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Dynamic Modeling of Operational Synchronization for Pharmaceutical Distribution Centers in Logistics Services Using the System Dynamics Approach

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A B S T R A C T

In recent years, the expansion of networking capabilities within the economic system and the ability to create smart, flexible markets with high efficiency and low cost have provided an exceptional opportunity for service-providing companies. These companies can, through participation in value chain management, transform supply chain architecture, thereby generating new markets and fresh demands for services centered on integration and coordination within the logistics system. The existence of a comprehensive, sustainable, and reliable logistics network enables the development of a range of small and medium-sized enterprises (SMEs) within the framework of e-commerce—enterprises that, in the absence of such a network, would lack sufficient economic justification due to limited market size. This article examines and analyzes the topic of dynamic modeling of operational synchronization for pharmaceutical distribution centers in logistics services using the system dynamics approach. The results indicate that supply chain resilience functions as a critical factor in responding to crises (such as pandemics, logistical disruptions, or sudden demand fluctuations) and prevents the degradation of service quality. The implementation of dynamic distribution leveraging advanced technologies, including artificial intelligence (AI) and the Internet of Things (IoT), enables rapid and intelligent decision-making in the face of disruptions. The increase in customer satisfaction within this loop creates positive pressure for the continuous improvement of infrastructure and processes, thereby strengthening the cycle of organizational learning and improvement.

Keywords: *Operational synchronization, pharmaceutical distribution, logistics services, system dynamics, service quality*

1. Introduction

The pharmaceutical industry demands not only accuracy in demand forecasting and inventory control but also strategic coordination across all tiers of the supply chain. Synchronization—defined as the alignment of logistical drivers and operations across all functional domains—is critical for ensuring that drugs and medical supplies are delivered on time, in optimal condition, and with minimal resource wastage. Synchronization becomes even more crucial when operating in environments prone to disruptions, including regulatory changes, pandemics, and fluctuating consumer demand patterns. According to (Barnabas Bitta, 2024), effective synchronization of logistics drivers directly impacts the optimization of supply chain operations, particularly in sectors such as pharmaceuticals, where time-sensitive products require tightly coordinated handling.

One of the foundational approaches for analyzing the behavior of complex systems such as pharmaceutical supply chains is system dynamics modeling. This methodology enables researchers and practitioners to simulate interdependent variables over time, considering both feedback loops and delays. By doing so, it becomes possible to predict emergent behaviors and optimize decision-making under uncertain conditions. As highlighted by (Brusset et al., 2022), modeling ripple effects and productivity impacts in the face of pandemic disruptions requires sophisticated analytical tools, such as system dynamics, to understand and mitigate cascading failures in global supply chains.

The importance of synchronization in pharmaceutical logistics is multifaceted. On one hand, it involves aligning inventory levels with real-time demand signals; on the other, it necessitates coordination among diverse stakeholders—including suppliers, manufacturers, distributors, regulatory bodies, and end-users. According to (Abdollahi et al., 2024), intelligent distributed supply chain management models can serve as robust frameworks for achieving this coordination, especially when augmented by artificial intelligence and IoT-enabled technologies. These technologies empower systems to react dynamically to external shocks and internal inefficiencies, thus ensuring service continuity and drug availability even under adverse conditions.

In recent years, the adoption of digital and intelligent systems in logistics operations has expanded significantly. As (Abdul Rahman et al., 2023) emphasized, decision analysis frameworks for warehouse performance indicators can substantially enhance logistical efficiency when they incorporate real-time data analytics and performance forecasting. Similarly, (Ajali, 2021) explored the role of intelligent systems in logistics and supply chain management, asserting that synchronized data flows and decision-making logic reduce bottlenecks and redundancy across the supply chain.

Pharmaceutical supply chains are inherently complex due to their regulatory constraints, temperature-sensitive goods, and life-saving implications. As a result, operational synchronization cannot rely solely on conventional logistics models; it must instead incorporate strategies for resilience, flexibility, and sustainable practices. As (Aldrighetti et al., 2023) pointed out, designing a resilience portfolio that integrates preparedness and recovery investment is essential for modern supply chains operating in high-risk environments. This is supported by (Aslam et al., 2020), who argued that achieving supply chain resilience requires a balance between ambidexterity (exploration vs. exploitation) and agility, allowing systems to flexibly respond to unforeseen disruptions.

In the context of pharmaceutical logistics, synchronization must also account for demand uncertainty and reverse logistics. For instance, (Akbarpour et al., 2020) developed an integrated relief chain network under uncertainty to address the fluctuating nature of demand during crises. This dynamic approach enables faster adaptation, ensuring critical medications are delivered where needed, without delays or excess stock. Similarly, (Foroughi & Kia, 2022) emphasized the importance of designing networks that consider both forward and reverse logistics under uncertain conditions—a particularly vital concern in pharmaceutical contexts involving product recalls or returns.

A critical dimension of synchronization is the integration of advanced information systems, especially those powered by IoT and artificial intelligence. As (Akbar et al., 2022) described, implementing a blockchain-based roadmap in healthcare logistics enhances visibility, traceability, and data integrity—elements that are essential for reliable synchronization across stakeholders. Likewise, (Mohghar et al., 2024) introduced a model based on fuzzy-intuitive analysis and AI methods to optimize reverse logistics planning, underlining the role of hybrid analytical techniques in streamlining pharmaceutical operations.

Furthermore, synchronization in pharmaceutical distribution is deeply influenced by service quality and customer satisfaction. (Lotfi Zadeh & Ehsani, 2021) explored how logistics service quality and procurement capabilities impact customer satisfaction, suggesting that aligned and transparent processes contribute to trust and loyalty. Additionally, (Asmahan Al & Asad, 2024) conducted a literature review on the effectiveness of logistics services, concluding that efficient logistics execution, underpinned by operational synchronization, significantly improves firm performance.

The integration of human decision-making into technological frameworks also plays a central role in synchronized supply chains. (Bharadwaj, 2023) emphasized that IT capabilities must be aligned with organizational strategies to yield meaningful performance gains. Meanwhile, (Sami'i et al., 2023) highlighted the importance of weighing costs and benefits of sustainable supply chains under uncertainty—an insight that reinforces the need for models that can flexibly assess trade-offs and simulate long-term outcomes.

Optimization of logistics routes, transport scheduling, and inventory control are likewise essential for achieving synchronization. According to (Babai et al., 2023), determining optimal order quantities under stochastic price and demand conditions enables better inventory alignment. Route optimization also plays a role in reducing delivery time and enhancing service levels, as explored by (Bajec & Tuljak-Suban, 2022), who proposed sustainable crowdshipping strategies for last-mile deliveries.

The necessity of system-level thinking is further underscored by (Nooraniyan & Saqaeian Nejad Isfahani, 2024), who estimated a comprehensive pharmaceutical supply chain model using factor analysis methods, and by (Moghadaspour, 2020), who presented a closed-loop supply chain model incorporating third-party factors. Both studies reveal that operational synchronization depends not only on internal coordination but also on the integration of external dynamics and stakeholders.

Healthcare supply chains are also tasked with ensuring safety and sustainability throughout all operations. In this regard, (Ala et al., 2023) used queuing theory and optimization techniques to resolve patient scheduling problems, while (Albukhitan, 2020) stressed the importance of developing digital transformation strategies in manufacturing, which is applicable to pharmaceutical logistics as well. Similarly, (Baldoni et al., 2019) reviewed the present and future of telepharmacy services, suggesting that remote and tech-enabled distribution models may become increasingly important for synchronized, patient-centered logistics.

The literature also reveals that robust pharmaceutical supply chain models must incorporate uncertainty mitigation strategies. For instance, (Faramarz Noori, 2019) proposed a robust-stochastic optimization approach to handle raw material purchasing and supply volatility. Likewise, (Derakhshi, 2020) developed a causal model for influencing factors on supply chain resilience, which supports the system dynamics modeling approach adopted in the current study.

Finally, it is essential to ensure that synchronization is achieved not only through infrastructure and algorithms but also through strategic alignment and governance. (Reza Jalil et al., 2021) introduced a model for coordinating service supply chains, while (Al Abbadi et al., 2021) and (Al Jabri et al., 2021) examined supply chain performance challenges in Oman, emphasizing the need for contextualized logistics strategies in emerging markets. (Augustine & Fulghum, 2019) also underscored the importance of integrating procurement and logistics for a more resilient supply chain structure.

In summary, the reviewed literature provides a robust foundation for developing a dynamic model of operational synchronization in pharmaceutical distribution logistics. By synthesizing perspectives from system dynamics, artificial intelligence, supply chain resilience, and service quality, this study seeks to design a holistic framework capable of enhancing efficiency, responsiveness, and sustainability across the pharmaceutical supply chain.

2. Methods and Materials

To design a causal dynamic model for operational synchronization in pharmaceutical distribution centers within logistics services, the study employed System Dynamics (SD) methodology. System dynamics is an approach for understanding the nonlinear behavior of complex systems over time through the use of feedback loops. This method was first introduced by Jay Forrester in 1961 in his book *Industrial Dynamics* and has since expanded rapidly.

In designing a dynamic system, the first step is to identify the model variables. The term closed boundary refers to a defined range that clearly separates relevant dynamic variables from unrelated ones. Each closed boundary includes feedback loops that interact with each other. The cumulative impact of these loops generates the desired behavior. Each feedback loop essentially acts as a cornerstone of the system's structure. This theory stands in contrast to traditional perspectives, which assumed unidirectional influence among phenomena. In system dynamics, behaviors emerge from feedback loops.

Therefore, the modeler must attempt to construct a chain of cause-and-effect relationships as a causal loop. The continuity of a dynamic system depends on the existence of such causal loops. The Vensim software was used to design the system dynamics model.

Table 1

List of Model Components

No.	Model Components
1	Demand Planning and Forecasting
2	Supply Chain Flexibility and Resilience
3	Inventory Monitoring and Control
4	Transportation Route Optimization
5	Dynamic and Flexible Distribution
6	Transportation Scheduling
7	Tracking and Monitoring Systems
8	Information Synchronization among Supply Chain Stakeholders
9	Use of IoT for Tracking
10	Providing Accurate Information to Customers
11	Supplier Relationship Management
12	Improving Customer Service Quality
13	Observing Hygiene Principles in Storage and Transportation
14	Compliance with Health and Sustainability Standards

3. Findings and Results

Assessing the impact of interrelations among indicators on their computed weights is a crucial part of evaluating internal communications in determining the final model. Therefore, a revision of the weight calculation method is required.

The weight of the indicators is calculated using the following formula:

Equation 1:

$$W = R_{ij} \times d_i$$

Where:

- W = Weight
- R_ij = Value assigned to the relationship between the need and the engineering technical requirement
- d_i = Importance level of the need
- i = Index of the need
- j = Index of the requirement

In this study, 14 components were identified in the first matrix.

To enhance understanding, the values derived from the Delphi analysis can be normalized. However, normalization is only feasible when the components are independent of one another. Therefore, to understand the relationships among the components, as previously stated, a γ (gamma) variable is defined to represent internal relations among identified components.

Ultimately, using the following formula, one can calculate new values of R by normalizing and considering internal relations:

Equation 2:

$$R''_{ij} = \frac{(\sum_{k=1}^{n} \gamma_{kj}).R_{ij}}{(\sum_{j=1}^{n}(\sum_{k=1}^{n} \gamma_{kj}).R_{ij})}$$

Where k and j represent engineering technical requirement indicators.

Additionally, when k = j, then γ_kj = 1.

As mentioned, the importance level is directly related to the final model. Thus, it is necessary to establish a relationship to apply the influence of β (beta) on the importance level. For this purpose, the following normalized formula is provided:

Equation 3:

$$d''_i = \frac{(\sum_{l=1}^{m} \beta_{il}).d_i}{\sum_{i=1}^{m}(\sum_{l=1}^{m} \beta_{il}).d_i}$$

Where β_il refers to the relationship between needs i and l.

Consequently, considering the above equations, new weights adjusted for the internal relations among model components can be calculated using the following formula:

Equation 4:

$$W''_j = \sum_{i=1}^{m} d''_i.R''_{ij}$$

Identification of Demand Forecasting and Inventory Improvement Loop (R1)

This loop is defined as follows:

Demand Planning and Forecasting → Accuracy in Inventory Monitoring and Control (+)

Inventory Monitoring and Control → Likelihood of Inventory Shortage or Surplus (–)

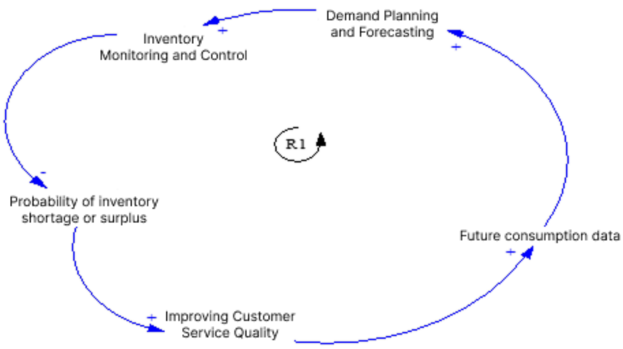
Reduction in Inventory Shortage or Surplus → Improved Customer Service Quality (+)

Customer Service Quality → Accuracy in Future Consumption Data (+)

Future Consumption Data → Demand Planning and Forecasting (+)

Figure 1

Feedback Loop R1



In this loop, the focus is on the accuracy of demand planning and pharmaceutical consumption forecasting, which leads to improved inventory monitoring and control. When forecasts are more precise, the likelihood of inventory shortages or surpluses decreases, which in turn enhances customer service quality. As service quality improves, more accurate feedback information on actual consumption is obtained, which contributes to the refinement of future forecasts. This reinforcing loop allows the supply chain to operate with minimal waste and maximum customer satisfaction.

In this key loop of the system dynamics model for operational synchronization in pharmaceutical distribution centers, the focus lies on the accuracy of demand planning and consumption forecasting, which serves as the fundamental basis for the performance of other supply chain components. Demand planning estimates future pharmaceutical needs by leveraging historical data, patient consumption patterns, disease seasonality, prescription information, and health policy guidelines. If these forecasts are highly accurate, they enable better coordination among production, warehousing, distribution, and ordering processes, thereby preventing conditions such as critical drug shortages or warehouse overstocking.

Inventory monitoring and control are heavily influenced by forecast accuracy. When forecasts are precise, orders are aligned with actual needs, and inventory levels in warehouses remain optimal. This not only reduces storage costs but also prevents spoilage of medications with limited shelf lives. Furthermore, better inventory management enhances the supply chain's readiness to meet urgent demands and respond to crises.

By optimizing inventory conditions, customer service quality significantly improves. Customers—pharmacies, healthcare centers, and end-users—receive their required medications in a timely manner and have a positive service experience. This satisfying experience increases trust in the brand and distribution network, and reinforces customer loyalty. As a result, the flow of orders becomes more stable and predictable.

The feedback data gathered from customer satisfaction or dissatisfaction constitutes valuable information regarding actual drug consumption. These data are directly integrated into the forecast revision cycle. With each iteration of this cycle, the forecasting model becomes more intelligent and the margin of error is reduced. This continuous learning loop generates systemic improvements and enhances performance sustainability through the reinforcement of positive feedback.

Within this process, the role of information technologies and integrated systems is vital. By utilizing analytical tools and machine learning algorithms, consumption data, customer feedback, and seasonal behaviors can be accurately analyzed and transformed into actionable behavioral patterns for future forecasts. This enhances planning precision and strengthens the feedback loop. The reinforcing loop not only increases operational efficiency but also enables the supply chain to deliver maximum value to customers with minimal resource waste. This is one of the primary advantages of system dynamics in designing logistics models, as it simplifies operational complexity and facilitates strategic decision-making in pharmaceutical distribution centers.

Identification of Supply Chain Resilience Loop (R2)

The relationships in the loop are defined as follows:

Supply Chain Flexibility and Resilience → Possibility of Dynamic and Flexible Distribution (+)

Dynamic Distribution → Reduction in Transport Scheduling Disruptions (–)

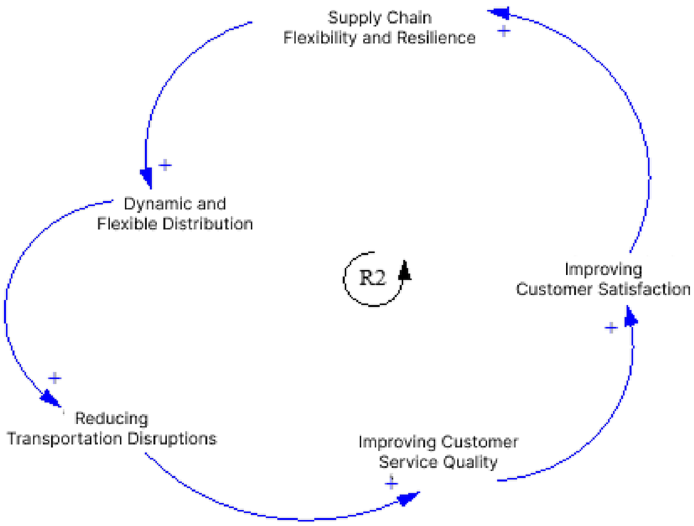
Reduced Transport Disruptions → Improved Customer Service Quality (+)

Service Quality → Increased Customer Satisfaction and Retention (+)

Customer Satisfaction → Enhanced Supply Chain Flexibility and Resilience (+)

Figure 2

Feedback Loop R2



This loop demonstrates that increasing supply chain flexibility and resilience enables the implementation of dynamic and adaptable distribution. Such a distribution approach can mitigate potential transport scheduling disruptions, thereby enhancing customer service quality. Improved service, in turn, elevates customer satisfaction and retention, reinforcing the need for greater flexibility and quicker responsiveness across the supply chain. This cycle enables the logistics system to become more resilient and adaptive to changes and disruptions.

In this reinforcing loop of the system dynamics model for operational synchronization in pharmaceutical distribution centers, the primary focus is on enhancing supply chain flexibility and resilience. This component acts as a cornerstone of stability under unstable conditions, such as health crises, transportation delays, sudden demand fluctuations, or supplier issues. Flexibility refers to the ability of the supply chain to quickly adapt to environmental changes, while resilience refers to its capacity to withstand disruptions and promptly return to normal operations. Together, they provide the foundation for uninterrupted and effective customer responsiveness.

Enhancing flexibility and resilience in the supply chain lays the groundwork for executing dynamic and flexible distribution. In this scenario, the system can make real-time and intelligent decisions regarding order dispatch, transportation resource allocation, and route reconfiguration. The use of advanced technologies such as artificial intelligence (AI), machine learning, and Internet of Things (IoT)-based systems plays a crucial role in transforming distribution from a static process into a dynamic and adaptive mechanism.

Dynamic distribution directly contributes to reducing transport scheduling disruptions. For instance, in cases of unexpected disturbances such as traffic congestion, vehicle breakdowns, or adverse weather conditions, the system automatically identifies the best alternative route or optimal next delivery time. This capacity to manage disruptions ensures that medications arrive on time, preventing shortages or dissatisfaction at consumption points. This is especially critical for time-sensitive medications, such as refrigerated or emergency drugs.

When distribution is executed smoothly and consistently, customer service quality increases. Healthcare centers, pharmacies, and patients—when receiving timely and accurate deliveries—develop greater trust in the distribution system. This trust enhances customer satisfaction and fosters long-term relationships between the distributing company and stakeholders. Within this cycle, customer satisfaction also serves as a source of data and feedback for improving future performance.

The rise in customer satisfaction and retention strengthens the demand for higher flexibility and faster responsiveness within the supply chain. In other words, customers begin to expect higher speed, precision, and transparency, which in turn exerts positive pressure on the improvement of infrastructure, processes, and responsiveness systems. This reciprocal interaction between performance enhancement and rising expectations places the system in a continuous learning and improvement loop.

This loop enhances the pharmaceutical logistics system's resilience and adaptability to environmental changes, crises, and disruptions. This endogenous stability within the model boosts efficiency, reduces disruption-related costs, and improves reliability across the entire pharmaceutical supply chain. This loop clearly illustrates the benefits of a system dynamics perspective in addressing the complex problem of pharmaceutical distribution—where components interact continuously and reciprocally rather than functioning in isolation.

Identification of the IoT-Based Smart Tracking Loop (R3)

The loop relationships are defined as follows:

Use of IoT for tracking → Enhanced accuracy of tracking and monitoring systems (+)

Accurate tracking and monitoring → Provision of precise information to customers (+)

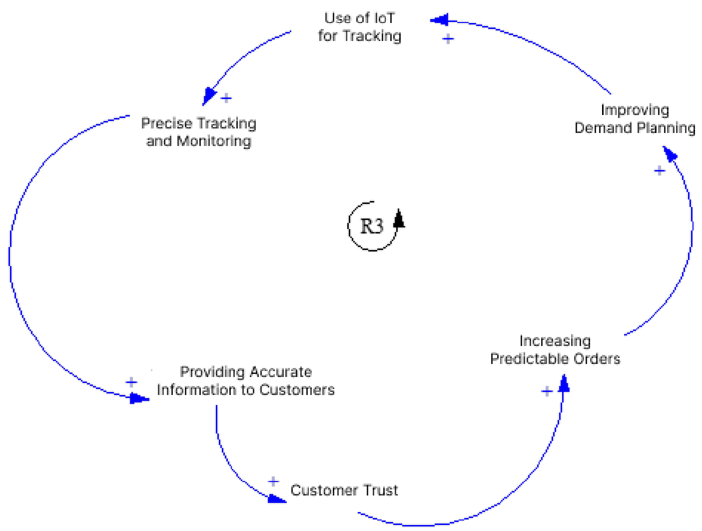
Provision of precise information → Increased customer trust (+)

Customer trust → Rise in scheduled orders (+)

Increase in predictable orders → Improved demand planning (+)

Figure 3

Loop R3



The application of Internet of Things (IoT) technology enhances the accuracy of tracking and monitoring systems and enables real-time, precise information to be delivered to customers. This transparency increases customer trust, which subsequently leads to a rise in scheduled and predictable orders. With improved predictability, demand planning becomes more accurate, allowing the entire supply chain to function in a smarter and more coordinated manner.

This loop emphasizes the pivotal role of advanced technologies in improving logistics performance and customer satisfaction.

In the system dynamics model for operational synchronization in the pharmaceutical supply chain, the use of IoT technology plays a vital and transformative role. By connecting physical objects—such as transportation vehicles, warehouse equipment, specialty medications, and environmental sensors—to an information network, IoT enables the reception, analysis, and transmission of real-time data. In the pharmaceutical distribution domain, IoT sensors can capture and transmit precise information such as the location of transport vehicles, storage temperature, humidity levels, shock impacts on packages, and even time of drug box openings. These data form the foundation for improving tracking and monitoring systems within the supply chain.

When tracking and monitoring are conducted with high accuracy, information transparency throughout the supply chain significantly increases. Customers—including pharmacies, hospitals, and end-users—can receive real-time updates on the status of their orders, including the exact location of pharmaceutical shipments and their anticipated delivery times. This transparency boosts customer trust in the distribution system, as they are informed of process details and can understand or follow up on delays or disruptions if they occur.

With increased customer trust, purchasing behavior becomes more predictable. When customers are confident in the reliability and accuracy of the supply chain’s performance, they place orders more regularly, systematically, and in accordance with actual demand. This results in a higher number of scheduled and predictable orders, which is a key success factor in pharmaceutical supply chains, as it reduces emergency or last-minute orders, thereby easing pressure on inventory, transportation, and distribution personnel.

As demand predictability improves, the quality of demand planning also increases. Procurement and logistics teams can place more accurate upstream orders from suppliers, manage warehouse inventories more efficiently, and organize transportation scheduling based on actual consumption patterns. This process not only reduces waste, shortages, or overstocking but also enhances the overall efficiency of the distribution system.

Ultimately, the positive feedback loop formed between the use of IoT, enhanced tracking systems, increased information transparency, improved customer trust, and better demand planning leads to greater smartness and synchronization across the supply chain. A system empowered by modern technologies, operating with high precision and agility, and generating higher stakeholder satisfaction, not only performs better in the short term but also develops into a sustainable competitive advantage over time.

Thus, this loop illustrates that IoT technology is not merely a technical tool, but a strategic enabler that connects operational, informational, and behavioral components within the supply chain, establishing a foundation for continuous improvement, agility, and customer satisfaction. In today's competitive environment, companies capable of effectively integrating this technology into their supply chains will pave the way for sustainability and growth.

Identification of the Route Optimization and Delivery Time Reduction Loop (R4)

The loop relationships are defined as follows:

Transportation route optimization → Reduction in transportation scheduling time (–)

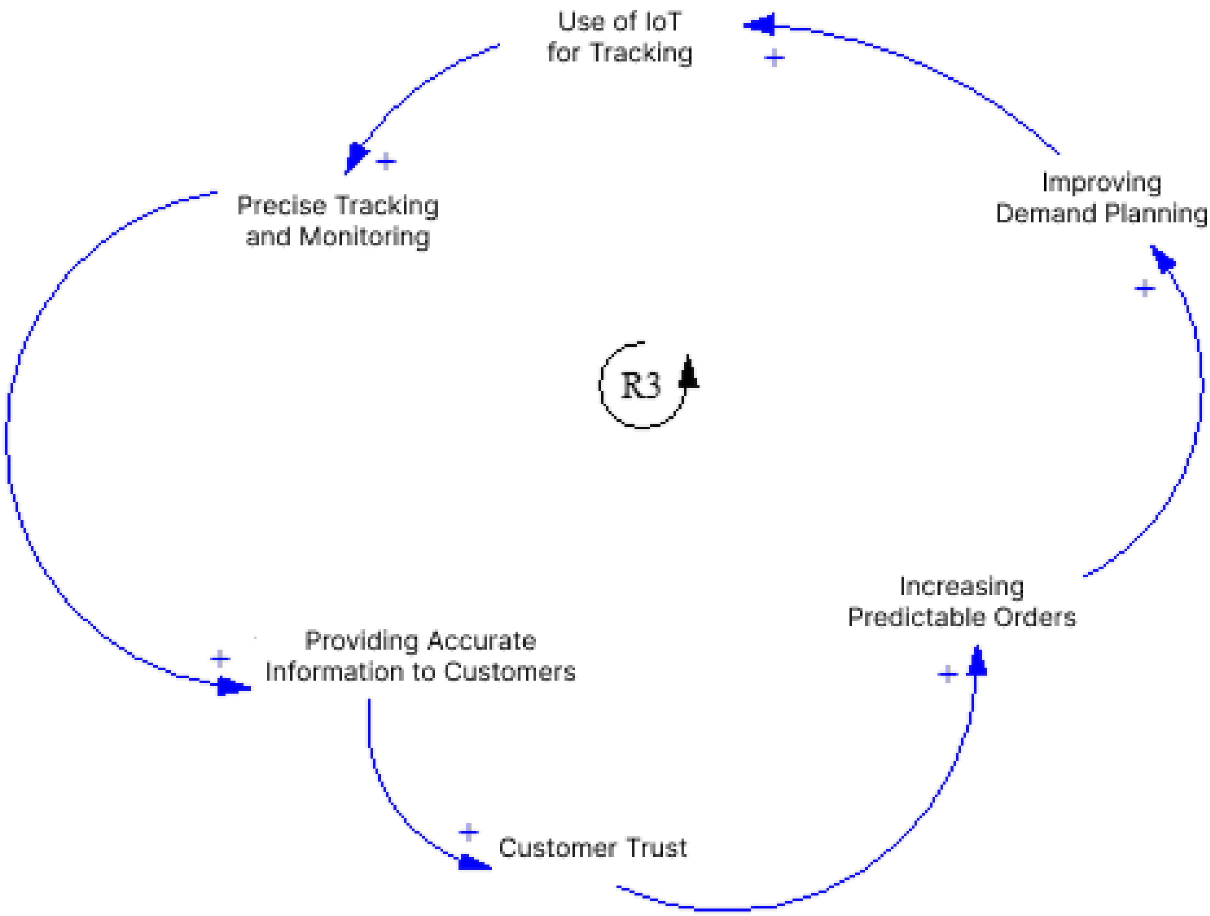
Reduction in transportation time → Improved customer service quality (+)

Improved service quality → Increased stable and predictable demand (+)

Increased predictability → Further improvement in route optimization (+)

Figure 4

Loop R4



This loop focuses on optimizing transportation routes to reduce scheduling and delivery times. Reduced transportation time directly enhances customer service quality, as timely delivery of medications is critical. Improved service quality leads to more stable and predictable demand, which in turn enables even better route optimization. This reinforcing cycle increases the efficiency and speed of logistics services while preventing resource and time waste.

In this optimization loop, the core objective is to improve transportation routing in order to minimize scheduling delays. With reduced transportation time, the delivery of goods and services becomes significantly faster and more efficient. In the pharmaceutical sector, where timely and rapid delivery of medications is of high importance, this plays a critical role; delays in drug delivery can have serious negative consequences for patient health and diminish customer trust in the distribution system. Therefore, reducing transportation time not only enhances customer satisfaction but also improves the overall quality of services delivered.

Enhanced customer service quality itself acts as a driving force for more stable and predictable demand. When customers are confident that their needed drugs or products will be delivered on time and in good condition, they are more inclined to make repeat purchases and continue using the service. This demand stability allows logistics companies to engage in more accurate and effective planning, leading to more optimal resource allocation.

Improved demand forecasting and increased stability facilitate more effective transportation route design and optimization. When demand patterns are more predictable, route planning can be conducted with greater accuracy, avoiding unnecessary or redundant shipments. Route optimization leads to fuel savings, reduced operational costs, and lower environmental pressures associated with transportation.

Moreover, this cycle operates as a reinforcing loop—meaning that improvements in one area enhance others, leading to ongoing systemic improvements. With increased logistics efficiency and service speed, companies can perform more competitively in the market and respond more quickly to customer needs. This leads to greater customer trust, higher retention rates, and ultimately, market share growth.

This trend significantly contributes to the reduction of resource and time waste. Lower transportation time means fewer costs related to delays, unnecessary storage, and logistical inefficiencies. Furthermore, with optimized routing, vehicles and human resources are better utilized, resulting in reduced workload stress and greater employee satisfaction.

The transportation route optimization loop not only enhances service quality and customer satisfaction but also leads to cost reduction and improved overall performance of the supply and distribution chain through strengthened internal cycles and increased efficiency. This approach represents an effective and sustainable solution for better logistics process management and enhancing service quality—especially in the pharmaceutical industry.

Identification of the Information Synchronization and Supply Chain Relationship Improvement Loop (R5)

The relationships in this loop are defined as follows:

Information synchronization among stakeholders → Accuracy of operational decision-making (+)

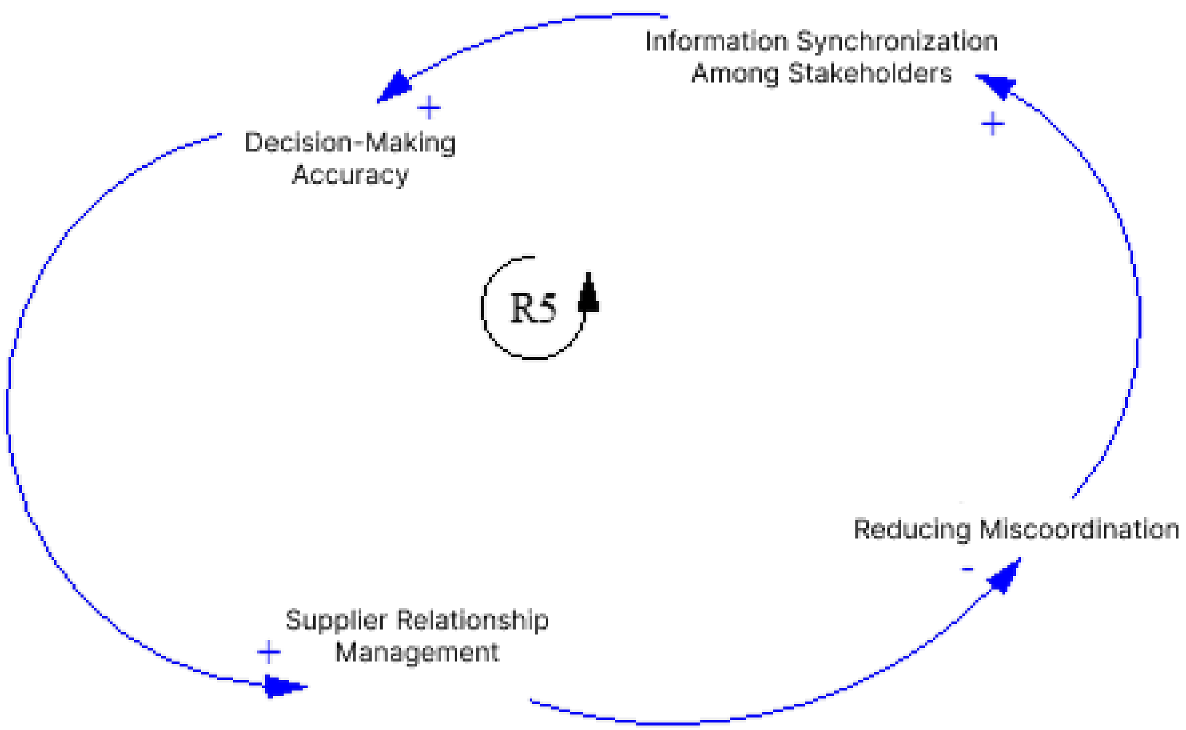
Decision-making accuracy → Supplier relationship management (+)

Effective supplier management → Reduced supply and inventory mismatches (–)

Reduced mismatches → Enhanced synchronization capability (+)

Figure 5

Loop R5



Information synchronization among supply chain stakeholders increases the accuracy and quality of operational decision-making. This improved decision-making enhances supplier relationship management and reduces supply and inventory mismatches. The reduction of such mismatches further increases the coordination and synchronization capacity within the supply chain. This loop enables all actors to operate based on up-to-date and aligned information, leading to improved efficiency and fewer operational errors.

Information synchronization plays a critical role in enhancing decision-making accuracy in complex supply chains where multiple actors—including suppliers, manufacturers, warehouse operators, distributors, and customers—interact, and each party's decision depends on the others. When data are shared transparently, in real time, and across all stakeholders, each can make more informed, holistic decisions. This is particularly vital for daily operational management, where any delay or error in information transmission may cause major disruptions.

Higher decision-making accuracy leads to better supplier relationship management. Suppliers, as the starting point of the supply chain, play a crucial role in sourcing raw materials and goods. When they receive timely and accurate data regarding market demand, inventory levels, delivery schedules, material quality, and other key indicators, they can plan more effectively. This coordinated data-driven cooperation prevents issues such as overstocking, shortages, and delivery delays.

Reducing mismatches in supply and inventory has highly positive ripple effects throughout the supply chain. Mismatches often cause material and information flow disruptions, higher inventory holding costs, and reduced customer satisfaction. By resolving these issues, synchronization between different parts of the chain increases dramatically. Each supply chain segment can better align its activities with others, reducing redundancy, delays, and operational errors—ultimately enhancing supply chain efficiency.

One of the most important benefits of this reinforcing loop is the continuous updating and transparency of information. When all actors in the supply chain have access to synchronized, accurate, and current information, faster and more optimal decisions can be made. This minimizes risks caused by incomplete or incorrect data, which often lead to poor decisions and costly outcomes. Moreover, synchronized information enables better monitoring of operational trends and improves risk management and crisis response. This synchronization process significantly boosts overall supply chain performance by reducing operational errors, improving coordination, and enhancing decision quality—leading to lower unnecessary costs and more efficient use of resources. The result is increased customer satisfaction and sustained competitive advantage. Therefore, information synchronization is not only critical for internal operations but is also a key success and sustainability factor for the entire supply chain.

Identification of the Health Compliance and Logistics Sustainability Loop (R6)

The relationships in this loop are defined as follows:

Compliance with hygiene protocols in storage and transport → Drug quality and consumer health (+)

Drug quality → Customer trust (+)

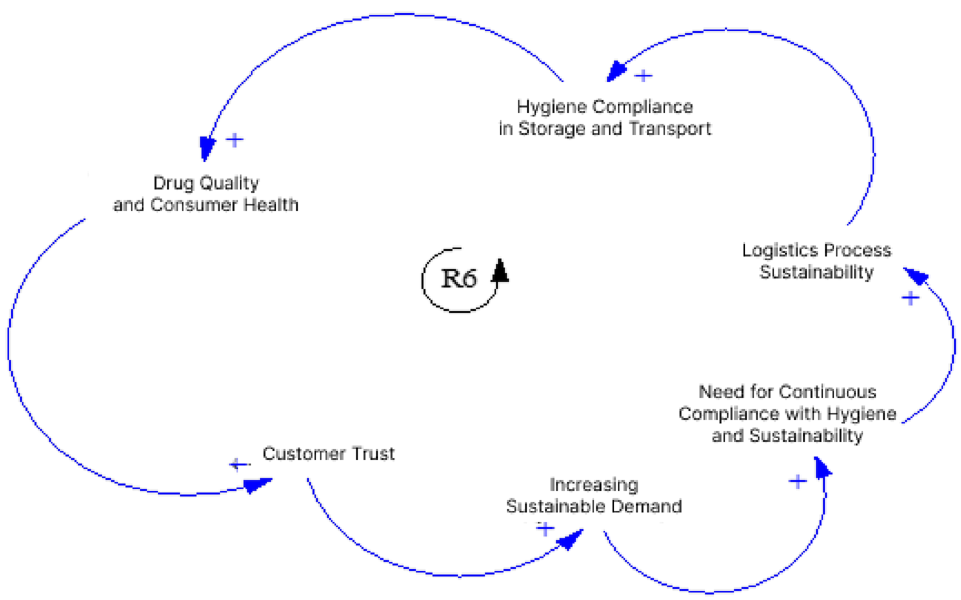
Customer trust → Increased stable demand (+)

Increased stable demand → Continuous adherence to hygiene and sustainability (+)

Compliance with sustainability standards → Sustainability of logistics processes (+)

Figure 6

Loop R6



This loop emphasizes the importance of hygienic practices in the storage and transportation of pharmaceuticals. Adhering to these practices ensures the quality of medicines and the health of consumers, which in turn builds customer trust. Increased trust leads to stable and consistent demand, which necessitates ongoing compliance with health and sustainability standards. This reinforcing cycle not only ensures public health but also promotes the sustainability of logistics processes and enhances the reputation of the distribution system.

The loop places special emphasis on compliance with hygiene protocols in pharmaceutical warehousing and transport processes—fundamental to ensuring drug quality and consumer health. Given the sensitive nature of medications and their direct impact on human well-being, they require special storage and transport conditions. Strict compliance with hygiene standards—such as maintaining appropriate temperatures, preventing contamination, controlling humidity, and secure packaging—ensures that medications reach consumers in optimal condition, preserving their effectiveness and safety. Failure to uphold these standards may reduce drug quality, result in adverse side effects, or even cause serious harm, which not only endangers patient health but also undermines public trust in the pharmaceutical distribution system.

Improving drug quality and consumer health directly contributes to customer trust. When consumers are confident that their medications are delivered safely, properly, and without any defect, their satisfaction increases, and this trust gradually evolves into long-term customer loyalty. Trust is a vital asset for any pharmaceutical distributor, enabling demand stability and continuity. Sustained demand allows companies to plan with higher accuracy and reliability, optimize resource allocation, and prevent unexpected market fluctuations.

To maintain and expand this reinforcing loop, ongoing adherence to hygiene and sustainability standards is essential. Consistent implementation of these standards not only ensures public health but also contributes to improving logistics processes and their efficiency. The use of modern technologies such as temperature control systems, smart sensors for monitoring storage and transportation conditions, and advanced packaging techniques helps maintain drug quality throughout the supply chain. Additionally, continuous staff training and cultivating a culture of hygiene awareness across the organization are key factors in sustaining this loop.

This process not only contributes to public health but also helps shape a positive and reliable image of the pharmaceutical distribution system in the public eye. A positive image translates into greater organizational credibility and a stronger market position. Companies that succeed in delivering safe, high-quality, and reliable services gain greater market share over time and attract stronger support from both customers and regulatory bodies. This reinforcing cycle, with its focus on hygiene compliance, enhances both public well-being and logistics process sustainability. These two interconnected dimensions—consumer health and supply system efficiency—mutually reinforce one another and form the foundation for sustainable development and long-term success in the pharmaceutical distribution industry.

Overall Causal Model

Causal loop diagrams provide a visual understanding of a system’s structure; however, they are not sufficient for analyzing system behavior over time. To better understand how the system behaves, the relationships between variables must be developed, and variable values need to be simulated over time. To do this, stock-and-flow diagrams must be designed. While causal loop modeling is done qualitatively, this stage requires the use of quantitative methods. *Formulation* refers to expressing the relationships among the variables of the conceptual model using mathematical equations, based on the stock-and-flow diagram.

Here, a system dynamics model is presented with six key feedback loops for operational synchronization of pharmaceutical distribution centers in logistics services. In this model, each of the 14 components is placed within one of the causal loops based on its specific role. The overall relationships in this model are defined as follows:

Demand Planning and Forecasting

This component is the starting point of the model, responsible for predicting drug consumption patterns using historical data, consumer behavior, and market information. The accuracy of these forecasts directly affects drug inventory levels, future orders, and the reduction of stockouts. Weakness in this component leads to chain disruptions across other loops.

Supply Chain Flexibility and Resilience

Resilience represents the supply chain’s ability to respond to crises such as sanctions, pandemics, or market fluctuations. Flexibility refers to the ability to adapt to rapid changes in demand or transportation conditions. This component prevents operational delays or stoppages during critical situations.

Inventory Monitoring and Control

Accurate monitoring of drug inventory at warehouses and distribution centers—through continuous data review and alignment with demand—plays a key role in reducing waste and shortages. Its integration with tracking and forecasting systems enables rapid and precise decision-making in pharmaceutical management.

Transportation Route Optimization

This component aims to reduce costs, delivery time, and fuel consumption. Selecting shorter and safer routes not only improves distribution speed but also preserves the quality of temperature-sensitive medications. The performance of this component relies on real-time data and demand forecasting.

Dynamic and Flexible Distribution

Dynamic distribution refers to the system's ability to rapidly adjust delivery schedules in response to real-time market changes or access constraints. Using information systems and IoT, the distribution network can modify routes, timing, or delivery sequences instantly—critical during crises or demand spikes.

Transportation Scheduling

Precise planning of shipping and delivery times reduces delays, route conflicts, and improves fleet efficiency. The coordination between scheduling and dynamic distribution is vital for cost reduction and service quality. Delays in this area may disrupt the entire supply chain.

Tracking and Monitoring Systems

Digital tracking systems (e.g., GPS, barcodes, RFID) enable visibility of drug status during all transportation and storage phases. These systems generate data that support inventory control, demand forecasting, and scheduling, allowing quick intervention during malfunctions.

Information Synchronization among Supply Chain Stakeholders

Rapid and transparent information exchange among suppliers, distributors, pharmacies, and hospitals prevents miscommunication, delays, or rework. Such synchronization forms the basis for integrated decision-making in the pharmaceutical supply chain and is one of the most important factors for operational sustainability.

Use of IoT for Tracking

IoT collects real-time data such as temperature, location, and vibration through sensors. This information is automatically transmitted to a central system and supports decisions on routing, temperature control, or emergency stops. Its role in enhancing system intelligence and pharmaceutical precision control is critical.

Providing Accurate Information to Customers

Customers, including pharmacies and patients, need to know when and in what condition they will receive their medications. Providing accurate information increases trust and reduces support inquiries. This component also strengthens the customer-to-distribution feedback loop.

Supplier Relationship Management

Effective supplier relationships provide greater supply chain flexibility during shortages or fluctuations. Rapid and accurate information exchange with suppliers can prevent production or delivery delays and ensure faster access during emergencies.

Improving Customer Service Quality

The ultimate goal of the model is to enhance customer satisfaction and experience. This component reflects the final performance of the supply chain—shaped by upstream factors such as timely delivery, accurate information, and transportation quality. Weakness here leads to a loss of trust and organizational credibility.

Compliance with Hygiene Protocols in Storage and Transport

For pharmaceuticals, maintaining appropriate temperature, humidity, and contamination prevention is crucial. This component plays a vital role in preventing drug spoilage and ensuring patient safety. Violation of this principle can lead to a distribution crisis.

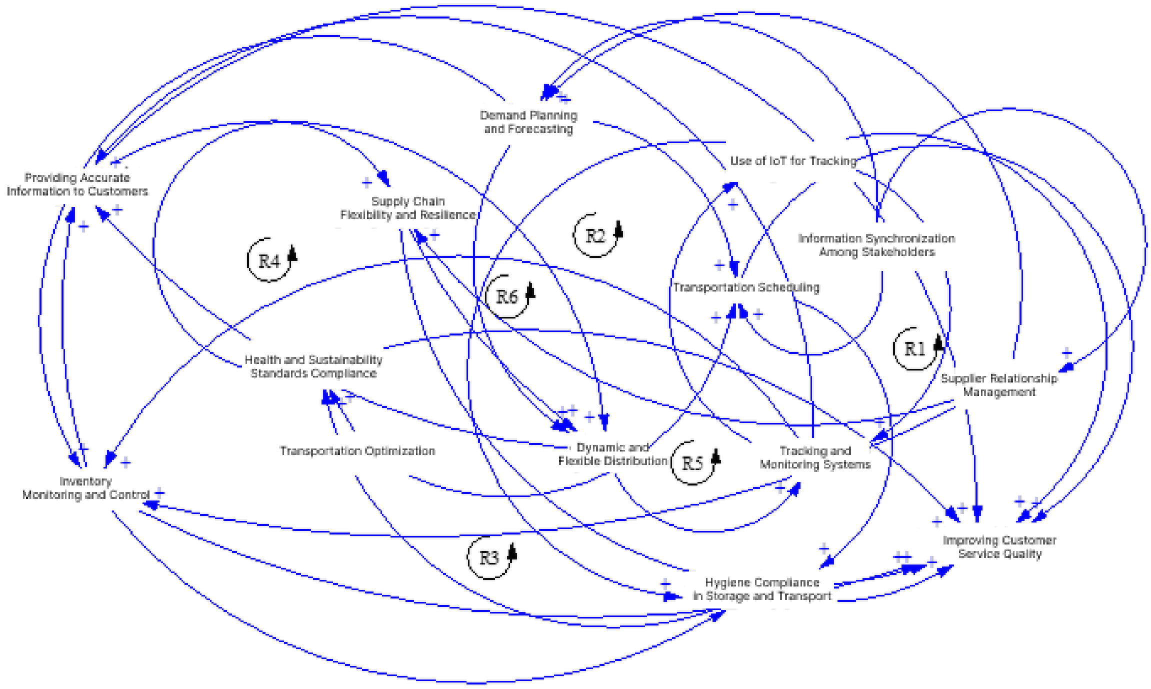
Compliance with Health and Sustainability Standards

Beyond hygiene in storage, the use of recyclable packaging, energy optimization, and resource conservation reflects the environmental responsibility of pharmaceutical distribution centers. This component creates long-term competitive advantages and contributes to the health of both society and nature.

Finally, the overall causal loop diagram is illustrated as follows:

Figure 7

Overall Causal Loop Diagram



Model Boundary Definition

The research variables are categorized into three main groups: (1) Endogenous variables, (2) Exogenous variables, and (3) Auxiliary variables (which are a combination of endogenous and exogenous). After analyzing the model, state, rate, and magnitude variables have been identified, and their details are presented in the table below.

Table 2

Description of the Variables Used in the System Dynamics Model

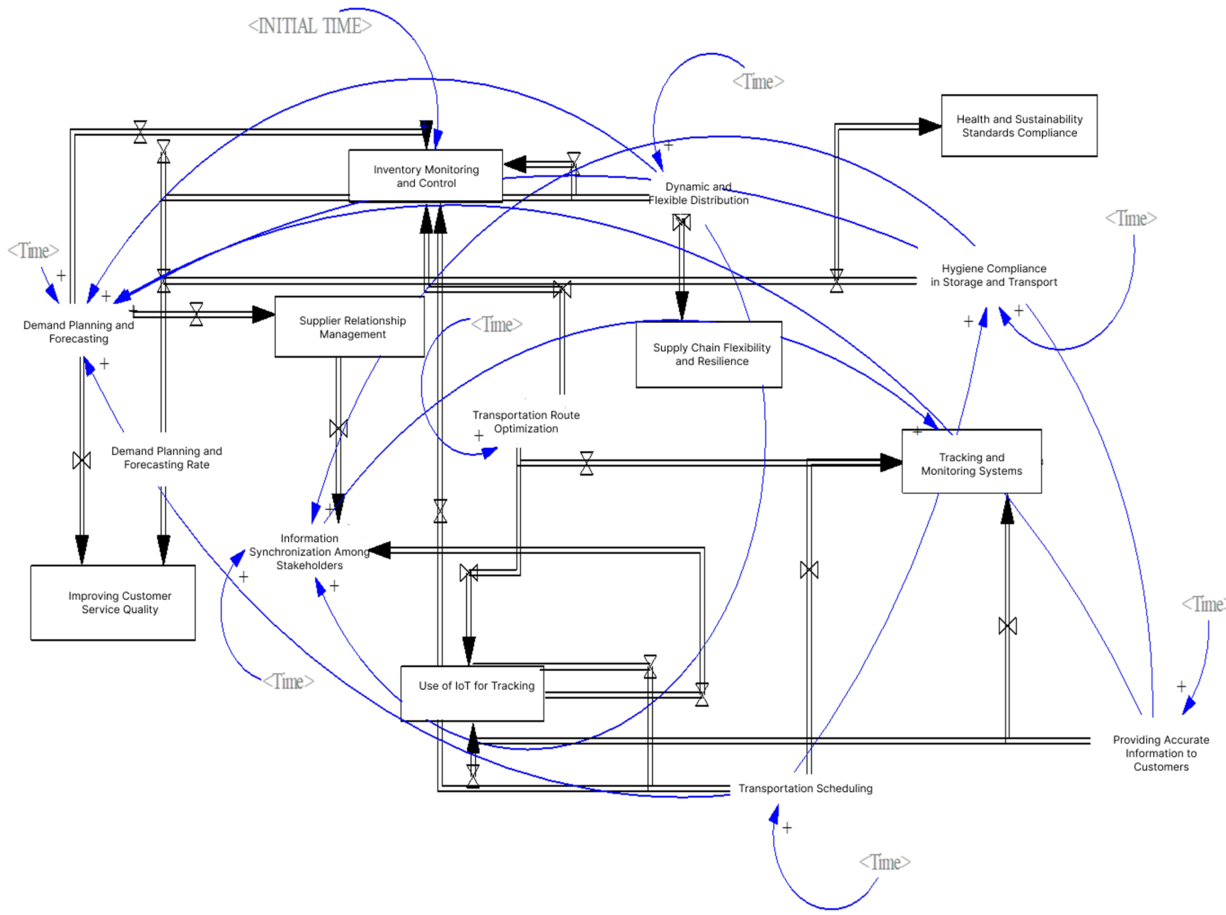
Model Component	Description	Variable Type	Variable Formula	Variable Unit
Demand Planning and Forecasting	Forecasting future demand for resource planning	Rate	Function of past average demand × market variability coefficient	Orders per day
Supply Chain Flexibility and Resilience	Ability to respond quickly to disruptions or crises	State	Aggregated supplier response time + safety stock	Dimensionless (index 0–1)
Inventory Monitoring and Control	Monitoring and managing pharmaceutical stock levels	State	Previous inventory + supplier input − distribution output	Pharmaceutical units
Transportation Route Optimization	Selecting routes with minimal cost and time	Rate	Cost minimization function = time × distance / accessibility	Minutes or kilometers
Dynamic and Flexible Distribution	Distribution adaptability to demand changes across regions	Rate	Regional demand × distribution flexibility coefficient	Shipments per day
Transportation Scheduling	Precise scheduling for shipment movements	Rate	Shipment time = available inventory / transport capacity	Hours
Tracking and Monitoring Systems	Control system for monitoring drug status during transport	State	% of monitored checkpoints / total route	Percentage (%)
Information Synchronization Among Stakeholders	Accurate and integrated data sharing among supply chain actors	Rate	Data sharing rate = updated data / communication delay	Data exchanges per hour
Use of IoT for Tracking	Use of sensors to monitor goods' conditions	State	Active sensors / in-transit packages	Percentage (%)
Providing Accurate Information to Customers	Real-time, precise status updates for customer orders	Rate	Customer data = system update rate × access rate	Messages or alerts per order
Supplier Relationship Management	Quality, stability, and coordination in supplier relations	State	Collaboration index = active agreements / total suppliers	Dimensionless (0–1)

Improving Customer Service Quality	Customer satisfaction with timing, accuracy, and product condition	State	Average customer rating × on-time delivery rate	Scale (0–100)
Hygiene Compliance in Storage and Transport	Preventive measures to ensure pharmaceutical safety	Rate	Compliance index = hygiene violations / total processes	Dimensionless
Health and Sustainability Standards Compliance	Compliance with environmental and health standards	State	Average compliance with GSP/GDP/ISO standards	Percentage (%)

The research variables in this study are classified into the three major categories mentioned above, each playing a specific role in the system dynamics analysis for the operational synchronization model in pharmaceutical distribution centers. Through detailed model analysis, variables have been identified in terms of state (e.g., fixed or changing), rate (i.e., rate of change over time), and magnitude (impact or importance in the system). These identifications support a better understanding of the interactions and effects among variables and their influence on the final model. The table serves as a reference for deeper analysis and implementation of the model in relevant simulation software.

Figure 8

Stock-and-Flow Diagram for Effective Implementation of the Dynamic Model for Operational Synchronization in Pharmaceutical Distribution Logistics



Model Structure Validation

Boundary Adequacy Test

The boundary adequacy test aims to answer whether all relevant concepts related to the issue have been included in the model. In this study, the proposed model was developed based on a literature review and qualitative analysis, and all key variables were incorporated into the dynamic model according to their recognized significance in prior research on operational synchronization in pharmaceutical logistics.

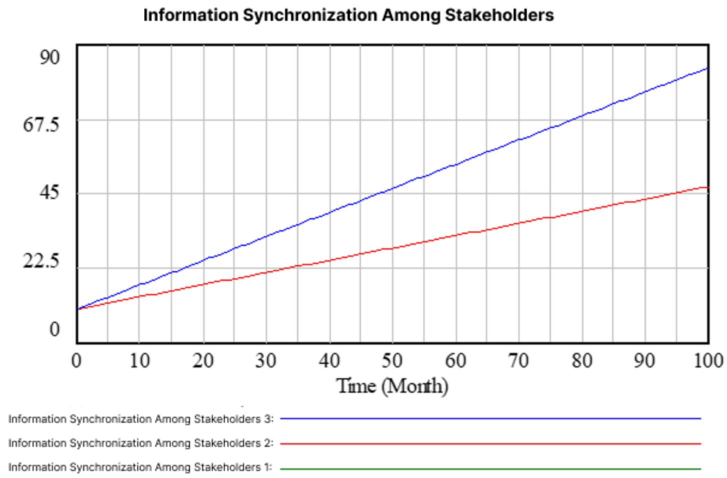
Furthermore, the necessity and importance of all mentioned variables were also examined through expert panel sessions, where decisions were validated based on academic and practitioner consensus. Thus, the final model variables reflect both research literature and expert-validated constructs. To evaluate whether the model's behavior changes significantly when boundary assumptions are altered, the presented model was tested by removing specific components and adjusting the boundary conditions.

Scenario 1 – Information Synchronization Among Stakeholders

Figure 8 shows the impact of improved information synchronization among stakeholders. Enhancing the level of information integration improves operational synchronization in pharmaceutical distribution logistics.

Figure 9

Structural Evaluation of Information Synchronization Among Stakeholders

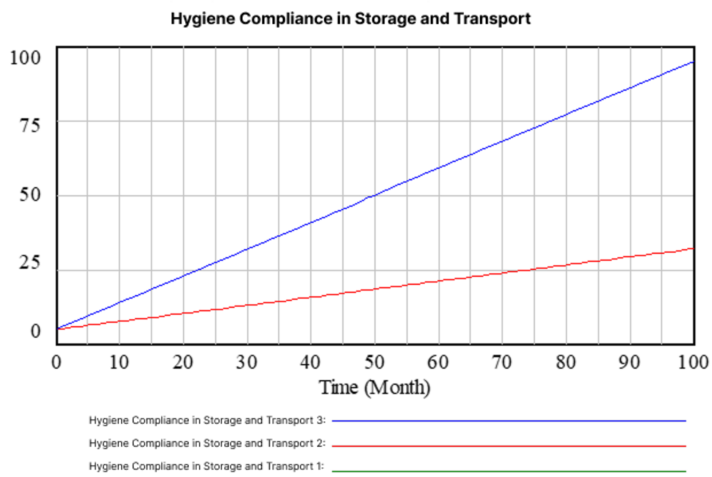


Scenario 2 – Hygiene Compliance in Storage and Transport

Figure 9 presents the impact of improved hygiene practices in storage and transport. This factor enhances transport conditions over time. Improved compliance leads to better operational synchronization in pharmaceutical logistics.

Figure 10

Evaluation of Hygiene Compliance in Storage and Transport

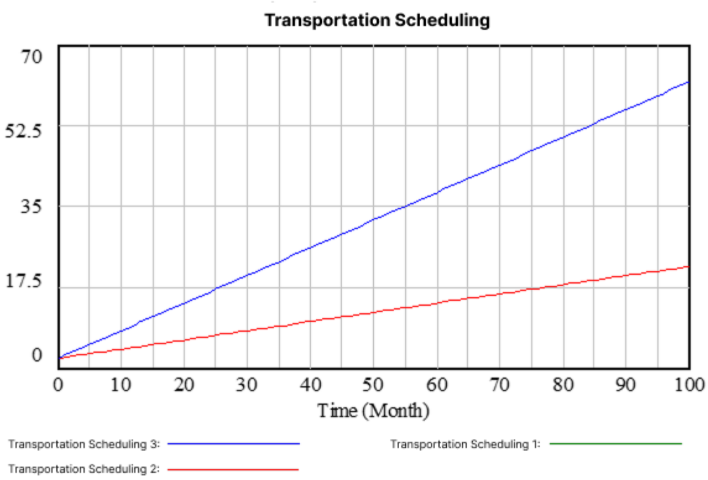


Scenario 3 – Transportation Scheduling

Figure 10 shows the effect of improved transportation scheduling. This factor grows based on the evolving transportation status. Enhancing transport scheduling improves operational synchronization in pharmaceutical distribution logistics over time.

Figure 11

Evaluation of Transportation Scheduling

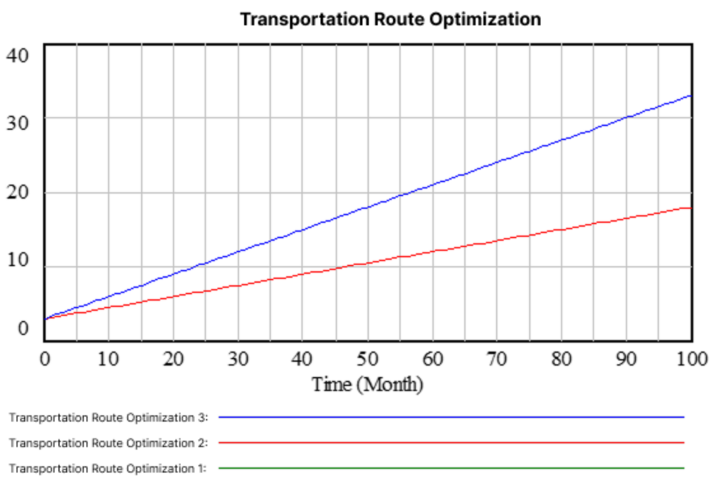


Scenario 4 – Transportation Route Optimization

Figure 11 illustrates the impact of route optimization in transport. As route conditions improve over time, operational synchronization in pharmaceutical distribution logistics also improves.

Figure 12

Evaluation of Transportation Route Optimization

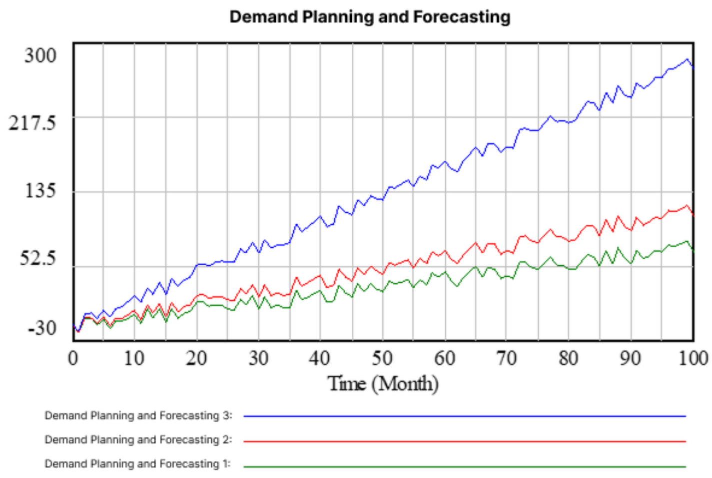


Scenario 5 – Demand Planning and Forecasting

Figure 12 demonstrates the effect of improved demand forecasting. This factor increases with the evolution of inventory control. Enhancing demand planning leads to improved operational synchronization in pharmaceutical logistics over time.

Figure 13

Evaluation of Demand Planning and Forecasting

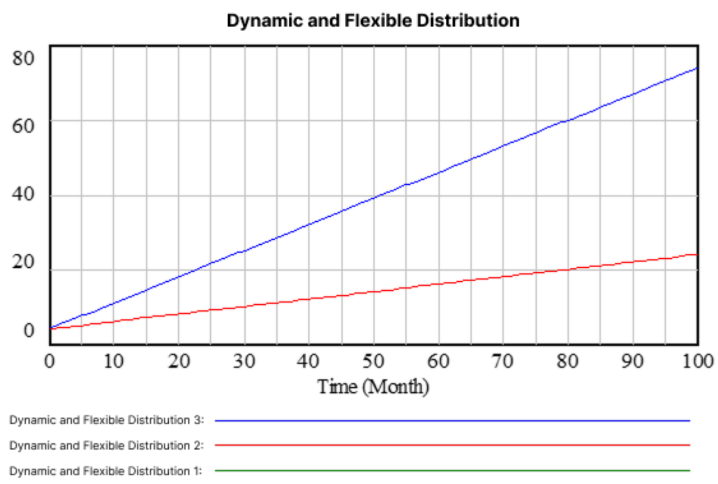


Scenario 6 – Providing Accurate Information to Customers

Figure 13 presents the effect of accurate information dissemination to customers. As this capability improves over time, the operational synchronization in pharmaceutical distribution logistics also improves.

Figure 14

Evaluation of Providing Accurate Information to Customers

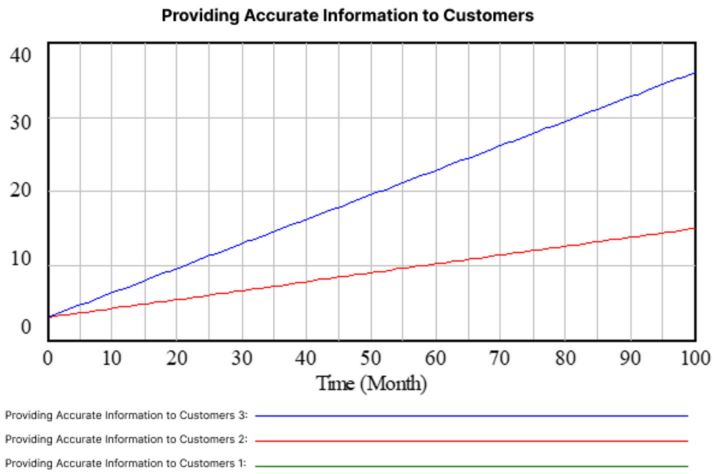


Scenario 7 – Dynamic and Flexible Distribution

Figure 13 shows the impact of dynamic and flexible distribution. As this capability evolves with transport improvements, the level of operational synchronization in pharmaceutical logistics also increases.

Figure 15

Evaluation of Dynamic and Flexible Distribution

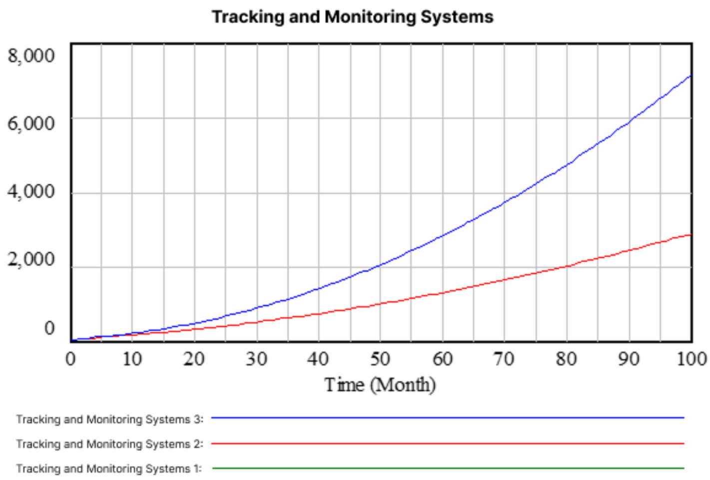


Scenario 8 – Tracking and Monitoring Systems

Figure 13 illustrates the impact of tracking and monitoring systems. As the transport tracking system improves, operational synchronization in pharmaceutical logistics enhances over time.

Figure 16

Evaluation of Tracking and Monitoring Systems



4. Discussion and Conclusion

The findings of this study, based on a system dynamics approach, reveal that operational synchronization in pharmaceutical distribution centers is significantly influenced by several interdependent components: demand forecasting accuracy, inventory control, transportation scheduling, route optimization, real-time tracking systems, stakeholder information synchronization, and technological infrastructure such as IoT and AI integration. The simulation results show that improvements in individual subsystems—especially information synchronization and hygiene compliance—can amplify systemic efficiency over time. The dynamic feedback loops identified in the model demonstrate that minor advancements in communication, traceability, or logistics responsiveness generate ripple effects that enhance resilience and operational stability across the pharmaceutical supply chain.

One of the most prominent outcomes observed in the scenario analysis was the critical role of real-time information synchronization among stakeholders. Enhanced data exchange between manufacturers, warehouses, distributors, and pharmacies substantially improved decision-making accuracy and reduced redundancies. This aligns with the conclusions of (Barnabas Bitta, 2024), who emphasized that synchronized logistics drivers are vital for optimizing operational flows. Additionally, (Abdul Rahman et al., 2023) highlighted that accurate and timely data sharing within warehouse systems improves logistics productivity, which is evident in this study's results showing reduced distribution delays under high synchronization conditions. The alignment of internal operations through digital connectivity also complements the work of (Ajali, 2021), who noted that intelligent systems reduce systemic inertia by facilitating faster feedback loops and operational corrections.

The impact of hygiene compliance in storage and transport emerged as another critical dimension of operational synchronization. Simulation results indicate that when hygiene protocols are strictly adhered to, the probability of drug spoilage and customer dissatisfaction significantly declines. This finding supports the insights of (Ala et al., 2023) and (Albukhitan, 2020), who argued that incorporating health and sustainability standards into logistical systems not only enhances product integrity but also boosts stakeholder confidence. Furthermore, (Baldoni et al., 2019) emphasized that technological intervention in pharmaceutical handling, including remote and sensor-enabled monitoring, is key to ensuring hygiene during delivery—an idea that aligns well with the current model's output emphasizing the role of IoT in tracking and quality control.

Transportation scheduling and route optimization were also found to have compounding effects on operational efficiency. The model revealed that improvements in delivery scheduling directly enhanced dynamic distribution flexibility, especially under conditions of high demand volatility. This mirrors the results of (Akbarpour et al., 2020), who suggested that robust pharmaceutical relief chains are most effective when transport operations are agile and responsive to shifting needs. (Babai et al., 2023) also supported this by demonstrating how demand-driven logistics frameworks reduce costs and improve order fulfillment. Moreover, the effectiveness of route optimization in last-mile delivery under sustainability constraints has been highlighted by (Bajec & Tuljak-Suban, 2022), a point echoed in this study's output showing reduced fuel consumption and lead times.

The positive influence of IoT-enabled tracking on customer satisfaction and operational agility was clearly observable in the model simulations. As sensor data on drug location, temperature, and handling conditions were incorporated into the decision-making system, stakeholder responsiveness improved, and the error rate decreased. These results strongly support the work of (Akbar et al., 2022), who illustrated that blockchain and IoT technologies increase visibility and accountability in healthcare logistics. Additionally, (Mohghar et al., 2024) emphasized the importance of AI-integrated fuzzy models in enhancing reverse logistics, highlighting the technological convergence necessary for dynamic distribution systems. These studies collectively reinforce the model's assertion that smart technologies are indispensable for real-time responsiveness in pharmaceutical supply chains.

Another key insight from the study was the reinforcing feedback between customer information accuracy and demand predictability. As more accurate information was shared with end-users (pharmacies and patients), the system recorded greater forecast precision and fewer emergency orders. This phenomenon supports the claims made by (Lotfi Zadeh & Ehsani, 2021), who linked service transparency with improved satisfaction and planning accuracy. Similarly, (Asmahan Al & Asad, 2024) found that timely and reliable logistics services significantly contribute to firm performance, especially when customer expectations are effectively managed through real-time updates. Therefore, accurate and accessible customer-facing data is not just a communication function—it plays a strategic role in operational planning.

The role of strategic supplier relationship management also became evident during simulation scenarios involving supply disruptions. The model showed that supply chain nodes with better contractual agreements and active data-sharing mechanisms with suppliers were more resilient to external shocks. These findings reflect the theoretical foundation laid by (Sami'i et al., 2023), who emphasized sustainable supplier engagement as a buffer against volatility. Moreover, (Aldrighetti et al., 2023) suggested that portfolios integrating supplier preparedness can increase system-wide resilience, which complements the results seen in our scenario tests.

Lastly, the broader implications of operational synchronization for pharmaceutical system sustainability were reflected in how individual improvements translated into organizational learning. As the model demonstrated, reinforcing loops between tracking accuracy, service quality, and feedback collection led to iterative system enhancements. This is consistent with the findings of (Bharadwaj, 2023), who discussed how IT capabilities, when aligned with firm strategy, result in superior adaptive capacity and firm performance. Similarly, (Reza Jalil et al., 2021) underscored the importance of service supply chain coordination in achieving operational excellence in healthcare-related systems.

Despite the comprehensive scope of this model, the study has several limitations. First, while system dynamics provides valuable insights into causal relationships and long-term behavior patterns, it lacks granularity in operational details that discrete-event or agent-based models can offer. The assumptions made to simplify causal loops—such as constant supplier lead time or linear response to demand shocks—may limit real-world applicability. Additionally, the model is contextually calibrated to pharmaceutical distribution systems with a moderate level of digital maturity; thus, generalization to less digitized or differently regulated markets may require adjustments. Lastly, the model relies on secondary validation through literature and expert assumptions rather than real-time field data, which, if included, would improve empirical accuracy.

Future research should explore hybrid modeling approaches that combine system dynamics with discrete-event or agent-based simulation, thereby capturing both macro-level feedback loops and micro-level operational behaviors. A comparative study across different pharmaceutical distribution networks—urban vs. rural, public vs. private—would also enhance the model's generalizability. Incorporating real-time empirical data through digital twins or live IoT feeds can significantly improve model calibration and decision-support validity. Moreover, future investigations could expand the model's scope by including regulatory compliance dynamics, environmental impact metrics, and labor productivity variables to create a truly integrated supply chain decision-making framework.

Organizations involved in pharmaceutical logistics should invest in technologies that enhance real-time data sharing, particularly IoT and AI-based systems. Building robust supplier partnerships with transparent data exchange agreements will enhance resilience during market disruptions. Logistics managers should prioritize synchronization not just in operations but in strategic planning, ensuring alignment between demand forecasting, inventory policies, and distribution scheduling. Additionally, customer-facing information systems should be designed to increase transparency and responsiveness, strengthening brand trust and minimizing service disruptions.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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