An Adaptive Approach for Efficient Hospital Supply Chain System Management

Pradeep G. Pai
Michael E. Kuhl
Industrial and Systems Engineering Department
Rochester Institute of Technology
Rochester, NY 14623 USA

Abstract

In healthcare, the primary goal is to deliver high quality care to patients. To accomplish this goal, the healthcare providers typically have significant investment in terms of inventory and supply chain management. Researchers have indicated great potential for optimizing healthcare inventory systems, especially within hospitals. To address the need for an efficient and effective hospital supply chain management system, we propose a method consisting of two components: (1) system design and optimization; and (2) system monitoring, evaluation, and forecasting. The system design and optimization methodology includes a simheuristic approach. To monitor the relevant system performance measures over time, control-chart like methods are utilized. When significant deviations in system performance occur, a re-evaluation of the inventory decision variables and/or system operations is conducted to maintain an efficient inventory system. Experimental results are presented to demonstrate the effectiveness of this methodology.

Keywords
Healthcare supply chain, forecasting, simulation

1. Introduction

Healthcare expenditures in the United States reached $3.3 trillion in 2016, more than ten times the $256 billion spent in 1980 [1]. Various reports indicate that supply chain costs in a hospital contribute between 25 – 40% of total healthcare expenditures [2, 3]. Studies suggest that optimizing demand management, inventory management and order management may facilitate significant supply chain cost savings in hospitals [4, 5]. For the healthcare sector in general, inventory accumulation and obsolescence of products are high, when compared to the industrial sector [6]. Hence exercising control over the purchase and monitoring of products within a hospital can have a significant impact on the hospital’s bottom line. However, since the primary focus of a hospital is the delivery of patient care, streamlining inventory of a diverse set of products in the hospital is not often prioritized. In this paper, supply chain management systems are analyzed, and a novel adaptive systems management approach is developed to enable the delivery of high quality patient care while minimizing system costs over time.

A healthcare supply chain typically consists of multiple suppliers, manufacturers, distributors, a centralized hospital inventory, multiple hospital units, and patients (see Figure 1). The echelons of a hospital supply chain system from the distributor to the patient are the primary consideration of this paper (outlined by the dashed box in Figure 1). The supply chain literature tends to focus on the design of supply chain systems or the determination of system values such as order quantity and reorder point at a particular point in time (typically the current time). Kelle et al. [7] use a simulation approach to reduce inventory expenditures for pharmaceuticals. They analyze the trade-off between the emergency shipments and required service levels, to reduce costs. In addition, Gebicki et al. [8] conduct a simulation study on inventory decisions based on service level, demand and cost to improve system performance. However, as time passes, changes in the system can render the supply chain system inefficient. That is, the optimal inventory policies and system operation decisions established based on system data at one point in time will become sub-optimal. To address this issue, we develop a system monitoring, forecasting and evaluation approach for timely analysis and adaptation of hospital inventory policies with the objective of maintaining an efficient system over time.
2. Design Methodology

Our methodology of an adaptive hospital supply chain management approach consists of two primary components: (1) system design and optimization; and (2) system monitoring, forecasting, and evaluation. Figure 2 illustrates the two components as a feedback loop. The adaptive approach extends the static system design and optimization methodology of Garg and Kuhl [9] to a dynamic method that monitors and makes adjustments to the system as needed over time. The system design and optimization component utilizes a simheuristic approach (an approach that combines simulation and meta-heuristics for stochastic optimization problems, see [10]) to evaluate alternative systems configurations and determine system decision variables (order quantities, reorder points, etc.) based on current data. Then, to monitor the relevant system performance measures over time, control-chart like methods are utilized. When significant deviations in system performance occur, a re-evaluation of the inventory decision variables and/or system operations is conducted to maintain an efficient inventory system. The methodology is designed for the portion of the hospital supply chain system that consists of the distributor, a centralized storage (inventory) location in the hospital that replenishes products for multiple hospital units, and care unit inventories for treatment of patients (see Figure 1).

3.1 System Design and Optimization

Supply chain system design is the initial step in our methodology. In particular, given the current demand for products within care units, alternative supply chain configurations are evaluated. Inventory decisions, such as when and how much to order, and decision regarding the operational aspects of the system including the type of replenishment system (e.g., Kanban, par level, etc.), personnel, periodic review frequency, among other system components. The method of Garg and Kuhl [9] can be used to compare alternative system configurations using a simheuristic approach where product inventory decision variables such as order quantity, reorder point, etc. are computed using traditional methods. These values are then used as a starting point for a simulation-based system optimization to evaluate alternative system...
configuration to select the most efficient system design based on performance measures such as cost and service level. Once the system design is selected it can be implemented. As the system functions and over time and conditions such as product demand rates change, the original optimal values of decision variable will no longer be optimal. In the next section, we discuss our method to address this issue.

3.2 System Monitoring, Evaluation, and Forecasting

The system monitoring, evaluation, and forecasting component of the methodology is used to track supply chain system performance metrics such as service level and cost. The objective is to determine the point at which the system has deviated significantly enough from the original optimal system performance to warrant changes to the system. In particular, we utilize a control-chart type method to monitor system performance metrics at user-specified intervals of time. For example, we may track the average cost each week. As the system changes over time, the performance measure will deviate from the optimal average cost. Limits are set on the control chart corresponding to a level of change deemed to be significant enough to take action – that is, to re-evaluate the supply chain decision variables to obtain the optimal values under the current (new) conditions.

Figure 3 depicts the control-chart type method used for monitoring and evaluation of the system over time. Let time \( S \) represent the point in time that the optimal system configuration is established. For a given performance metric, \( V \), the dotted line, \( P(t) \), represents the optimal expected value of the performance metric, \( V \), established at the evaluation point. That is, at time \( S \), the optimal expected value of \( V \) is \( P(S) \). Given \( P(S) \), a threshold, \( T(S) \), is established for the control chart at time \( S \). As time passes, the performance measure, \( V(t) \), is tracked and plotted. Due to changes in the system over time (e.g. changes in demand, lead time, etc.) the system configuration established at time \( S \) becomes sub-optimal which is reflected in the deviation of the performance measure \( V(t) \). When \( V(t) \) reaches the threshold value, \( T(S) \), the system is re-evaluated (at time \( R \)) and a new optimal configuration is determined. Note that the new optimal expected value of \( V \), \( P(R) \), may not return to \( P(S) \) as uncontrollable factors (that is, factors outside of the hospital such as product cost, transportation cost, etc.) contribute to the increased optimal value. Finally, a new threshold value, \( T(R) \), is established and the monitoring process continues.

To determine the extent of the changes that need to be made, a hierarchical approach is used (see Figure 4). First the system level performance metrics are evaluated. If the threshold is exceeded, optimization is done for the entire system under the new conditions. If not, the location level performance measure are evaluated such as central storage or individual unit performance metrics. If a location level metric exceed the threshold, the optimization is conducted only for that unit. Otherwise, the product level metrics are evaluated. If performance measure for a product exceeds the threshold, the optimization is conducted for that product. If none of the performance measures at any of the three levels have exceeded their respective thresholds, forecasting is done to predict when a re-evaluation action may be required. As it will take time and effort to do the optimization, the forecast will be helpful for planning for this activity.
As the variation in performance measure which may be significant in relatively short intervals of time. We utilize an exponential smoothing approach which allows easier tracking of true changes in the mean of the metric. As discussed in Soyiri and Reidpath [11], the Holt-Winter method [12] has been used successfully for forecasting in healthcare. Therefore, we utilize this method to predict the performance metrics into the future. The forecasting method involves determining level and trend corresponding to the actual values. The level and trend parameters are then used to forecast the future performance. The forecasting equation is given by:

\[ \hat{X}_{t+h} = l_t + hb_t \]

where \( l_t \) is the level component estimate for time \( t \); \( b_t \) is the trend component estimate for time \( t \); and \( h \) is the forecasting period. The level and trend parameters are calculated as follows:

\[ l_t = \alpha X_t + (1 - \alpha)(l_{t-1} + b_{t-1}) \]
\[ b_t = \beta (l_t - l_{t-1}) + (1 - \beta)b_{t-1} \]

where \( \alpha \) is the smoothing parameter for the level, such that \( 0 \leq \alpha \leq 1 \), and \( \beta \) is the smoothing component for the trend, such that \( 0 \leq \beta \leq 1 \).

Figure 4: Hierarchy for evaluation of performance metrics and forecasting

3. Example of the Adaptive Approach
To illustrate the monitoring and evaluation framework, we have constructed a simulation model that represents a small hospital with a central storage with three products and two care units with three products each. In addition, we assume that the following are provided for each product:

- Mean product demand and its variance in each hospital unit;
- Mean lead time and its variance for delivering the product;
- Inventory related costs at units and central storage; and
- Penalty cost per unit of demand met by emergency stock.

We have applied a \((Q, R)\) inventory replenishment model with stochastic demand. The product demand at units is modeled to increase with a trend based on a normal distribution. The initial values for order quantity \( Q \), reorder level \( R \) and safety stock are determined using established methods (see [13]). The simulation model is built using SIMIO simulation software. Inventory replenishment at central storage and hospital units is assumed to follow a periodic review model. We have set up the performance review period to a week and the simulation model runs for 100 weeks. The simulation model records all the transactions every week. Total demands, demands met, total inventory costs are used to determine the system cost, total cost for each unit, system service level, location service level and product service level. After each performance review period, the performance metrics for different levels are monitored using a control chart and the heuristic set up decides the level of re-evaluation required.

In the simulation model built, service level and cost were monitored at different levels and re-evaluation decision was made. For example, if we consider system cost monitoring, initially with optimal inventory policies the system cost is
steady. As time progresses, with increase in demand variations the system cost increases as shown in Figure 5a. The system cost forecast predicts the system cost to be within threshold for the near future periods. But the forecast clearly shows an increasing trend and hence the system cost is bound to exceed the threshold limit. The monitoring process continues as usual and the system cost exceeds the threshold during week 33 as shown in Figure 5b. The heuristic enables the system level evaluation and the inventory policies for all the products in each location is re-evaluated. System optimization module considers the current demand and variation for each product to derive new inventory policy. After evaluation the system adopts the new inventory policies and other operational aspects and the monitoring system keeps track of the cost. This cycle repeats itself and results in either system or location or product re-evaluation to maintain system efficiency.

A comparison of system cost for a system with evaluation module versus a system without evaluation module is shown in Figure 6. Different levels of evaluation ensure that the system efficiency is maintained, and the cost remains in control. The service level comparison is shown in Figure 7.
4. Conclusion

The supply chain monitoring system described in this paper has the potential to be an effective approach for determining the evaluation points and the extent for maintaining an efficient system. The method tracks the system behavior, through a monitoring process, thereby aiding in the decision about the extent of evaluation. This cycle repeats to keep the total inefficiency cost over the horizon at a minimum and makes the system robust against variations. Overall, the supply chain management system could provide hospitals with an ability to adapt to changes in demand and other system conditions over time.

References