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Inventory and Commitment Decisions for On-demand Warehousing System^{*}

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Abstract. The on-demand warehousing system is a service that makes a connection between e-commerce sellers and warehouse providers who have excess capacity for sharing warehouse spaces. The e-commerce sellers can create a distribution network strategy and manage the varying demands of customers by utilizing this system. In this study, we focused on inventory and commitment decisions that impacted the use of shared warehouses from the standpoint of e-commerce sellers. We proposed a mathematical model, which incorporated inventory and commitment decisions to maximize total profits. A small-scale experiment was conducted, and the result showed that the commitment decisions could affect total profits of e-commerce sellers considerably.

Keywords: Shared warehouse · Inventory model · On-demand warehousing · Commitment decisions

1 Introduction

On-demand warehousing marketplaces, such as FLEXE and Mychango, have emerged as the new alternative to old warehousing solutions. This service system connects warehouse providers who have excess space with e-commerce sellers who need flexible warehouse solutions. Instead of leasing warehouse space, e-commerce sellers can rent spaces for short durations (e.g., days or months) through commitments with warehouse providers. From the standpoint of e-commerce sellers, employing the on-demand warehousing system could be a low-risk strategy to match unexpected customer demands and prevent the overflow of inventory. In addition, e-commerce sellers could secure warehousing and fulfillment solutions instantly and build a distribution network strategy.

Several studies regarding the on-demand warehousing system and warehouse capacity sharing have been conducted in the past ([1], [2], [3], [4], [5]). In particular, Van et al. [5] studied for dynamic shipments of inventories that took into

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account up-to-date inventory information. To deal with the sequential decision-making problem, the authors of this study employed the Markov decision process and obtained the optimal order and shipment decisions for small networks. Feng et al. [2] studied an integrated inventory model with warehouse capacity sharing via transshipment. To develop an optimal transshipment policy, they established nonlinear programming models and genetic algorithms. To the best of our knowledge, our study is a first step toward considering *commitment* decisions for the on-demand warehousing system.

Throughout this study, we used the term *retailer* to refer to e-commerce sellers and *provider* to refer to warehouse providers who have excess capacity. We defined the *inventory holding costs* as the costs incurred while holding inventory or stock in a warehouse. These costs included the warehousing costs incurred, such as labor and utilities. The *commitment costs* were incurred when the retailer and provider made a commitment for sharing warehouse space. We considered a realistic situation in which the retailer could use three types of warehouses: (i) the retailer's own warehouse (*retailer's warehouse*), (ii) the warehouse of a provider connected through an on-demand warehouse platform that offers excess warehouse capacity (*provider's warehouse*), and (iii) the warehouse that charges a higher unit inventory holding cost than the retailer's and provider's warehouses but that is always accessible without any commitment (*emergency warehouse*). The retailer is allowed to use the provider's warehouse only if a commitment between a retailer and a provider is made for utilizing the provider's warehouse. We started this research from following two research questions:

- (1) When the retailer can use all three types of warehouses, how should the retailer utilize warehouses for holding inventory within the entire planning horizon?
- (2) If there exist two types of commitments (*long-term* and *short-term*) for using the provider's warehouse, what is the best commitment strategy to maximize the retailer's profit?

2 Problem description and mathematical formulation

To develop a mathematical model for inventory and commitment decisions for an on-demand warehousing system, we defined the following notations of indices, sets, and parameters:

Indices and sets

\mathcal{T}	set of periods $\{1, 2, \dots, T\}$
\mathcal{I}	set of items $\{1, 2, \dots, I\}$
t	index for set of periods \mathcal{T}
i	index for set of items \mathcal{I}

Parameters

L	duration of long-term commitment
S	duration of short-term commitment
C^r	capacity of retailer's warehouse
C_t^o	capacity of provider's warehouse at period t
$s_{i,t}$	supply of item i at period t
$d_{i,t}$	demand of items i at period t
$r_{i,t}$	sales revenue per unit per period for items i at period t
$h_{i,t}^r$	inventory holding cost of retailer's warehouse per unit per period for item i at period t
$h_{i,t}^o$	inventory holding cost of provider's warehouse per unit per period for item i at period t
$h_{i,t}^e$	inventory holding cost of emergency warehouse per unit per period for item i at period t
c_t^l	commitment cost for total duration of a long-term commitment at period t
c_t^s	commitment cost for total duration of a short-term commitment at period t
t_L	$\min\{t + L - 1, T\}$, $t \in \mathfrak{T}$
t_S	$\min\{t + S - 1, T\}$, $t \in \mathfrak{T}$
t'_L	$\max\{t - L + 1, 1\}$, $t \in \mathfrak{T}$
t'_S	$\max\{t - S + 1, 1\}$, $t \in \mathfrak{T}$

Decision variables

p_t	equals 1 if a long-term commitment is made at period t , 0 otherwise
q_t	equals 1 if a short-term commitment is made at period t , 0 otherwise
a_t	equals 1 if items can be stored at provider's warehouse due to the long-term commitment at period t , 0 otherwise
b_t	equals 1 if items can be stored at provider's warehouse due to the short-term commitment at period t , 0 otherwise
$u_{i,t}$	the number of item i held in inventory at retailer's warehouse from period t to $t + 1$
$v_{i,t}$	the number of item i held in inventory at provider's warehouse from period t to $t + 1$
$w_{i,t}$	the number of item i held in inventory at emergency warehouse from period t to $t + 1$
$x_{i,t}^r$	flow of item i from external suppliers to retailer's warehouse at period t
$x_{i,t}^o$	flow of item i from external suppliers to provider's warehouse at period t
$x_{i,t}^e$	flow of item i from external suppliers to emergency warehouse at period t

$y_{i,t}^r$	the number of item i delivered to customers from retailer's warehouse at period t
$y_{i,t}^o$	the number of item i delivered to customers from provider's warehouse at period t
$y_{i,t}^e$	the number of item i delivered to customers from emergency warehouse at period t

To incorporate the inventory and commitment decision from the perspective of the retailer, we considered the multi-period and multi-item inventory model based on the discrete-time planning horizon. We assumed two assumptions to present our problem. First, transshipment between warehouses is not allowed, which means that items must be stored at the assigned warehouse until they are sold to customers. Second, transportation of items is not considered. Therefore, transportation costs and freight fleets are excluded in this study. We took into account three types of a retailer's decisions as follows:

- (1) Inventory decisions: When the retailer receives items from external suppliers at period t , the retailer should make a decision of storage location for ordered items among the retailer's, provider's, and emergency warehouses. We assumed that the average inventory holding costs of warehouses within the entire planning horizon were in the following order (from cheap to expensive): provider's warehouse ($\sum_{t \in \mathcal{T}} h_{i,t}^o/T$) < retailer's warehouse ($\sum_{t \in \mathcal{T}} h_{i,t}^r/T$) < emergency warehouse ($\sum_{t \in \mathcal{T}} h_{i,t}^e/T$).
- (2) Commitment decisions: Fig.1 illustrates a simple example of commitments for a provider's warehouse. In this example, we assumed that the durations of long-term commitments and short-term commitments were four days and two days, respectively. Since a long-term commitment was made at period 1, the retailer can use the provider's warehouse until period 4. To utilize space continuously, the retailer makes a short-term commitment at period 5. At last, because the retailer does not need to use the provider's warehouse at period 7, commitments are not made, and every item stored at a provider's warehouse should be sold (i.e., $v_{i,t} = 0; \forall i \in \mathcal{I}$). We assumed that the short-term commitment cost per period (c_t^s/S) was more expensive than the long-term commitment cost (c_t^l/L). The retailer should make commitment decisions for a provider's warehouse considering total inventory and costs within the entire planning horizon.
- (3) Delivery decisions: The retailer sells items to meet demands. Considering the inventory holding costs and the availability of the provider's warehouse, the retailer should decide from which warehouses the items should be sold to customers.

Based on the notations of the parameters and decision variables, we developed the total revenue, total inventory holding costs, and total commitment costs function within the planning horizon as follows:

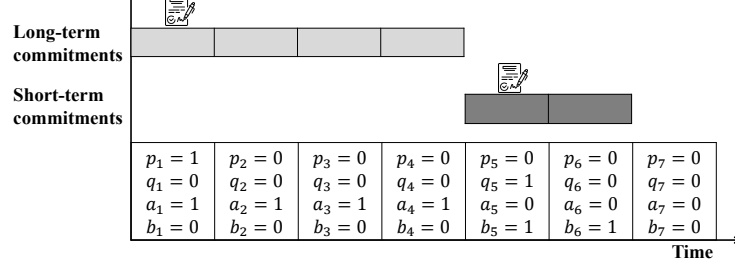


Fig. 1: Simple example of long-term and short-term commitments for provider's warehouse

$$\text{Total revenue (TR)} = \sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} [r_{i,t}(y_{i,t}^r + y_{i,t}^o + y_{i,t}^e)] \quad (1)$$

$$\text{Total inventory holding costs (THC)} = \sum_{i \in \mathcal{I}} \sum_{t \in \mathcal{T}} [h_{i,t}^r u_{i,t} + h_{i,t}^o v_{i,t} + h_{i,t}^e w_{i,t}] \quad (2)$$

$$\text{Total commitment costs (TCC)} = \sum_{t \in \mathcal{T}} [c_t^l p_t + c_t^s q_t] \quad (3)$$

Every decision variable is defined with integer variables for reflecting the behavior of commitments and properties of products. Therefore, we developed the following integer program.

$$\max \quad \text{TR} - \text{THC} - \text{TCC} \quad (4)$$

$$\text{s.t.} \quad x_{i,t}^r + x_{i,t}^o + x_{i,t}^e = s_{i,t} \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{I}; \quad (5)$$

$$y_{i,t}^r + u_{i,t} = u_{i,t-1} + x_{i,t}^r \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{I}; \quad (6)$$

$$y_{i,t}^o + v_{i,t} = v_{i,t-1} + x_{i,t}^o \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{I}; \quad (7)$$

$$y_{i,t}^e + w_{i,t} = w_{i,t-1} + x_{i,t}^e \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{I}; \quad (8)$$

$$y_{i,t}^r + y_{i,t}^o + y_{i,t}^e \leq d_{i,t} \quad \forall t \in \mathcal{T}, \forall i \in \mathcal{I}; \quad (9)$$

$$\sum_{i=1}^I u_{i,t} \leq C^r \quad \forall t \in \mathcal{T}; \quad (10)$$

$$\sum_{i=1}^I v_{i,t} \leq C_t^o (a_t + b_t) \quad \forall t \in \mathcal{T}; \quad (11)$$

$$\sum_{\tau=t}^{t_L} p_\tau \leq 1 \quad \forall t \in \mathcal{T}; \quad (12)$$

$$\sum_{\tau=t}^{t_S} q_\tau \leq 1 \quad \forall t \in \mathcal{T}; \quad (13)$$

$$\sum_{\tau=t'_L}^t p_\tau = a_t \quad \forall t \in \mathfrak{T}; \quad (14)$$

$$\sum_{\tau=t'_S}^t q_\tau = b_t \quad \forall t \in \mathfrak{T}; \quad (15)$$

$$a_t + b_t \leq 1 \quad \forall t \in \mathfrak{T}; \quad (16)$$

$$p_t + q_t \leq 1 \quad \forall t \in \mathfrak{T}; \quad (17)$$

$$p_t + q_t \leq C_t^o \quad \forall t \in \mathfrak{T}; \quad (18)$$

$$u_{i,0}, v_{i,0}, w_{i,0} = 0 \quad \forall i \in \mathfrak{I}; \quad (19)$$

$$x_{i,t}^r, x_{i,t}^o, x_{i,t}^e, y_{i,t}^r, y_{i,t}^o, y_{i,t}^e, u_{i,t}, v_{i,t}, w_{i,t} \in \mathbb{Z}^+ \quad \forall t \in \mathfrak{T}, \forall i \in \mathfrak{I}; \quad (20)$$

$$a_t, b_t, p_t, q_t \in \mathbb{B} \quad \forall t \in \mathfrak{T}; \quad (21)$$

The objective function (4) maximizes the total profits within the entire planning horizon. Constraint (5) represents the flow of items from external suppliers to the three types of warehouses. Constraints (6), (7), and (8) are the balance equations of inventory for a retailer's, a provider's, and emergency warehouses, respectively. Constraint (9) represents that the retailer cannot sell more items than are demanded. Constraints (10) and (11) show the capacity of a retailer's and a provider's warehouses, respectively. Constraints (12) and (13) represent the condition that making another commitment is not allowed until the present commitment expires. Constraints (14), (15), and (16) ensure that items are allowed to be stored at a provider's warehouse only if a long-term or short-term commitment has been made. Constraint (17) illustrates the condition that only one commitment should be made among long-term and short-term commitments at period t . Constraint (18) represents the condition that any commitment cannot be made when there is no storage space in the provider's warehouse. Constraint (19) enforces that initial inventory at every warehouse is zero. Constraint (20) ensures that decision variables for inventory, $x_{i,t}$, $y_{i,t}$, $u_{i,t}$, $v_{i,t}$, and $w_{i,t}$, are non-negative integer variables. Constraint (21) ensures that decision variables for commitments, a_t , b_t , p_t , and q_t , are binary variables.

3 Computational experiment

We conducted a small-scale experiment to identify the effects of some parameters on the commitments. We considered three types of modified problem instances (*Type*) from a basic instance (*Basic*). First, we changed the duration of the commitments while maintaining the commitment costs per period (c_t^s/S and c_t^l/L). Next, we changed the costs of the commitments per period. At last, we changed the inventory holding costs of the provider's warehouse ($h_{i,t}^o$). Table 1 presents the information of varying parameters depending on the three types of modified problem instances. Except for the parameters mentioned in Table 1, the values of other parameters, such as supply and demand, remained static.

Every experiment was implemented in the condition of ten periods and two items. According to the above properties of modifications, we implemented seven computational experiments, and the term *Case* is utilized to refer to these experiments.

Table 1: Information of varying parameters depending on the problem instances

Parameters	Basic	Type 1		Type 2		Type 3	
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
L	3	5	3	3	3	3	3
S	1	1	2	1	1	1	1
$c_t^l^*$	18	30	18	24	12	18	18
$c_t^s^*$	10	10	20	10	10	10	10
$h_{i,t}^r^{**}$	10	10	10	10	10	10	10
$h_{i,t}^o^{**}$	4	4	4	4	4	7	10
$h_{i,t}^e^{**}$	30	30	30	30	30	30	30

* The value is consistent for all period t .

** The value is consistent for all period t and item i .

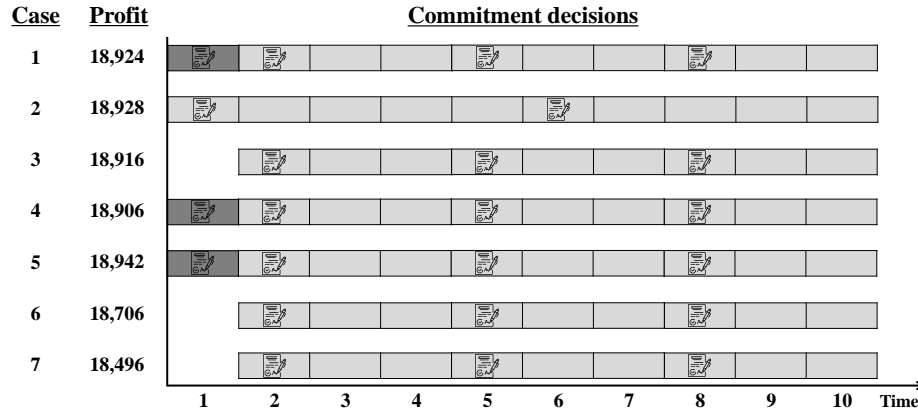


Fig. 2: Experimental results of commitment decisions

Fig.2 presents the experimental results of commitment decisions, including the information about the total profits and the periods when the commitments were made, for every case. Except for Case 2, where the entire period could have been covered by two long-term commitments, all cases had three long-term commitments at periods 2, 5, and 8. A short-term commitment was also made

in Case 1, Case 4, and Case 5, whereas the other cases did not have such a commitment. For Case 3, it cost at least 18 to access the provider's warehouse, which was quite expensive. For Case 6 and Case 7, since the inventory holding costs were more expensive than in other cases, the retailer chose to use more of the retailer's warehouse capacity for the first period.

The results were intuitive, since the profit change followed the changes of the costs in reverse order. Expanding the duration of a long-term commitment to five days increased the profit because the provider's warehouse was accessible within entire periods only with long-term commitments (Case 2). When the short-term commitment was held for two days, the total cost for the commitments decreased while the retailer lost access to the provider's warehouse for one period. Therefore, inventories were held with higher inventory holding costs, which resulted in a profit decrease (Case 3). The profit decreased/increased when the cost of a long-term commitment per period increased/decreased (Case 4 and Case 5). When the inventory holding cost for the provider's warehouse increased, the profit decreased considerably (Case 6 and Case 7). Because $h_{i,t}^e$ was the most expensive among inventory holding costs of other warehouses, the products were held in the emergency warehouse when the retailer's warehouse and the provider's warehouse had no capacity. In addition, the products held in the emergency warehouse were delivered to the customers before the retailer's warehouse and the provider's warehouse for minimizing the inventory holding costs.

4 Conclusions

We proposed a mathematical formulation for a retailer's inventory and commitment decisions for an on-demand warehousing system. Based on the proposed mathematical formulation, we conducted computational experiments to identify how commitment decisions affected the retailer's profit and strategy for utilizing a provider's warehouse. Resulting from this, we had a clue for the two research questions. As we might expect and confirm from the experiment, the retailer tries to fully utilize the provider's warehouse with the long-term commitments due to its reasonable cost. The retailer starts to stock its inventory in the provider's warehouse first, if available, next moves to its own and the emergency warehouse, consequently. On the other hand, inventories are removed from the emergency warehouse first, leading up to the retailer's and then to the provider's, with an opposite order of stocking. In the case of the commitment, the retailer tries to cover the entire period with the long-term commitments, while the short ones are used to fill up the blank periods if necessary.

In this study, we assumed that the demands were deterministic. However, for real-world application, an assumption that the demand is given could be unrealistic. Therefore, for further research, we intend to extend our study for dealing with the condition of uncertain demand through the multistage stochastic programming approach or the robust optimization approach.

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