Hospital Inventory Management
New Trends in Healthcare

Claudia Rosales
Michigan State University

Michael Magazine and Uday Rao
University of Cincinnati

In collaboration with
Sylvain Laundry – HEC Montreal
Richard Philippe – Logi-D
Problem Motivation

- Supplies management – significant costs involved 30-40% of the average hospital’s budget (Neil, 2005)
  
- Many different supplies

- Many different locations

- Little or no visibility of inventory at point-of-use

- Stock rotation is critical

- Focus on patient care
Traditional Hospital Inventory Practices

Service Centers

Central Warehouse

Nurse Servers
Inventory management at hospitals

• Bijvank and Vis (2012)
• Little and Coughlan (2008)
• Lapierre and Ruiz (2007)
• Opolon, et al. (2009)
• Landry and Beaulieu (2009)

Impact of technology adoption

• Delen (2007)
• Lee and Ozer (2007)
• Gaukler et al. (2008)
• Cakici et al. (2010)
Dealing with inventory complexities

- Automated Dispensing Machines (ADMs)
  - Computerized cabinet allows inventory visibility at point-of-use
  - 90% of large hospitals (> 300 beds) have ADMs (*)

- Hospital Substituted nurse servers for Pyxis Supply Stations

(*)Pedersen et al., 2006
Benefits of ADMs

• Improve the dispensing and control of medical supplies

• Allows continuous time tracking of inventory

• Improve billing accuracy

• Enabled the use of new/improved inventory replenishment practices

• Hospital management unsure how to take advantage of new technology
New Inventory Practices

Using ADMs

- Inventory is tracked continuously
  - A par value
  - Refill level
  - Critical level
  - Stockout level

- Between shifts if inventory hits critical level - item is replenished
  - Should we replenish if close to periodic replenishment?
  - What are the benefits of allowing the replenishment of a critical item?
  - How much improvement do we get versus traditional periodic replenishment?
What Makes this Problem Challenging?

• Hybrid Inventory Policy
  – Periodic \((s,S)\) replenishment – Beginning of shift
  – Continuous \((Q,R)\) replenishment – out of cycle – whenever needed

• Optimal policy – likely non-stationary

Behavior of non-stationary \(R\)
What Makes this Problem Challenging?

- There is a “fixed cost” of performing a replenishment - the out-of-cycle replenishment is considered more costly
  
  \[
  \text{out of cycle fixed cost (} k_o \text{) > periodic fixed cost (} k_p \text{)}
  \]
- There is no restriction to the number of out-of-cycle replenishments
- Holding costs associated with limited space available
- Penalty cost when stock-outs occur wasting valuable nurse time
- Many items (> 100)
Single Item Hybrid Policy Solution Approach

- No simple closed form expression for average cost given \( s, S, R, Q \)
- Cost function – not convex

1. Develop a stochastic optimization heuristic using simulation
2. Obtain approximate parameter expressions using the optimal solution to deterministic Hybrid policy
Optimization Heuristic

- Search heuristic
  - Coded in C++
  - Iteratively searches for \((R,Q)\) and \((s,S)\) values until convergence is reached
  - Heuristic is re-started with different starting points looking for better local optima
  - Simulation is used to evaluate long run average cost

- Cost within 1% of optimal vs. exhaustive grid search

- Heuristic used to test different scenarios
Hybrid Cost Function

![Graph showing Hybrid, Periodic, Continuous, and Deterministic Cost Functions over time (T).]
Single Item - Insights Obtained

• High economic benefits possible for hybrid - up to 18% improvement

• Significant differences observed in parameter values – $S << S_{\text{periodic}}$

• Hybrid – flexible, can behave as periodic policy, or approach continuous policy

• Hybrid provides maximum benefit when cost of periodic and continuous policy is equal
Approximate Solution From Deterministic Hybrid

• Estimates for the stochastic hybrid policy parameters

\[(S - s) = (S_d^* - s_d^*) \quad Q = Q_d^*\]

\[s = s_d^* + \text{safety stock} \] (periodic replenishment interval + order lead time)

\[R = R_d^* + \text{safety stock} \] (order lead time)

– Estimated parameters performed well for hospital conditions tested

– Parsimonious solution for large number of items still needed
Dealing with Multiple Items
The Two-Bin System

• Motivated by lean principles

• Each item’s inventory stored in two bins – primary and secondary

• Stock from primary bin is consumed first - secondary bin becomes the new primary

• No manual counting necessary / No need to track individual item consumption

• Number of items per bin usually selected to provide a pre-specified number of inventory turns.
Two Bin System - Advantages

- No need to track individual item inventory continuously
- Fewer parameters to be defined for inventory control
- Replenishment can be triggered periodically or by accumulation of empty bins
- Can be used for all types of products (drugs, supplies, office, etc)
Two-Bin Replenishment System with RFID

- Each bin carries one RFID tag
- When a bin is emptied, the RFID tag is placed on the board and read
- Information is downloaded to MM information system
- Depending on system conditions, a replenishment is triggered
  - If order triggered – stock delivered after some time
  - While replenishment is processed – more bins may become empty
Two Bin-RFID System in Hospitals

- Hospitals used to periodic replenishment –

- With RFID – hospitals don’t always take advantage of additional information
  - system conditions that should trigger replenishment are not defined

- Several factors may trigger an order
  - When a predetermined number of tags appear on the board
  - When a tag of a primary bin has been on the board for a predetermined period of time
  - When the tag of a secondary bin appears on the board
Hospital Data

- Access to over one year of data
- Data for two different hospitals

<table>
<thead>
<tr>
<th>P2124C</th>
<th>P2124C</th>
<th>1002720</th>
<th>Bandage rayonne extensible non sterile 15.0cm x 4.5m</th>
<th>N</th>
<th>9</th>
<th>6</th>
<th>5</th>
<th>P</th>
<th>2010-09-19 07:56:52.580</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
<tr>
<td>P2124C</td>
<td>P2124C</td>
<td>1002720</td>
<td>Bandage rayonne extensible non sterile 15.0cm x 4.5m</td>
<td>N</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>P</td>
<td>2010-09-19 07:56:52.580</td>
</tr>
</tbody>
</table>
Hospital Data

- Hospital Data – using a Two-Bin RFID System under periodic review
  - Several departments within the hospital
  - Data for one year / hundreds of different items

<table>
<thead>
<tr>
<th>Hospital Department</th>
<th>Item Code</th>
<th>Item Description</th>
<th>units/bin</th>
<th>Bin type</th>
<th>Bin on Board</th>
<th>Replenishment Ordered</th>
<th>Replenishment Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>E3511</td>
<td>8901713</td>
<td>Intravascular catheter 1”</td>
<td>36</td>
<td>P</td>
<td>6/27/11 8:02 PM</td>
<td>6/28/11 7:20 AM</td>
<td>6/28/11 11:24 AM</td>
</tr>
</tbody>
</table>

- We were able to obtain from the data:
  - Average demand rates for each item
  - Number of item’s per department
  - Average replenishment lead time
  - Hospital provided information for fixed order cost and stockout costs
Two Bin System - Options for Improvement

- Traditionally bins replenished daily (periodically) - filling up all empty bins

- Bin replenishment involves time/effort
  - fixed replenishment cost

- In case of stockouts – nurse procures item
  - stockout cost

- Too many items to replenish
  - Cost-efficient & practical
1) Improvement: **Parameter Improvement**

- Optimize periodic review parameters to minimize cost – **Find right replenishment cycle** (daily, weekly, etc.)
- Assuming bin demand follows a Poisson Process
- Average cost per unit time $J^P(T) \ ; \ T =$ periodic replenishment cycle (decision variable)

\[
J^P(T) = \frac{1}{T} \left[ K (1 - p(0, \lambda NT)) + \eta_L C(1, T - L) \\
+ (N - \eta_L) C(2, T - L) + \eta_1 C(1, L) \\
+ \eta_2 (\rho + \hat{\rho} L) \right]
\]

Model parameters:

$L =$ delivery lead time; $N =$ number of items; $\rho =$ stockout costs per unit; $\rho =$ stockout cost per unit time; $\lambda =$ bin consumption rate; $K =$ fixed order cost
1) Parameter Improvement....

- We show quasi-convexity of $J^p(T)$ with respect to $T$ (under conditions we specify).

- We can find the optimal average cost for the periodic review model $J^p(T)$ and the optimal review interval $T$ using a search procedure that finds:

$$T^* = \arg \min_T J^p(T)$$

- We use C++ and a Golden Section search approach to find the optimal average cost $J^p(T)$ and the optimal review interval $T^*$
2) Improvement: **Policy Improvement**

- Use of technology to improve inventory visibility – continuous review inventory model

- We formulate a Semi-Markov Decision model

  - Estimate the average cost per unit time $J^C$ under continuous review

  - Similar parameters as in periodic review

  - Orders triggered when:
    - a) secondary bin empty
    - b) when $n^*$ primary bins are empty (decision variable)
2) Policy Improvement...

Bellman optimality equations

\[
 h_{(n_1,0)} = \min_{a \in \{1,0\}} \left[ G_{(n_1,0)}(a) - \bar{\tau}_{(n_1,0)}(a) J^c \right. \\
+ \left. \sum_{i=0}^{N} \sum_{j=0}^{1} P_{(n_1,0)(i,j)}(a) h_{(i,j)} \right], \quad n_1 \in \{1, \ldots, N\}
\]

\[
 h_{(0,0)} = \left[ G_{(0,0)}(0) - \bar{\tau}_{(0,0)}(0) J^c + \sum_{i=0}^{N} \sum_{j=0}^{1} P_{(0,0)(i,j)}(0) h_{(i,j)} \right]
\]

\[
 h_{(n_1,1)} = \left[ G_{(n_1,1)}(1) - \bar{\tau}_{(n_1,1)}(1) J^c + \sum_{i=0}^{N} \sum_{j=0}^{1} P_{(n_1,1)(i,j)}(1) h_{(i,j)} \right], \quad n_1 \in \{1, \ldots, N\}
\]

Using Linear Programming this model can be solved to obtain the optimal cost $J^c$ and the optimal number of bins that should trigger a replenishment $n^*$
Parameter vs. Policy Improvement

• From hospital data we obtained a base scenario (median values)
  – $T = 24$ hrs; $N = 200$; $\lambda = 0.0028$ bins/hr;
  – $\rho = 55$ $$/\text{bin}; K = 100$ $$/\text{replenishment};$
  – $\bar{\rho} = 0.04$ $$/\text{bin/hr}$. (Damodaran, 2012)

• We obtained the optimal average cost per unit time under periodic, $J^P(T^*)$, and continuous review, $J^C^*$, as well as the current hospital periodic average cost per unit time $J^P(T)$.

<table>
<thead>
<tr>
<th>Parameter Modified</th>
<th>Value</th>
<th>Continuous Review</th>
<th>Periodic Review</th>
<th>Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$J^C^*$ ($$/\text{hr})$</td>
<td>$n^*$</td>
<td>$J^P(T^*)$ ($$/\text{hr})$</td>
</tr>
<tr>
<td>Base Scenario</td>
<td></td>
<td>2.63</td>
<td>33</td>
<td>7.33</td>
</tr>
</tbody>
</table>
Parameter vs. Policy Improvement

- Lower values of $\lambda$ (more items per bin) favor the use of periodic review with parameter optimization

- Factor such as expiration dates and inventory rotation should be taken into consideration
Parameter vs. Policy Improvement

- Costs increase more dramatically under periodic review as N increases

- Less expensive to have a smaller number of large storage rooms than a large number of small storage units. Need to balance with the need to supply stock close to the point-of-use
Parameter vs. Policy Improvement

- Storage areas where most items are non-critical could be replenished using periodic review.

- Storage areas where most items are fairly critical and/or expensive (cath lab) can see great benefits from policy improvement.

Impact of changes in Average Cost with changes in $\rho$.
Future Work - Impact of Different Demand Processes

• Exponential inter-arrival times good fit for several items, but not all

• Other distributions (Weibull, Beta, Erlang) provided good fit for several items

• Test robustness of results under different distributions

• Simulation model test results under real hospital data
Conclusion

- Expensive items can be closely monitored with ADM machines using simple expressions to compute inventory policy parameters.

- For inexpensive, yet critical items, the two-bin system provides a more parsimonious inventory management system.

- Under the two-bin system, policy improvement (with the use of RFID or barcodes) provides greatest benefits.
Conclusion

• The benefits of policy improvement should be compared to the cost of investing in new technology such as RFID or barcodes.

• We provide a tool that can estimate the economic benefits of technology investment, and can provide hospital management guidelines to improve the use of available resources.
Questions?
Thank you!