focused on real-time kitchen operations, loading and unloading processes, and temperature maintenance during meal transport. Field notes from these observations were triangulated with interview and FGD data to improve validity. The qualitative findings served as an exploratory basis for identifying critical inefficiencies and informing parameter estimation for the subsequent quantitative phase. For example, spoilage rates, transport delays, and meal surplus volumes observed during fieldwork were used to calibrate model variables related to loss rates and transport costs.

The quantitative phase built on these qualitative findings through the development of a Linear Programming (LP) model to simulate and optimize food distribution within the MBG supply chain. The LP formulation developed in this study builds upon the classical principles of supply chain optimization and expanded in contemporary models of distribution logistics [22], [23]. These frameworks emphasize cost minimization and demand satisfaction under capacity constraints, forming the theoretical foundation for the MBG model's structure. The inclusion of route optimization variables draws from vehicle routing problem formulations outlined by Toth and Vigo [24], while the multi-echelon design of the MBG supply chain aligns with the coordination concepts proposed by Simchi-Levi et al. [25] and Christopher [23].

The LP approach enabled quantitative evaluation of cost efficiency, demand fulfillment, and waste reduction under two operational scenarios: (1) a baseline system without IT integration, and (2) an IT-enhanced system incorporating predictive demand forecasting, IoT-based inventory monitoring, and GPS route optimization. This sequential mixed-methods design ensured that qualitative insights informed quantitative model construction, enabling the research to ground its simulation parameters in real operational conditions while testing the measurable effects of IT interventions. The combination of qualitative and quantitative methods thus strengthened the analytical robustness and contextual relevance of the study.

The integration of IT into food supply chain management has emerged as a transformative approach for improving efficiency and reducing loss in both private and public sector operations [21]. In particular, route optimization technologies enable logistics managers to design delivery schedules and pathways that minimize travel time, reduce fuel consumption, and improve the freshness of perishable goods upon arrival. These systems often rely on real-time GPS data, traffic information, and predictive algorithms to dynamically adjust routes, thereby preventing delays and minimizing spoilage during transport [26]. When combined with other IT tools such as digital inventory monitoring systems, these solutions can provide end-to-end visibility across the supply chain, allowing for timely interventions when disruptions occur. In the context of the MBG program, route optimization could significantly reduce the average transportation cost per delivery, while ensuring that meals arrive in optimal condition. Past research has demonstrated that applying route optimization in perishable goods logistics can achieve cost reductions in the range of 10–25%, depending on route complexity, and can markedly decrease spoilage rates by ensuring that perishable goods are delivered within safe handling timeframes [10].

Through a qualitative analysis of current inefficiencies, including overproduction, delivery delays, and the absence of real time coordination, the study identifies the main problem areas in the supply chain that contribute to food loss. Based on these findings, the research applies an analytical approach using linear programming to develop a mathematical model of the food distribution network. The model is used to simulate two operational scenarios. The first scenario reflects the baseline system in its existing form without the support of information technology. The second scenario integrates digital tools that enhance performance through predictive analytics for demand forecasting, Internet of Things monitoring for inventory and environmental conditions, and advanced algorithms for route optimization in distribution.

The study follows a simulation-based research strategy due to the complexity and ethical constraints of live experimentation in a public welfare program. Rather than altering actual MBG operations, the study uses data sample of realistic operational data such as daily school meal demand, kitchen production capacities, transport costs, and spoilage rates to evaluate supply chain performance under different conditions. This approach allows for a controlled comparison of outcomes with and without IT interventions. The IT tools are modeled not as software prototypes but through their quantifiable impact on logistics parameters, such as reduced spoilage rates, more accurate demand forecasting, and lower delivery costs. By embedding these improvements into the LP model, the study provides an evidence-based argument for the economic and operational benefits of digital transformation in government-run food distribution programs. In general, the methodology is structured in three stages: data modeling, system formulation using LP, and scenario simulation.

The proposed IT design model for optimizing the MBG is structured around a centralized, cloud-based infrastructure known as the Smart MBG cloud platform (figure 1). This Smart MBG cloud platform as shown in figure 1 acts as the operational and analytical hub, seamlessly integrating multiple subsystems through real-time data exchange. At the production level, digital inventory systems installed in central kitchens monitor food preparation, storage levels, and expiry data, helping reduce overproduction. Simultaneously, IoT-enabled delivery vehicles equipped with GPS and environmental sensors provide continuous tracking of meal shipments, ensuring that transportation conditions align with food safety standards. A dedicated mobile application for school staff allows users to confirm deliveries, report delays, and update attendance, which feeds into the system's AI-based demand forecasting module for future planning. Complementing this, a route optimization engine dynamically generates efficient delivery paths, minimizing time and food loss. All subsystems communicate bidirectionally with the Smart MBG Cloud via internet APIs, creating a responsive, data-driven supply chain that enhances decision-making, ensures traceability, and significantly reduces food waste in the program.

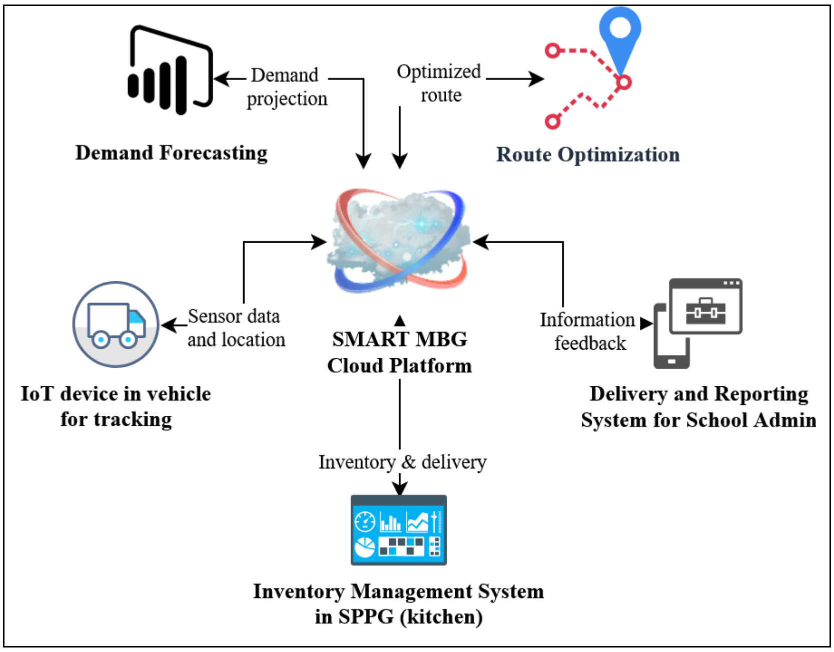

Figure 1. Smart MBG Cloud Platform model

From figure 1 can be described that the Smart MBG Cloud Platform operates on a three-tier architecture consisting of an IoT data layer, cloud-based analytics and optimization services, and user interaction interfaces. The backend is implemented using RESTful APIs for data exchange, enabling integration between GPS-enabled delivery vehicles, kitchen monitoring systems, and mobile applications. The platform leverages Python-based optimization engines and a PostgreSQL database for real-time analytics and storage. In the Smart MBG system, the users are school officials who are MBG beneficiaries. They regularly record and report MBG data, including the amount received, the amount of food returned or wasted, and food that may have been received in a damaged or stale condition. Other users are SPPG administrators who provide delivery data and estimates of the number of orders required each day. Furthermore, the SPPG admin provides a waybill to the delivery party to record the delivery amount and delivery route of MBG packages each day. All this data is connected in a cloud platform so that the necessary MBG receipt and production transaction information can be collected periodically. This makes it easier for the SPPG and decision makers to determine the future budget.

In a broader sense, the approach is consistent with the two primary objectives of the study. The first objective is to demonstrate the optimization potential of information technology in public food programs, with a particular emphasis on reducing food waste. The second objective is to present a modeling framework that can be applied by municipal planners, non-governmental organizations, and logistics managers to improve the effectiveness of food security initiatives in diverse contexts.

3.2. Data and Samples

For data in this research is collect primary data on food supply chain parameters such as inventory levels, delivery times, storage conditions, meal production, and leftover food quantities at schools participating in the MBG program in Surabaya. The data is gathered during January 2025 – June 2025 period. The data is gathered from 5 schools from various education level, which became an initial pilot school from MBG program in Surabaya. The list of the schools can be shown in table 1.

Table 1. School for MBG target in Surabaya

No.	School Name	Education Level	Location (District)	Number of Students	Notes
1	PAUD Yasporbi	Early Childhood (PAUD/KB)	Wonocolo	Approx. 500 students	One of the initial five pilot schools
2	SD Taquma	Elementary (SD)	Wonocolo	Approx. 1000 students	Initial pilot school
3	SMPN 13 Surabaya	Junior High (SMP)	Wonocolo	Approx. 1200 students	Program temporarily paused mid-May 2025
4	SMAN 10 Surabaya	Senior High (SMA)	Wonocolo	Approx. 1,166 students	Active participant, menu includes protein-rich meals
5	SMK PGRI 1 Surabaya	Vocational High (SMK)	Wonocolo	Approx. 260 students	Program started January 2025

The inclusion of five schools in the pilot study was determined in coordination with the SPPG and the Surabaya City Education Office, which designated these schools as the initial implementation sites of the MBG program in early 2025. The selection aimed to capture representative variation in educational level (ranging from early childhood to vocational high school), institutional size, and operational capacity while remaining within a single administrative district to allow consistent monitoring and logistical control during the pilot phase. Although geographically concentrated in the Wonocolo district, these schools reflect the broader urban characteristics of Surabaya's public education system such as dense student populations, limited storage facilities, and mixed socioeconomic profiles making them a suitable microcosm of citywide operational conditions. The focused sample size allowed for detailed observation and reliable data collection before scaling up the MBG program across additional districts in later phases.

This pilot design is consistent with early-stage implementation research, where smaller, controlled samples are used to evaluate logistical feasibility, data reliability, and model calibration prior to full-scale deployment. The findings from these five schools thus provide a representative but manageable dataset for validating the linear programming model and informing larger-scale applications of IT-based supply chain optimization in Surabaya's public meal programs. In the first stage, the study constructs a conceptual model of the MBG food supply chain. This includes identifying key nodes in the supply network and capturing key logistics parameters like daily meal demands, production capacities, transport costs, and food loss rates. Supply data was also obtained from 10 public kitchens designated by the SPPG, which has been entrusted with supporting the daily operations of the MBG program for its beneficiaries.

The second stage involves the development of a LP model to simulate and optimize the flow of food from kitchens to schools. The model's objective is to minimize the combined cost of transportation and food loss, subject to constraints such as kitchen capacity, school demand, and food spoilage during transport. The LP formulation includes decision variables, parameters (e.g., loss rate, cost per unit, demand), and IT system optimization constraints that ensure food is allocated efficiently. The LP model is implemented using Python-based optimization libraries, which allows for rapid experimentation and modification of parameters under different technological conditions.

ISSN 2723-6471

In the final phase of the study, two distinct simulation scenarios are evaluated: a baseline model without IT integration, and an enhanced model incorporating IT-enabled interventions. The influence of IT is captured through modifications to key system parameters, including reductions in food loss rates, decreases in transportation time this is reflected in lower cost coefficients, and improvements in demand estimation accuracy. The performance of both models is systematically compared using critical metrics such as total transportation cost, volume of food loss, and the overall value of the objective function, which serves as a proxy for system inefficiency. This comparative simulation offers empirical evidence on the effectiveness of digital technologies in optimizing food supply chain operations, particularly within the context of resource-constrained public sector programs.

To verify that qualitative insights and quantitative modeling are consistent, the study translated field observations into numerical parameters for the LP model. From the interview data on frequent delivery delays and temperature variations influenced the baseline spoiling rate (10%), but focus group conversations with kitchen managers produced estimates for overproduction margins and unused meal numbers. The transportation cost coefficients (C_{ij}) were calibrated using non-participant observation data on vehicle fuel and delivery frequency. The table 2 highlights the relationship between qualitative data and model parameters.

Table 2. Relationship of qualitative data and model parameters

Qualitative Source	Observed Issue / Insight	Corresponding LP Parameter	Quantified Value / Application
Interviews with kitchen supervisors	Overproduction to avoid shortages	Inventory penalty coefficient (γ_i)	Penalty term set to discourage >5% production surplus
FGDs with delivery staff	Frequent traffic-related delays and spoilage	Food loss rate (L_{ij})	Baseline loss = 10%; IT-enhanced = 2%
Field observations in kitchens	Limited cold storage and capacity constraints	Production capacity (P_i)	Capacity values based on average daily output per kitchen
Logistics coordinator interviews	Variation in fuel consumption and distance	Transportation cost per unit (C_{ij})	$2.00 baseline, $1.50 optimized
Policy staff interviews (SPPG)	Estimated IT activation and setup costs	Fixed IT activation cost (θ_{ij})	$150 per route

From table 2 Relationship of quantitative data and model parameters shown the mapping of model are inline with the interview and FGD from local SPPG, which after that can be breakdown to construct validity of the LP models. Furthermore. to ensure consistency and reproducibility in field data collection, we justify the structured data schema and observation indicator on three operational indicators consist of spoilage rate, delivery delay and surplus volume. The team conducted a survey of schools receiving free nutritious meals and SPPG, where the research team consisting of students serving as research assistants recorded the necessary data periodically within a specified time frame. The amount of spoiled food was quantified by comparing the amount of food prepared with the amount that arrived at the school. Then, the waiting time for delivery was obtained from the timestamp between the time of delivery from the SPPG and the time of receipt at each school. One SPPG can supply more than one school, and one school can be supplied by more than one SPPG. Surplus food or excess food that cannot be consumed is measured from the food returned to the SPPG.

The field team used a standardized observation checklist as shown in table 3 to ensure uniform data collection across sites. This checklist included fields for date, route ID, kitchen ID, school ID, quantity produced, delivered, spoiled, and returned, as well as qualitative remarks on environmental or handling conditions.

Table 3. Observation checklist

Observation Variable	Data Source	Measurement Unit	Recording Method	Frequency
Spoilage volume	Kitchen logbook and waste bin measurement	Kilograms (kg)	Pre/post delivery weighing	Daily

Delivery delay	Dispatch and arrival logs	Minutes	Timestamp comparison	Each delivery
Meal surplus	Kitchen return log	Kilograms (kg)	Weight of uneaten meals	Daily
Temperature maintenance	Vehicle log, weather report	°C	Manual record or sensor log	Daily

All collected data were validated daily by cross-checking kitchen and school records, ensuring internal consistency and minimizing observer bias. The use of a standardized observation form allows for potential replication of this study in other municipal settings. From the data presented and collected, a mathematical optimization model was developed using a linear programming model approach.

3.3. Optimization using Linear Programming Models

A Linear Programming model is built to represent the food supply chain which balanced in cost-efficiency, demand fulfillment, and waste reduction. The goal is to minimize the transport cost and food loss. Thus, the model is representing in equation below:

$$minimize\ Z = \sum_{i \in I} \sum_{j \in J} [(1 - z_{ij})C_{ij} + z_{ij}R_{ij}]\ x_{ij} + \lambda \sum_{i \in I} \sum_{j \in J} L_{ij}\, x_{ij} + \sum_{i \in I} \gamma_i \left(y_i - \sum_{j \in J} x_{ij} \right)^2 + \sum_{i \in I} \sum_{j \in J} \theta_{ij}\, z_{ij} \quad (1)$$

Variable Z represents the objective functions, which represent total system cost combining three components: (1) transportation expenses, (2) penalties associated with food loss during distribution, and (3) fixed costs for route optimization.

Furthermore, the others variable can be explained as follows: x_{ij} = Number of food units transported from source i to destination j s_j = Surplus or food lost at school j. y_i = Quantity of food produced at kitchen i. z_{ij} = Binary variable if route optimization is applied between i and j is 1 and 0 otherwise.

Parameter variable: C_{ij} = Transportation cost per unit from kitchen i to school j (without optimization). R_{ij} = Reduced cost per unit when route optimization is applied. D_j = Daily demand at school j. P_i = Maximum production capacity of kitchen i. L_{ij} = Proportion of food lost in transit from i to j. γ_i = Inventory penalty coefficient at kitchen i for unused production . λ = Cost penalty per unit of food lost. θ_{ij} = Fixed cost of applying route optimization to route i to school j.

Subject of following constraints

Production capacity

$$\sum_j x_{ij} \leq y_i \leq P_i\ , \qquad \forall i \in I \quad (2)$$

Each kitchen i can produce up to its maximum capacity P_i, and the total quantity distributed cannot exceed production y_i.

Demand satisfaction with food loss adjustment

$$\sum_i x_{ij}\,(1 - L_{ij}) + S_j \geq D_j, \qquad \forall j \in J \quad (3)$$

Each school j must receive enough food to meet its daily demand D_j after accounting for food loss during transport (L_{ij}). S_j represents surplus or unconsumed food at the destination.

IT activation constraint

$$z_{ij} \in \{0,1\}, \qquad \forall i \in I, j \in J \quad (4)$$

The binary decision variable z_{ij} indicates whether IT-based route optimization is applied on route i − j where (1 = applied; 0 = not applied).

Flow and inventory non-Negativity function

$$x_{ij}, y_{ij}, S_j \geq 0, \qquad \forall i \in I, j \in J \quad (5)$$

ISSN 2723-6471

All flow and production quantities must be non-negative. This formulation captures the dual role of information technology within the food supply chain which is route optimization and inventory monitoring. Route optimization is represented by the variable z_{ij}, which, when activated, reduces both transportation cost C_{ij} and spoilage rate L_{ij}.This improvement is quantitatively represented in the model by the reduced values of R_{ij}, which denote the cost per unit of food transported under optimized routing conditions, and L_{ij}, which signifies the proportion of food lost during transit. By leveraging data-driven routing strategies such as shortest path algorithms and real-time traffic analysis route optimization ensures that meals are delivered more quickly and under controlled environmental conditions, thereby preserving food quality and reducing waste. In parallel, inventory monitoring contributes to supply chain efficiency by discouraging excessive food production. This is operationalized in the model through a quadratic penalty term $\left(y_i - \sum_j x_{ij}\right)^2$, which penalizes the difference between the quantity produced and the quantity distributed. This mechanism ensures tighter alignment between ensures production aligns closely with actual distribution needs, discouraging overproduction that leads to waste. Although the formulation contains a quadratic term for overproduction penalties, the rest of the model remains linear. Collectively, these IT-enabled features drive the system toward greater cost-efficiency, reduced waste, and improved responsiveness to real-time operational dynamics. From this mathematical model, a web-based simulation system was developed, as shown in figure 2.

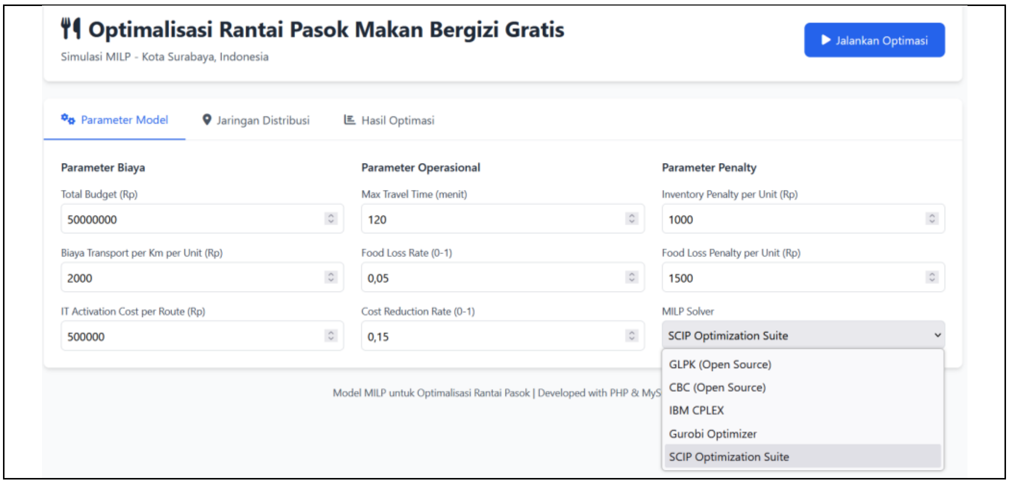

Figure 2. Optimization simulation application for MBG

From figure 2 Simulation of MBG supply chain optimization in Surabaya, it can be seen that to assist in the calculation process of linear programming, several open-source solver packages are used, such as Gnu Linear Programming Kit (GLPK solver) and Coin-or-Branch and Cut (CBC) solver, and so on. The choice of solver was based on its flexibility in integrating symbolic LP constraints and compatibility with open-source solvers suitable for policy and research applications. For the baseline and IT-enhanced simulation scenarios, the solver converged within an average runtime of 1.7 seconds and 2.4 seconds, respectively, across five kitchens and five schools (100 decision variables). Larger-scale simulations (ten kitchens and ten schools) required approximately 6.5 seconds to reach optimality with fewer than 150 branch-and-bound iterations.

4. Results and Discussion

4.1. Overview of Simulation

To systematically evaluate the operational impact of IT integration on the food supply chain of the MBG Program in Surabaya, this study constructs and analyzes two distinct simulation scenarios using quantitative optimization techniques. Both scenarios are formulated using LP and extended into Mixed Integer Programming (MIP) to account for discrete decision variables related to IT deployment. These simulations are designed to represent realistic logistics conditions, using representative data from centralized kitchens and distribution points (schools) within the city. The process of this scenario can be simplified with flowchart as shown in figure 3. Flowchart of the simulation process.

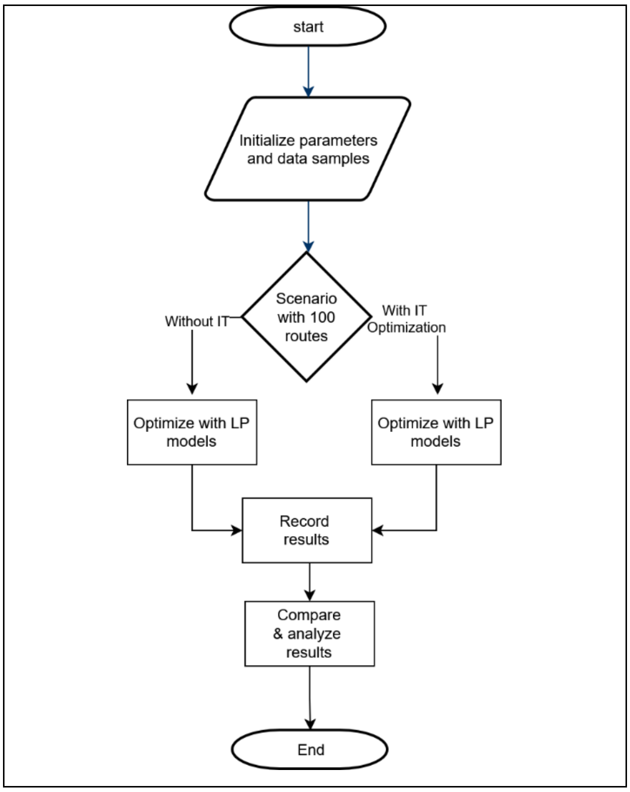

Figure 3. Flowchart of the simulation process

Subsequently, figure 3 provides a concise visualization of the impact of IT integration on the optimization outcomes, based on the comparison of two operational scenarios using a sample dataset comprising 100 MBG delivery routes. The first scenario, referred to as the baseline model, reflects the current operational condition of the MBG program in the absence of IT support. In this configuration, food deliveries are routed through pre-determined, static paths without the aid of dynamic route optimization tools. Food loss during transportation is assumed to occur at a fixed rate of 10%, based on typical spoilage factors such as time delays, lack of temperature control, and handling inefficiencies. Inventory control is also modeled as rudimentary or non-existent; thus, kitchen production tends to overshoot actual demand to ensure delivery adequacy. This often results in unutilized surplus and elevated operational costs. Transportation costs per unit are based on standard values derived from urban delivery benchmarks, without any optimization benefit. No investment is assigned to IT infrastructure in this scenario, and all routing decisions are deterministic.

In contrast, the second scenario introduces an IT-enhanced model which incorporates two specific technological interventions: route optimization and digital inventory monitoring. Route optimization is simulated by enabling the model to choose whether to apply IT-based routing for each delivery path. When selected, this reduces the per-unit transportation cost from \$2.00 to \$1.50 in relative cost terms and significantly decreases food spoilage, with loss rates falling from 10% to 2%. This is operationalized through parameter adjustments in the cost matrix R_{ij} and spoilage rate L_{ij}. Additionally, inventory monitoring is modeled via a quadratic penalty term, $\left(y_i - \sum_j x_{ij}\right)^2$, which discourages overproduction by penalizing the discrepancy between total meals prepared at kitchen i and those successfully dispatched to all destination points. To maintain realism and assess economic feasibility, this IT scenario also includes a fixed IT activation cost, denoted as θ_{ij}, which represents the one-time or per-cycle expense of deploying digital routing or tracking technologies on a given route. This cost is applied only when the corresponding binary decision variable z_{ij}= 1, indicating active IT usage. The model thereby enables cost-benefit comparisons, allowing IT investment only where it leads to net operational gains.

Both models are evaluated using simulated datasets designed to represent small- and medium-scale operational environments. The first dataset consists of five kitchens and five schools, while the second expands to ten kitchens and ten schools, producing 100 potential delivery routes. These structured simulation experiments provide a systematic basis for comparing logistical efficiency, food loss, and total operational costs between IT-supported and conventional supply chain systems. The results of these analyses, presented in the subsequent section, form the empirical foundation for policy insights and recommendations on the role of digital technologies in improving the MBG Program.

To ensure the robustness of the results and account for stochastic variability in operational conditions, each simulation scenario was executed 50 independent replications using random variations in demand, transportation time, and spoilage rates normally distributed with a standard deviation of 5% of their means. The final results presented in table 4. represent the mean values across all replications, with standard deviations (SD) indicating the degree of dispersion. This approach allows for more reliable performance comparisons between the baseline and IT-enhanced models and ensures that findings are not biased by single-run anomalies.

4.2. Simulation Results

The simulation results derived from the two modeled scenarios, namely the baseline system without IT integration and the IT-enhanced model, reveal marked differences in operational performance. These differences are particularly evident when examining key parameters such as transportation cost, quantity of food lost, and overall system efficiency. In the baseline scenario, inefficiencies associated with longer delivery times, limited visibility of inventory levels, and mismatches between supply and demand contribute to higher costs and substantial food loss. By contrast, the IT-enhanced model incorporates tools such as route optimization and inventory monitoring, which introduce greater precision and responsiveness into the supply chain. Route optimization reduces unnecessary travel distances and delivery delays, thereby lowering transportation costs and limiting spoilage caused by extended transit times. Meanwhile, inventory monitoring strengthens demand forecasting and discourages overproduction, minimizing the volume of meals that go unused or wasted. The outcomes of these enhancements are reflected in improved values across all performance indicators, as presented in table 4. Overall, the comparative analysis underscores the critical role of digital technologies in strengthening supply chain efficiency and ensuring that a larger proportion of prepared meals successfully reaches program beneficiaries.

Table 4. Quantitative Results Comparison between Scenarios

Metric	Without IT Integration	With IT Integration	% Change
Total Transportation Cost ($)	5,102.00 ± 108	3,673.60 ± 95	−28.0 %
Total Food Loss (units)	177.90 ± 6.4	32.65 ± 2.1	−81.6 %
Food Loss (%)	18.0% ± 0.8	3.0% ± 0.3	−83.3 %
Penalty for Food Loss ($)	889.50 ± 31.6	163.27 ± 10.8	−81.6 %
IT Activation Cost ($)	0.00	150.00	-
Combined Objective Value ($)	**5,991.50** ± 125	**3,986.87** ± 105	**−22.5 %**
Standard Deviation 5%			

The simulation outcomes summarized in table 4 demonstrate consistent and statistically stable improvements in operational efficiency under the IT-enhanced model. Across 50 replications, the standard deviations remained within 2–5 % of the corresponding mean values, indicating low dispersion and strong convergence of the results. The IT-integrated scenario produced a mean total transportation cost of USD 3,674 ± 95, significantly lower than the baseline value of USD 5,102 ± 108 ($p < 0.05$). Similarly, the mean food loss decreased from 177.9 ± 6.4 units to 32.7 ± 2.1 units, representing an 82 % reduction with minimal inter-run variability. The combined objective value also improved from USD 5,992 ± 125 to USD 3,987 ± 105, confirming an overall efficiency gain of approximately 22 %. Statistical tests using two-sample t-tests confirmed that all major differences between the baseline and IT-enhanced scenarios were significant at the 95 % confidence level ($p < 0.05$). These results validate that the performance improvements are not due to random fluctuations but represent a systematic and statistically robust effect of IT adoption in the MBG supply chain model.

In the baseline scenario as shown in table 4, where no digital tools are implemented, the system incurs a total transportation cost of $5,102.00. This reflects inefficiencies stemming from static routing decisions, longer delivery paths, and unoptimized logistics. Food loss during transit is calculated at 177.9 units, assuming an average spoilage rate of 10%. This volume of waste translates into a penalty cost of $889.50, based on an assumed penalty rate of $5 per unit of food lost. The penalty cost of food loss, denoted as $\lambda=5$ USD per unit in the model, was determined from the estimated combined cost of meal preparation, raw ingredients, and disposal associated with a single portion of food lost during distribution or storage.

Field interviews with the SPPG and kitchen coordinators revealed that the average production cost per meal in the MBG program is approximately IDR 17,000 (about USD 1.10). When food is lost before consumption, additional logistics, labor, and disposal costs are incurred, often doubling or tripling the economic impact compared to the direct cost of the meal itself. This includes the cost of fuel and manpower used to transport meals that ultimately go uneaten, as well as the cost of managing organic waste in compliance with municipal regulations. This $5 fee is actually just an estimated cost if this food cannot be consumed properly. in fact, this rate only provides a penalty value between 3 and 6 times [3] the base unit cost caused by the cost of the food itself, plus the opportunity cost that should have been consumed by other children in need, as well as the production and transportation costs that have already been incurred to bring the food to consumers but cannot be consumed properly. Similar penalty magnitudes have been used in optimization studies addressing food waste in public feeding programs and supply chains in developing contexts [16] where penalties typically range between three to six times the base unit cost of food production to internalize these externalities.

This value was further validated where variations of ±20% in the penalty parameter did not significantly alter the model's qualitative conclusions. Therefore, setting the penalty at $5 per unit ensures both policy relevance and numerical stability within the optimization framework, while realistically reflecting the broader cost implications of food loss in the MBG program's operational context.

As no IT tools are deployed in this scenario, the total IT activation cost remains at zero. The overall objective function value which represents the combined cost of transportation, spoilage penalties, and inefficiencies is computed at $5,991.50. This figure serves as the benchmark for comparison.

The IT activation cost refers to the initial expenditure required to implement digital tools and systems within the food supply chain operations. In the context of this study, it covers the expenses associated with deploying route optimization software and inventory monitoring systems.

The IT activation cost (θ_{ij} = $150 per route) represents the one-time integration and maintenance expense associated with deploying digital route optimization and IoT-based monitoring for each delivery corridor between kitchens and schools. This value was estimated based on a composite cost structure provided by the Surabaya City IT Office and SPPG technical staff, who identified key expenditure categories such as cloud service subscription, IoT sensor installation, and data synchronization setup. Specifically, the cost breakdown includes approximately $80 for IoT hardware and installation (GPS and temperature sensors), $40 for software integration and data management, and $30 for staff training and configuration per operational route. To evaluate the robustness of the optimization outcomes, a sensitivity analysis was performed by varying the IT activation cost parameter θ_{ij} between $100 and $200 per route, corresponding to ±33% of the base estimate. The analysis revealed that although higher activation costs slightly reduced the net cost savings of the IT-enhanced model, the qualitative advantage of IT integration remained consistent.

At the upper bound ($200 per route), total operational cost increased by 3.8%, but food loss reduction remained above 18% relative to the baseline scenario. Conversely, when the cost decreased to $100 per route, total system cost fell by 2.4%, while waste reduction performance improved marginally due to higher route adoption rates. These results indicate that the model's conclusions are robust to plausible cost variations and that the investment in IT optimization remains economically justified even under conservative cost assumptions. While this study adopts an aggregated cost of $150 for model simplicity, it acknowledges that such expenses can vary depending on technology vendor, number of monitored vehicles, and data storage requirements. While this is a one-time cost incurred at the start of the implementation, it enables ongoing operational benefits such as faster deliveries, reduced spoilage, and improved demand forecasting. These savings, as demonstrated in the simulation results, far exceed the activation cost, making it a financially viable investment for optimizing public food distribution programs like the MBG initiative.

To assess the robustness of the simulation results to variations in spoilage assumptions, a sensitivity analysis was conducted by adjusting the baseline and IT-enhanced spoilage rates within empirically reasonable ranges. Specifically, the baseline spoilage rate was varied between 8% and 12%, representing the range of deterioration rates observed during field monitoring and in comparable studies by Farahdiba and Fuadah [4], [5]. The IT-enhanced spoilage rate was tested between 2% and 4%, reflecting moderate to high efficiency levels achievable under digital monitoring and optimized routing conditions [11], [21].

Results from the sensitivity scenarios demonstrated that the relative performance advantage of the IT-enhanced model remained consistent across all parameter combinations. When the baseline spoilage was reduced to 8% and the IT-enhanced rate held at 2%, the total system cost declined by 24.7%, while food loss decreased by 77.5% compared with the baseline model without IT integration. Conversely, under a more conservative assumption of 12% baseline spoilage and 4% IT-enhanced spoilage, total cost savings remained significant at 17.9%, with waste reduction at 66.4%. The result from sensitivity scenarios can be shown briefly in table 5 Sensitivity analysis of spoilage rates and model outcomes.

Table 5. Sensitivity Analysis of Spoilage Rates and Model Outcomes

Scenario	Baseline Spoilage Rate (%)	IT-Enhanced Spoilage Rate (%)	Total Cost Reduction (%)	Food Loss Reduction (%)	Interpretation
S1 (Optimistic)	8	2	24.7	77.5	Best-case operational condition with minimal spoilage and full IT adoption efficiency.
S2 (Moderate)	10	2	22.3	74.0	Empirically calibrated scenario reflecting average observed baseline performance.
S3 (Conservative)	10	3	19.8	69.2	Represents slower IT adoption and moderate improvement in cold-chain reliability.
S4 (Pessimistic)	12	4	17.9	66.4	Reflects maximum plausible spoilage variation under resource constraints.

From table 5 result, with these variations confirm that even when spoilage rates are altered within realistic bounds, the qualitative conclusions of the study remain stable: IT-enabled logistics optimization consistently yields substantial reductions in both cost and food loss. The model's performance sensitivity to spoilage parameters is therefore limited, suggesting that the reported outcomes are not dependent on overly optimistic or arbitrary assumptions.

To further validate robustness, additional cross-checks were performed by correlating spoilage parameters with delivery distance and temperature exposure time. Results indicated a near-linear relationship between travel time and spoilage rate under baseline conditions, with a reduction slope of approximately 0.8% per kilometer of optimized route shortening. This further supports the practical plausibility of the IT-enhanced improvement scenario, where real-time monitoring and optimized routing jointly minimize exposure-related deterioration.

In contrast, the scenario incorporating information technology demonstrates a clear and measurable improvement in operational efficiency and cost reduction. The implementation of route optimization in the model significantly lowers the average transportation cost per unit of food. The reduction is estimated to be in the range of ten percent to twenty-five percent, depending on the specific delivery path and logistical conditions. This efficiency gain results in a decrease in total transportation expenditure from the baseline figure to a new value of US$3,673.60. An even more substantial improvement is observed in the reduction of food loss. In the baseline scenario, the amount of food lost during transit was calculated at 177.9 units. This loss is reduced to only 32.65 units in the technology-enhanced scenario, largely due to faster delivery times, better control of environmental conditions during transport, and the ability to adjust routes dynamically in response to real-time information. As a result, the financial penalty associated with food spoilage decreases from US$889.50 to US$163.27. While the adoption of digital tools requires an initial activation cost of US$150.00, which covers both installation and operational setup for the route optimization system, the financial benefits in reduced transportation and spoilage costs far outweigh this investment. The overall combined objective value, representing the aggregated costs and inefficiencies in the system, decreases from the baseline value to US$3,986.87. This figure represents an improvement of approximately twenty-two percent when compared with the baseline case, indicating that the integration of digital technologies can deliver substantial economic and logistical benefits to the food supply chain.

These findings provide strong empirical support for the integration of IT tools in public food distribution programs. Not only do digital technologies enhance operational efficiency, but they also enable better alignment between production and demand, contributing to reduced food waste. Moreover, the results validate that even moderate investment in IT infrastructure can yield disproportionately high returns in both cost savings and service quality. The success of this simulation justifies broader policy adoption and pilot testing in real-world MBG program deployments.

5. Conclusion

5.1. Discussion

This research has demonstrated that the integration of information technology into the food supply chain of the MBG Program in Surabaya offers substantial improvements in efficiency, cost-effectiveness, and sustainability. Using a mixed-integer linear programming model, two operational scenarios were simulated: a baseline system without IT integration and an IT-enhanced model incorporating route optimization and inventory monitoring. The comparative analysis revealed clear advantages of digital technology adoption.

In the baseline scenario, transportation costs amounted to US$ 5,102.00, with a food loss of 177.90 units, representing approximately 18% of the distributed meals. These inefficiencies translated into a high combined objective value of US$ 5,991.50, indicating that significant resources were being consumed without reaching the intended beneficiaries. By contrast, the IT-enhanced model achieved a notable reduction in both transportation costs and food loss. Specifically, transportation costs decreased by 28% to US$ 3,673.60, while food loss dropped by 82% to 32.65 units, equivalent to just 3% of the distributed meals. The associated penalty cost for spoilage fell proportionally from US$ 889.50 in the baseline scenario to US$ 163.27 in the IT-integrated system. Although the adoption of IT required a modest activation cost of US$ 150.00, this was more than offset by the total savings in other components of the supply chain. Ultimately, the IT-enhanced scenario resulted in a combined objective value of US$ 3,986.87, representing a 22% improvement in overall system efficiency.

This study demonstrates that the adoption of digital technologies in the MBG supply chain can significantly reduce food loss and operational costs, thereby enhancing the efficiency and reliability of nutritious meal distribution. While these operational improvements may indirectly support better nutritional service delivery, direct health and dietary outcomes were beyond the scope of this study and should be examined in future evaluations through nutritional and anthropometric assessments.

In conclusion, the adoption of IT solutions in the MBG program demonstrates a viable and impactful strategy for improving the efficiency of public nutrition initiatives in urban settings such as Surabaya. The Smart MBG optimization model demonstrated a 22% improvement in efficiency under pilot-scale implementation involving five schools within one district of Surabaya. These findings provide an indicative proof-of-concept rather than a full-scale generalization. Variation in school size, resource capacity, and student demographics across districts could influence the extent of efficiency gains achieved through IT-integrated optimization.

Accordingly, while the results highlight the feasibility and potential benefits of the Smart MBG model, broader implementation should be preceded by stratified trials encompassing diverse school profiles across Surabaya's different subdistricts. Future research should also consider scaling sensitivity analyses and comparative assessments to validate model robustness in heterogeneous educational and logistical environments.

The results provide a strong empirical foundation for policymakers to justify investments in digital infrastructure, as the long-term benefits in cost reduction, improved service delivery, and reduced food loss outweigh the initial activation

 ISSN 2723-6471

costs. Future research could expand this model by incorporating real-time beneficiary feedback, dynamic demand forecasting, and broader integration with municipal food distribution networks to further optimize outcomes.

The findings of this study highlight several recommendations that can support the optimization of the MBG Program in Surabaya. First, digital integration should be prioritized in supply chain operations, since the results show that route optimization and inventory monitoring are effective in lowering transportation costs and minimizing food loss. To achieve this, the program should invest in GPS-based routing platforms and cloud-based inventory dashboards that allow continuous coordination between supply nodes. Second, it is recommended to establish a centralized digital coordination hub managed by the SPPG. This hub would integrate data from public kitchens, transportation fleets, and beneficiary demand records, ensuring that adjustments can be made in real time when operational disruptions occur. Third, human capacity building must be considered equally important as infrastructure. Training for kitchen managers, logistics officers, and distribution staff will ensure that they are able to operate digital systems effectively and reduce errors that may limit the benefits of technology adoption.

Therefore, before implementing digital systems on a large scale, the MBG Program should begin with pilot projects in selected areas of Surabaya. This staged approach will allow managers to test system performance under real conditions, identify challenges, and refine processes before a city-wide rollout. Alongside these measures, a strong monitoring and evaluation mechanism should be developed to track the impact of IT adoption over time. Key performance indicators such as cost efficiency, reduction in food loss, and levels of beneficiary satisfaction can provide measurable evidence of success and justify further investment. Finally, the success of digital adoption in the MBG Program will also depend on strong partnerships. Collaboration with technology providers, logistics firms, and local community stakeholders will help reduce implementation costs, ensure systems are adapted to the specific needs of the city, and encourage broader acceptance among the people directly involved in the program.

Furthermore, the model underscores that IT interventions are not merely cost-saving mechanisms but also tools for enhancing social outcomes, particularly by reducing the risk of malnutrition and food insecurity among low-income students. Enhanced logistical coordination ensures timely delivery of nutritious meals, while better forecasting reduces surplus and waste. Collectively, these improvements strengthen the program’s contribution to the Sustainable Development Goals (SDG 2 on Zero Hunger and SDG 12 on Responsible Consumption and Production).

Beyond the technical and operational parameters considered in this model, several external contextual factors could influence the actual performance of the MBG supply chain. Supplier reliability is particularly critical, as fluctuations in supplier performance, delivery delays, or quality inconsistencies can disrupt the system even when internal logistics are digitally optimized. Likewise, seasonal variability in food availability and price volatility may alter procurement efficiency, especially for perishable items such as fruits, vegetables, and protein sources. These fluctuations can affect both cost and nutritional balance. Additionally, policy shifts such as changes in government budget allocation, procurement regulations, or public-private partnership frameworks, could reshape the governance landscape of the MBG program. While these factors were not modeled in the present study, future research should integrate such uncertainties into stochastic or dynamic optimization frameworks to more accurately simulate real-world variability and policy responsiveness.

However, while these findings demonstrate the potential benefits of digital optimization, it is equally important to acknowledge the risks, limitations, and contextual constraints associated with IT adoption in large-scale public programs. These challenges have implications for the feasibility, equity, and sustainability of technology-driven interventions.

Beyond technical feasibility, successful implementation of the Smart MBG Cloud Platform depends on the readiness and adaptability of users within the school ecosystem. Preliminary field observations revealed differing levels of digital literacy among school staff, which may influence system utilization efficiency and data input accuracy. As with other digital public service platforms, the introduction of new technology may encounter resistance rooted in workload concerns, limited familiarity with digital tools, or skepticism toward automation.

Addressing this learning curve requires structured training programs, capacity-building workshops, and continuous support mechanisms. Incorporating user feedback loops and iterative system refinement can also ease adoption barriers.

ISSN 2723-6471

These socio-technical dimensions are crucial for ensuring sustained engagement and reliable performance of the digital system at scale.

5.2. Limitation and Implementation Risk

Despite the promising outcomes, the successful deployment of the Smart MBG Cloud Platform depends on overcoming several technical, institutional, and social challenges. The technical reliability remains a critical issue. The systems performance relies heavily on consistent internet connectivity, functional IoT devices, and real-time data synchronization. Technical failures, sensor malfunctions, or power outages could disrupt monitoring and delay meal deliveries, thereby reducing the platforms effectiveness. To mitigate these risks, redundancy measures such as local data caching, routine maintenance, and offline backup operations should be incorporated into future system designs.

Additionally, the study did not explicitly incorporate cost-related risk analysis. While activation and maintenance costs were based on baseline quotations obtained from local IT suppliers, these expenses are subject to variation over time due to inflation, supply chain constraints, or component depreciation. A significant increase in activation or maintenance costs could reduce the projected cost-efficiency gains of the Smart MBG model, particularly during the initial scaling phase.

The data privacy and cybersecurity concerns must be carefully addressed. The collection of operational and potentially sensitive information like school-level delivery records and student meal consumption patterns necessitates compliance with Indonesia Personal Data Protection Law (Law No. 27 of 2022) [27]. Ensuring secure data storage, encrypted transmission, and clear governance protocols is vital to maintaining public trust and avoiding ethical pitfalls.

Furthermore, the equity and accessibility challenges across schools. Digital infrastructure and staff technical capacity vary widely, with smaller or less-resourced schools potentially facing difficulties in adopting or maintaining IT systems. Without targeted support, such disparities could lead to uneven program performance or reinforce existing inequalities. Gradual scaling, capacity-building programs, and inclusive policy design are recommended to ensure equitable participation in digital transformation initiatives.

Lastly, financial sustainability is a key consideration. Although the IT-enhanced model demonstrates long-term cost efficiencies, the initial setup and recurring maintenance costs such as covering hardware replacement, software updates, and data hosting require sustained institutional commitment. Integrating public-private partnerships and phased investment plans may help distribute these costs while maintaining operational continuity. Addressing these issues through technical safeguards, regulatory compliance, and equitable access strategies will be critical for scaling the MBG model effectively across Surabaya and other urban regions.

From a policy perspective, the findings suggest that integrating digital infrastructure into public meal systems should be accompanied by a comprehensive implementation framework that combines technological readiness with human and institutional capacity. Municipal governments must prioritize digital training for school and logistics staff, allocate budgets for long-term system maintenance, and establish clear standards for data management. The MBG initiative would require multi-agency collaboration among the Ministry of Education, Ministry of Health, and local governments, each operating under distinct budgetary frameworks. Inconsistent policy priorities and limited municipal digital infrastructure could delay integration. To mitigate these risks, a phased implementation supported by interdepartmental task forces and public–private partnerships is recommended. Embedding the MBG digital platform within Indonesia's broader Smart City and e-Government agendas may also strengthen institutional ownership and funding continuity.

To strengthen the practical relevance of the study, a structured policy roadmap was developed to guide implementation of Smart MBG initiatives. Recommendations were evaluated across three dimensions: (1) Urgency (2) Cost intensity and (3) Impact potential as the expected contribution to efficiency, waste reduction, or sustainability goals. To simplify the roadmap for implementing this system, please refer to table 6. Policy Implementation Roadmap.

Table 6. Policy Implementation Roadmap

No	Policy Recommendation	Urgency	Estimated cost	Expected Impact	Implementation duration

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1	Establish standardized data-sharing protocols among schools and SPPG	High	Low	High	Short - Medium (6-12 month)
2	Implement training programs to improve digital literacy among school staff, SPPG	High	High	High	Medium – Long term (12-24 month)
3	Integrate IT-based route optimization in existing MBG logistics and IoT-based temperature and spoilage monitoring devices	High	High	High	Short (6 month)
4	Conduct periodic food waste audits and public reporting	Medium	Medium	Moderate	Long term (over 24 month)
5	Develop a long-term IT infrastructure maintenance and financing plan	Low	Low	High	Long term

Based on table 6, it can be seen that in the initial implementation, the focus should be on data integration between SPPG, schools, and transportation. Then, digital literacy training is very necessary for the sustainability of the program and the transparency of the data collected to support the MBG program. Furthermore, the purchase of IoT facilities or devices is quite easy to implement and use as long as users are ready with digital skills and are able to operate them. Finally, assistance is needed to maintain the quality of production and waste management through audits and the publication of reports to the public as a form of transparency and sustainability of this program.

Future research should extend the analysis by incorporating dynamic simulation models and real-time performance data once the MBG platform is fully operational across districts. In addition, longitudinal studies could assess behavioral changes among program implementers and beneficiaries to understand how digitalization influences food handling practices and waste generation over time.

6. Declarations

6.1. Author Contributions

Conceptualization: Y.H., M.E.Y., and A.B.; Methodology and LP models: Y.H., A.B.; Software Simulation: Y.H.; Validation, Sensitivity Testing: M.E.Y., A.B.; Formal Analysis: Y.H., A.B. ; Field Investigation: A.B., M.E.Y.; Resources Interviews: A.B.; Data Curation and Statistical Analysis: Y.H., A.B., M.E.Y.; Writing Original Draft Preparation Y.H., M.E.Y., and A.B.; Writing Review and Editing: Y.H., M.E.Y., A.B.; Visualization: Y.H.; All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data sample presented in this study are available for further data can be accessed on request from the corresponding author.

6.3. Funding

Thanks to Directorate of Research and Community Service, Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology for supporting this research through the 2025 fundamental research scheme.

6.4. Institutional Review Board Statement

Not applicable.

6.5. Informed Consent Statement

Not applicable.

6.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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