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On two-echelon inventory systems with Poisson demand and lost sales

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Abstract

We derive approximations for the service levels of two-echelon inventory systems with lost sales and Poisson demand. Our method is simple and accurate for a very broad range of problem instances, including cases with both high and low service levels. In contrast, existing methods only perform well for limited problem settings, or under restrictive assumptions.

Key words: inventory, spare parts, lost sales.

1 Introduction

We consider a two-echelon inventory system for spare part supply chains, consisting of a single central depot and multiple local warehouses. Demand arrives at each local warehouse according to a Poisson process. Each location controls its stocks using a one-for-one replenishment policy. Demand that cannot be satisfied from stock is served using an emergency shipment from an external source with infinite supply and thus lost to the system. It is well-known that the analysis of such lost sales inventory systems is more complex than the equivalent with full backordering (Bijvank and Vis [3]). In particular, the analysis of the central depot is complex, since (i) the order process is not Poisson, and (ii) the order arrival rate depends on the inventory states of the local warehouses: Local warehouses only generate replenishment orders if they have stock on hand.

In the literature, solutions have been found for specific cases. Andersson and Melchiors [2] approximate the arrival process at the depot by a Poisson distribution with a rate depending on the fill rates at the local warehouses. Given these fill rates, they compute the mean waiting time of replenishment orders at the central depot. This waiting time is input for the computation of the fill

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rates at the local warehouses. This yields an iterative procedure that gives reasonably accurate results in general. However, we find that the procedure often does not converge when a lot of stock is kept at the central depot, with little stock kept locally. Such a setting is quite common in practice, since a supplier will try to keep most stock centrally to benefit from risk pooling.

Seifbarghy and Jokar [6] consider a similar model with a lot size that may be larger than 1. Their model is limited to cases with identical retailers. Their approach is similar to Andersson and Melchiors [2], and they limit their experiments to problem instances with high service levels. In contrast to these papers, Hill et al. [4] explicitly use arrival rates that depend on the number of outstanding orders at the central depot. They assume that (i) each local warehouse may only have one replenishment order outstanding at any time, and (ii) the transportation time from depot to local warehouse is at least the central depot lead time. The second assumption is particularly restrictive, since upstream lead times tend to exceed downstream lead times in practice.

In this paper, we develop approximations for the service level that are accurate for a very broad range of cases: the accuracy of the approach does not depend on the stock levels at the various locations in the system. As a result, the approach works well for both high and low service levels. Furthermore, the approach can handle settings with non-identical local warehouses and no assumptions are made on the maximum number of outstanding orders.

To facilitate the analysis, we make one key assumption on the product flows that seems very reasonable from a practical perspective: Demand at a local warehouse is only lost if it cannot be satisfied from local stock, central stock or any replenishment order in transit between the depot and a local warehouse. The logic is that an emergency shipment from a (remote) external supplier generally takes more time than a shipment between the depot and each warehouse, and so it does not make sense to use the emergency option if the depot still has stock on hand. For each local warehouse, we specify (i) the fraction of demand satisfied through the two-echelon inventory system and (ii) the related mean waiting time. The remaining demand is met through emergency shipments and faces the emergency shipment time as delay waiting for parts. By combining the two times, we are able to compute the overall expected downtime waiting for parts, which is a key performance indicator in multi-items spare part inventory optimization.

A key feature of our method is that we use state-dependent order arrival rates at the central warehouse. In the next section we define our model and give our analysis. We present the results from numerical experiments in Section 3, and give our conclusions in Section 4.

2 Model

2.1 Notation and assumptions

Consider a two-echelon network consisting of a central depot and K local warehouses (Figure 1). We use index 0 for the central depot and indices $1 \ldots K$ for the local warehouses. Demand occurs at local warehouse k according to a Poisson process with rate m_k. The inventory at stock point k is controlled using an $(S_k - 1, S_k)$ base stock policy. The transportation time between the central depot and local warehouse k is deterministic and equal to L_k, while the replenishment lead time to the central depot is assumed to be exponentially distributed with mean L_0. The latter assumption facilitates an analysis using Markov chains. Also, the performance of these types of models are not very sensitive to the lead time distribution, see Alfredsson and Verrijdt [1].

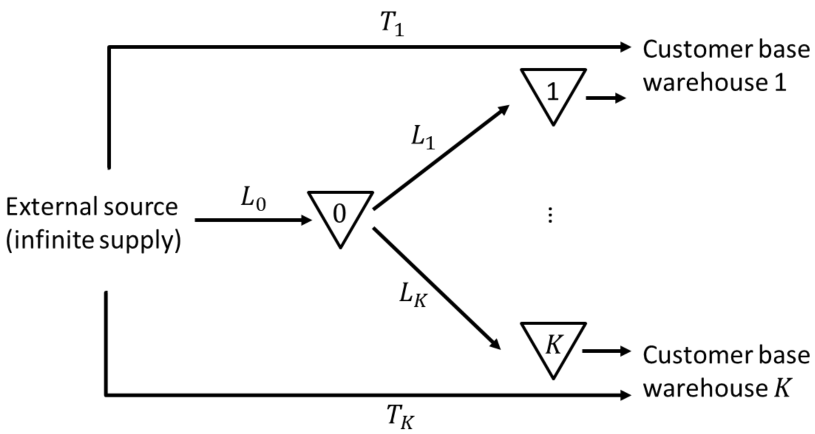

Figure 1. A graphical representation of the supply system

A demand arriving at local warehouse k is served through the two-echelon network if an item is available at the local warehouse, the central depot or in the transport pipeline in between. Otherwise, the demand is satisfied using an emergency channel at additional costs with mean emergency lead time $T_k > L_k$. We assume that the emergency channel has infinite capacity.

Our performance indicators are the fraction of warehouse k demand that is satisfied through the regular channel, α_k, and the expected waiting time for demand satisfied through the regular channel $E[W_k]$ $(k = 1 \ldots K)$. These performance indicators enable us to evaluate:

- the total relevant costs per year as $h_0 S_0 + \sum_{k=1}^{K} \{h_k S_k + C_k(1 - \alpha_k) m_k\}$, where h_k denotes the item holding costs per year at stock point k and C_k denotes the additional emergency shipment costs to local warehouse k (above the costs of supply through the regular channel);
- the downtime waiting for parts $DTWP_k$ at local warehouse k as $\alpha_k E[W_k] + (1 - \alpha_k) T_k$.

2.2 Analysis

We first derive an approximation for the fractions of demand served through the regular channel, α_k. Next, we provide an approximation for the mean waiting times $E[W_k]$.

Fraction of demand served through the regular channel α_k

We note that the decision whether to use the emergency channel does not depend on the transportation time L_k between the central depot and local warehouse k. Therefore, we can determine α_k by setting L_k to zero and analyzing the pipeline *to* the central depot: a demand at warehouse k can always be satisfied through the regular channel if the central depot has stock on-hand, which is equal to having fewer than S_0 items in resupply at the depot. Otherwise, this demand can only be satisfied through the regular channel *if* warehouse k has stock on-hand, which is equal to having fewer than S_k backorders at the depot destined for warehouse k.

Let $\beta_k(i)$ denote the probability of having fewer than S_k depot backorders for warehouse k, given that we have i items in resupply at the central depot. Note that $\beta_k(i) = 1$ for $i < S_0$. Approximating the arrival process at the depot by a Poisson process, we can model the pipeline to the depot by a one-dimensional continuous-time Markov chain, with state i denoting the number of items in resupply (see Figure 2). In the figure, we use the following notation:

- M denotes the demand rate when the depot has stock on-hand i.e. $M = \sum_{k=1}^{K} m_k$
- $M(i)$ is the demand rate in state $i \geq S_0$, i.e. $M(i) = \sum_{k=1}^{K} m_k \beta_k(i)$
- μ is the regular replenishment rate with $\mu = 1/L_0$.
- S_{Tot} is the maximum number that can be in the pipeline, so $S_{Tot} = \sum_{k=0}^{K} S_k$

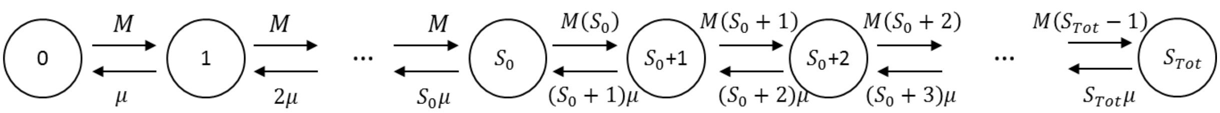

Figure 2. The Markov chain characterizing the number of items in resupply at the central depot

The demand rates become state-dependent once we have S_0 or more items in resupply: Then, the depot is out of stock, and further arrivals from warehouse k can only occur if that warehouse has stock on-hand (with probability $\beta_k(i)$). As a result, we can have at most S_{Tot} items in resupply, since the depot and all warehouses are out of stock then. We let $\pi(i)$ denote the steady-state probability of having i items in resupply at the central depot and find:

$$\alpha_k = \sum_{i=S_0}^{S_{Tot}} \beta_k(i)\, \pi(i) \tag{1}$$

We determine $\beta_k(i)$ ($i \geq S_0$), as follows: $\beta_k(i) = 1 - \Pr\{DBO_k(i - S_0) = S_k\}$. Here, $DBO_k(n)$ denotes the number of depot backorders for local warehouse k if we have n depot backorders in total. We know that $DBO_k(n)$ can never exceed S_k. If $S_k \to \infty\ \forall k$, the joint distribution of $DBO_k(n)$ ($k = 1..K$) is a K-category multinomial distribution with number of trials n and success probabilities $q_k = m_k / \sum_{h=1}^{K} m_h$. Let us denote this probability distribution by

$$p_n(x_1, .., x_K) = Pr\{DBO_1(n) \leq x_1, .., DBO_K(n) \leq x_K\} \quad (2)$$

Now, it is also clear that the joint probability distribution for finite values of S_k has a *truncated* multinomial distribution, as we condition on the upper bounds S_k for the warehouse k backorders:

$$p_n(x_1, .., x_K | S_1, .., S_K) = \frac{Pr\{DBO_1(n) \leq x_1, .., DBO_K(n) \leq x_K\}}{Pr\{DBO_1(n) \leq S_1, .., DBO_K(n) \leq S_K\}} \quad (3)$$

We thus find $\Pr\{DBO_k(n) = y_k\}$ as below, with $\beta_k(i) = 1 - \Pr\{DBO_k(i - S_0) = S_k\}$:

$$\Pr\{DBO_k(n) = y_k\} = p_n(S_1, .., y_k, .., S_K | S_1, .., S_K) - p_n(S_1, .., y_k - 1, .., S_K | S_1, .., S_K) \quad (4)$$

For a fast evaluation of cumulative multinomial probability distribution function, we use the powerful method by Levin [5], see Appendix for a brief description.

Mean waiting time $E[W_k]$

The waiting time of a customer served through the regular channel equals the time that his request is backordered in expectation of a pending item arrival. We thus find $E[W_k]$ through Little's law: $E[W_k] = E[BO_k]/\alpha_k m_k$, with $E[BO_k]$ denoting the expected number of backorders at warehouse k. We can determine $E[BO_k]$ from the distribution of the items in resupply to warehouse k, a random variable that we denote by X_k. We find: $\Pr\{BO_k \leq x\} = \Pr\{X_k \leq S_k + x\}$.

We note that X_k consists of two elements: backorders *at the central depot* for that warehouse and items in the transport pipeline between the depot and the warehouse, which we denote by Q_k. These elements are not independent: if we have fewer than S_k depot backorders for warehouse k, a new demand can still be met through the regular channel, further increasing the transport pipeline. In contrast, if we have S_k depot backorders for warehouse k, new demand cannot be met through the regular channel: both the depot and warehouse k are out of stock then and the transport pipeline only contains items that have been reserved for earlier demand. In this case, the transport pipeline cannot increase further; we need to wait for a backorder to arrive at the depot before replenishments through the regular channel are again possible.

We approximate the distribution of X_k as follows: if we have fewer than S_k depot backorders for warehouse k, we consider the depot backorders to be independent of the transport pipeline Q_k. In that case, Q_k has a Poisson distribution with mean $m_k L_k$. In contrast, if we have S_k depot backorders, we ignore the items in the transport pipeline. We find for the distribution of X_k:

$$\Pr\{X_k = y\} = \begin{cases} \sum_{x_k=0}^{S_k-1} \Pr\{DBO_k = x_k\} \Pr\{Q_k = y - x_k\}, \; y \neq S_k \\ \sum_{x_k=0}^{S_k-1} \Pr\{DBO_k = x_k\} \Pr\{Q_k = y - x_k\} + \Pr\{DBO_k = S_k\}, \; y = S_k \end{cases} \tag{5}$$

We find the distribution of DBO_k by first computing the conditional depot backorder distribution $DBO_k(n)$ for all $n \in \{S_0 + 1, \dots, S_{Tot}\}$ using equations (2) through (4). We then find:

$$\Pr\{DBO_k = x_k\} = \sum_{i=S_0+1}^{S_{Tot}} DBO_k(i - S_0)\, \pi(i) \tag{6}$$

Finally, note that when $S_k = 0$, $E[W_k] = L_k$.

3 Numerical results

We test our model on instances where the transportation time L_k from the depot to each warehouse is zero and instances where this time is positive. When L_k is zero and $S_k > 0$ at all local warehouses, our model is similar to that of Andersson and Melchiors [2]. For these instances, we compare both models to simulation. For instances with positive L_k, we only compare our model to simulation. For each performance measure (i.e. the fraction of demand served though the regular channel α_k and the down time waiting for parts $DTWP_k$), we compute the relative deviation of the model values to those found through simulation.

3.1 Comparison to Andersson and Melchiors for negligible transportation times

We test 12 problem instances with negligible transportation times (see Table 1).

Parameter	**Values**	
Number of local warehouses	5	
L_0 (days)	5, 15	
T_k (days)	2	
$[m_1, m_2, m_3, m_4, m_5]$	$[0.01, 0.02, 0.04, 0.08, 0.1]$, $[0.02, 0.08, 0.08, 0.08, 0.0.8]$	$[0.1, 0.2, 0.4, 0.8, 1]$, $[0.2, 0.8, 0.8, 0.8, 0.8]$
Average value for α_k	≥ 0.8	≤ 0.5, ≥ 0.8

Table 1. Tested settings for problem instances with negligible transportation times

The last row in the table shows the service level for the instances: the average α_k over all local warehouses is either high (at least 0.8) or low (at most 0.5). We cannot reach any specific values of α_k, since our stock levels are discrete and often relatively small. Note that all instances with low demand rates have high service levels: since S_k must be larger than zero for us to compare our model to that of Andersson and Melchiors (AM model in short), we find high service levels for instances with low demand rates even if we keep minimal stock.

Table 2 gives the aggregate results. For the AM model, we aggregated the results over all instances where convergence occurred (9 out of 12 instances). Clearly, our method is very accurate: even the maximum deviation is well below 0.5%. In contrast, the AM method is much less accurate. Also, the AM method does not converge when a lot of stock is kept at the depot with little stock kept locally. We tested three such instances. In one case ($[m_1, \ldots, m_5] = [0.2, 0.8, 0.8, 0.8, 0.8]$, $L_0 = 15$ days, and $[S_0, \ldots, S_5] = [8,1,1,1,1,1]$), α_1 kept iterating between 0.30 and 0.90, with α_k ($k = 2, \ldots, 5$) iterating between 0.10 and 0.68. The AM model does not converge in such cases, because it assumes that the arrival rate at the depot does not depend on the system's state, whereas the arrival rate is in fact heavily dependent on the on-hand stock at the depot: the rate is high if the warehouse has stock on-hand, and very low otherwise.

	Deviations in α	
	Average	Maximum
Current method (12 instances)	0.03%	0.13%
Method Andersson and Melchiors (9 instances)	0.93%	4.77%

Table 2. The accuracy of our method and that of Andersson and Melchiors (5 local warehouses, $L_k = 0$)

3.2 Accuracy of our model for instances with positive transportation times

We test 8 instances with 5 warehouses and 8 with 20 warehouses (see Table 3). Note that for instances with 20 warehouses we combine specific values for L_0 with specific demand rates.

Parameter	Values
Num. warehouses	5
L_k ($k \geq 1$) (days)	0.5, 1.5
T_k (days)	2
Average α_k	≥ 0.8
L_0 (days)	5, 15
$[m_1, m_2, m_3, m_4, m_5]$	$[0.01, 0.02, 0.04, 0.08, 0.1]$, $[0.1, 0.2, 0.4, 0.8, 1]$

Parameter	Values	
Num. warehouses	20	
L_k ($k \geq 1$) (days)	0.5, 1.5	
T_k (days)	2	
Average α_k	≥ 0.8	
L_0 (days)	5	15
$[m_1 - m_4, m_5 - m_{20}]$	$[0.02, 0.08]$, $[0.2, 0.8]$	$[0.02, 0.05]$, $[0.2, 0.5]$

Table 3. Setting values for instances where $L_k > 0$ for local warehouses

Table 4 shows the accuracy and computation time (in milliseconds) of our method. We find very accurate values for $DTWP_k$: the average deviation is below 0.5%. Furthermore, the deviations are only relatively large for very small waiting times: in the setting with a deviation of 5.5%, the simulated waiting time was 0.0015, while the computed waiting time was 0.0016. The computation times are also very reasonable, with the computation time for cases with even 20 local warehouses being only a fraction of a second.

	deviation in α		**deviation in $DTWP$**		**computation time (ms)**	
Num. warehouses	Average	Maximum	Average	Maximum	Average	Maximum
5	0.01%	0.11%	0.46%	5.55%	3	16
20	0.02%	0.12%	0.19%	1.08%	56	125

Table 4. The accuracy and computation time of our method for cases where $L_k > 0$

4 Conclusions

In this paper, we developed a simple, fast and accurate approximation for a two-echelon inventory model with Poisson demand, one-for-one replenishment and lost sales. In contrast to methods published before, we do not need restrictive assumptions, and our approximations perform well for the full range of service levels. The simplicity of our model arises from the fact that we do not need an iterative procedure as in Andersson and Melchiors [2]. Therefore, our method is fast and very suitable to be applied as a building block in multi-item spare part inventory optimization.

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Appendix: Evaluating the multinomial probability distribution function

Define $p_n(x_1, .., x_K)$ as a cumulative multinomial probability distribution function with K classes, n trials and success probability q_k for class k with $\sum_{k=1}^{K} q_k = 1$. Levin [5] proves that for any real number s, it holds that

$$p_n(x_1, .., x_K) = \frac{n!}{s^n e^{-s}} \{\prod_{k=1}^{K} Pr\{X_k \leq x_k\}\} Pr\{W = n\} \quad \text{(A1)}$$

where the X_k are independent Poisson distributed random variables with means $s \cdot q_k$, and W is a sum of independent truncated Poisson random variables. That is, $W = \sum_{k=1}^{K} Y_k$, where Y_k has a truncated Poisson distribution with mean $s \cdot q_k$ and upper bound x_k. As Levin [5] states, s is a tuning parameter which may be chosen for convenience and stable computation. He suggests to set $s = n$, because then Stirling’s approximation can be used to compute the first term in the formula (A1): $\frac{n!}{s^n e^{-s}} \approx \sqrt{2\pi n}$. Finally, $\Pr\{W = n\}$ can either be evaluated using explicit convolutions (what we did in our numerical experiments) or using a Normal approximation.

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