Journal of Medical Systems (2022) 46: 32
https://doi.org/10.1007/s10916-022-01822-2

IMPLEMENTATION SCIENCE & OPERATIONS MANAGEMENT

Optimizing the Medication Distribution Process for Inpatient Units

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Received: 1 February 2022 / Accepted: 20 April 2022 / Published online: 3 May 2022

Abstract

Pharmacy robots and automated dispensing cabinets are commonly used to distribute medications to inpatient units efficiently and safely. Decisions regarding the use of these technologies are often made without full knowledge regarding system effects. This paper determines a cost effective and safe way to distribute medications to patients across a hospital system by minimizing the distribution cost and missing dose rate. A mathematical model is formulated which captures key aspects of the pharmacy distribution process to determine a primary pathway to distribute each medication and dose type to each unit. The model focuses on three primary distribution pathways: cart fill via pharmacy robot, cart fill via pharmacy technician, and automated dispensing cabinets. The problem is solved using a complete year of data from the Geisinger Medical Center. The model results demonstrate the trade-off between pharmacy technician and nurse workload and missing dose rates that occur as hospitals move from a centralized pharmacy to automated dispensing cabinets. These results demonstrate the importance of evaluating the labor effort and missing dose rates when determining the best method to distribute medication.

Keywords Mathematical modeling · Inpatient medication distribution system · Optimization · Automated dispensing cabinets · Pharmacy robot

Introduction

The hospital pharmacy department is responsible for providing patients medication at scheduled administration times. There are currently many pathways for medication to travel from the pharmacy to the inpatient unit, creating a challenging logistics problem. Three standard pathways used to distribute medication are cart fill via robot, cart fill via pharmacy technician and Automated Dispensing Cabinets (ADCs). The effectiveness of a pathway is evaluated by the percentage of missing doses that occur and the labor costs to distribute the medication. In this paper, we develop a mathematical model to determine the best method to distribute medications in order to reduce both the labor costs and the number of missing doses.

To reduce the number of missing medications, hospitals may utilize a robot within the central pharmacy or ADCs on the inpatient units to dispense medications. The robot picks with high accuracy; however, sometimes it can drop medications or the doses may be misplaced in transit from the central pharmacy to the inpatient unit. An ADC stores medication at the point of use so missing doses only occur when there is a stock out or the nurse does not administer the medication. While both of these technologies are effective at reducing the number of missing doses, they are not utilized together within a single pathway. For example, a single dose cannot be selected by the robot in the central pharmacy and placed into an ADC, making the robot and the ADC competing technologies in the pharmacy distribution process.

This article is part of the Topical Collection on *Implementation Science & Operations Management*

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When ADCs are the primary method used to distribute medication, pharmacists can be employed on the inpatient units to improve patients' quality of service. The concept of a decentralized pharmacy model was first studied by Greth et al. [1] who demonstrated decentralization increased pharmacists' clinical duties and reduced medication errors. These results were supported by the Pharmacy Practice Model Initiative [2] and Providence Health Services [3]. Additional studies found the use of ADCs can also lead to a significant decrease in missing doses and the time to initial dose [4–6]. Effective ADC implementation requires proper inventory management policies and multiple studies have focused on improving the use of space and decreasing selection errors by focusing on medication strengths [7], prescription frequency [8], and the ADC layout [9].

Robots are implemented in central pharmacies to help decrease picking errors and the labor necessary to sustain a centralized pharmacy model. Robots have become incredibly efficient, with one robot recording zero incorrect picks [10]. Multiple daily cart fills completed with a robot can reduce the lead-time for peak medication administration times, increase the number of first doses dispensed from the pharmacy, and reduce the number of missing medications [11].

While both robots and ADCs can decrease missing doses, determining how best to use them is a challenge. In practice, larger hospitals are more likely to use a robot, approximately 66% of hospitals use ADCs as the primary distribution method, and most hospitals use ADCs in some form [12]. One simulation study compared an existing cart fill system with three alternatives and found that increased ADC usage led to increased nursing time to retrieve medications which their current staffing could not support [13]. Similarly, another study found the nursing labor associated with the cart fill system was much less while the system cost remained the same due to the increase in pharmacy technician labor [14].

In addition to the distribution pathway, another factor to consider is the dose type. Each dose type differs in the lead time that the pharmacy has to prepare the dose and smaller lead times correlate with higher missing dose rates. For instance, for doses delivered by the cart fill, a STAT dose is more likely to be a missing dose than a maintenance dose because there is only a half-hour to prepare a STAT dose and get it to the unit in comparison to a maintenance dose which has scheduled administration times known hours in advance. Therefore, the probability of experiencing a missing dose depends on the pathway through which the medication is distributed and the dose type.

Many studies have focused on improving pharmaceutical distribution within hospitals by analyzing the changes in pharmacy operations or missing doses. This paper proposes an approach that captures the medication distribution process from the hospital pharmacy to the inpatient units which incorporates both the workload of all employees who are involved in the medication distribution process and the quality of service provided by the system. Using this approach, hospitals can determine how to best utilize available pharmacy technology to reduce the average number of missing doses and the labor required to distribute medication to the inpatient unit for the entire hospital.

Methods

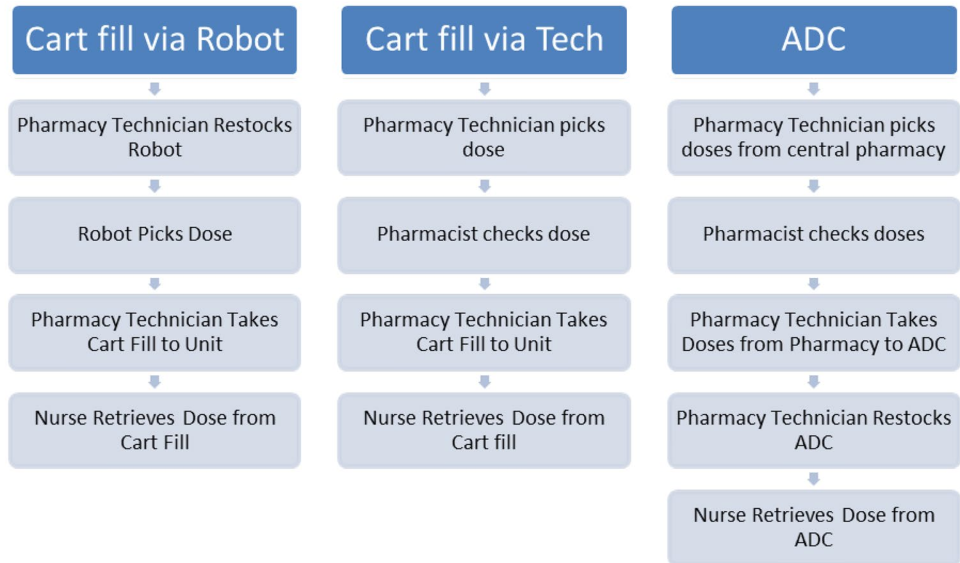
In process engineering, standardization is one key to reducing errors and improving safety. By identifying a standard pathway to distribute each medication and dose type to each unit the pharmacy system can decrease the number of missing medications and increase patient quality of care while decreasing the labor required to distribute the medication. The staff activities which occur in the distribution process for each of the three primary distribution pathways are presented in the flow chart in Fig. 1. The transportation cost from the central pharmacy to the unit is not included under the assumption it is the same across all pathways. Upon retrieving the medication from the ADC or cart fill, the nurse administers the medication to the patient. This medication administration cost is not included in the model under the assumption that it is the same regardless of delivery pathway.

In order to determine the minimal cost and missing dose rate, the mathematical model provided in Appendix 1 was formulated and solved. The mathematical model has two objectives, (1) to minimize the average labor cost to distribute medication from the inpatient pharmacy to the inpatient units and (2) to minimize the missing dose rate on each unit. The costs captured within the model are average medication picking costs, robot restocking costs, ADC restocking costs, cart fill preparation costs, and nurse queueing costs. The missing dose rates are determined by the dose type and the distribution pathway.

The average labor costs include pharmacy technician, pharmacist, and nurse time engaging in medication distribution activities. The picking activity times are from the time studies conducted in Gray et al. [13] and confirmed with pharmacy experts from Geisinger. The workload for the cart fill via robot pathway stems from the nurse retrieving the medication from the patient's envelope. In the cart fill via pharmacy technician pathway, the workload includes the pharmacy technician picking the medication, the pharmacist checking the medication, and the nurse picking the medication from the patient's envelope. Lastly, for medications distributed via the ADC, the picking cost is the time the nurse spends picking the medication from the ADC.

The robot restocking cost is based on the time required to restock a single rod within the robot and the number of

Fig. 1 The staff activities that are included within the cost calculation of each pathway



doses per rod to reflect the restocking cost per dose. The ADC daily restocking cost is calculated using the cost to restock a pocket of the ADC and the restocking frequency, which is based on the standard par levels set by the hospital and average daily demand. The hospital uses a maximum par level of 3 times the daily demand and a minimum par level of 1.5 times the daily demand. The cart fill preparation costs include the time to label and prepare the envelope for each patient. Since patients can receive multiple medications from both cart fill and ADCs, patient medication data was used to determine a function which accurately depicts the number of patients receiving cart fill medications based on the percentage of doses stored in the ADC. As more medications are distributed through the ADC, nurses will need to access the ADC more often, which can result in nurses waiting to access the ADC. The nurse queueing cost is a function which captures the time nurses spend waiting to retrieve doses from the ADC based on the percentage of doses stored in the ADC. It is assumed that every patient has medication in the ADC when more than 11% of doses are stored in the ADC and the nurse retrieves medication from the ADC for each patient during the major medication administration times. We assume nurses follow the recommended practice to visit the ADC and retrieve the medications for one patient and administer the patient's medications before obtaining medication for another patient.

In the mathematical model in Appendix 1, the primary decision variable determines the distribution pathway for each medication and dose type to each unit. Additional decision variables determine whether or not the pharmacy uses a robot and how many ADCs are needed on each unit. To ensure that all requirements of the pharmacy distribution system are met, the following constraints define the possible pathways to deliver medications:

- Every medication and dose type combination has one distribution pathway to each unit.
- STAT doses may not be routed through the robot due to time constraints.
- If First Doses, Maintenance Doses, or PRN doses of a medication are distributed to a unit via the ADC then STAT doses of the medication are also distributed via the ADC.
- If maintenance doses are distributed to a unit via the ADC then first doses of the medication are also distributed via the ADC.

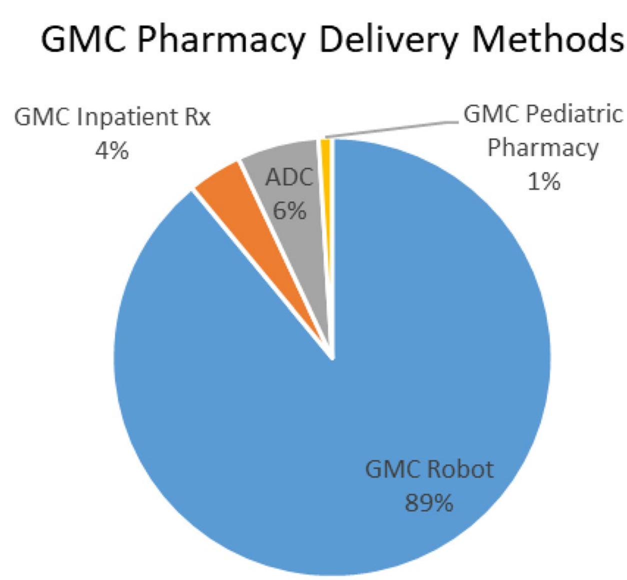


Fig. 2 Current methods used to distribute uncontrolled unit dose medications to inpatient units from the central pharmacy at GMC

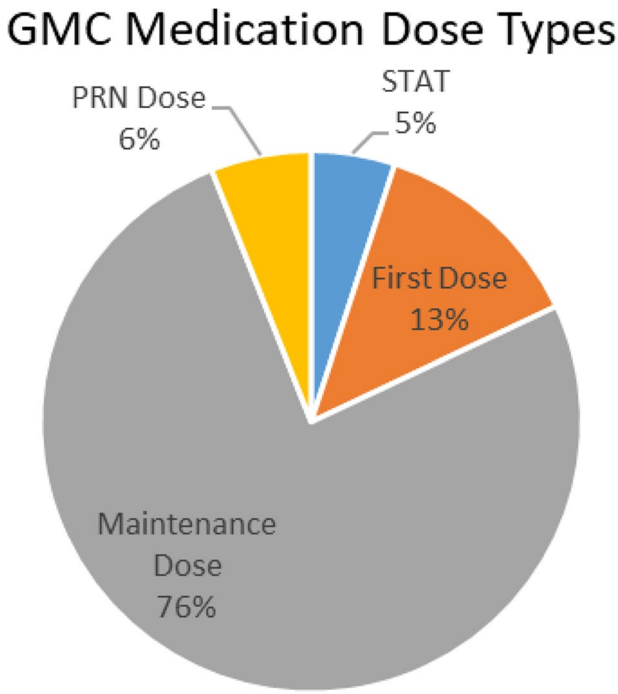


Fig. 3 Percentage of uncontrolled unit dose medications in each dose type category

- The number of ADCs needed on each unit cannot exceed the space limitations of the unit.
- The number of unique medications dispensed by the robot cannot exceed the unique medication capacity of the robot.
- The number of doses dispensed by the robot cannot exceed the robot's throughput.
- The number of doses dispensed by the robot must exceed the minimum cost effectiveness throughput of the robot.

Additionally, there are constraints used to formulate the cart fill preparation costs and the nurse queueing costs based on the percentage of doses routed through the ADC.

Results and discussion

Geisinger is an integrated health services organization which serves more than 3 million residents throughout 45 counties in central, south-central, northeast Pennsylvania, and southern New Jersey. Geisinger Medical Center (GMC), the flagship hospital, has 24 inpatient units and 560 beds. For this project, a year of

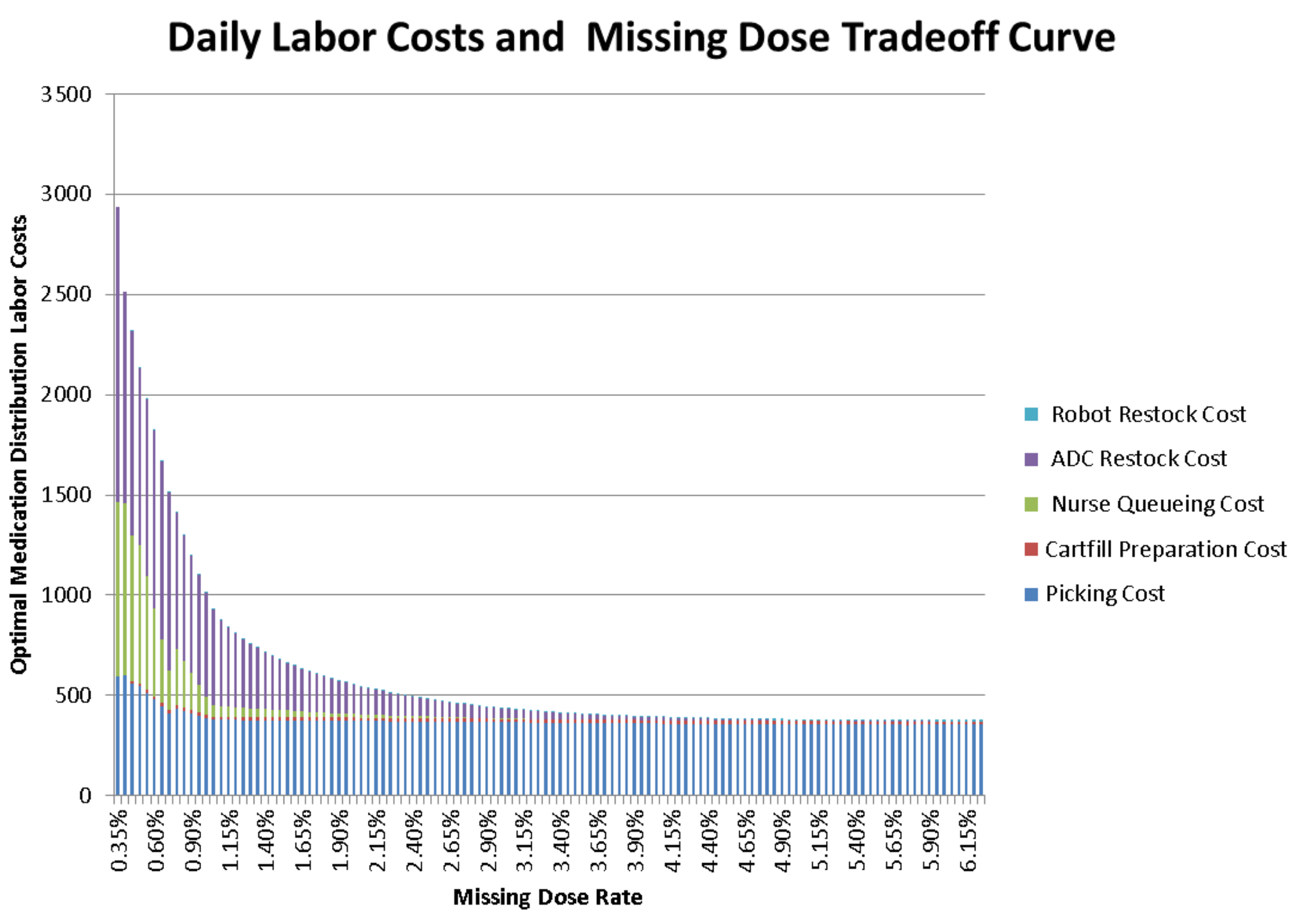


Fig. 4 Efficient frontier showing trade-offs between medication distribution costs and missing dose rate

data for unit dose medications was analyzed. The pharmacy processed approximately 2,300 medication orders every day which translated to 8,800 medications dispensed from the central pharmacy, of which an average of 8,600 were administered to patients. There were 3,350 unique medication types and 1,105 were non-controlled unit dose medications. In this paper a missing dose is defined as any STAT dose that is not given within a half hour of being ordered or any other dose that is not given to the patient within an hour of the scheduled administration time. Note that this definition can include doses that are either missing or not given to the patient; however, due to the limitations in the available data, it is not possible to determine why a dose was not given.

Under current operations at Geisinger, there are five primary locations within GMC that can dispense unit doses: the unit dose robot, the inpatient pharmacy, ADCs, the pediatric pharmacy, and the operating room pharmacy. Figure 2 shows their relative frequency of use. Most of the unit doses administered to patients in the hospital are dispensed through the pharmacy robot and the ADCs and pharmacy technicians are used to distribute other medication types which the robot cannot process. Figure 3 shows the portion of all medications that are STAT, first, maintenance, and PRN doses. Most uncontrolled unit doses distributed at GMC are maintenance doses, although there are some exceptions.

The mathematical model is solved using data from GMC, the flagship hospital for Geisinger. The focus of the problem is solely on non-controlled unit dose medications because these medication types can be distributed through all three pathways. Due to the large problem size, the model is solved for the five inpatient units with the highest dose volume: one orthopedic unit, two med/surg units, one cardiac med/surg unit, and an intensive care unit. The medication order, dispense, and administration data for one year is used to solve the model. The solutions for these units are presented in Figs. 4, 5, 6 and 7. Currently the model permits an unconstrained number of ADCs on each unit to examine the effects of a fully decentralized medication storage model. However, the model does allow for limitations on the number of ADCs to properly account for space constraints that exist within hospital units. The unconstrained solution determines that each unit requires at most 4 ADCs to store the necessary medication.

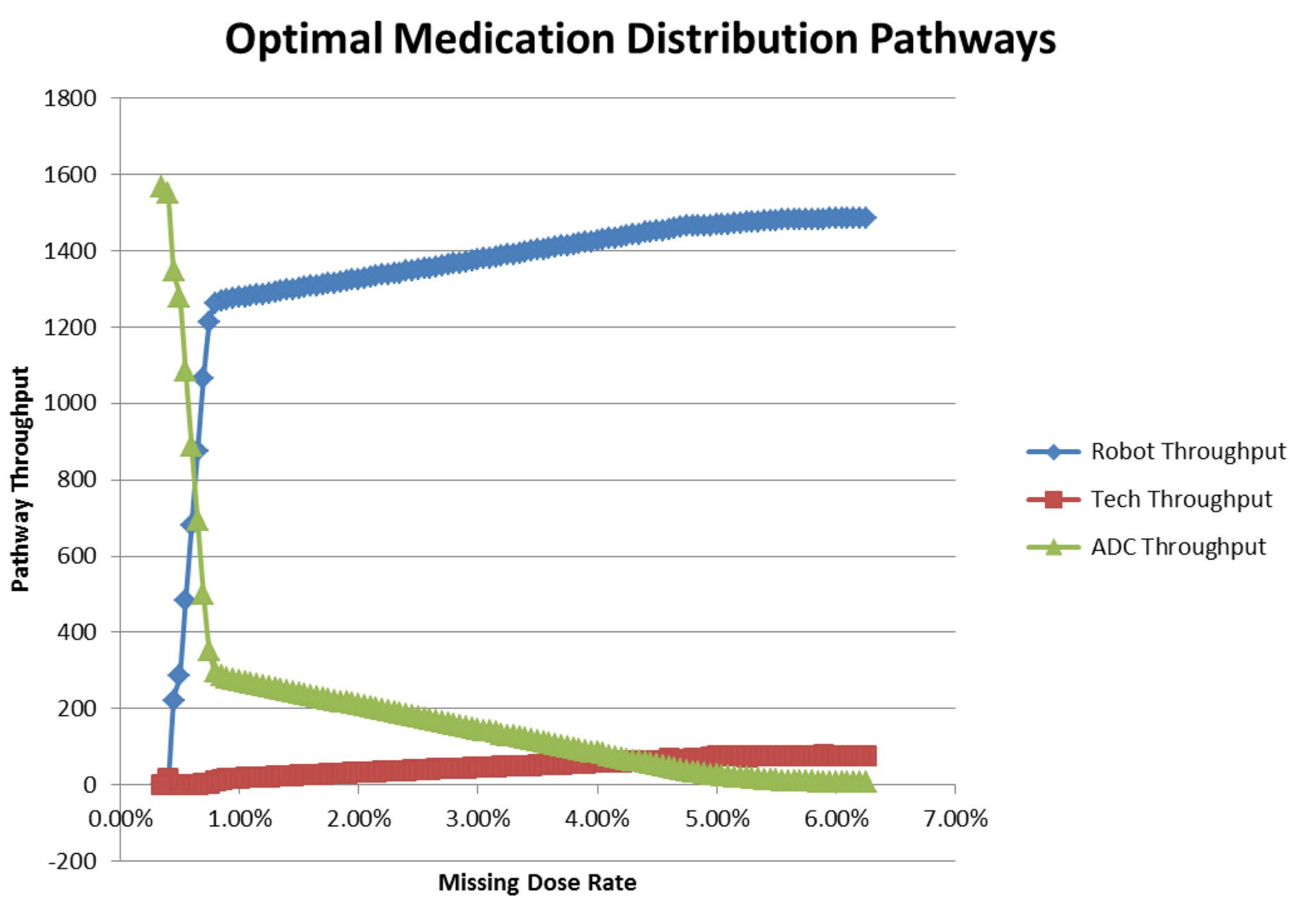


Fig. 5 The optimal throughput of each pathway based on the cost and missing dose rate efficient frontier

When solving a multi-objective model with two objectives with different units, such as labor costs and missing dose rate, it is often difficult to determine a “best” solution. Therefore, a set of solutions that trade-off the two objectives, referred to as an efficient frontier, is given. In this research, the efficient frontier is found by determining the minimal cost for each missing dose rate. With an efficient frontier no single answer is “right”, instead there are many possible options and the hospital determines which option is best given their available resources and service goals.

The bar chart in Fig. 4 shows the efficient frontier for the medication distribution labor costs versus the missing dose rate. The stacked bars demonstrate the amount of the daily labor costs comprised of the five components of the objective function: cart fill preparation cost, robot restocking cost, picking cost, ADC restocking cost, and nurse queueing cost. The results indicate that the cost to prepare the cart fill and restock the robot are minimal in comparison to the picking costs, ADC restocking costs, and nurse queueing costs.

Figure 5 indicates the dose routing pathways as a function of the missing dose rate. The ADC and pharmacy technician both process very few doses initially and the minimal missing dose solution has the ADC processing all doses. Figure 4 shows that increased ADC usage requires more staffing resources for restocking and obtaining medication compared to the robot which requires minimal restocking effort and cart fill preparation. The picking costs remain relatively constant with a slight increase as more doses are processed through the ADC indicating the increased time to pick each individual dose.

The results demonstrate that the volume of STAT and first doses play an important role in deciding which medications are added to the ADC due to their high missing dose rate when delivered via cart fill. Thus, when the missing dose tolerance is higher, the targets can be met by adding STAT and first doses to the ADC. In comparison, maintenance doses and PRN doses have a relatively small difference in the missing dose rate between the robot and the ADC. Thus, a dramatic increase in the number of doses added to the ADC occurs when a lower missing dose rate is achieved because the ADC must process more than just STAT and first doses to meet the missing dose rate goal.

While the model focuses on the labor costs of the medication distribution process, it is also important to consider the pharmacy technician and nursing time required. Due to the small number of cart fill doses processed manually, the amount of time the pharmacist spends on dose distribution activities is very small and therefore is not considered.

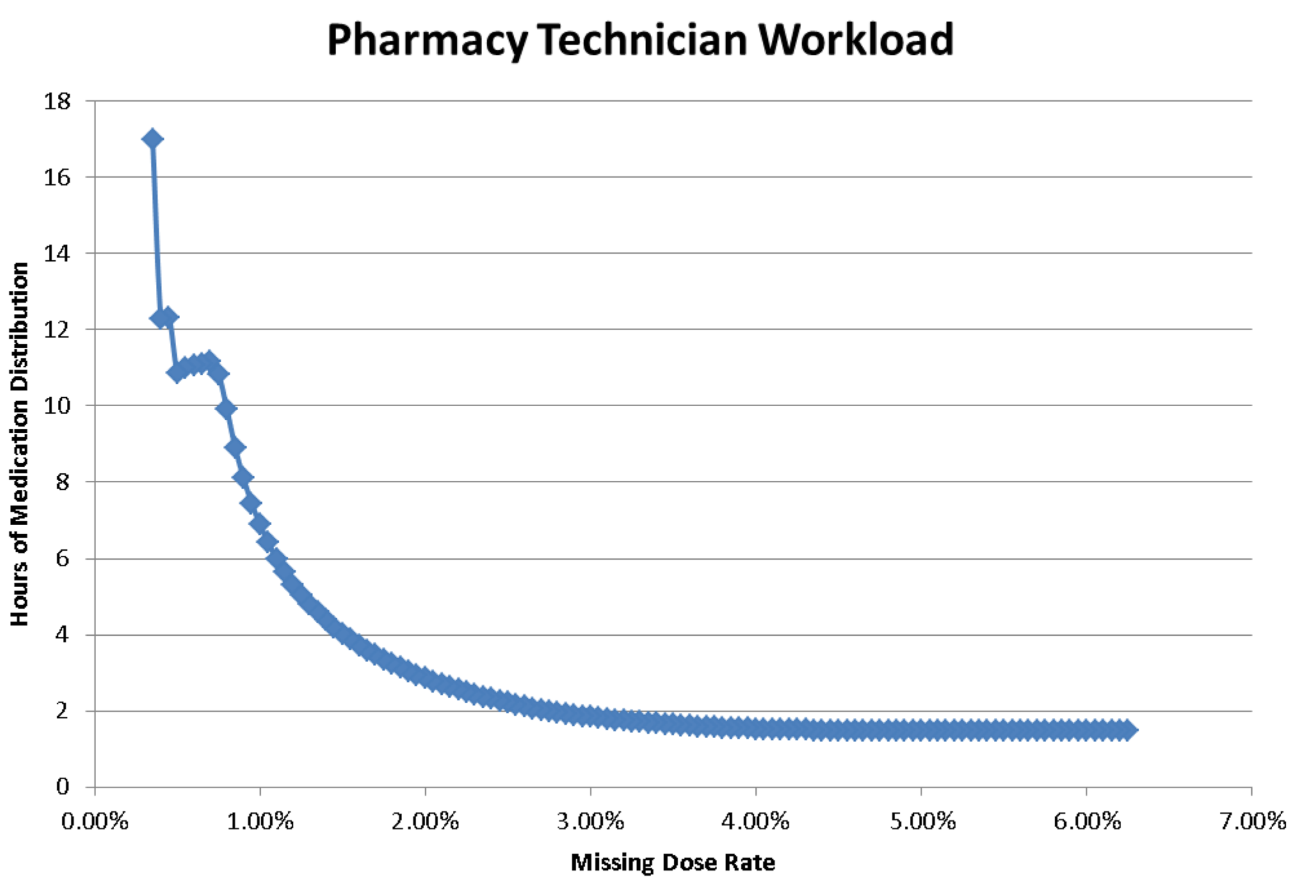


Fig. 6 Total pharmacy technician time spent on medication distribution activities based on cost and missing dose rate efficient frontier

Figure 6 illustrates the total pharmacy technician time that is required for the minimum cost at each missing dose rate. As the missing dose rate is restricted and the pharmacy begins distributing more medication through the ADC, the amount of pharmacy technician labor required for the medication distribution process grows rapidly. This is attributed to the increase in ADC stocking activities which require more time than picking an order in the central pharmacy or restocking the robot. The cost plateau that occurs at a missing dose rate of 0.70% is a result of the significant increase in the number of doses that are distributed via the ADC. The doses added to the ADC are maintenance doses and PRN doses for medication which is already stored in the ADC, so the restocking cost will not change as these doses are added. As a result, there is a decrease in the number of doses processed through the robot and a decrease in the time the pharmacist technician spends restocking the robot and preparing the cart fill. These factors all lead to a decrease in the total labor costs.

Figure 7 plots the total time an individual nurse spends on medication retrieval including the time waiting to access the ADC and the time to pick the medication. Similar to the pharmacy technician, with increased ADC usage, the average nurse time required to perform medication retrieval tasks increases. When minimal doses are stored in the ADC, the average nurse spends a total of 10 min a day retrieving unit dose medications. However, as more doses are routed through the ADC the nurse time increases due to the increase in picking and waiting time. In the maximum case the average time an individual nurse will spend on medication retrieval activities for only unit dose medications can reach over 50 min. Despite the increase in nurse queueing and retrieval time, utilizing the ADC decreases the frequency of missing doses, in turn reducing the nurse workload resulting from replacing missing medications.

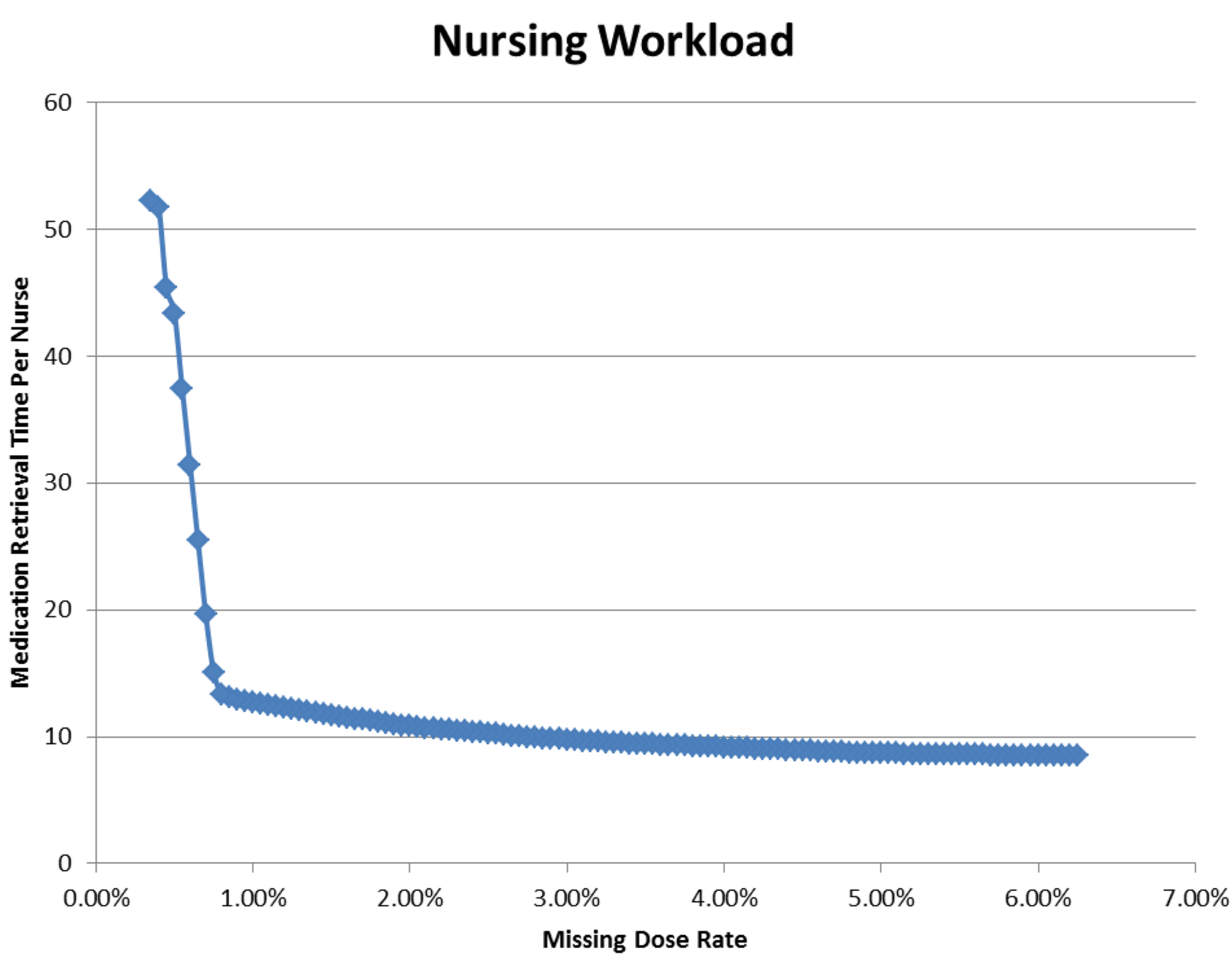


Fig. 7 Medication retrieval time for each nurse within the medication distribution process

Conclusion

In this paper, a mathematical model was formulated to reduce cost and missing dose rates in the pharmacy distribution system while capturing key aspects of the pharmacy distribution process. The results show that distributing medication via ADCs increases quality of care by decreasing the missing dose rate. As a result of improved care, the hospital can expect a drastic increase in the required pharmacy technician effort and nurse administration effort. Thus, the decision to utilize a centralized or decentralized pharmacy should consider the current resource levels and the additional burden on nurses.

The model expands the current pharmacy literature by creating a generalized model which can be implemented by any hospital. The model solutions provide decision makers the ability to determine the best solution for their system based on their goal missing dose rate. The missing dose rates in the model can be improved by considering variation in demand and alternative inventory policies. The primary limitation of the model is that it does not account for the labor effort required to replace a missing dose or allow for the possibility of subsequent missing doses after the first occurs.

The current model analyzes the system and determines the routing pathways for the medication based on the daily demand. Our analysis does not consider the variation in demand that can occur throughout the day. This limits our current analysis as we cannot use the current mathematical model to determine pharmacy staffing levels throughout the day. Future work will incorporate these considerations to determine how best to staff the hospital, including determining if it is safe to have hours of the day with very few pharmacy staff, in order to be most cost effective while still providing quality service.

Appendix 1

The notation for the mathematical model is given in Tables 1, 2, and 3. Table 1 gives the description of the indices used in the model. Table 2 provides definitions for the decision variables that are determined by the model. Table 3 provides definitions of the parameters used in the model objectives and constraints.

The multi-objective linear program to determine the minimal workload cost to deliver medications and the minimal missing dose rate is given below.

$$llMin w_1\left(\sum_{i,j,k,l} c_l d_{ijk} u_{ijkl} + \Lambda_1 \sum_{i,j,k} \frac{d_{ijk} u_{ijk1}}{\Delta} + \Lambda_3 \sum_{i,k,q} x_{ikq} + \Xi e\left(\chi_0 + 0.91\chi_1 + 0.65\chi_2\right) + \sum_{i,k,q} \xi_{Nurse} \Omega N_k \phi_k\right.$$

$$Min w_2\left(\sum_{i,j,l} \mu_{jl} d_{ijk} u_{ijkl}\right) \quad \forall k$$

$$s.t.$$

$$\begin{aligned}
&\textstyle\sum_l u_{ijkl} = 1 \quad \forall i,j,k \\
&u_{i1k1} = 0 \quad \forall i,k \\
&u_{i1k3} \geq u_{i2k3} \quad \forall i,k \\
&u_{i2k3} \geq u_{i3k3} \quad \forall i,k \\
&u_{i1k3} \geq u_{i4k3} \quad \forall i,k \\
&\textstyle\sum_q r_q x_{ikq} = \sum_j u_{ijk3} \quad \forall i,k \\
&\textstyle\sum_{q=4}^{6} x_{ikq} = u_{i4k3} \quad \forall i,k \\
&\textstyle\sum_q x_{ikq} \leq 1 \quad \forall i,k \\
&\textstyle\sum_{i,q} p_{ikq} x_{ikq} \leq B w_k \quad \forall k \\
&w_k \leq s_k \quad \forall k \\
&\textstyle\sum_{i,j,k} d_{ijk} u_{ijk1} \leq n\gamma \\
&\textstyle\sum_{j,k} u_{ijk1} \leq JK\beta_i \quad \forall i \\
&\textstyle\sum_i \beta_i \leq v\gamma \\
&\chi_0 + \chi_1 + \chi_2 + \chi_3 = 1 \\
&\chi_0 \leq \Upsilon_0 \\
&\chi_1 \leq \Upsilon_0 + \Upsilon_1 \\
&\chi_2 \leq \Upsilon_1 + \Upsilon_2 \\
&\chi_3 \leq \Upsilon_2 \\
&\Upsilon_0 + \Upsilon_1 + \Upsilon_2 = 1 \\
&\frac{\sum_{i,j,k} d_{ijk} u_{ijk3}}{\sum_{i,j,k} d_{ijk}} \geq 0.69\chi_1 + 0.90\chi_2 + \chi_3 \\
&\phi_k \geq 148 \frac{\sum_{i,j} d_{ijk} u_{ijk3}}{\sum_{i,j} d_{ijk}} - 17.32 \quad \forall k
\end{aligned}$$

Table 1 Model indices descriptions

Index	Description
i	Medication Type
j	Dose Type
k	Unit
l	Pathway
q	Medication dose type combination that is distributed through the ADC
$Tech$	Pharmacy Technician
$Nurse$	Nurse

Table 2 Model decision variable descriptions

Decision Variable	Description
u_{ijkl}	Indicator that medication i with dose type j is delivered to unit k via pathway l
x_{ikq}	Indicator that dose type combination q is stored in the ADC on unit k for medication i
w_k	Number of ADCs required on unit k
γ	Indicator that a robot is needed in the hospital central inpatient pharmacy
β_i	Indicator that medication i is routed through the hospital robot
ϕ_k	Average time nurses queue at the ADC on unit k
χ_m	The set of variables used to determine the percentage of patients using cart fill when m is the number of vertices in the piecewise function
Υ_m	The set of binary variables to determine the segment of the piecewise function that is used to determine the cart fill preparation cost based on the percentage of doses routed through the ADC where m is the number of piecewise segments in the cart fill function

Table 3 Model parameter descriptions

Parameter	Description
ξ_{Tech}, ξ_{Nurse}	Average salary of pharmacy technician and nurse, respectively
Λ_l	Inventory replenishment cost for technology used in pathway l
Δ	Average number of medications that can be stored on a single rod in the robot
Ξ	Average census of the hospital
e	Cost to label patient envelope
Ω	Number of large medication administrations that occur in the hospital
N_k	Number of patients on unit k
p_{ikq}	The integer number of bins in the ADC required to hold the par level of medication i on unit k when dose combination q is held in the ADC
r_q	The number of dose types stored in the ADC under dose combination q
B	The total number of bins in an ADC
s_k	The maximum number of ADCs that can be used in unit k
c_l	The cost to pick an individual dose in pathway l
d_{ijk}	The average daily demand of medication i dose type j on unit k
n	Throughput capacity of the robot
v	Unique medication capacity of the robot
μ_{jl}	The percentage of missing doses resulting from dose type j and distribution pathway l

Declarations

Conflict of interest There is no financial support or personal connections that create a conflict of interest with our work.

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