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The capacitated multi-echelon inventory system with serial structure:
2. An average cost approximation method

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THE CAPACITATED MULTI-ECHelon INVENTORY SYSTEM WITH SERIAL STRUCTURE: 
2. AN AVERAGE COST APPROXIMATION METHOD

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This paper considers a multi-echelon, periodic review inventory model with discrete demand. We assume finite capacities on various production/order sizes and backordering of excess demand. We have already seen that modified base-stock policies work quite well under an average cost criterion. Here a method will be presented which provides an approximation of the average costs corresponding to a modified base-stock policy in a certain class of multi-echelon serial systems. In this the moment-iteration method developed by De Kok plays a central role.

1. Introduction. In this paper we consider a basic production (or inventory) model, in which the stock of a single item must be controlled under periodic review. We assume demands in each period to be independent, nonnegative, and integer-valued. Further, all stockouts are backordered and production, holding, and shortage costs are linear. There are no fixed order costs.

For the long-run-average cost criterion Federgruen and Zipkin[1986] have shown that in the capacitated 1-echelon inventory system with serial structure a modified base-stock policy is the optimal periodic review strategy: If the echelon stock has dropped below a certain level, enough should be produced to raise total stock to that level if attainable; otherwise, the maximum feasible amount should be produced. On the other hand, if the echelon stock is above that level, nothing should be produced.

Analyzing the capacitated $N$-echelon serial system with $N \geq 2$ we numerically proved in a preceding manuscript (Speck and Van der Wal[1991]) the possible appearance of a so-called 'push ahead'-effect within the optimal policy: Due to certain combinations of already known yet to arrive shipments, magnitude of demand, and finite capacities it might sometimes be
profitable to exploit the maximum capacity in order to possibly avoid future ordering limitations.

Neither of the aforementioned papers gives an exact calculation of the average cost for the optimal policy. But already a few approximation methods have been developed, that successfully cope with the difficulties arising from the finite capacities, such as an application of the moment-iteration method of De Kok[1989], and a related method of Zijm (unpublished manuscript). Both methods however are as yet only applicable to the capacitated 1-echelon serial system.

This paper focuses on the development of an average cost approximation method on behalf of the $N$-echelon serial system with $N \geq 2$. In section 2 we introduce notation, definitions, and assumptions. Section 3 contains a detailed description concerning the average cost calculation when employing a modified base-stock policy. The moment-iteration method of De Kok will be brought forward, which fills an essential part in our approximation method. For clarity reasons we will illustrate our approximation method on the basis of the capacitated 2-echelon serial system.

2. Definitions and assumptions. As already mentioned we will restrict ourselves to the capacitated 2-echelon serial system. Extension of the method given in section 3 to the $N$-echelon serial system with $N > 2$ is possible, but very laborious.

First of all we recapitulate the model definitions as given in Speck and Van der Wal[1991]:

1. We define the echelon stock of a given installation as the stock at that installation plus all the stock in transit to or on hand at any installation downstream minus the backlogs at the most downstream installation.

2. Next, the echelon inventory position of an installation denotes the echelon stock plus all items heading for that installation, that already left the preceding installation (or the external supplier).

The capacitated 2-echelon model we analyzed is characterized by the following parameters:

\[ U_i = \text{maximal production/order size}, \ i = 1, 2. \]

\[ l_1 = \text{leadtime of the route from installation 2 to installation 1}. \]

\[ l_2 = \text{leadtime of the route from external supplier to installation 2}. \]

\[ p = \text{shortage cost per unit per period at echelon 1}. \]
$h_i =$ additional holding cost per unit per period at echelon $i$, $i = 1, 2$.

$x_i =$ stock at echelon $i$ at the beginning of a period, $i = 1, 2$.

$y_i =$ inventory position at echelon $i$ at the beginning of a period, $i = 1, 2$.

$D_t =$ demand in period $t$, $t \in \mathbb{N}$.

$q_w =$ $P\{D = w\}$, $w = 0, 1, \ldots$, the demand probabilities.

$F(u) = \sum_{w=0}^{u} q_w$, $u \in \mathbb{N}$, the demand distribution.

We assume $U_i$ to be finite for $i = 1, 2$, while $x_i$ and $y_i$ are always integer-valued and may be negative since stockouts are backordered.

\[ L_1(x_1) := \sum_{w=0}^{\infty} q_w [(h_1 + h_2)(x_1 - w)^+ + p (x_1 - w)^-] - h_2 x_1 \quad (1) \]

\[ L_2(x_2) := h_2 x_2. \quad (2) \]
Finally, referring again to Speck and Van der Wal[1991] we assume without loss of generality

\[ 0 < U_2 \leq U_1. \]

3. Construction of an approximation method. De Kok[1989] has shown that an approximation of the average costs corresponding to a modified base-stock policy in the capacitated \( N \)-echelon serial system with \( N = 1 \) and \( I_1 \in IN \) can be obtained by reformulating the problem as a \( D|G|1 \) queue. This is done by comparing the shortfall on the desired echelon inventory level to the length of a waiting-queue.

Suppose we want to determine the average costs associated with the modified base-stock policy \( d_1 \), with \( d_1 \in IN \). Let \( W_t \in IN \) be the shortfall on the desired echelon inventory position level \( d_1 \) at the beginning of period \( t \). Then, starting from a shortfall of \( W_t \) on \( d_1 \) at the beginning of period \( t \) and meeting demand \( D_t \) leads to a shortfall of \( W_t + D_t \) at the end of period \( t \). If this amount exceeds the capacity \( U_1 \), then the shortfall at the beginning of period \( t + 1 \) shrinks to \( W_t + D_t - U_1 \); on the contrary, if \( W_t + D_t \leq U_1 \), then the shortfall is neutralized and the ideal level, \( d_1 \), again is achieved. Hence

\[ W_{t+1} = \max(0, W_t + D_t - U_1). \]

This is the well-known relation for the waiting-time of the \((t + 1)\)st customer in the standard \( D|G|1 \) queue, for which De Kok has developed a moment-iteration method. The algorithm will be shown later on; it enables us to derive approximations for the waiting-time distribution for instance.

So if we take the collection of echelon inventory positions associated with the modified base-stock policy \( d_1 \),

\[ \mathcal{Z}[d_1] = \{d_1, d_1 - 1, d_1 - 2, \ldots \}, \]

or, equivalently, the set of shortfall positions,

\[ \mathcal{W} = \{0, 1, 2, \ldots \}, \]

as state space we are able to form the enclosed transition matrix, say \( Q_1 \) by
means of (4):

\[
Q_1 := \begin{pmatrix}
F(U_1) & q_{u_1+1} & q_{u_1+2} & \cdots & \cdots \\
F(U_1 - 1) & q_{u_1} & q_{u_1+1} & \cdots & \cdots \\
F(U_1 - 2) & q_{u_1-1} & q_{u_1} & \cdots & \cdots \\
\vdots & \vdots & \vdots & \ddots & \\
\vdots & \vdots & \vdots & \ddots & \\
\end{pmatrix}
\]  

(7)

Notice its fine diagonal structure, apart from the first column. Then, the exact average costs going with the modified base-stock policy \( d_1 \) is given by

\[
g = Q_1^\infty r[d_1],
\]

in which \( Q_1^\infty \) denotes the equilibrium matrix, and \( r[d_1] \) the cost vector consisting of the expected costs per state from \( Z[d_1] \). The equilibrium matrix \( Q_1^\infty \), here consisting of identical rows of equilibrium probabilities \( \pi_0^*, \pi_1^*, \pi_2^*, \ldots \), can be constructed by solving the system

\[
\begin{cases}
\pi Q_1 = \pi \\
\sum_{i=0}^{\infty} \pi_i = 1,
\end{cases}
\]

(9)
in which \( \pi \) denotes a vector of probabilities. The fact of having a non-finite transition matrix \( Q_1 \) however, causes the system (8) to be infinite and therefore does not permit an exact calculation of the equilibrium probabilities \( \pi_i^* \). But we can derive approximations \( \tilde{\pi}_i^* \) by using De Kok’s moment-iteration method: Every \( \pi_i^* \), denoting the equilibrium probability on a gap of \( i \) items on level \( d_1 \), in fact specifies the probability on a customer’s waiting-time of \( i \) units in a \( D|G|1 \) equilibrium system!

**Algorithm 1 (Moment-iteration)**

**Initialisation:** Choose \( \mathbb{E}\{W_0\} = 0 \) and \( \mathbb{E}\{W_0^2\} = 0 \).

**Iteration:** Compute

\[
\begin{align*}
\mathbb{E}\{W_n + D_n\} &= \mathbb{E}\{W_n\} + \mathbb{E}\{D_n\}; \\
\mathbb{E}\{(W_n + D_n)^2\} &= \mathbb{E}\{W_n^2\} + 2\mathbb{E}\{W_n\}\mathbb{E}\{D_n\} + \mathbb{E}\{D_n^2\}.
\end{align*}
\]
Fit a distribution function $\hat{F}_{W_n+D_n}$ to the first two moments of $W_n + D_n$. Then calculate

$$\mathbb{E}\{W_{n+1}\} = \int_{U_1}^{\infty} (y - U_1) \, d\hat{F}_{W_n+D_n}(y),$$
$$\mathbb{E}\{W_{n+1}^2\} = \int_{U_1}^{\infty} (y - U_1)^2 \, d\hat{F}_{W_n+D_n}(y).$$

Termination: Stop whenever

$$|\mathbb{E}\{W_{n+1}\} - \mathbb{E}\{W_n\}| < \varepsilon_1 \quad \text{and} \quad |\mathbb{E}\{W_{n+1}^2\} - \mathbb{E}\{W_n^2\}| < \varepsilon_2,$$
for some prespecified $\varepsilon_1 > 0$ and $\varepsilon_2 > 0$. Then

$$F_W(y) \approx \hat{F}_{W_n+D}(U_1 + y), \quad y > 0. \quad (12)$$

This method has been grafted upon fitting distributions to the first two moments of an arbitrary distribution. E.g. Tijms[1986] provides us a method in which mixtures of Erlang distributions yield excellent results.

Thus, applying of the moment-iteration method of De Kok provides an accurate approximation for the waiting-time distribution of the equilibrium system, or translated to the inventory system, an approximation for the equilibrium distribution of the shortfall. Then, discretizing the generated waiting-time, or shortfall-amount, distribution we obtain the estimated equilibrium probabilities $\tilde{\pi}_i$. Truncating (8) finally results in an adequate approximation of the average cost associated with a modified base-stock policy $d_1$.

So far the recapitulation of an application of De Kok’s moment-iteration method to the capacitated 1-echelon serial system.

We have been able to extend the idea of De Kok to the $N$-echelon inventory serial system with $N \geq 2$, but in which $l_i = 1$ for all $1 \leq i \leq N$. Suppose we want to determine the average cost corresponding to the modified base-stock policy characterized by echelon inventory position levels $(d_2, d_1)$. We explicitly assume the system to start from the ideal echelon inventory stock levels $d_i, i = 1, 2$. This leads to the definition of the state space $Z[(d_2, d_1)]$ belonging to the modified base-stock policy $(d_2, d_1)$ as the collection of possible echelon inventory positions $(z_2, z_1)$ at the beginning of a period before meeting demand:

$$Z[(d_2, d_1)] := \{ (z_2, z_1) \in \mathbb{Z}^2 \mid z_1 \leq d_1, \quad z_1 \leq z_2 \leq d_2 \}. \quad (13)$$
Thus, at the beginning of the first period the system finds itself in the situation as depicted underneath.

![Diagram]

Consequently, when demand equals $D$ in the first period the stock at echelon 1 and 2 amounts to $d_1 - D$ respectively $d_2 - D$ (remember $l_2 = l_1 = 1$), and thus there is a physical stock of $d_2 - d_1$ on hand at installation 2!

![Diagram]

Then, by looking at the amount $d_2 - d_1$ available at installation 2 there are three separate cases distinguishable:

1. $0 \leq d_2 - d_1 \leq U_2$
2. $U_2 < d_2 - d_1 \leq U_1$
3. $U_1 < d_2 - d_1$.

First of all we can skip the case $U_1 < d_2 - d_1$. Namely, every modified base-stock policy $(d_2, d_1)$ aims at a stock of $d_2 - d_1$ on hand at installation 2.
at the end of an arbitrary period. In the case $U_1 < d_2 - d_1$ this means going for a strictly positive stock at installation 2 during the next period, for at most $U_1$ can be shipped. For this stock amount holding costs are charged, while no advantage is yielded by this stock, see the analogous argument that established the preliminary result in Speck and Van der Wal[1991].

In the other two cases the state space $\mathbb{Z}[ (d_2, d_1) ]$ reduces to an irreducible state space in each case. Suppose we practise a modified base-stock policy $(d_2, d_1)$ in which $0 \leq d_2 - d_1 \leq U_2$. Then we are able to construct a partial flow scheme containing the possible transitions from the ideal state $(d_2, d_1)$:

By considering the possible transitions from the other states depicted above we finally attain an irreducible state set $\mathbb{Z}_1[ (d_2, d_1) ]$,

$$\mathbb{Z}_1[ (d_2, d_1) ] := \{ (d_2, d_1) , (d_2, d_1 - 1), \ldots , (d_2, d_2 - U_2), (d_2 - 1, d_2 - U_2 - 1), (d_2 - 2, d_2 - U_2 - 2) , \ldots \}.$$
The corresponding transition matrix has the following structure:

\[
\begin{pmatrix}
F(d_2 - d_1) & q_{d_2} & q_{d_2+1} & q_{d_2+2} \\
F(d_2 - d_1) & q_{d_2} & q_{d_2+1} & q_{d_2+2} \\
F(d_2 - d_1) & q_{d_2} & q_{d_2+1} & q_{d_2+2} \\
\vdots & \vdots & \vdots & \vdots \\
F(d_2 - d_1) & q_{d_2} & q_{d_2+1} & q_{d_2+2} \\
F(d_2 - d_1 - 1) & q_{d_2} & q_{d_2} & q_{d_2+1} \\
F(d_2 - d_1 - 2) & q_{d_2} & q_{d_2+1} & q_{d_2+2} \\
\vdots & \vdots & \vdots & \vdots \\
F(a) & q_{a+1} & q_{a+2} & q_{a+2} \\
F(a - 1) & q_{a} & q_{a+1} & q_{a+2} \\
F(a - 2) & q_{a} & q_{a} & q_{a+2} \\
\vdots & \vdots & \vdots & \vdots 
\end{pmatrix}
\]

For the remaining case \((U_2 < d_2 - d_1 \leq U_1)\) a similar flow scheme can be drawn, which shows the reduction of \(Z[(d_2, d_1)]\) to an irreducible state space \(Z_2[(d_2, d_1)]\),

\[
Z_2[(d_2, d_1)] := \{ (d_2, d_1), (d_2 - 1, d_1), \ldots, (d_1 + U_2, d_1), \\
(d_1 + U_2 - 1, d_1 - 1), (d_1 + U_2 - 2, d_1 - 2), \ldots \}
\]

In this case we obtain a nicely structured transition matrix, reminiscent of the one in the 1-echelon system.

\[
\begin{pmatrix}
F(U_2) & q_{U_2+1} & q_{U_2} & q_{U_2+1} & q_{U_2+2} \\
F(U_2 - 1) & q_{U_2} & q_{U_2} & q_{U_2} & q_{U_2+1} \\
F(U_2 - 2) & q_{U_2-1} & q_{U_2-2} & q_{U_2-2} & q_{U_2} \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
F(a) & q_{a+1} & q_{a+2} & q_{a+2} & q_{a+2} \\
F(a - 1) & q_{a} & q_{a+1} & q_{a+2} & q_{a+2} \\
F(a - 2) & q_{a} & q_{a} & q_{a} & q_{a+2} \\
\vdots & \vdots & \vdots & \vdots & \vdots 
\end{pmatrix}
\]

in which \(a := 2U_2 - d_2 + d_1\).

By joining the states \((x_2, x_1) \in Z_1[(d_2, d_1)] \) in which \(x_2 = d_2\) to one state
(d_2, 
), and carrying out a corresponding clustering within the transition matrix associated with \( Z_1[(d_2, d_1)] \), we achieve both transition matrices being the same:

\[
Q_2 := \begin{pmatrix}
F(U_2) & q_{v2+1} & q_{v2+2} & \cdots & \cdots \\
F(U_2 - 1) & q_{v2} & q_{v2+1} & \cdots & \cdots \\
F(U_2 - 2) & q_{v2-1} & q_{v2} & \cdots & \cdots \\
\vdots & \vdots & \vdots & \ddots \\
\vdots & \vdots & \vdots & \ddots 
\end{pmatrix}
\]  

(14)

Inherently, \( Z_1[(d_2, d_1)] \) changes to

\[
Z_1[(d_2, d_1)] = \{ (d_2, *), (d_2 - 1, d_2 - U_2 - 1), (d_2 - 2, d_2 - U_2 - 2), \ldots \}
\]

The exact average costs associated with the modified base-stock policy \((d_2, d_1)\) is given by

\[
g = Q_2^\infty r_1[(d_2, d_1)]
\]  

or

\[
g = Q_2^\infty r_2[(d_2, d_1)],
\]  

depending on the value of \( d_2 - d_1 \). In both cases \( Q_2^\infty \) is the equilibrium matrix of the system, and \( r_i[(d_2, d_1)] \) for \( i = 1, 2 \) the cost vector consisting of the expected 1-period costs per state out of the state space \( Z_i[(d_2, d_1)] \) associated with a modified base-stock policy \((d_2, d_1)\). The costs are defined as

\[
r(z_2, z_1) := \int_0^\infty \{ L_2(z_2 - w) + L_1(z_1 - w) \} dF(w).
\]  

(17)

Evidently, when at the beginning of a period \( t \) the inventory position of echelon \( i, i = 1, 2, \) is raised to level \( z_i \), then the stock of echelon \( i \) equals \( z_i - D_t \) at the beginning of period \( t+1 \). Then the costs at the end of period \( t + 1 \) associated with echelon \( i \) amount to \( L_i(z_i - D_t) \).

The equilibrium probabilities \( \pi_0^*, \pi_1^*, \pi_2^*, \ldots \) again can be derived by solving the system

\[
\begin{cases}
\pi Q_2 = \pi \\
\sum_{i=0}^\infty \pi_i = 1
\end{cases}
\]  

(18)

10
Notice that in case of $0 \leq d_2 - d_1 \leq U_2$ the equilibrium probabilities of the states $(d_2, d_1), (d_2, d_1 - 1), \ldots , (d_2, d_2 - U_2)$ are obtained by multiplying the equilibrium probability $\pi_0^*$ by the relative probabilities within the junction state $(d_2, \ast)$.

Though in general it is not possible to determine the equilibrium probabilities $\pi_J^*$ exactly we can provide estimations $\tilde{\pi}_J^*$. Namely, as $Q_2$ has the very same structure as the matrix $Q_1$ in the capacitated 1-echelon serial system, we again invoke the moment-iteration method of De Kok in order to achieve an approximation for the waiting-time (or 'shortfall') distribution $F_W$ of the equilibrium system. Discretisation of this generated distribution $F_W$ then yields us an approximation for the probabilities $\pi_J^*$:

$$\tilde{\pi}_0^* := F_W(\frac{1}{2}),$$
$$\tilde{\pi}_i^* := F_W(i + \frac{1}{2}) - F_W(i - \frac{1}{2}), \quad i \geq 1.$$

Truncating (15) or (16) yields an estimation of the average costs associated with the modified base-stock policy $(d_2, d_1)$, provided that the demand distribution $F$ is explicitly given in order to calculate exactly the expected 1-period costs $r(z_2, z_1)$ per state $(z_2, z_1)$ in (17). If only the first two moments of the demand $D$ are given, we can only approximate the expected 1-period costs: As in the first iteration of algorithm 1 a distribution is fitted to the moments of $D$, we have $\tilde{F}_{W_0 + D_0}$, or $\tilde{F}_D$, at our disposal. By means of this fitted distribution $\tilde{F}_D$ we can easily determine the (approximated) expected 1-period costs.

We have executed the average cost approximation on a class of 2-echelon serial systems, in which, besides $l_2 = l_1 = 1$,

$$\mathbb{E}\{D\} = 100$$
$$\sigma\{D\} = 70$$
$$h_1 = 2$$
$$h_2 = 2$$
$$\mu = 200$$
$$\varepsilon_1 = 10^{-3}$$
$$\varepsilon_2 = 10^{-3}.$$

Notice that due to the values of $\mathbb{E}\{D\}$ and $\sigma\{D\}$ the demand distribution is approximated by an Erlang mixture with the same scale parameter,
according to Tijms[1986].

First we generated the average cost of an optimal (i.e. base-stock) policy for the uncapacitated system by means of the program LIJNSYSTEEM3 given in Van Houtum and Zijm[1990]. LIJNSYSTEEM3 provides an estimation of the optimal (base-stock) policy by a recursive calculation of incomplete convolutions in which the fit-method described in Tijms[1986] is used, plus an exact calculation of the average costs associated with the generated base-stock policy. At the chosen parameter values this happens to be the base-stock policy \((d_2^\infty, d_1^\infty) = (614.1, 498.9)\). Assuming the demand distribution to be exactly an Erlang mixture with the same scale parameter we see that the average cost \(g^\infty\) associated with \((614.1, 498.9)\) amounts to 1669.03.

Next, for increasing \(U_2\) we have determined the average costs associated with the modified base-stock policy \((d_2^\infty, d_1^\infty) = (614, 498)\), see table 1. Thereoff successively can be read the capacity \(U_2\), the average shortfall

<table>
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<tr>
<th>(U_2)</th>
<th>(\mathbb{E}{W})</th>
<th>(n)</th>
<th>(\tilde{g})</th>
<th>ctime</th>
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<td>0.02</td>
<td>3</td>
<td>1669.3</td>
<td>3.4 s</td>
</tr>
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Table 1: Increasing \(U_2\)

\(\mathbb{E}\{W\}\) on the desired echelon inventory levels in the equilibrium system, the
number of moment-iterations $n$ carried out, the generated average cost approximation $\bar{c}$ attached to $([d_2^\infty], [d_1^\infty])$, and an indication of the consumed calculation time in seconds $ctime$ on an Olivetti M240 PC with numerical coprocessor.

Probabilities smaller than $10^{-8}$ were set equal to 0.

We find that both average shortfall and average costs decrease if $U_2$ increases, which is according to our expectations. Further we see that the average cost $\bar{c}$ converges towards 1669 ($U_2 = 500$ almost corresponds with the infinite capacity case). But we have to keep in mind, that 1669.03 is the exact average cost belonging to the modified base-stock policy (614.1,498.9), not (614,498)!

Further research however pointed out that the exact average cost associated with the base-stock policy (614,498) in the uncapacitated model amounts to 1669.04, thus indicating the average cost function to be very flat near the minimum.

4. Finding a nearly optimal modified base-stock policy. The cost calculation method presented above enables us, referring to our conclusions in Speck and Van der Wal (1991), to derive a nearly optimal modified base-stock policy serving in its turn as an approximation for the optimal periodic review policy.

If for the capacitated 2-echelon serial system an initial average cost value is given associated with an optimal base-stock policy $(d_2^\infty, d_1^\infty)$ from the uncapacitated model, then the search for a nearly optimal modified base-stock policy can be restricted to the grid points of the upper right quadrant in the 2-dimensional space with $(d_2^\infty, d_1^\infty)$ as origin. The extensive scale of numerical procedures then enables us to achieve a further efficient reduction of the searching process.

References


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