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Artículos

Dynamic Analysis of a Humanitarian Aid Delivery System in Disaster Situations*

Análisis dinámico de un sistema de entrega de ayudas humanitarias en situaciones de desastre

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Abstract:

Objective: The occurrence of various natural and/or anthropogenic disasters in different cities around the world has generated negative consequences for the economic conditions and food security of the population. This situation has led various relief agencies and local administrations to consolidate food aid distribution strategies aimed at reducing people's suffering. In this paper, system dynamics is used as a tool to analyze the effectiveness of a humanitarian aid delivery prioritization model employed by a city in central Valle del Cauca in the event of a disaster.
Materials and Methods: A system dynamics model was constructed that considers the relationships between different variables that constitute the food kit distribution system in the city under study. This model can be utilized to make decisions that improve food security among the population.
Results and Discussion: Among the main findings, the current distribution system fails to meet the expected demand for food kits. This suggests the need for the creation of a donation and volunteer program to expand the capacity for assistance and enhance the food security of the population.
Conclusion: The methodology presented in this research serves as a reference framework for the distribution of humanitarian aid in future disasters within a city.
Keywords: Humanitarian Logistics, Distribution, Disasters, System Dynamics.

Resumen:

Objetivo: la ocurrencia de diferentes desastres naturales y/o antropogénicos en diferentes ciudades del mundo han generado consecuencias negativas en las condiciones económicas y de seguridad alimentaria de la población, lo que lleva a diferentes organismos de socorro y administraciones locales a consolidar estrategias de distribución de ayuda alimentaria buscando disminuir el sufrimiento de las personas. Este trabajo utiliza la dinámica de sistemas como herramienta para analizar la efectividad de un modelo de priorización de entrega de ayuda humanitaria utilizado por una ciudad del centro del Valle del Cauca en presencia de un desastre.
Materiales y Métodos: se construyó un modelo de dinámica de sistemas considerando las relaciones entre las diferentes variables que componen la estructura del sistema de distribución de kits alimentarios en la ciudad objeto de estudio de tal manera que pueda ser utilizado para la toma de decisiones que mejoren la seguridad alimentaria de la población.
Resultados y Discusión: entre los principales resultados se tiene que el sistema actual de distribución no logra satisfacer la demanda esperada de kits alimentarios, sugiriendo la creación de un programa de donación y voluntariado para ampliar la capacidad de atención y mejorar la seguridad alimentaria de la población.
Conclusiones: la metodología presentada en la investigación se convierte en un marco de referencia para la distribución de ayudas humanitarias para futuros desastres en una ciudad.
Palabras clave: logística humanitaria, distribución, desastres, dinámica de sistema.

Author notes

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Introduction

Today, disasters frequently occur in cities and towns around the world primarily resulting from natural events, diseases, or human actions. This reality necessitates careful planning and execution of various response activities aimed at reducing loss of life and alleviating the suffering of affected populations [1-3]. In coordinating these disaster response efforts, multiple stakeholders must manage the flow of people, equipment, and materials. This network is referred to as humanitarian supply chains, which face significant management challenges due to uncertain factors such as unpredictable victim demand, destabilized infrastructure with limited access to roads and energy sources, time pressures, and resource shortages [4]. Among the response strategies commonly employed by various Colombian cities is the distribution of food kits to ensure food security for the population. This approach [5] aligns with proposals that advocate for food distribution with a humanitarian focus as a means to address disasters, while also aiming to fulfill two sustainable development goals: eradicating hunger and achieving peace and justice.

A literature search was conducted on the development of aid distribution models in disaster contexts. The most representative references include the following: [6] formulate a mathematical model to support the sustainable distribution of humanitarian aid after a catastrophe, considering factors such as multiperiod decision-making, insufficient supplies, and the presence of numerous warehouses and destinations. Similarly, [7] designs a supply chain for the short-term distribution of critical products to affected populations, explicitly considering the impact of unsatisfied demand over time under conditions of uncertainty by introducing a dispersion factor. Additionally, [8] establishes a model for delivering water in various forms (self-storage and bottled) to disaster victims, accounting not only for logistical costs associated with transportation but also for social costs related to the lack of care for victims.

[9] develops a stochastic mixed-integer linear programming model that integrates pre- and post-disaster activities, including warehouse location, inventory levels, equitable distribution of humanitarian aid, donation planning, and disaster budget management. Additionally, [10] establishes a model for allocating emergency materials in a disaster context, considering multiple rescue sites, affected areas, and time periods. This model enables decision-makers to balance efficiency, effectiveness, and equity in delivering humanitarian aid. In contrast, [11] proposes a collaborative humanitarian supply chain involving several relief organizations to determine how to procure, preposition, and distribute humanitarian aid before and after a disaster.

Although the mathematical modeling approach has been the most widely used method to address these issues, some authors, such as [12], employ system dynamics as a methodology to measure the sustainability performance of three last-mile logistics strategies for a local food cooperative: (1) a centralized distribution network with a deliver-and-collect option, (2) a decentralized distribution network with a home delivery option, and (3) a distributed network based on a collective logistics concept. Additionally, [13] utilizes an agent-based simulation model to evaluate various coordination and transportation mechanisms, establishing the delivery capacity of a humanitarian aid network and providing decision support.

Colombia is highly susceptible to disasters due to its geographic, hydroclimatological, and geological characteristics [14]. Therefore, it is essential to establish efficient management strategies to ensure a rapid response, thereby reducing the number of injuries and fatalities. The city under study has a population of 127,545, with 110,905 residing in the municipal capital and 16,640 in the rural area, according to data from the 2018 Population and Housing Census conducted by the National Administrative Department of Statistics (DANE). Furthermore, the city has a proportion of threatened areas of 53.29 % according to data from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM). This indicates significant exposure to hydrometeorological disasters, primarily floods, which can severely impact the population and infrastructure.

In response to this issue, the city mayor's office decided to allocate budget funds for the purchase and distribution of food kits to vulnerable families. However, during the first month of implementing this strategy, approximately 15,000 requests were received from affected families, while the municipal administration could only deliver an average of 3,000 survival kits per disaster. Therefore, it is essential to evaluate the effectiveness of a model for delivering humanitarian aid to analyze the proposed system's behavior and prioritize the distribution of food kits to the most vulnerable families, thereby reducing the risk of food insecurity in the population.

Despite the significant increase in assistance during humanitarian emergencies, little is known about how effectively these humanitarian aid programs are targeted to those most in need [15]. In this paper, the elements inherent to the distribution of humanitarian aid are analyzed in the context of disasters to evaluate the effectiveness of different strategies for distributing food kits to the affected population. The paper is organized as follows: Section 2 presents the methodology used to evaluate the distribution model; Sections 3 and 4 outline the main results and provide a discussion; and finally, Section 5 presents the key conclusions of the study.

Materials and methods

System dynamics is a methodology used to analyze the relationships between the various variables that constitute the structure of a complex system. This understanding allows for an in-depth analysis of the system's long-term behavior. The applications of system dynamics extend beyond organizational contexts; they are frequently employed to evaluate decision-making behavior in environmental and social systems [16].

The decision to analyze the effectiveness of a model for delivering humanitarian aid aims to establish a strategy that enables the local administration of a city to identify the crucial variables involved in the distribution of food kits. This approach will help improve food security for the population. Importantly, [17] highlights the importance of simulation strategies in analyzing and projecting the behavior of various public policies within society.

Importantly, system dynamics has been utilized as a strategy evaluation tool in business contexts. For example, [18] assesses the impact of a volume flexibility project on logistics costs and service levels in the supply chain of perishable products via system dynamics. Similarly, as an extension of that study, a practical application to a papaya distribution supply chain in northern Valle del Cauca was presented [19]. Moreover, system dynamics have also supported decision-making for local governments; for example, [20] proposes integrating a system dynamics model, participatory modeling, and the analytical network process (ANP) to select green projects within national calls for proposals aimed at promoting environmental care and peacebuilding in communities affected by violence.

For the application of system dynamics, the methodology outlined in Figure 1 is followed. Initially, a characterization of the humanitarian supply chain is conducted, leading to the construction of a causal diagram that illustrates the relationships among all the variables involved in the system. This provides a broader and clearer understanding of reality. Next, a Forrester diagram is created to quantify the relationships previously depicted in the causal diagram. Finally, simulations are carried out, and the main results obtained are analyzed.

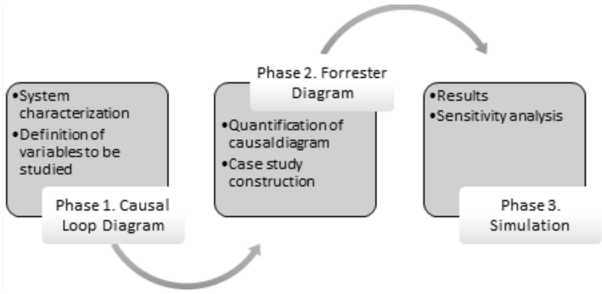

FIGURE 1.
System dynamics implementation methodology
Source: Authors' own creation.

Results

Causal loop diagram

The supply chain for humanitarian aid in the city under study consists of a main collection center, satellite centers by commune, and families to be served. The risk management secretary estimates the number of kits that can be requested from the collection center and sends an order form specifying the number of kits to be delivered to each satellite center. At these temporary delivery centers, personnel must be available to receive and distribute supplies according to a delivery list that organizes families by socioeconomic stratum. In some communities, temporary centers are not established, and deliveries are made door to door. Based on the identification of the chain, a causal diagram is constructed to illustrate the main relationships between the actors in the network.

Causal loop diagrams are specific tools for system dynamics modeling that address the system as a whole through simulation, illustrating the influence of one subsystem on others [21]. Figure 2 shows that as the gap between the supply and demand for food kits widens, there is a growing need to acquire donations, either through the municipal administration's own resources or by promoting strategies to encourage donations from the population. Importantly, the amount of products the government can provide directly depends on the available capital budget for this purpose. As more donations arrive, the available inventory increases, allowing more vulnerable families to be served, which in turn reduces the number of families in need of assistance and decreases the demand for products.

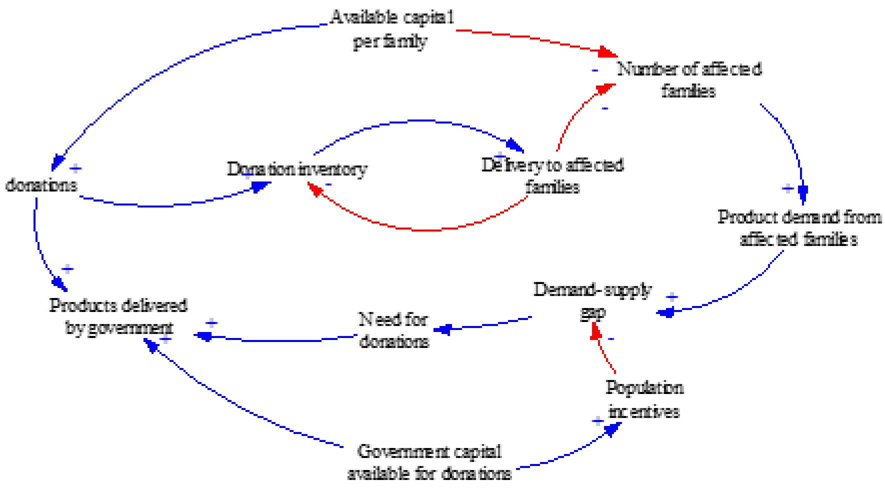

FIGURE 2.
Relationship between donations and food kit deliveries
Source: Authors' own creation.

Figure 3 shows that as disaster recovery time increases, informal unemployment increases, which in turn reduces the amount of capital available for the most vulnerable families. Additionally, the decrease in families' available cash leads to an increase in requests for food kits.

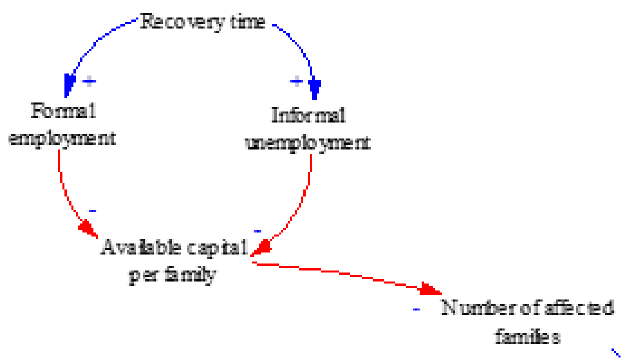

FIGURE 3.
Relationship between recovery time and number of affected families
Source: Authors' own creation.

As shown in the analysis conducted with the causal diagrams presented above (the complete causal diagram is displayed in Figure 4), there are several reasons why a family may become a disaster victim and require food aid during a disaster. In the following chapter, we analyze the impact of different prioritization metrics on the delivery of food kits through the construction of a Forrester diagram.

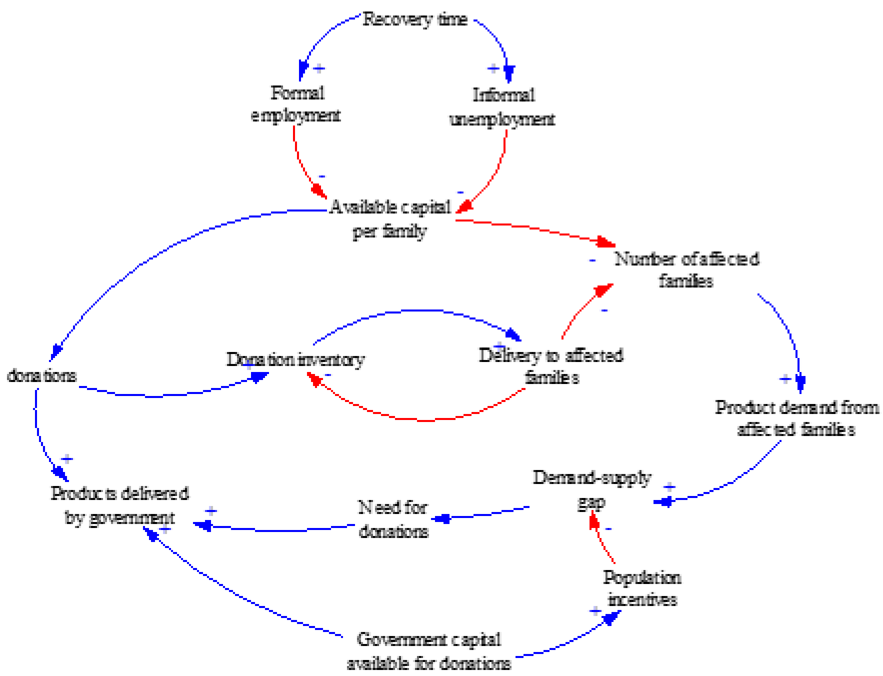

FIGURE 4.
Complete causal loop diagram
Source: Authors' own creation.

Forrester diagram

After developing causal diagrams, Forrester diagrams for the respective simulations were created. Forrester diagrams provide a graphical representation of dynamic systems by qualitatively modeling the relationships between the components using symbols that correspond to a dynamic interpretation of the system [22]. The Forrester diagram was constructed on the basis of the distribution scheme used by a small city in Valle del Cauca. Figure 5 illustrates the behavior of the inventory of food kits, where the two main inputs are donations from the population and the markets purchased with funds allocated for this purpose.

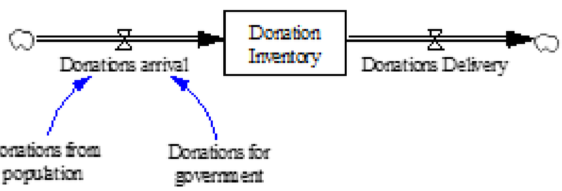

FIGURE 5.
Relationship between the arrival and delivery of donations
Source: Authors' own creation.

The delivery of donations is explained in greater detail in Figure 6, which shows that requests for kits fall within two categories: families with individuals injured in the disaster and families who, owing to recovery time, have lost their daily income and lack access to basic food security. The delivery aims to serve a percentage of families from each group, and the challenge of this research lies in determining how to allocate resources between these two large groups of applicants. Additionally, delivery is constrained by the city's daily capacity to distribute humanitarian aid and the available inventory of donations.

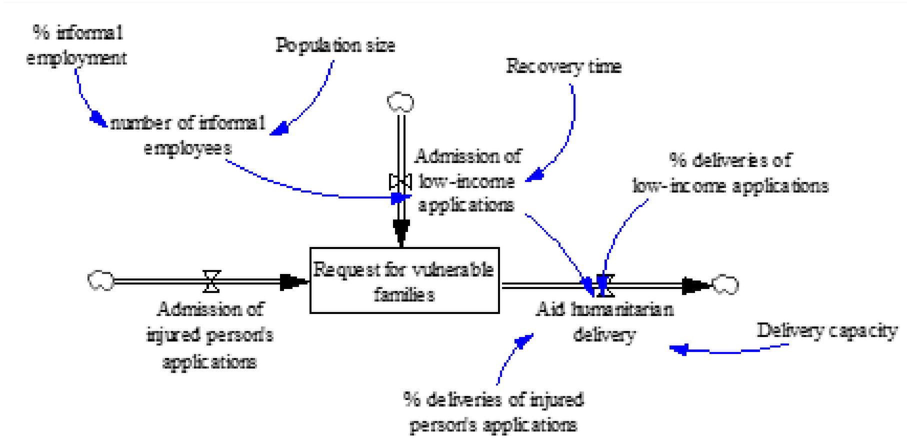

FIGURE 6.
Prioritization of humanitarian aid distribution
Source: Authors' own creation.

Once the Forrester diagrams are defined, we construct the equations for calculating each of the flow, auxiliary and level variables illustrated in the diagram. Table 1 provides a detailed overview of the equations used for each variable.

TABLE 1.
Equations constructed for the Forrester diagram variables

Type of Variable	Variable name	Equation
Level	Donation inventory	Donation arrival – Donation delivery
Level	Request for vulnerable families	Admission of low-income applications + Admission of injured person applications – Aid humanitarian delivery.
Flow	Donations arrival	Donations from population + Donations for government
Flow	Donation delivery	Aid humanitarian delivery
Flow	Admission of injured person applications	RANDOM NORMAL (100, 1000, 500,200, 100)
Flow	Admission of low-income applications	PULSE TRAIN (1, 1, 1, Recovery time) * number of informal employees
Flow	Aid humanitarian delivery	MIN (delivery capacity, %deliveries of low-income applications*Admission of low-income applications + %deliveries of injured person applications*Admission of injured person applications)
Auxiliary	Number of informal employees	Population size*% informal employment.
Auxiliary	Donations from population	RANDOM UNIFORM (50, 150, 100)

Auxiliary	Donations from government.	RANDOM UNIFORM (220, 500, 220)
Auxiliary	Recovery time	RANDOM UNIFORM (60, 120, 60)
Auxiliary	%deliveries of low-income applications	RANDOM UNIFORM (0.2, 0.5, 0.2)
Auxiliary	%deliveries of injured person applications	RANDOM UNIFORM (0.4, 0.5, 0.4)
Auxiliary	Delivery capacity	RANDOM NORMAL (150, 950, 400,100, 100)
Auxiliary	% informal employment	RANDOM UNIFORM (0.3, 0.5, 0.4)
Auxiliary	Population size	RANDOM NORMAL (15000, 25000, 20000,2000, 15000)

Source: Authors' own creation.

Simulation

The simulation was conducted via the Vensim DSS program over a 360-day period. The data entered into the model were obtained directly from the municipal administration of the city under study.

Figure 7 illustrates the behavior of the donation inventory, which is replenished in large quantities each month when the municipal administration purchases markets with allocated funds. It can also be observed that during the final days of the month, the inventory available for delivery to the vulnerable population relies solely on the quantities donated by third parties.

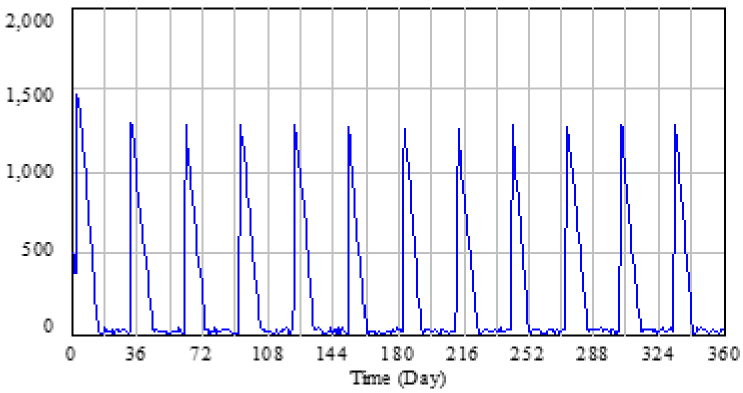

FIGURE 7.
Donation inventory behavior
Source: Authors' own creation.

Figure 8 illustrates the delivery of food kits to the vulnerable population. In this graph, daily deliveries peak at 200 food kits (the maximum delivery capacity) at the beginning of each month when inventory is available in large quantities. However, at the end of each month, only the kits donated by third parties are delivered, as these are the only ones available at that time.

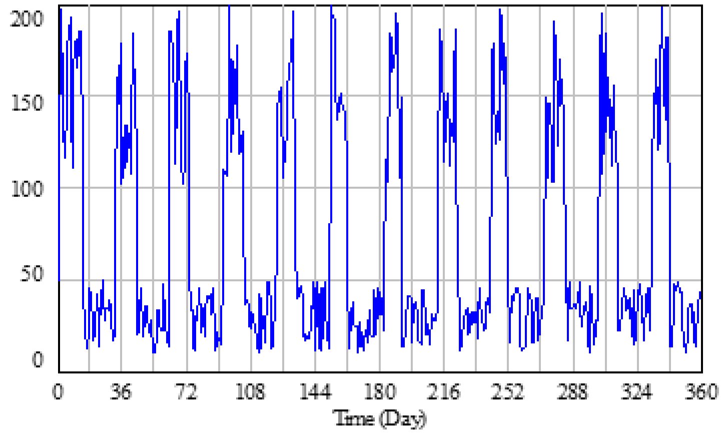

FIGURE 8.
Delivery behavior of food kits
Source: Authors' own creation.

Figure 9 shows that while it is possible to deliver donations to the vulnerable population, the demand from families far exceeds what can be provided. This results in a growing number of assistance requests, which reach nearly 800,000 pending requests for food kit deliveries by the end of the simulation.

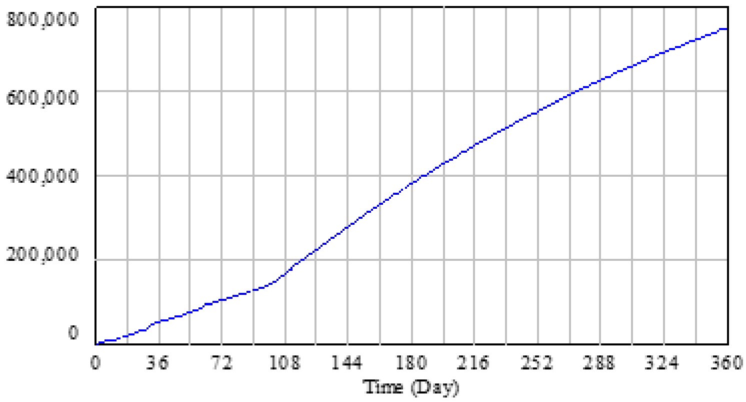

FIGURE 9.
Behavior of requests from the vulnerable population
Source: Authors' own creation.

Table 2 presents a sensitivity analysis conducted with the simulation model, evaluating the expected impact of a campaign currently promoted by the municipal administration to encourage donations from third parties to assist the most vulnerable populations. The analysis revealed that the campaign increased the average number of kits delivered by 113 % and increased the inventory available for food security by 141 %. Interestingly, the average number of requests throughout the year is reduced by only 3 % compared with that in the initial scenario. This suggests that a donation incentive campaign should be accompanied by a strategy to engage more volunteers in the delivery process, allowing for an increase in the current daily distribution capacity.

TABLE 2.
Sensitivity analysis resulting from the implementation of a campaign to encourage donations

Variable	Current Status	Donation campaign	Effect
Average kit delivery	72	153	113 %
Average donation inventory	268	646	141 %
Average Request	370.225	358.062	-3,3 %

Source: Authors' own creation.

Discussion

This article examines the application of system dynamics to analyze, model, and study the behavior of a humanitarian aid delivery strategy implemented in a city in central Valle del Cauca in response to the economic crisis caused by a disaster. As noted by [23], disasters impact the socioeconomic conditions of the population and have contributed to increased poverty in urban areas, which often jeopardizes the food security of the most vulnerable households.

Additionally, the establishment of a distribution network is crucial for implementing humanitarian aid delivery strategies. It is often impractical to deliver food kits to the entire population, necessitating the use of satellite distribution centers. These centers are typically located nearby and are supplied by a central warehouse, which uses a diverse and trained fleet of vehicles [24].

This research introduces a decision-support tool for city administrations, as highlighted in articles such as [25], which discuss the need for innovative mechanisms to enhance the management of nonprofit organizations and government efforts in humanitarian aid distribution.

Finally, it is essential to emphasize the existing needs of the city under study to promote a donation and volunteer program aimed at bridging the current gap between food supply and demand for the most vulnerable populations.

Conclusions

System dynamics enables the analysis of the behavior of food kit deliveries in a city in Valle del Cauca by identifying and defining the variables that have the greatest impact on decision-making, such as injury rates, available funding for purchasing food kits, the distribution capacity of the system, and the behavior of donations from third parties, among others.

Furthermore, the simulated model confirms the existing gap between the supply of food kits and the growing demand from the vulnerable population. The analysis also examined the impact of a campaign aimed at encouraging third-party donations in the city, revealing that average deliveries and inventory increased by more than 100 %. However, requests from vulnerable families decreased by only 3 %, suggesting the need for additional administrative strategies, such as initiatives to expand the current group of volunteers responsible for the distribution process in satellite centers located throughout the city's neighborhoods.

This research serves as a preliminary approach to the problem at hand, and future studies are expected to conduct sensitivity analyses on other key parameters of the model, such as injury rates and recovery times. Additionally, it would be valuable to explore the impact of government income distribution on the inventory of donations and the needs of vulnerable families awaiting assistance.

Acknowledgments

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Notes

* Research article.

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