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# Computing non-stationary $(s, S)$ policies using mixed integer linear programming 

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#### Abstract

This paper addresses the single-item single-stocking location non-stationary stochastic lot sizing problem under the $(s, S)$ control policy. We first present a mixed integer non-linear programming (MINLP) formulation for determining near-optimal $(s, S)$ policy parameters. To tackle larger instances, we then combine the previously introduced MINLP model and a binary search approach. These models can be reformulated as mixed integer linear programming (MILP) models which can be easily implemented and solved by using off-the-shelf optimisation software. Computational experiments demonstrate that optimality gaps of these models are less than $0.3 \%$ of the optimal policy cost and computational times are reasonable.


Keywords: inventory, $(s, S)$ policy, stochastic lot-sizing, mixed integer programming, binary search

## 1. Introduction

Stochastic lot sizing is an important research area in inventory theory. One of the landmark studies is Scarf (1960), which proved the optimality of $(s, S)$ policies for a class of dynamic inventory models. The $(s, S)$ policy features two

[^0]control parameters: $s$ and $S$. Under this policy, the decision maker checks the opening inventory level at the beginning of each time period: if it drops to or below the reorder point $s$, then a replenishment should be placed to reach the order-up-to-level $S$. Unfortunately, computing optimal $(s, S)$ policy parameters remains a computationally intensive task.

Since Scarf's landmark study, the $(s, S)$ policy has been object of extensive research. For instance, Johnson \& Thompson (1975); Sethi \& Cheng (1997); Chen \& Song (2001); Hu et al. (2016) investigated demand correlation; more recently, (Qiu et al., 2017; Lim \& Wang, 2017) investigated demand distributional ambiguity.

In the literature, studies on $(s, S)$ policy can be categorized into stationary and non-stationary. A number of studies investigated the computation of stationary $(s, S)$ policy parameters, e.g. (Iglehart, 1963, Veinott et al., 1965 Archibald \& Silver, 1978, Stidham, 1977; Sahin, 1982, Federgruen \& Zipkin, 1984; Zheng \& Federgruen, 1991; Feng \& Xia, 2000). However, there has been an increasing recognition that lot-sizing studies need to be undertaken for nonstationary environments (Graves, 1999).

In this work, we focus on the single-item single-stocking location stochastic lot-sizing problem under non-stationary demand, fixed and unit ordering cost, holding cost and penalty cost. Only two studies investigated computations of $(s, S)$ policy under non-stationary stochastic demand Askin, 1981, Bollapragada \& Morton, 1999).

Askin (1981) adopted the "least cost per unit time" approach in selecting order-up-to-levels and reorder points under a penalty cost scheme. Decision makers first determine desired cycle lengths and order-up-to-levels. Then, reorder points are decided by means of a trade-off analysis between expected costs per period in cases of ordering and not ordering.

As Bollapragada \& Morton (1999) pointed out, the approach discussed by Askin (1981) is computationally expensive because of the need of convolving demand distributions. In contrast, Bollapragada \& Morton (1999) proposed a stationary approximation heuristic for computing optimal $(s, S)$ policy pa-
rameters. Firstly, decision makers precompute pairs of $(s, S)$ values for various demand parameters and tabulate results. Here, a large number of efficient algorithms exist for generating the stationary table, e.g. (Federgruen \& Zipkin, 1984, Zheng \& Federgruen, 1991, Feng \& Xiao, 2000). Secondly, order-up-tolevels and reorder points can be read from stationary tables by averaging the demand parameters over an estimate of the expected time between two orders. However, this algorithm relies upon complex code, particularly for generating stationary tables.
(Askin, 1981, Bollapragada \& Morton, 1999) do not provide a satisfactory solution to the problem of computing near-optimal $(s, S)$ policy parameters: they rely on ad-hoc computer coding and provide relatively large optimality gaps. A recent computational study (Dural-Selcuk et al., 2016) estimated the optimality gap of (Askin, 1981, Bollapragada \& Morton, 1999) at 3.9\% and $4.9 \%$, respectively; these figures are in line with those reported in the original works. These drawbacks motivate the investigation of simple and yet effective heuristic methods for computing $(s, S)$ policy parameters; methods that do not need dedicated computer coding and that can provide better optimality gaps.

The aim of this paper is to introduce two new heuristics to compute nearoptimal $(s, S)$ policy parameters. We build upon Rossi et al. (2015), which discussed mixed-integer linear programming (MILP) heuristics for approximating optimal $(R, S)$ policy parameters - under this policy, the replenishment intervals $R$ and order-up-to-levels $S$ are determined at the beginning of the planning horizon, while associated order quantities are decided only when orders are issued. The $(R, S)$ policy is effective in dealing with system nervousness (Tunc et al., 2013), while the $(s, S)$ policy is cost-optimal (Scarf, 1960). Our two mixed-integer nonlinear programming (MINLP)-based heuristics leverage two key building blocks: modeling techniques originally discussed in Rossi et al. (2015), and $K$-convexity of the problem cost function, originally discussed in Scarf (1960). In contrast to other approaches in the literature, our heuristics can be easily implemented and solved by using off-the-shelf mathematical programming packages such as IBM ILOG optimisation studio.

Our contributions to literature on stochastic lot-sizing are the following.

- We introduce the first mixed integer non-linear programming (MINLP) model to compute near-optimal $(s, S)$ policy parameters.
- We show that this model can be approximated as a mixed integer linear programming (MILP) model by piecewise linearising the cost function; this approximation can be solved by using off-the-shelf software.
- To tackle larger instances, we combine the previously introduced MINLP model and a binary search procedure; this latter approach requires dedicated code, but scales better than the previous one.
- Computational experiments demonstrate that optimality gaps of our models are tighter than existing algorithms (Askin, 1981; Bollapragada \& Morton 1999) in the literature, and computational times of our models are reasonable.

The rest of this paper is organised as follows. Section 2 describes the problem setting and a stochastic dynamic programming (SDP) formulation. Section 3 discusses the notion of $K$-convexity and introduces relevant $K$-convex cost functions which are approximated by an MINLP model in Section 4 Section 5 presents an MINLP heuristic for approximating $(s, S)$ policy parameters. Section 6 introduces an alternative binary search approach for computing $(s, S)$ policy parameters. A detailed computational study is given in Section 7 Finally, we draw conclusions in Section 8 .

## 2. Problem description

We consider a single-item single-stocking location inventory management system over a $T$-period planning horizon. We assume that orders are placed at the beginning of each time period, and delivered instantaneously. Ordering costs $c(\cdot)$ comprise a fixed ordering cost $K$ for placing an order, and a linear ordering cost $c$ proportional to order quantity $Q$. Demands $d_{t}$ in each period $t=1, \ldots, T$
are independent random variables with known probability distributions. At the end of period $t$, a linear holding cost $h$ is charged on every unit carried from one period to the next; and a linear penalty cost $b$ is occurred for each unmet demand at the end of each time period.

For a given period $t=\{1, \ldots, T\}$, let $I_{t-1}$ denote the opening inventory level and $Q_{t}$ represent the order quantity.

The immediate expected holding and penalty costs at period $t$ can be expressed as

$$
\begin{equation*}
f_{t}(y)=\mathrm{E}\left[h \max \left(y-d_{t}, 0\right)+b \max \left(d_{t}-y, 0\right)\right] \tag{1}
\end{equation*}
$$

where E denotes the expectation taken with respect to the random demand $d_{t}$.
The ordering cost $c\left(Q_{t}\right)$ is defined as:

$$
c\left(Q_{t}\right)= \begin{cases}K+c Q_{t}, & Q_{t}>0 \\ 0, & Q_{t}=0\end{cases}
$$

Let $C_{t}\left(I_{t-1}\right)$ represent the expected total cost of an optimal policy over periods $t, \ldots, T$ when the initial inventory level at the beginning of period $t$ is $I_{t-1}$. We model the problem as a stochastic dynamic program (Bellman, 1957) via the following functional equation

$$
\begin{equation*}
C_{t}\left(I_{t-1}\right)=\min _{Q_{t}}\left\{c\left(Q_{t}\right)+f_{t}\left(I_{t-1}+Q_{t}\right)+\mathrm{E}\left[C_{t+1}\left(I_{t-1}+Q_{t}-d_{t}\right)\right]\right\} \tag{2}
\end{equation*}
$$

where

$$
C_{T}\left(I_{T-1}\right)=\min _{Q_{t}}\left\{c\left(Q_{T}\right)+f_{T}\left(I_{T-1}+Q_{T}\right)\right\}
$$

represents the boundary condition.

## 3. The optimality of $(s, S)$ policies in stochastic lot sizing

Scarf (1960) proved that the optimal policy in the dynamic inventory problem is always of the $(s, S)$ type based on a study of the function $G_{t}(y)+c y$, where

$$
\begin{equation*}
G_{t}(y)=f_{t}(y)+\mathrm{E}\left[C_{t+1}\left(y-d_{t}\right)\right] \tag{3}
\end{equation*}
$$

and $y$ is the stock level immediately after purchases are delivered (see Scarf, 1960, Eq. (4)).

Since we consider a non-stationary environment, values of the $(s, S)$ policy parameters will depend on the given period $t$. Let $\left(s_{t}, S_{t}\right)$ denote the policy parameters for period $t$. Function $G_{t}(y)+c y$ can be used to identify optimal policy parameters $\left(s_{t}, S_{t}\right)$. In particular, the order-up-to-level $S_{t}$ is defined as the value minimising $G_{t}(y)+c y$; whereas the parameter $s_{t}$ is given by the value $s_{t}<S_{t}$ such that $G_{t}\left(s_{t}\right)+c s_{t}=G_{t}\left(S_{t}\right)+c S_{t}+K$ (see Scarf, 1960, Eq. (5)). $K$ convexity of the function $G_{t}(y)+c y$ ensures the uniqueness of $s_{t}$ and $S_{t}$ (Scarf, 1960).

Example. We illustrate the concepts introduced on a 4-period example. Demand $d_{t}$ is normally distributed in each period $t$ with mean $\mu_{t}=$ $\{20,40,60,40\}$, for $t=1, \ldots, 4$ respectively. Standard deviation $\sigma_{t}$ of demand in period $t$ is equal to $0.25 \mu_{t}$. Other parameters are $K=100, h=1, b=10$, and $c=0$. We plot $G_{1}(y)$ in Fig. 1 for initial inventory levels $y \in(0,200)$. The order-up-to-level is $S_{1}=70, G_{1}\left(S_{1}\right)=263$, the reorder point is $s_{1}=14$, and $G_{1}\left(s_{1}\right)=363$. Note that $G_{1}\left(s_{1}\right)+c s_{1}=G_{1}\left(S_{1}\right)+c S_{1}+K$. The optimal policy is to order up to 70 if the initial inventory drops below 14 .


Figure 1: Plot of $G_{1}(y)$

## 4. MINLP approximation of $G_{t}(y)$ function

In this section, we exploit an MINLP model to approximate the function $G_{t}(y)$ in Eq. (3). Our model follows the control policy known as "static-dynamic uncertainty" strategy, known as $(R, S)$ policy, originally introduced in Bookbinder $\& \operatorname{Tan}(1988)$. Under this strategy, the timing of orders and order-up-to-levels are expected to be determined at the beginning of the planning horizon, while associated order quantities are decided upon only when orders are issued. As illustrated in Rossi et al. (2015), this strategy provides a cost performance which is close to the optimal "dynamic uncertainty" strategy. However, optimal $(s, S)$ parameters cannot be immediately derived from existing mathematical programming models operating under a static-dynamic uncertainty strategy, such as (Tarim \& Kingsman, 2006; Rossi et al. 2015). We next illustrate how a model operating under a static-dynamic uncertainty strategy can be used to approximate the function $G_{t}(y)$ in Eq. (3). In the rest of this section, without loss of generality, we focus on the case $G_{1}(y)$.

Consider a random variable $\omega$ and a scalar variable $x$. The first order loss function is defined as $L(x, \omega)=\mathrm{E}[\max (\omega-x, 0)]$, where E denotes the expected value with respect to the random variable $\omega$. The complementary first order loss function is defined as $\hat{L}(x, \omega)=\mathrm{E}[\max (x-\omega, 0)]$. Like Rossi et al. (2015), we will model non-linear holding and penalty costs by means of this function.

Let $t=1, \ldots, T$ and consider three sets of decision variables: $\tilde{I}_{t}$, the expected closing inventory level at the end of period $t$, with $I_{0}$ denoting the initial inventory level; $\delta_{t}$, a binary variable which is set to one if an order is placed in period $t ; P_{j t}$, a binary variable which is set to one if the most recent replenishment up to period $t$ was issued in period $j$, where $j \leq t$ - if no replenishment occurs before or at period $t$, then we let $P_{1 t}=1$, this allows us to properly account for demand variance from the beginning of the planning horizon in Constraints (9) and 10). Let $\tilde{d}_{j t}$ denote the expected value of the demand over periods $j, \ldots, t$, i.e. $\tilde{d}_{j t}=\tilde{d}_{j}+\cdots+\tilde{d}_{t}$. Decision variables $H_{t} \geq 0$ and $B_{t} \geq 0$ represent end of period $t$ expected excess inventory and back-orders, respectively.

An MINLP formulation for the non-stationary stochastic lot-sizing problem under the "static-dynamic" uncertainty strategy, obtained following the modelling strategy in Rossi et al. (2015), is shown in Figure 2 ,

$$
\begin{equation*}
\min \left(\sum_{t=1}^{T}\left(K \delta_{t}+h H_{t}+b B_{t}\right)+c \tilde{I}_{T}+c \sum_{t=1}^{T} \tilde{d}_{t}-c I_{0}\right) \tag{4}
\end{equation*}
$$

Subject to, $t=1,2, \ldots, T$

$$
\begin{array}{ll}
\delta_{t}=0 \rightarrow \tilde{I}_{t}+\tilde{d}_{t}-\tilde{I}_{t-1}=0 & \\
\tilde{I}_{t}+\tilde{d}_{t}-\tilde{I}_{t-1} \geq 0 \\
\sum_{j=1}^{t} P_{j t}=1 & \\
P_{j t} \geq \delta_{j}-\sum_{k=j+1}^{t} \delta_{k}, & j=1,2, \ldots, t \\
P_{j t}=1 \rightarrow H_{t}=\hat{L}\left(\tilde{I}_{t}+\tilde{d}_{j t}, d_{j t}\right), & j=1,2, \ldots, t \\
P_{j t}=1 \rightarrow B_{t}=L\left(\tilde{I}_{t}+\tilde{d}_{j t}, d_{j t}\right), & j=1,2, \ldots, t \\
P_{j t} \in\{0,1\}, & j=1,2, \ldots, t \\
\delta_{t} \in\{0,1\} & \tag{12}
\end{array}
$$

Figure 2: The formulation of the non-stationary stochastic lot-sizing problem

The objective function (4) minimizes the expected total cost over the planning horizon. In the objective function, expected variable ordering costs are reformulated via $c \sum_{t=1}^{T} Q_{t}=c \tilde{I}_{T}+c \sum_{t=1}^{T} \tilde{d}_{t}-c I_{0}$ by using the reformulation strategy originally introduced in Tarim \& Kingsman (2004) at p. 112 - note that term $c \sum_{t=1}^{T} \tilde{d}_{t}-c I_{0}$ is a constant. Constraints $\sqrt[5]{5}$ is an indicator constraint (Belotti et al. 2016) capturing the reorder condition. Constraints (6) are the inventory balance equations. Constraints (7) indicate the most recent replenishment before period $t$ was issued in period $j$. Constraints (8) identify uniquely the period in which the most recent replenishment prior to $t$ took
place. Constraints (9) and (10) are indicator constraints modelling end of period $t$ expected excess inventory and back-orders by means of the first order loss function.

We now discuss how to adapt the model in Fig. 2 in order to compute, for a given $y$, an approximate value of $G_{1}(y)$; see Eq. (3). We call this modified model MINLP- $s$, and use superscript $s$ to label decision variables in this model.

In addition to constraints in Fig. 2, MINLP- $s$ features constraint

$$
\begin{equation*}
\delta_{1}^{s}=0 \tag{13}
\end{equation*}
$$

which forces the model not to issue an order in period 1 . When $\delta_{1}^{s}=0$, the objective function (4) becomes
which denotes the expected total cost of controlling the system optimally over the planning horizon $1, \ldots, T$ when the initial inventory level is $I_{0}^{s}$ and no order is issued in period 1 ; hence $c\left(\tilde{I}_{1}^{s}+\tilde{d}_{1}-I_{0}^{s}\right)=0$.

MINLP- $s$ can be reformulated into an MILP model by using the approach discussed in Rossi et al. (2015) to piecewise linearise loss functions in constraints (9) and 10 . For further details please refer to Appendix A.

Example. In Fig. 3, we plot $G_{1}^{s}(y)$ obtained via the MILP-s for the same 4-period numerical example in Fig. 1 with initial inventory level $I_{0}^{s} \in(0,200)$.

Since $G_{1}^{s}(y)$ approximates $G_{1}(y)$, we can now use $G_{1}^{s}(y)+c y$ to find approximate values $\hat{S}_{1}$ and $\hat{s}_{1}$ for $S_{1}$ and $s_{1}$.

## 5. An MINLP-based model to approximate $(s, S)$ policy parameters

In this section we exploit the results presented in the previous section to introduce an MINLP-based heuristic for approximating optimal $(s, S)$ policies. To


Figure 3: Plot of $G_{1}^{s}(y)$
the best of our knowledge, this is the first MINLP model in the literature for computing near-optimal $(s, S)$ policy parameters.

In a similar fashion to "MINLP-s", we introduce "MINLP-S" to be the approximation of $C_{t}\left(I_{t-1}\right)$ in Eq. (22). Similarly to Eq. (14), let the objective function $C_{1}^{S}\left(I_{0}\right)$ of MINLP- $S$ denote the expected total cost of controlling the system optimally over the planning horizon $1, \ldots, T$ given the initial inventory level $I_{0}$. We use the superscript $S$ to represent decision variables in MINLP- $S$,

$$
\begin{equation*}
C_{1}^{S}\left(I_{0}\right)=\sum_{t=1}^{T}\left(K \delta_{t}^{S}+h H_{t}^{S}+b B_{t}^{S}\right)+c \tilde{I}_{T}^{S}+c \sum_{t=1}^{T} \tilde{d}_{t}-c I_{0} \tag{15}
\end{equation*}
$$

MINLP-S imposes the constraint

$$
\begin{equation*}
\delta_{1}^{S}=1 \tag{16}
\end{equation*}
$$

which forces the model to place a replenishment in period 1.
In the MINLP-S model, $\hat{S}_{1}$ denotes an approximation of the optimal order-up-to-level $S_{1}$. Since $G_{1}^{s}\left(I_{0}^{s}\right)$ is an approximation of $G_{1}\left(I_{0}^{s}\right)$, by leveraging Scarf's result (see Scarf, 1960, Eq. (4)) on the study of $G(y)+c y$, we can identify $\hat{s}_{1}=$ $I_{0}^{s}$ such that $G_{1}^{s}\left(I_{0}^{s}\right)+c I_{0}^{s}=G_{1}^{s}\left(\hat{S}_{1}\right)+c \hat{S}_{1}+K$. Therefore, we can approximate
$s_{1}$ by imposing the constraint

$$
\begin{equation*}
G_{1}^{s}\left(I_{0}^{s}\right)+c I_{0}^{s}=C_{1}^{S}\left(I_{0}^{S}\right)+c I_{0}^{S} \tag{17}
\end{equation*}
$$

in which $I_{0}^{S}$ represents an approximation $\hat{S}_{1}$ of the optimal order-up-to-level $S_{1}{ }^{1}$. Note that $C_{1}^{S}\left(I_{0}^{S}\right)$ includes the fixed ordering cost $K$ because of Constraint (16); variable ordering cost in $C_{1}^{S}\left(I_{0}^{S}\right)$ is zero because $I_{0}^{S}$ is its global minimizer. Therefore Eq. 17 is equivalent to $G_{1}^{s}\left(I_{0}^{s}\right)+c I_{0}^{s}=G_{1}^{s}\left(\hat{S}_{1}\right)+c \hat{S}_{1}+K$.

Finally, since $s_{1} \leq S_{1}$, we introduce an additional constraint to ensure that the reorder point is not greater than the order-up-to-level,

$$
\begin{equation*}
I_{0}^{s} \leq I_{0}^{S} \tag{18}
\end{equation*}
$$

Note that, in contrast to the true value $G_{1}(y)+c y$, there is no guarantee that $K$-convexity holds for its approximation $G_{1}^{s}(y)+c y$. For some instances we may therefore have multiple values $\hat{s}_{1}$ such that holds. As we will demonstrate in our computational study, leaving to the solver the freedom to choose one of such values in a non-deterministic fashion leads to competitive results.

MINLP- $S$ and MINLP- $s$ are connected by Eq. 17), in such a way the order-up-to-level $S_{1}$ and the reorder point $s_{1}$ are approximated simultaneously. For the joint MINLP model, in addition to decision variables in MINLP- $S$ and MINLP$s$, we consider $I_{0}^{S}$, a dummy variable representing the approximate order-up-tolevel $\hat{S}_{1}$; and $I_{0}^{s}$, which captures the approximate reorder point $\hat{s}_{1}$.

Our holistic MINLP model objective features two parts: the first part, $C_{1}^{S}\left(I_{0}\right)$, comes from MINLP- $S$; the second part, $G_{1}^{s}\left(I_{0}^{s}\right)+c I_{0}^{s}-f_{1}\left(I_{0}^{s}\right) \approx \mathrm{E}\left[C_{2}\left(I_{0}^{s}-\right.\right.$ $\left.d_{1}\right)$ ], from MINLP- $s$. Note that the term $f_{1}\left(I_{0}^{s}\right)$, which enhances computational performance of the model, can be introduced because holding and penalty costs in period 1 for model MINLP-s are already uniquely determined by equation (17.) After dropping the constant term $c \sum_{t=1}^{T} \tilde{d}_{t}-c I_{0}$ in the first part and the constant term $c \sum_{t=1}^{T} \tilde{d}_{t}$ in the second part, we minimise the following holistic

[^1]objective function
\[

$$
\begin{equation*}
\min \left(\sum_{t=1}^{T}\left(K \delta_{t}^{S}+h H_{t}^{S}+b B_{t}^{S}\right)+c \tilde{I}_{T}^{S}+\sum_{t=2}^{T}\left(K \delta_{t}^{s}+h H_{t}^{s}+b B_{t}^{s}\right)+c \tilde{I}_{T}^{s}\right) \tag{19}
\end{equation*}
$$

\]

Constraints of the joint MINLP model are those of both MINLP-S and MINLP-s in addition to the linking constraints (13), 16, 17) and 18. After solving the joint MINLP model over planning horizon $k, \ldots, T$, the estimated order-up-to-level $\hat{S}_{k}$ is equal to $I_{k-1}^{S}$, and the estimated reorder point $\hat{s}_{k}$ is equal to $I_{k-1}^{s}$. As previously discussed, the joint MINLP model can be linearised via the piecewise-linear approximation proposed in Rossi et al. (2015). In our MILP model, (9) and (10) are modelled via the piecewise OPL expression (IBM, 2011). For a complete overview of the MILP model refer to Appendix B.

Example. We now use the same 4-period numerical example in Fig. 3 to demonstrate the modelling strategy behind the joint MINLP heuristic (MP). We observe that, for period 1, the approximated order-up-to-level is $S_{1}=70.3$, the reorder point is $s_{1}=15.0$, and $G_{1}^{s}\left(s_{1}\right)=366$ (363, after simulation) as shown in Fig. 1. By solving the joint MINLP model repeatedly, $s_{t}, S_{t}$, and $G_{t}^{s}\left(s_{t}\right)$, for $t=1, \ldots, 4$, are estimated as shown in Table 1. We also compare our results against the optimal solutions obtained via SDP in Table 1 note that although different order-up-to-levels, e.g. $S_{2}$, are obtained, the optimal expected total costs are similar.

|  | MP |  |  |  |  | SDP |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| t | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |  |
| $s_{t}$ | 15.0 | 29.0 | 58.1 | 29.0 | 14.0 | 29.0 | 58.0 | 28.0 |  |
| $S_{t}$ | 70.3 | 54.0 | 117 | 54.0 | 70.0 | 141 | 114 | 53.0 |  |
| $G_{t}^{s}\left(s_{t}\right)$ | 366 | 311 | 193 | 118 | 363 | 303 | 190 | 118 |  |

Table 1: Optimal $(s, S)$ policy parameters obtained via the joint MINLP heuristic and the stochastic dynamic programming

## 6. A binary search approach to approximate $(s, S)$ policy parameters

The joint MINLP heuristic presented in the last section is valuable, since it can be easily linearised into an MILP model that can be solved by off-the-shelf solvers. However, according to our experience it can only effectively tackle smallsize instances. To preserve the advantage of relying on an MILP model, one may investigate efficient reformulations, valid inequalities, or may explore cut generation techniques that enhance computational performances; we however choose to leave this investigation as future work.

In order to tackle larger-size problems, in this section we introduce an efficient approach that combines the model MINLP-s discussed in Section 5 and a binary search strategy. This approach relies on the MINLP models previously introduced, but it has the disadvantage of requiring dedicated code for the search procedure.

Our binary search strategy (Algorithm 1) is structured as follows.
Computation of $S$ (lines 2-3). We first let $I_{0}^{s}$ to be a decision variable in MINLP-s and minimise $G_{1}^{s}\left(I_{0}^{s}\right)+c I_{0}^{s}$ to estimate the order-up-to-level $\hat{S}_{1}$.

Computation of $s$ (line5, 17). Since $G_{1}^{s}\left(I_{0}^{s}\right)$ is an approximation of $G_{1}(y)$, we can conduct a binary search to approximate the reorder point $\hat{s}_{1}$ by $I_{0}^{s} \leq \hat{S}_{1}$ at which $G_{1}^{s}\left(I_{0}^{s}\right)+c I_{0}^{s}=G_{1}^{s}\left(\hat{S}_{1}\right)+c \hat{S}_{1}+\mathrm{K}$. When the binary search terminates, the estimated reorder point $\hat{s}_{k}$ is equal to $I_{k-1}^{s}$.

By repeating this procedure (line 1) over the planning horizon $k, \ldots, T$, we find pairs of $\hat{S}_{k}$ and $\hat{s}_{k}$, where $k=1, \ldots, T$.

Example. We illustrate the solution method discussed via the same 4period numerical example presented in Fig. 1 We assume the step size of the binary search is 0.01 . The order-up-to-level $\hat{S}_{1}=70.3$ and $G_{1}^{s}(70.3)=266$. We then set low $=-200$, high $=70.3$. While low $<$ high, the mid is updated via the comparison of $G_{1}^{s}\left(I_{0}^{s}\right)+K$ and $G_{1}^{s}\left(\hat{S}_{1}\right)+K$. Eventually, we obtain the reorder point $\hat{s}_{1}=15$ at which $G_{1}^{s}\left(\hat{s}_{1}\right)+c \hat{s}_{1}=G_{1}^{s}\left(\hat{S}_{1}\right)+c \hat{S}_{1}+$ K. By repeating this procedure we obtain $\hat{S}_{t}, \hat{s}_{t}$, and $G_{t}^{s}\left(s_{t}\right)$, for each period $t=1, \ldots, 4$ as displayed in Table 2 After simulation, we obtain the expected total cost 363.

```
Data: costs (ordering cost, holding cost, penalty cost), mean demand
``` and standard deviation of each period, stepsize
Result: pairs of \(s\) and \(S\) for each time period
```

for k=1 to T do

```

Minimize MINLP-s in Section 5 in OPL;
Obtain \(G_{k}^{s}\left(\hat{S}_{k}\right)\) and \(\hat{S}_{k}\);
low \(=\) a large negative integer; high \(=\hat{S}_{k} ;\)
while low < high do
mid \(=\) low \(+\operatorname{round}((h i g h-l o w) / 2)\);
Run the MINLP-s with \(I_{k-1}^{s}=m i d\) in OPL;
Obtain current cost \(G_{k}^{s}\left(I_{k-1}^{s}\right)\);
if \(G_{k}^{s}\left(I_{k-1}^{s}\right)-G_{k}^{s}\left(\hat{S}_{k}\right)-K-c\left(\hat{S}_{k}-I_{k-1}^{s}\right)<0\) then
high \(=\) mid - stepsize;
else if \(G_{k}^{s}\left(I_{k-1}^{s}\right)-G_{k}^{s}\left(\hat{S}_{k}\right)-K-c\left(\hat{S}_{k}-I_{k-1}^{s}\right)>0\) then
\(l o w=m i d+\) stepsize;
else
\(\hat{s}_{k}=I_{k-1}^{s} ;\)
low \(=h i g h ;\)
end
end
end
Algorithm 1: The binary search algorithm
\begin{tabular}{|l|cccc|}
\hline t & 1 & 2 & 3 & 4 \\
\hline\(s_{t}\) & 15 & 29.0 & 58.1 & 29.0 \\
\(S_{t}\) & 70.3 & 54.0 & 116 & 54.0 \\
\(G_{t}^{s}\left(s_{t}\right)\) & 366 & 311 & 193 & 118 \\
\hline
\end{tabular}

Table 2: Near-optimal \((s, S)\) policy parameters obtained via the binary search approach

\section*{7. Computational experiments}

In this section we present an extensive analysis of the heuristics discussed in Sections 5 (MP) and 6 (BS). We first design a test bed featuring instances defined over an 8-period planning horizon (Section 7.1). On this test bed, we assess the behaviour of the optimality gap and the computational efficiency of both the MP and BS heuristics. Then we assess the computational performance of the BS heuristics on a test bed featuring larger instances on a 25 -period planning horizon (Section 7.2). For all cases, MINLP models are solved by employing the piecewise linearisation strategy discussed in Rossi et al. (2015), which can be easily implemented in OPL by means of the piecewise syntax. Numerical experiments are conducted by using IBM ILOG CPLEX Optimization Studio 12.7 and MATLAB R2014a on a \(3.2 \mathrm{GHz} \operatorname{Intel}(\mathrm{R})\) Core(TM) with 8 GB of RAM.

\subsection*{7.1. An 8-period test bed}

We consider a test bed which includes 540 instances. Specifically, we incorporate ten demand patterns displayed in Fig. 4. These patterns comprising two life cycle patterns (LCY1 and LCY2), two sinusoidal patterns (SIN1 and SIN2), a stationary pattern (STA), a random pattern (RAND), and four empirical patterns (EMP1, ..., EMP4). Full details on the experimental set-up are given in Appendix C. Fixed ordering cost \(K\) ranges in \(\{200,300,400\}\), proportional ordering cost \(c\) ranges in \(\{0,1\}\), and the penalty cost \(b\) takes values \(\{5,10,20\}\). We assume that demand \(d_{t}\) in each period \(t\) is independent and normally distributed with mean \(\tilde{d}_{t}\) and coefficient of variation \(c_{v} \in\{0.1,0.2,0.3\}\); note that \(\sigma_{t}=c_{v} \tilde{d}_{t}\). Since we operate under the assumption of normality, our models can be readily linearised by using the piecewise linearisation parameters available in Rossi et al. (2014). However, the reader should note that our proposed modelling strategy is distribution independent, see Rossi et al. (2015).

We set the SDP model discussed in Section 2 as a benchmark. We compare against this benchmark in terms of optimality gap and computational time. First of all, we obtain optimal parameters for each test instance by implementing


Figure 4: Demand patterns in our computational analysis
an SDP algorithm in MATLAB. Then, we solve each instance by adopting both modelling heuristics presented in Section 5 and 6 Specifically, for the MP heuristic we employ seven segments in the piecewise-linear approximations of \(B_{t}\) and \(H_{t}\) (for \(t=1, \ldots, T\) ) in order to guarantee reasonable computational performances; for the BS heuristic, whose computational performance is only marginally affected by an increased number of segments in the linearisation, we employ eleven segments and a step size 0.1. To estimate the cost of the policies obtained via our heuristics, we simulate all policies via Monte Carlo Simulation (10,000 replications).

Table 3 gives an overview of optimality gaps (\%) of methods discussed in this study for different pivoting parameters. It is difficult to make a general remark with respect to demand pattern, and fixed ordering cost; while the proportional ordering cost has a negative correlation with the optimality gap. An increase in proportional ordering cost slightly reduces the optimality gap. While an increase in penalty cost increases the optimality gap. Specifically, when penalty cost increases from 10 to 20 , the optimal gap rises from \(0.25 \%\) to \(0.42 \%\) and from \(0.27 \%\) to \(0.35 \%\), respectively. Similarly, an increase in coefficient of variation increases the optimality gap. For example, the optimality gap of the BS heuristic increases significantly from \(0.16 \%\) to \(0.40 \%\) as the coefficient of variation increases from 0.1 to 0.3 . Overall, the average optimality gap of the MP heuristic is \(0.29 \%\), and that of the BS heuristic is \(0.26 \%\). This discrepancy ought to be expected, since in the case of the BS method a higher number of segments has been employed.

Existing heuristics Askin (1981) and Bollapragada \& Morton (1999) were reimplemented by Dural-Selcuk et al. (2016) and assessed on a test bed that neatly resembles the one adopted in this work. As shown in Dural-Selcuk et al. (2016), Askin's optimality gap is \(3.9 \%\), and Bollapragada and Morton's is \(4.9 \%\). The optimality gap of our heuristic is \(0.29 \%\) when seven segments are employed in the piecewise linearisation, and it drops to \(0.26 \%\) when eleven segments are employed. Our models outperform both Askin (1981) and Bollapragada \& Morton (1999) in terms of optimality gap on the test bed here considered.
\begin{tabular}{|lrl|}
\hline Modelling methods & MP & BS \\
\hline Demand pattern & & \\
LCY1 & 0.25 & 0.33 \\
LCY2 & 0.11 & 0.18 \\
SIN1 & 0.13 & 0.20 \\
SIN2 & 0.10 & 0.19 \\
STA & 0.50 & 0.14 \\
RAND & 0.16 & 0.22 \\
EMP1 & 0.41 & 0.35 \\
EMP2 & 0.86 & 0.52 \\
EMP3 & 0.15 & 0.19 \\
EMP4 & 0.28 & 0.28 \\
\hline Fixed ordering cost & & \\
200 & 0.31 & 0.29 \\
300 & 0.24 & 0.22 \\
400 & 0.34 & 0.27 \\
\hline Proportional ordering cost & \\
0 & 0.33 & 0.29 \\
1 & 0.26 & 0.23 \\
\hline Penalty cost & 0.25 & 0.26 \\
\hline 0 & 0.42 & 0.35 \\
\hline Average & 0.27 \\
\hline Coefficient of variation & \\
0.1 & 0.22 & 0.16 \\
\hline 0 & 0.26 & 0.22 \\
\hline
\end{tabular}

Table 3: Average optimality gaps \% of the 8-period numerical experiment for different pivoting parameters

We also assess the accuracy of our models by comparing the costs predicted by our models against the costs obtained via simulation. We note that both MP and BS heuristics have high accuracy for the 8-period numerical experiments. For further details please refer to Table D.8 in Appendix D

Table 4 shows computational times of our models for different pivoting parameters. Note "STDEV" in Table 4 represents the standard deviation. Overall, the computational time of BS method remains stable for different set-up parameters; while that of MP and SDP algorithms fluctuate. We observe that the fixed ordering cost, proportional ordering cost, penalty cost, and coefficient of variation do not have significant effect on the computational efficiency of BS and SDP algorithms. However, the computational time of MP heuristic drops significantly with the increase of fixed ordering cost, and proportional ordering cost; while grows greatly with the increase of the coefficient of variation. On average, the computational time of MP, BS, and SDP are \(7.89 \mathrm{~s}, 7.01 \mathrm{~s}\), and 53.03 s .

\subsection*{7.2. A 25 -period test bed}

As shown in Section 7.1 for the 8-period test bed, both the MP and the BS methods provide tight optimality gaps and acceptable computational efficiency. We now extend the 8 -period test bed to 25 periods with larger instances. Demands of LCY1, LCY2, SIN1, SIN2, STA, and RAND are generated with expressions (20), 21), 22), 23), 24), and (25) in Fig. 5. Demands of EMP1, EMP2, EMP3 and EMP4 are derived from Strijbosch et al. (2011). Full details are given in Appendix C. Assume that fixed ordering cost ranges in \(\{500,1000,1500\}\), proportional ordering cost ranges in \(\{0,1\}\), penalty cost takes values \(\{5,10,20\}\), and the coefficients of standard deviations are \(\{0.1,0.2,0.3\}\).

We obtain optimal \((s, S)\) parameters and record computational times obtained via the BS method. For the first 15 periods we perform binary search with step size 1 in order to ensure fast convergence; for the last 10 periods, we adopt a step size 0.1 to enhance accuracy. The number of segments used in the piecewise linearisation is eleven. To estimate the cost of the policy obtained via
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline \multirow{2}{*}{Settings} & \multicolumn{2}{|r|}{MP} & \multicolumn{2}{|r|}{BS} & \multicolumn{2}{|r|}{SDP} \\
\hline & Mean & STDEV & Mean & STDEV & Mean & STDEV \\
\hline \multicolumn{7}{|l|}{Demand pattern} \\
\hline LCY1 & 3.54 & 0.98 & 7.17 & 1.21 & 13.58 & 0.86 \\
\hline LCY2 & 6.26 & 4.52 & 7.29 & 1.06 & 13.61 & 0.81 \\
\hline SIN1 & 4.67 & 3.20 & 6.48 & 0.69 & 13.31 & 1.11 \\
\hline SIN2 & 4.15 & 1.89 & 6.41 & 0.63 & 13.60 & 0.82 \\
\hline STA & 5.52 & 3.68 & 6.48 & 0.72 & 9.95 & 2.29 \\
\hline RAND & 3.60 & 0.87 & 7.11 & 1.32 & 710.12 & 2.95 \\
\hline EMP1 & 7.65 & 6.21 & 7.32 & 0.96 & 121.81 & 28.60 \\
\hline EMP2 & 14.03 & 13.60 & 7.28 & 1.19 & 107.20 & 7.37 \\
\hline EMP3 & 14.32 & 11.81 & 7.02 & 0.83 & 104.41 & 10.17 \\
\hline EMP4 & 15.12 & 15.35 & 7.52 & 1.20 & 122.71 & 27.79 \\
\hline \multicolumn{7}{|l|}{Fixed ordering cost} \\
\hline 200 & 10.29 & 11.18 & 7.11 & 1.00 & 53.03 & 51.94 \\
\hline 300 & 7.17 & 6.94 & 6.99 & 1.00 & 53.07 & 51.98 \\
\hline 400 & 6.19 & 5.40 & 6.93 & 1.08 & 52.99 & 51.91 \\
\hline \multicolumn{7}{|l|}{Proportional ordering cost} \\
\hline 0 & 8.49 & 9.06 & 7.64 & 0.99 & 60.21 & 60.12 \\
\hline 1 & 7.28 & 7.57 & 6.38 & 0.59 & 45.85 & 40.85 \\
\hline \multicolumn{7}{|l|}{Penalty cost} \\
\hline 5 & 8.05 & 7.92 & 6.96 & 0.90 & 53.08 & 52.03 \\
\hline 10 & 8.72 & 10.60 & 6.86 & 1.02 & 52.74 & 51.94 \\
\hline 20 & 6.84 & 8.84 & 7.17 & 1.14 & 52.97 & 51.85 \\
\hline \multicolumn{7}{|l|}{Coefficient of variation} \\
\hline 0.1 & 6.42 & 6.16 & 7.00 & 1.08 & 53.06 & 51.96 \\
\hline 0.2 & 7.98 & 8.92 & 7.02 & 0.99 & 53.01 & 51.92 \\
\hline 0.3 & 9.26 & 9.43 & 7.01 & 1.03 & 53.02 & 51.95 \\
\hline Average & 7.89 & 8.39 & 7.01 & 1.03 & 53.03 & 51.85 \\
\hline
\end{tabular}

Table 4: Average computational times (seconds) of the 8-period numerical for different pivoting parameters
\[
\begin{array}{ll}
d_{t}=\operatorname{round}\left(\frac{190 \times e^{-(t-13)^{2}}}{2 \times 5^{2}}\right), & t=1,2, \ldots, T \\
d_{t}=\operatorname{round}\left(\frac{170 \times e^{-(t-13)^{2}}}{2 \times 6^{2}}\right), & t=1,2, \ldots, T \\
d_{t}=\operatorname{round}(70 \times \sin (0.8 t)+80), & t=1,2, \ldots, T \\
d_{t}=\operatorname{round}(30 \times \sin (0.8 t)+100), & t=1,2, \ldots, T \\
d_{t}=100, & t=1,2, \ldots, T \\
d_{t}=\operatorname{round}(\operatorname{random}(0,250)), & t=1,2, \ldots, T \tag{25}
\end{array}
\]

Figure 5: Expressions for generating demand data
our approximation, we simulate each instance ten thousand times in MATLAB.
We observe that the BS model has high accuracy even for the large-size numerical experiments. We report detailed model accuracy in Table D.9 in Appendix D.

In Table 5. we summarise computational times of the BS model for different pivoting parameters. It is difficult to make a general remark with respect to demand patterns. An increase in fixed ordering cost significantly decreases the computational time. For instance, the computational time drops from 934.92 s to 546.75 s as the fixed ordering cost increases from 500 to 1500 . An increase in proportional ordering cost decreases the computational time. In contrast, an increase in coefficient of variation increases the computational time. For instance, when the coefficient of variation rises from 0.1 to 0.2 , the computational time increases from \(679.34 s\) to \(809.34 s\). On average, the computational time is \(748.20 s\) and the standard deviation is \(616.43 s\).

\section*{8. Conclusion}

In this paper we discussed two MINLP-based heuristics for tackling non-stationary stochastic lot-sizing problems under \((s, S)\) policy.
\begin{tabular}{|lcc|}
\hline Settings & Mean & standard deviation \\
\hline Demand pattern & \\
LCY1 & 531.66 & 204.45 \\
LCY2 & 740.73 & 322.92 \\
SIN1 & 500.44 & 177.17 \\
SIN2 & 1622.92 & 624.58 \\
STA & 1709.00 & 706.67 \\
RAND & 407.08 & 131.11 \\
EMP1 & 633.09 & 126.63 \\
EMP2 & 188.19 & 37.45 \\
EMP3 & 974.93 & 305.16 \\
EMP4 & 173.95 & 44.87 \\
\hline Fixed ordering cost & \\
500 & 934.92 & 811.90 \\
1000 & 762.96 & 540.73 \\
1500 & 546.75 & 341.41 \\
\hline Proportional ordering cost \\
0 & 827.15 & 680.28 \\
1 & 669.25 & 534.88 \\
\hline Penalty cost & \\
5 & 713.45 & 564.80 \\
10 & 782.53 & 669.09 \\
20 & 744.28 & 612.21 \\
\hline Coefficient of variation & \\
0.1 & 679.34 & 567.29 \\
\hline & 755.92 & 619.07 \\
\hline & 809.34 & 656.18 \\
\hline & 748.20 & 616.43 \\
\hline
\end{tabular}

Table 5: BS heuristics on a 25-period test bed, average computational times (seconds) with different setting parameters

Our first heuristic - the first MINLP heuristic for computing near-optimal non-stationary \((s, S)\) policy parameters - is based on mathematical programming models that can be solved by using off-the-shelf optimization packages. These MINLP models can be linearised via the approach discussed in Rossi et al. (2015) and can be implemented in OPL by adopting the piecewise expression.

Our second heuristic is a binary search strategy that leverages the aforementioned MINLP models and can tackle larger-size problems. However, this latter heuristic requires dedicated code.

We conducted an extensive computational study comprising 540 instances. We considered ten demand patterns, three fixed ordering costs, two proportional ordering cost, three penalty costs and three coefficients of variation.

We first conducted a numerical study on small instances (8-period). We investigated the performance of both models by contrasting costs of the policy obtained with our models against costs of the optimal policy obtained via the stochastic dynamic programming. Optimality gaps observed are generally below \(0.3 \%\). Our sensitivity analysis showed that the optimality gap is tighter when the demand keeps stable, and performance deteriorate with the increase of the penalty cost and the coefficient of variation; both heuristics provide tighter gaps than those reported in the literature Askin, 1981; Bollapragada \& Morton, 1999).

The computational study carried out on larger instances (25-period) showed that the computational efficiency of the binary search approach is reasonable: around 748.20 s on average.

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\section*{Appendix A. The piecewise OPL constraint}

Rossi et al. (2015) piecewise linearised loss functions in constraints 9 and 10 . by employing piecewise linear approximations based on Jesen's and EdmundsonMadanski inequalities. An alternative strategy is to model these non-linear functions by exploring the piecewise syntax in OPL. By using this syntax, a piecewise function is specified by giving a set of slopes which represent the linear variation for each linear segment; a set of breakpoints at which slopes change; and the function value at a known point.
```

piecewise(i in 1..W){
slope[i] -> breakpoint[i];
slope[W+1]
}(<knownpoint>,<valuepoint>)<value>;

```

Figure A.6: The syntax of the piecewise command in OPL

The piecewise syntax in OPL is given in Figure A.6. W is the number of breakpoints of the piecewise function. slope[i] and breakpoint [i] denote slope and breakpoint of segment \(i\). Segment \(i\) goes from breakpoint \((i-1)\) to breakpoint \((i)\). <valuepoint> is the function value at a known point <knownpoint>. Finally, <value> represents the value at which we evaluate the function.

For the OPL piecewise syntax, there are three key components: slope, breakpoint, and function value at a known point. The following lemmas will demonstrate how to deduce their values. Let \(\Omega\) be the support of \(\omega\). Let \(\left(\Omega_{i}\right)_{i=1, \ldots, W+1}\) be a partition of \(\Omega\) in \(W+1\) segments.

Lemma 1. The slope of \(i^{\text {th }}\) segment is written as
\[
l_{i}=\sum_{k=1}^{i-1} p_{k}, i \in\{1,2, \ldots, W+1\}
\]
where \(p_{i}=\operatorname{Pr}\left\{\omega \in \Omega_{i}\right\}=\int_{\Omega_{i}} g_{\omega}(t) d t, g_{\omega}(\cdot)\) denotes the probability density function of \(\omega\).

Proof 1. Observation from Rossi et al. (2014), Lemma 11.

Lemma 2. The \(i^{\text {th }}\) breakpoint can be written as
\[
X_{i}=E\left[\omega \mid \Omega_{i}\right], i \in\{1,2, \ldots, W\}
\]

Proof 2. Observation from Rossi et al. (2014), Lemma 11.

Note that when \(\omega\) follows a normal distribution with mean \(\mu\) and standard deviation \(\sigma\), then \(\hat{L}_{\text {up }}(x, \omega)=\sigma \hat{L}_{\text {up }}\left(\frac{x-\mu}{\sigma}, Z\right)\), where \(Z\) follows a standard normal distribution, see Lemma 7 in Rossi et al. (2014).

Lemma 3. Assume that the partition of \(\Omega\) is symmetric with respect to 0 , then the function value \(\hat{L}_{u p}(x, \omega)\) at point 0 can be written as follows.
\[
\hat{L}_{u p}(0, \omega)= \begin{cases}-\sum_{k=1}^{\frac{W+1}{2}} p_{k} E\left[\omega \mid \Omega_{k}\right]+e_{W}, & \text { W is odd } \\ -\frac{1}{2}\left(\sum_{k=1}^{\frac{W}{2}} p_{k} E\left[\omega \mid \Omega_{k}\right]+\sum_{k=1}^{\frac{W}{2}+1} p_{k} E\left[\omega \mid \Omega_{k}\right]\right)+e_{W}, & \text { W is even }\end{cases}
\]
where \(e_{W}\) represents the approximation error.

Proof 3. Since the partition of \(\Omega\) is symmetric when \(W\) is odd, \(x=0\) is the central breakpoint. Hence, the function value at this breakpoint can be calculated directly. However, when \(W\) is even, the function value at point \(x=0\) is the average of nearest two symmetric breakpoints \(X_{\frac{W}{2}}\) and \(X_{\frac{W}{2}+1}\).

Following Lemma 1, 22 and 3, constraint (9) and 10 in Fig. 2 can be expressed as Eq. A.1 and A.2 in Fig. A.7. for \(t=1, \ldots, T\).
\[
\begin{aligned}
& P_{j t}=1 \rightarrow H_{t}=\text { piecewise }\left\{l_{i} \rightarrow X_{i} ; 1\right\}\left(0, \hat{L}_{u p}\left(0, d_{j t}\right)\right) \tilde{I}_{t}, \\
& i=1, \ldots, W ; j=1, \ldots, t . \quad \text { (A.1) } \\
& P_{j t}=1 \rightarrow B_{t}=\text { piecewise }\left\{-1+l_{i} \rightarrow X_{i} ; 0\right\}\left(0, \hat{L}_{u p}\left(0, d_{j t}\right)\right) \tilde{I}_{t}, \\
& i=1, \ldots, W ; j=1, \ldots, t . \quad \text { (A.2) }
\end{aligned}
\]

Figure A.7: Rewriting holding and penalty costs by adopting piecewise syntax

\section*{Appendix B. The MILP model}

The joint MILP model to calculate near-optimal \((s, S)\) policy parameters for the non-stationary stochastic lot-sizing problem is presented below. \({ }^{2}\) In the joint MP model, constraints (B.3) represent the costs of controlling the system optimally when the initial inventory level is \(I_{0}^{s}\); constraints (B.14) denote the costs of controlling the system optimally when the initial inventory level is \(I_{0}^{s}\), and no order is placed in period 1. These two constraints are connected via constraints B.27) such that the order-up-to-level \(S_{1}\) and reorder point \(s_{1}\) are approximated by \(I_{0}^{S}\) and \(I_{0}^{S}\) respectively.

\footnotetext{
\({ }^{2}\) The loss function is piecewise linearized via constraints B.10, B.11, B.22, and B.23.
}
\[
\begin{aligned}
& \min \left(\sum_{t=1}^{T}\left(K \delta_{t}^{S}+h H_{t}^{S}+b B_{t}^{S}\right)+c \tilde{I}_{T}^{S}+\sum_{t=2}^{T}\left(K \delta_{t}^{s}+h H_{t}^{s}+b B_{t}^{s}\right)+c \tilde{I}_{T}^{s}\right) \\
& \text { Subject to, } t=1, \ldots, T \\
& C_{1}^{S}\left(I_{0}^{S}\right)=\sum_{t=1}^{T}\left(K \delta_{t}^{S}+h H_{t}^{S}+b B_{t}^{S}\right)+c \tilde{I}_{T}^{S}+c \sum_{t=1}^{T} \tilde{d}_{t}-c I_{0}^{S} \\
& \tilde{I}_{t}^{S}+\tilde{d}_{t}-\tilde{I}_{t-1}^{S} \geq 0 \\
& \delta_{t}^{S}=0 \rightarrow \tilde{I}_{t}^{S}+\tilde{d}_{t}-\tilde{I}_{t-1}^{S}=0 \\
& \sum_{j=1}^{t} P_{j t}^{S}=1 \\
& P_{j t}^{S} \geq \delta_{j}^{S}-\sum_{k=j+1}^{t} \delta_{k}, j=1, \ldots, t \\
& \delta_{1}^{S}=1 \\
& I_{0}^{S}=\tilde{I}_{1}^{S}+\tilde{d}_{1} \\
& H_{t}^{S} \geq\left(I_{t}^{S}+\sum_{j=1}^{t} d_{j t} P_{j t}^{S}\right) \sum_{k=1}^{i} p_{k}-\sum_{j=1}^{t}\left(\sum_{k=1}^{i} p_{k} E\left[d_{j t} \mid \Omega_{i}\right]-e_{W}\right) P_{j t}^{S}, \quad i=1, \cdots, W \\
& \text { (B.10) } \\
& B_{t}^{S} \geq-I_{t}^{S}+\left(I_{t}^{S}+\sum_{j=1}^{t} d_{j t} P_{j t}^{S}\right) \sum_{j=1}^{i} p_{k}-\sum_{j=1}^{t}\left(\sum_{k=1}^{i} p_{k} E\left[d_{j t} \mid \Omega_{i}\right]-e_{W}\right) P_{j t}^{S}, \quad i=1, \cdots, W \\
& \text { (B.11) } \\
& \text { (B.12) } \\
& P_{j t}^{S} \in\{0,1\}, j=1, \ldots, t \\
& \delta_{t}^{S} \in\{0,1\} \\
& \text { (B.13) } \\
& G_{1}^{s}\left(I_{0}^{s}\right)=\left(h H_{1}^{s}+b B_{1}^{s}\right)+\sum_{t=2}^{T}\left(K \delta_{t}^{s}+h H_{t}^{s}+b B_{t}^{s}\right)+c \tilde{I}_{T}^{s}+c \sum_{t=2}^{T} \tilde{d}_{t}-c I_{1}^{s} \\
& \tilde{I}_{t}^{s}+\tilde{d}_{t}-\tilde{I}_{t-1}^{s} \geq 0 \\
& \delta_{t}^{s}=0 \rightarrow \tilde{I}_{t}^{s}+\tilde{d}_{t}-\tilde{I}_{t-1}^{s}=0 \\
& \sum_{j=1}^{t} P_{j t}^{s}=1 \\
& P_{j t}^{s} \geq \delta_{j}-\sum_{k=j+1}^{t} \delta_{k}^{s}, j=1, \ldots, t \\
& \delta_{1}^{S}=0 \\
& \text { (B.19) } \\
& P_{j t}^{s}=1 \rightarrow H_{t}^{s}=\text { piecewise }\left\{l_{i} \rightarrow X_{i} ; 1\right\}\left(0, \hat{L}_{u p}\left(0, d_{j t}\right)\right) \tilde{I}_{t}^{s}, \quad i=1, \ldots, W \\
& \begin{aligned}
i & =1, \ldots, W \\
j & =1, \ldots, t
\end{aligned} \\
& \text { (B.20) } \\
& P_{j t}^{s}=1 \rightarrow B_{t}^{s}=\text { piecewise }\left\{-1+l_{i} \rightarrow X_{i} ; 0\right\}\left(0, \hat{L}_{u p}\left(0, d_{j t}\right)\right) \tilde{I}_{t}^{s} \quad \begin{array}{ll}
i=1, \ldots, W \\
& j=1, \ldots, t
\end{array} \\
& j=1, \ldots, t_{(\text {B.21) }} \\
& H_{t}^{s} \geq\left(I_{t}^{S}+\sum_{j=1}^{t} d_{j t} P_{j t}^{s}\right) \sum_{k=1}^{i} p_{k}-\sum_{j=1}^{t}\left(\sum_{k=1}^{i} p_{k} E\left[d_{j t} \mid \Omega_{i}\right]-e_{W}\right) P_{j t}^{s}, \quad i=1, \cdots, W \\
& \text { (B.22) } \\
& B_{t}^{S} \geq-I_{t}^{S}+\left(I_{t}^{S}+\sum_{j=1}^{t} d_{j t} P_{j t}^{S}\right) \sum_{j=1}^{i} p_{k}-\sum_{j=1}^{t}\left(\sum_{k=1}^{i} p_{k} E\left[d_{j t} \mid \Omega_{i}\right]-e_{W}\right) P_{j t}^{s}, \quad i=1, \cdots, W \\
& \text { (B.23) } \\
& \text { (B.24) } \\
& \text { (B.25) } \\
& \text { (B.26) } \\
& \text { (B.27) }
\end{aligned}
\]

\section*{Appendix C. Test bed}

Periodic demands with different demand patterns under the eight period computational study are displayed in Table C.6. The demand of each period under the twenty-five periods numerical example is shown in Table C.7. The first column represents period indexes; the rest columns denote various demands.
\begin{tabular}{|l|cccccccccc|}
\hline Period & LCY1 & LCY2 & SIN1 & SIN2 & STA & RAND & EMP1 & EMP2 & EMP3 & EMP4 \\
\hline 1 & 15 & 3 & 15 & 12 & 10 & 2 & 5 & 4 & 11 & 18 \\
2 & 16 & 6 & 4 & 7 & 10 & 4 & 15 & 23 & 14 & 6 \\
3 & 15 & 7 & 4 & 7 & 10 & 7 & 26 & 28 & 7 & 22 \\
4 & 14 & 11 & 10 & 10 & 10 & 3 & 44 & 50 & 11 & 22 \\
5 & 11 & 14 & 18 & 13 & 10 & 10 & 24 & 39 & 16 & 51 \\
6 & 7 & 15 & 4 & 7 & 10 & 10 & 15 & 26 & 31 & 54 \\
7 & 6 & 16 & 4 & 7 & 10 & 3 & 22 & 19 & 11 & 22 \\
8 & 3 & 15 & 10 & 12 & 10 & 3 & 10 & 32 & 48 & 21 \\
\hline
\end{tabular}

Table C.6: Demand data of the 8-period computational analysis

\section*{Appendix D. Model accuracy}

We employ the index of model accuracy ( \(=\frac{\mid \text { model result-simulation result } \mid}{\text { simulation result }} \times\) \(100 \%\) ) to evaluate the cost measure. We report the model accuracy of the 8 -period numerical experiment in Table. D.8, and the 25 -period numerical experiment in Table. D. 9 .
\begin{tabular}{|l|cccccccccc|}
\hline Period & LCY1 & LCY2 & SIN1 & SIN2 & STA & RAND & EMP1 & EMP2 & EMP3 & EMP4 \\
\hline 1 & 11 & 23 & 130 & 122 & 100 & 178 & 2 & 47 & 44 & 49 \\
2 & 17 & 32 & 150 & 130 & 100 & 178 & 51 & 81 & 116 & 188 \\
3 & 26 & 42 & 127 & 120 & 100 & 136 & 152 & 236 & 264 & 64 \\
4 & 38 & 55 & 76 & 98 & 100 & 211 & 467 & 394 & 144 & 279 \\
5 & 53 & 70 & 27 & 77 & 100 & 119 & 268 & 164 & 146 & 453 \\
6 & 71 & 86 & 10 & 70 & 100 & 165 & 489 & 287 & 198 & 224 \\
7 & 92 & 103 & 36 & 81 & 100 & 47 & 446 & 508 & 74 & 223 \\
8 & 115 & 120 & 88 & 103 & 100 & 100 & 248 & 391 & 183 & 517 \\
9 & 138 & 136 & 136 & 124 & 100 & 62 & 281 & 754 & 204 & 291 \\
10 & 159 & 150 & 149 & 130 & 100 & 31 & 363 & 694 & 114 & 547 \\
11 & 175 & 161 & 121 & 118 & 100 & 43 & 155 & 261 & 165 & 646 \\
12 & 186 & 168 & 68 & 95 & 100 & 199 & 293 & 195 & 318 & 224 \\
13 & 190 & 170 & 22 & 75 & 100 & 172 & 220 & 320 & 119 & 215 \\
14 & 186 & 168 & 11 & 71 & 100 & 96 & 93 & 111 & 482 & 440 \\
15 & 175 & 161 & 42 & 84 & 100 & 69 & 107 & 191 & 534 & 116 \\
16 & 159 & 150 & 96 & 107 & 100 & 8 & 234 & 160 & 136 & 185 \\
17 & 138 & 136 & 140 & 126 & 100 & 29 & 124 & 55 & 260 & 211 \\
18 & 115 & 120 & 148 & 129 & 100 & 135 & 184 & 84 & 299 & 26 \\
19 & 92 & 103 & 114 & 115 & 100 & 97 & 223 & 58 & 76 & 55 \\
20 & 71 & 86 & 60 & 91 & 100 & 70 & 101 & 0 & 218 & 0 \\
21 & 53 & 70 & 18 & 73 & 100 & 248 & 123 & 0 & 323 & 0 \\
22 & 38 & 55 & 14 & 72 & 100 & 57 & 99 & 0 & 102 & 0 \\
23 & 26 & 42 & 50 & 87 & 100 & 11 & 31 & 0 & 174 & 0 \\
24 & 17 & 32 & 104 & 110 & 100 & 94 & 82 & 0 & 284 & 0 \\
25 & 11 & 23 & 144 & 127 & 100 & 13 & 0 & 0 & 0 & 0 \\
\hline
\end{tabular}

Table C.7: Demand data of the 25-period computational analysis
\begin{tabular}{|lrl|}
\hline Modelling methods & MP & BS \\
\hline Demand pattern & & \\
LCY1 & 1.52 & 0.66 \\
LCY2 & 7.47 & 3.42 \\
SIN1 & 0.99 & 0.37 \\
SIN2 & 0.84 & 0.30 \\
STA & 1.25 & 0.66 \\
RAND & 4.57 & 2.10 \\
EMP1 & 8.75 & 4.50 \\
EMP2 & 6.82 & 3.05 \\
EMP3 & 1.83 & 0.81 \\
EMP4 & 2.59 & 0.73 \\
\hline Fixed ordering cost & & \\
200 & 3.14 & 1.36 \\
300 & 3.71 & 1.66 \\
400 & 4.15 & 1.96 \\
\hline Proportional ordering cost & \\
0 & 4.00 & 0.58 \\
1 & 3.33 & 4.72 \\
\hline Average gap & 3.66 \\
\hline 10 & 2.42 & 1.18 \\
\hline Penalty cost & 1.33 \\
\hline 0.2 & 2.94 & 1.33 \\
\hline Coefficient of variation & \\
\hline 0.1 & 2.47 \\
\hline
\end{tabular}

Table D.8: Model accuracy of the 8-period numerical experiments
\begin{tabular}{|lr|}
\hline Modelling method & BS \\
\hline Demand pattern & \\
LCY1 & 2.32 \\
LCY2 & 2.97 \\
SIN1 & 2.65 \\
SIN2 & 2.50 \\
STA & 1.90 \\
RAND & 2.81 \\
EMP1 & 4.15 \\
EMP2 & 5.19 \\
EMP3 & 3.79 \\
EMP4 & 5.55 \\
\hline Fixed ordering cost & \\
500 & 3.27 \\
1000 & 3.46 \\
1500 & 3.42 \\
\hline Proportional ordering cost \\
0 & 3.52 \\
1 & 3.24 \\
\hline Average gap & \\
\hline & 3.34 \\
\hline Coefficient of variation \\
0.1 & 4.34 \\
\hline 0 & 2.56 \\
\hline 0 & 3.13 \\
\hline
\end{tabular}

Table D.9: Accuracy of the 25-period numerical experiments```


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[^1]:    ${ }^{1} I_{0}^{S}$, which is a dummy variable, should not be confused with the actual initial inventory level $I_{0}$, which is needed to account for variable ordering costs.

