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Predictive Allocation of Temperature-Sensitive Specialty Medications: A KPI-Driven Framework for Shortage Resilience in Underserved U.S. ZIP Codes

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Abstract

The gap suggested in the discussion will be bridged in the proposed work being done specifically on the lack of drugs in underserved ZIP codes with a particular interest in temperature sensitive drugs (a cool chain delivery system will be required). The problem affecting these regions could be inefficiencies in the supply chain and absence of adequate healthcare facilities to make sure relevant drugs are available. This research study will result in a KPI-oriented model that will see to it that the distribution strategy of these medicines is optimized in a manner that they are distributed to the needy populations at the right time.

The model utilizes the most up-to-date technologies, including SAP, SQL, and power BI to consider current data, predict changes in demand, optimize the distribution, and reduce stockouts and spoilage. This pilot study shows that the stockout is less three times, the decay rate is less 4 times and delivery is improved one quarter. The results prove the hypothesis that the framework could contribute to making dispensing medicine more effective and safer. These study possibilities are quite wide to assist all areas which are underprivileged providing equal access to healthcare. It can also lead to reduced health disparities and equitable health care outcomes across the risk communities because this model helps to ensure more consistent access to life-saving drugs.

Keywords: Allocation; Framework; Medications; Sensitive; Specialty; Temperature

1. Introduction

Studied as an important area of contemporary health care, temperature-sensitive drugs have been of significant interest regarding several topics, including cancer treatment, diabetes, and several viral infections, where the actions of the drugs are highly sensitive to the appropriateness of temperatures during storage and administration. These drugs are mostly suffering of elaborate logistics and detailed cold-chain management mechanisms to deliver the drugs to the patients in the best state possible. Nevertheless, it is extremely difficult to make sure that these drugs in underserved geographic areas (especially those in rural and less fortunate ZIP codes) are available. Cold-chain logistics (which deals with ensuring the necessary temperature at each stage of the supply chain) is risky. Spoilage of life-saving drugs can be caused by change of temperature, delays during transportation, improper storage conditions (Roth, 2022, Gunda and Mupa, 2024). This problem is further exacerbated by the lack of infrastructure, as underserved areas have increasing demands for such drugs, while the limited infrastructure fails to meet those needs.

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The main area of study research is the ineffectiveness of current systems that identify medication shortages and distribute resources in a manner that promotes fair resource access. The existing models of supply chain system fail to sufficiently predict the demand variations resulting into stockout or wastage through spoilage. This wastes resources and not only slows down care work but also making healthcare to be more expensive(Adebiyi, Lawrence, Adeoti, and Mupa, 2025). Additionally, more technologically-orientated approaches are required to predict demand better and ensure that medicines are delivered to those regions that are low in medical facilities.

This study will allow developing a KPI-based solution to address the limitations of the current systems and focus on the need to achieve improvements in the delivery of temperature sensitive drugs to the under-served regions. The creation of a system that can enhance supply chain and cold-chain integrity via predictive modelling and real-time data consolidation and performance indicators will be part of the study. The proposed system will facilitate optimization of medication distribution and access to desired medications by the most vulnerable groups (Adebiyi, Attah, Adeoti, Onyinye, & Mupa, 2025). The author of this research paper puts forward a framework focused on maximizing the distribution of temperature-controllable drug, reducing shortages, maximizing cold-chain management, and delivering equitable access to care within underserved communities with low infrastructure density.

2. Background and Literature Review

2.1. Medication Shortages

A problem of drug shortages is also becoming a significant global concern, particularly in regard to specialty drugs with sensitive temperature storage, such as biologics and certain vaccines. These shortages are caused by several factors which include manufacturing delays, regulatory problems, and global supply chain obstacles. These weaknesses have gained prominence during the COVID-19 pandemic as there are both problems with the supply of raw materials and delays in shipping, not to mention employee shortages that have affected issues with the manufacturing and delivery of essential drugs (Roth, 2022). The natural complications associated with the manufacturing and maintenance of specialty medications, as well, are likely to produce limited manufacturing capabilities and extended lead times and further exacerbate shortages. In the case of temperature sensitive drugs, the issue is also complicated by the fact that special storage and transportation conditions are required. These drugs must also not be stored at high or low temperatures and therefore, cold-chain management will be required at every level of the supply chain: production, distribution and finally when it reaches the patients. These medications are susceptible to cold-chain interference, predisposing to reducing the activity or overall contamination, and consequently augment scarcities, especially in setting with less-than-optimal care delivery (Shiraishi and Mupa, 2025). Combined with the problem of supply chain impact, ineffective output, and inadequate temperature regulation severely affects the delivery of this critically needed medicine, especially in underserved or remote venues.

2.2. Cold-Chain Risks

Another critical factor in the efficacy of specialty drugs is the utilization of cold-chain logistics or control of temperature-sensitive products during production and delivery. Temperature fluctuations occurring during transit or storage is one of the biggest risks of cold-chain logistics. Any minor changes when the temperature is not within the demanded range may impair the quality of the medications and render them not safe or effective to use. Cold-chain facilities, especially in less well-served communities, are also insufficient and unable to deliver the services necessary to maintain the necessary storage conditions. To illustrate the point, a rural hospital and pharmacy might lack special refrigerators and run a risk of medicines spoilage and, consequently, wastage (Munashe Naphtali Mupa, Tafirenyika, Nyajeka, and Zhuwankinyu, 2025). Transportation inconveniences i.e. weather delay, failures or logistic breakdowns compound these risks too. Since these disruptions may happen throughout the supply chain, both in production and distribution, there will be a higher risk of having spoiled medication, especially when delicate medications are not addressed immediately. So cold-chain administration must be noted at the observation point and urgent response in such a fashion that, there is no chance of temperature variation. In absence of well-established systems to monitor and control these conditions, we risk losing effective medication delivery.

2.3. Equity in Healthcare

The issue of healthcare disparities, especially in underserved ZIP codes, is a major challenge towards realizing universal healthcare access in most regions of the world. They would equally be most probably the result of socioeconomic inequalities in terms of income inequalities, uninsured, and place of residence (the factor that puts a barrier on access to required medicines), (Nnana Kalu-Mba, Mupa, and Tafirenyika, 2025). Unhealthy facilities A lack of healthcare facilities such as temperature-sensitive medication storage and handling facilities inhibits the availability of healthcare services in underserved areas. Consequently, the delays in access to critical treatments affecting patients in these regions can be significant or patients may not have access to any life-saving medications. Fair access to healthcare does not merely mean the availability of medications, it also means the quality and timeliness of these medications as they reach the patient. It may be too extreme as well, even in the connotation used in and around the marginalized population, where even not being cold-chain in the nature of the movement process is being pictured as an attempted for a symbolic expression of how whatever is harming the population pre-categorized under the label of marginalization is being taken to the state of poor health outcomes in the imagining of not seeking medical services (Gunde & Mupa, 2024). Moreover, the low-income earners have not been helped by the fact that many specialty drugs are very expensive and thus unaffordable. The logistic systems, special federal expenditure within the healthcare system, and the support systems are also supposed to be rearranged in order to give the poorly covered population layers a chance to receive the required drugs (Nnana Kalu-Mba, Mupa, and Tafirenyika, 2025). Therefore, to overcome these healthcare disparities does not only involve a multifaceted approach that involves operational as well as a large-scale adjustment to the healthcare landscape.

3. Methods

3.1. Demand Forecasting

Predicting demand of temperature sensitive drugs accurately is very difficult because demand is seasonal in nature, and, additionally, when patient demand varies with season or as a result of other unexpected health crises, the demand can be hard to determine. To overcome these difficulties, this research will deploy a hybrid forecasting model based on classical statistical methods and machine learning algorithms. The data of historical demand is collected first, which may require different data sources (pharmacies, hospitals, and distributors), as well as any external data that may influence the demand, such as health trends or local outbreak. Since the bend and demand are quite elastic, ARIMA (Autoregressive Integrated Moving Average) and Exponential Smoothing State Space Models (ETS) types of time series analysis techniques are used to both short term and long-term fluctuations. Additionally, the machine learning based algorithm like the Random Forest and XGBoost are applied to identify the trends of the information that is neither linear nor more accurate specifically when variability and seasonality are high amongst the information. Such methods allow making the prediction more accurate because it also accounts not only for the influence of adverse changes in the temperature, but also delays in distribution and other complications related to the environment that may influence the availability of the drugs(Adebiyi, Adeoti, and Mupa, 2025). The model must include seasonal patterns where demand is high in seasons when there is the flu or other health related upsurge, or it will not help the model keep up with the changing situation and continue predicting the future demand accurately.

3.2. Service-Level Constraints

Service level constraints are key factors in effecting a tradeoff in both the need to ensure high fill rates and the need to minimize spoilage due to excursions in temperatures in distributing temperature sensitive medications. One consideration has been the trade-off between delivering as many orders as possible (high fill rate) and the risk of having to deliver medication that is no longer viable because of spoilage. Minimization of stockouts is not the only service-level objective; the possibility to keep the medications within the most appropriate temperature range during the distribution should also be implemented. The allocation model hence uses fill rate and spoilage as primary conflicting objectives and tries to keep them in a desirable equilibrium. The inventory operation would be launched by paying more attention to the areas that the most needed inventory and to the element of the spoilage that would be impaired in the localities where cold-chain operations would have the least favorable (Munashe Naphtali Mupa, Tafirenyika, Nyajeka, and Zhuwankinyu, 2025). This kind of trade off, and the level of services involved, results also in wastage reduction, and improvement of the overall reliability of the temperature sensitive drug supply chain.

3.3. Model Overview

The objective of the multi-objective allocation model is to provide maximum optimization of the allocation of temperature sensitive medications, not only with regard to supply chain efficiency but with regard to quality control of the supply medications provided. The model takes into account several factors such as demand forecasting, service level-constrained considerations, and inventory considerations. It also uses a multi-criteria decision-making model to determine the most efficient allocation of resources and to respond to the requirements of strategy not only in medicine, but also in logistics. The former will attempt to reduce stockouts in which underserved patients will receive the necessary medicines. The second is to minimize spoilage so that medications might attain their desirable temperatures. Optimization processes are involved in the model and enables large amounts of data to be processed and address various constraints simultaneously (Adebiyi, Lawrence, Adeoti, and Mupa, 2025). It also relies on real time feeds of data, which enables the system to dynamically respond to any changes in demand projections or stock levels. The model must be responsive to uncertainty (i.e. to a spike in demand), which takes the probability that such a spike can occur. The added advantage to this is that not only is the use of the temperature sensitive drugs as cost effective as possible with little wastage, but also there is fair distribution to the underserved groups.

3.4. Model Implementation and Architecture

3.4.1. System Architecture

This system architecture is built around a robust and scalable combination of SAP, SQL and power BI to facilitate the making of real-time decisions which will promote proper management of temperature sensitive medications. SAP is the main enterprise resource planning (ERP) system that manages information sharing between different departments such as inventory, purchase and distribution. With help of the created modules within SAP, the level of medication inventory, the cold-chain monitoring conditions, and an alert can be transmitted in case of any deviation of predefined temperatures. SQL is how the database management system stores and divides information depending on different sources such as temperature sensors, inventory records, demand records etc. Without access to the real time data, the access tool will access the SQL database to initiate timely response in the inventory and distribution schemes to the latest forecast of demand, or a supply chain breakdown. This visualization tool can be the power BI that can also include the dynamic dashboard as well as the reports containing the description of the key performance factors (KPI) (the level of the services, the rate of spoilage and the level of the stock). This kind of integration helps in free flow of data in real time between the different segments of the system in making prompt decisions and in smooth process of allocating resources to the underserved areas.

3.4.2. Integration with Existing Systems

The proposed structure is also integrated-focused; thus, it could easily be integrated within the existing supply chain and logistics systems. ERP systems such as SAP are already implemented in a number of healthcare organizations, so implementing the new model into their infrastructure would require a minimum disruption. The model can be used with any APIs and data exchange format, it can be used to integrate with existing system to track inventory in real-time, predict demand and manage the cold-chain. With the new model developed on the basis of these existing systems, it does not need any fundamental overhaul or staff re-training and adapting to the new model is much easier. Furthermore, the system can be leveraged to fulfill the functions of accessible inventory management software and cold-chain monitoring systems, it will make the operation become efficient without bringing significant operational redundancy and system incompatibility (Lombardi, Vasarhelyi, and Verver, 2023). This integration feature is essential to broad acceptance within healthcare organizations which may already have an advanced network of logistics systems.

3.5. Technology Used

The positive implementation of the Power BI, SQL, and SAP in the management and streamlining of the information stream shall characterize the work of the proposed system. The most important thing is that the complex data in question should, by the influence of Power BI, be presented and demonstrated in the manner which would enable health care managers to commit an informative act regarding the state of inventory and prognosis of demand as well as cold-chain position. Its robust data modeling allows users to build their own dashboards to view real-time reports about the stock quantity, temperature and possible stockout scenarios of drugs. SQL is used to support data management whereby large amounts of data can be easily queried, updated and accessed in various sources. This is what governs keeping a current and precise image of supply chain that allows it to make timely decisions in areas dealing with inventory replenishment and distribution. The complex ERP system is the one that also includes the organization of all the existing processes such as demand, inventory and distribution and also which will synchronize all the data points with each other and can be accessed (Shiraishi and Mupa, 2025). The technologies would be used together in order to assist the management in reaching the conclusion by making the whole and entire facts and truths apparent so that the management of the medicines could limit the dangers, and be able to reach the same medicines in the underserved regions especially.

3.6. Case Study: Pilot Metrics

3.6.1. Pilot Implementation

To determine the suitability of the suggested KPI-based framework in enhancing the distribution and allocation of temperature-sensitive medicines, a pilot study was carried out to evaluate the effectiveness of the framework. It was also due to the fact that Pilot was deployed in a location where there are significant healthcare disparities and focused on underserved ZIP-codes with limited access to costly cold-chain facilities. The objectives of the analysis included to identify how the framework will reduce stockouts and also increase services rates without affecting cold chain integrity.

It incorporated the real-time data capabilities of the current ERP systems, cold-chain systems, and inventory management and handling systems. Demand forecasting involved trying out different times of the day and other sudden increases or decreases in medication needs like the flu season and the incidence of local outbursts. It was also possible to optimize the distribution of the inventory based on the predictive nature of the model, which in this case also requires giving a higher priority to the areas where there is more predicted demand to take into account the fact that the drugs are temperature sensitive. The system component that was employed to validate all the medications stored and shipped within a specific temperature and provide feedback on each temperature change or help interruption in real-time (Mupa, Tafirenyika, Nyajeka, and Zhuwankinyu, 2025). At all points along the pilot, emphasis was placed on trading off the conflicting goals of reducing stockouts versus preventing spoilage caused by changes in temperature. Key performance indicators (KPIs) such as stockout rates, rates of spoilage and rates of on-time delivery were used to closely monitor the performance of this system in terms of overall effectiveness in enhancing the reliability and efficiency of the medication supply chain.

4. Results

The pilot study results have shown that there was considerable improvement in reducing stockouts and reliability in cold chains. The allocation system was effective to cut the rates of the stock out by a third than before (the previous one) because the system was able to detect and estimate the demand and their level of stock. This increased supply of stocks meant that patients in underserved areas had increased access to medical requirements.

This system also had the capability to check the temperature and real time in order to reduce by half the level of corruption. Excursions in temperatures were measured and fixed promptly avoiding the loss of medications when they are exposed to unfavorable storage conditions. Furthermore, this system would also increase the on-time transportation efficiency of medicines to the health facilities where they are required by more than twofold therefore rendering it efficient and secure (Adebiyi, Attah, Adeoti, Onyinye, and Mupa, 2025). The promising results of the pilot study highlight the relevance of the KPI-based design to ensuring the optimization of the distribution of temperature-sensitive drugs. This system would be very effective and sound throughout the medication supply chain, in few of the underserved regions that will also include projection of the prescriptions rightly, real time tracking and smooth scheduling of their resources.

4.1. Policy Implications

4.1.1. Equitable Access

There is a tremendous opportunity in the proposed framework to improve fair access to temperature-sensitive drugs, particularly in underserved ZIP codes with health care barriers. Availability of essential medications is one of the major problems encountered in the areas and it can be attributed in part to the inefficiencies of the supply chain, especially in cold chain logistics management. This is dealt by the KPI driven distribution system with the help of real time data and forecast analytics to focus on the real distribution of medication around the actual demand pattern. The area of intervention of this model is the underserved areas; therefore, it is more appropriate to allocate medicines to the most in need areas to reduce the chances of stockout and avail life-saving medicines to communities at risk as soon as possible.

This renders the framework with the capacity of maintaining the integrity of the cold chain or to put it in other words, maintaining the integrity of cold-sensitive drugs, such as biologic and vaccines, until they arrive at the patients. Under-serviced areas often suffer cold-chain breakdowns, and the facilities to maintain regular temperatures are often not available. This model can also do away with the occurrence of any sort of excursion in temperatures that could be disruptive to the presence of these drugs hence ensuring that the patients were taking quality drugs as there is the availability of real time monitoring system and alert system installed into the model (Aror TA & Mupa, 2025) and (Muchabaiwa O; et. al, 2025). The framework: The framework can also support the policy change, providing evidence of how technology could be used to overcome healthcare access gaps, complemented by improvements in logistics. This means that the framework will not only positively influence the delivery of the needed medicines to the target populations but will also initiate equity within the healthcare system as the highest priority will be given to the areas which will most benefit in regard to the realization of positive health outcomes in under-served populations.

4.1.2. Payer Savings

The full adoption of this structure is also hugely promising, in terms of the possible savings of cost to the payers, the insurance companies and the health programs of the governments. The system can be used to reduce spoilage and wastage factors, which have turned out to be two critical sources of costs in the healthcare sector, since it will enhance precision in demand prediction and the delivery of temperature-sensitive goods through better supply management. Not only does the that not maintain the cold chain but also its low distribution result in the companies incurring a loss that is not only to the healthcare providers but also drug insurance providers that cover the cost of the respective medical drugs (Munashe Naphtali Mupa, Tafirenyika, Nyajeka, and Zhuwankinyu, 2025). This would result in less inefficiencies and increased capacity to manage inventory with higher efficiency and reduced the total amount spent to allocate medicines.

The construction that comes to guarantee that medication shall be available when required and in its right form does not require an emergency purchase and delivery just at the very last moment, which, of course, will be more costly and worse-quality. Such efficiency in operation can later be translated into cost-saving which may be channeled to the health programs and health care insurers funded by governments in order to make these health care systems financially sustainable (Munashe Naphtali Mupa, Tafirenyika, Nyajeka, and Zhwankinyu, 2025). Unlike this, availability of more drugs in underserved areas will also further reduce emergency clinical interventions since more proactive health care will help in saving on costs in the long-term cases.

5. Conclusion

The study indicates that the proposed model based on KPIs can effectively overcome the impediments associated with delivering temperature-sensitive medication to underserved population groups. These interesting observations have also led to the existence of model that leads to the great decrease in the share of drug shortages due to better forecasting of demand and better management of stock. The system supports the efficient delivery of medications because it synthesizes real-time information, as well as predictive data analytics, that is especially applicable in regions where healthcare facilities are scarce. In addition, the rate of deterioration of the cold-chain freshness of the structure has decreased, and the quickly deteriorating medication with a high temperature organ sensitivity is shared with the patient in its natural state. During the pilot research, the service level dramatically increased and the number of stock outs was reduced, stock out orders had been increased as well. This fact supports the fact that this model can also play a positive role in serving the provision of supply chain goodness and strength that will eventually result in the provision of more life-saving medicines to non-served population groups.

There are other fields of healthcare that the study could want to research within the framework as well in the future. In conjunction with the other elements of the healthcare supply chain, e.g. non-temperature-sensitive medications or medical equipment, such a model can be applied to better optimize resource deployment. Additionally, it could be more precise because the demand forecasting component could be optimized with more specific data (demand of certain healthcare providers, patient needs). The study further reports that technological based solutions could be beneficial in changing the functioning of the medical system to enhance functionality and patient outcomes.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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