

Dynamic Stochastic Multiple Knapsack Problem with Multi-type Items

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Abstract

We examine the dynamic stochastic multi-type multiple knapsack problem. Its dynamic programming formulation is computationally prohibitive to solve directly. To address this, we first develop a canonical bid-price control policy, a threshold policy that accepts items above a certain type-value and rejects those below. However, since this policy provides a uniform bid-price across all knapsacks, it cannot distinguish between them and requires a feasibility check for each item. We then develop a pattern-based bid-price control, which assigns a bid-price to an entire item configuration rather than to individual size. This policy offers a superior approximation of the dynamic program's value function. Finally, we propose a dynamic primal policy to capture information potentially absent from the dual formulation. The numerical results show that the performances of the pattern-based bid-price control and dynamic primal policy are better than the traditional bid-price control.

Keywords: multi-type multiple knapsack problem, revenue management, bid-price control.

1 Introduction

The dynamic stochastic multiple knapsack problem with multi-type items extends the classical knapsack problem to a dynamic and multi-dimensional setting, where items of distinct types arrive sequentially, and decisions to accept or reject them must be made immediately without knowledge of future arrivals. Each item is characterized by a type-dependent size and value, and must be placed into one of multiple knapsacks with non-identical capacities. This framework captures critical resource allocation challenges across various domains, including cloud computing, advertising systems, production planning, and energy management.

In online advertising, the problem provides a foundational framework for modeling a specific, yet relevant, aspect of real-time ad allocation. This problem can be abstracted as one where a platform must assign dynamically arriving ad campaigns from a finite set of types to heterogeneous slot inventories with varying capacities. In this formalization, campaigns of the same type share identical sizes and values, representing a standardized product. For example, the platform manages distinct advertising slot inventories, differentiated by their single-dimensional capacity, abstracted as "total available

impressions.” Their capacities are: 500,000 impressions and 1,000,000 impressions. Ad requests are from various advertisers but are grouped into a finite set of types. All requests of the same type have identical contractual requirements and value per campaign. Type-A (Luxury Auto Advertisers): Each campaign from this category requires $size = 100,000$ impressions and pays $value = \$30,000$. Type-B (Fast-Moving Consumer Goods Advertisers): Each campaign requires $size = 200,000$ impressions and pays $value = \$45,000$. Type-C (Local Service Advertisers): Each campaign requires $size = 150,000$ impressions and pays $value = \$30,000$. The DSMKP thus captures the core challenge of sequentially allocating these stochastic, typed requests to maximize revenue under capacity constraints.

The DSMKP also provides a simplified yet insightful model for cloud resource scheduling. Here, **servers** (knapsacks) differ only in their total compute capacity, and tasks (items) arrive online from a finite set of **types** with fixed sizes and values. This abstraction allows for a focused study on the core problem of allocating stochastic, typed workloads to maximize revenue. While real-world systems are far more complex, this model isolates the critical trade-off between accepting an incoming task and reserving capacity for future, potentially more profitable ones.

In modern manufacturing, the problem arises when heterogeneous production lines (knapsacks) with varying capacities must dynamically process incoming customer orders (items) of distinct types—such as urgent or standard—each with a specific processing time and profit margin. Similarly, in smart grid operations, the same structural problem emerges when multiple energy storage units (knapsacks) with distinct capacities must fulfill randomly arriving energy requests (items) from electric vehicles or industrial users, which are categorized by priority and have different energy demands and economic values. In both cases, despite vastly different domains, the core challenge remains the same: to make real-time, irrevocable decisions on accepting and assigning typed items to knapsacks to maximize total reward, without knowing future arrivals. The DSMKP provides a unified formalism to study this essential trade-off between utilizing current capacity and reserving it for future, potentially more valuable opportunities, making it a critical tool for optimizing online decision-making under uncertainty.

These applications underscore the broad applicability of the DSMKP in real-world systems where heterogeneous resources must be allocated dynamically under uncertainty. Developing efficient algorithms for this problem—with guarantees on scalability and robustness—is therefore of significant theoretical and practical interest. This paper aims to address this gap by proposing novel strategies for the DSMKP and validating them in one or more of the above domains.

We develop several policies for DSMKP. The rest of this paper is structured as follows. We review the relevant literature in Section 2. Section 3 presents the bid-price and resolving dynamic primal policies to assign the incoming requests. Section 6 presents the experimental results and provides insights gained from implementing dynamic primal. Conclusions are shown in Section 7.

Knapsacks (Servers - Varying Single-Dimensional Capacity): A cloud provider manages multiple servers. These servers are functionally identical, and the only difference between them is their total available capacity, abstracted as “compute units.”

Their capacities are, for example: Server 1: 100 units, Server 2: 150 units, Server 3: 200 units.

Key Point: Any task can be assigned to any server with sufficient remaining capacity.

Items (Tasks - Multi-type with Fixed Properties): Incoming user tasks belong to a finite set of types. Each task type has a deterministic resource requirement (size) and an associated reward (value).

Type-1 (High-Priority Task): Size = 20 units, Value = \$50. Type-2 (Medium-Priority Task): Size = 30 units, Value = \$60. Type-3 (Low-Priority Batch Task): Size = 40 units, Value = \$60.

2 Literature Review

The Multiple Knapsack Problem (MKP) (Martello and Toth, 1990) is a well-studied combinatorial optimization problem with broad practical implications. Existing literature has largely concentrated on establishing bounds or competitive ratios for general MKP instances Khuri et al. (1994); Ferreira et al. (1996); Pisinger (1999); Chekuri and Khanna (2005). In contrast, our work focuses on analyzing the specific solution characteristics of the multi-type multiple knapsack problem, providing a more tailored understanding of its dynamic form.

A closely related stream of research addresses the Dynamic Stochastic Knapsack Problem, as examined in Kleywegt and Papastavrou (1998, 2001) and Papastavrou et al. (1996). These studies typically consider a single knapsack setting where requests arrive sequentially, with resource requirements and rewards revealed only upon arrival. However, they do not incorporate multiple knapsacks, which limits their applicability to more complex resource allocation settings.

In comparison, the DSMKP generalizes this framework by introducing multiple knapsacks, significantly increasing the complexity of real-time decision-making. Moreover, in DSMKP settings, additional information—such as the arrival probabilities of different item types—is often available, enabling more informed and potentially more effective allocation strategies.

Research on dynamic and stochastic variants of the Multiple Knapsack Problem (MKP) remains relatively limited. The literature can be broadly categorized into two streams. One stream focuses on dynamic online settings, where items arrive sequentially with no prior information, as seen in studies on the online multiple knapsack problem (Bienkowski et al., 2020; Sun et al., 2020). Another stream investigates stochastic models, such as the two-stage stochastic MKP with capacitated knapsacks across predefined scenarios (Tönissen et al., 2017). Our work bridges these aspects by considering a setting where the arrival probability of each item type is known in advance. This key information enables the development of more proactive and potentially more effective allocation strategies.

Generally speaking, the DSMKP problem is related to the Revenue Management (RM) problem. RM has been extensively studied in industries such as airlines, hotels, and car rentals, where the core challenge is to dynamically allocate perishable inventory to maximize revenue (van Ryzin and Talluri, 2005). Network revenue management (NRM) extends this framework by considering multiple interconnected resources (e.g., flight legs, hotel nights) and interdependent demands (Williamson, 1992).

The standard NRM problem is typically formulated as a dynamic programming (DP) model, where decisions involve accepting or rejecting requests based on their revenue contribution and remaining capacity (Talluri and van Ryzin, 1998).

A fundamental challenge, however, is the “curse of dimensionality”, as the state space grows ex-

ponentially with problem size, making exact DP solutions computationally intractable. Consequently, various approximate control policies have been developed, including bid-price controls (Adelman, 2007; Bertsimas and Popescu, 2003), booking limits (Gallego and van Ryzin, 1997), and dynamic programming decomposition methods (Talluri and van Ryzin, 2006; Liu and van Ryzin, 2008).

However, a significant challenge arises because the number of states grows exponentially with the problem size, rendering direct solutions computationally infeasible. To address this, various control policies have been proposed, such as bid-price (Adelman, 2007; Bertsimas and Popescu, 2003), booking limits (Gallego and van Ryzin, 1997), and dynamic programming decomposition (Talluri and van Ryzin, 2006; Liu and van Ryzin, 2008).

In our problem, items often request multiple units simultaneously, requiring decisions that must be made on an all-or-none basis for each request. This requirement introduces significant complexity in managing group arrivals (Talluri and van Ryzin, 2006).

A notable study addressing group-like arrivals in revenue management examines hotel multi-day stays (Bitran and Mondschein, 1995; Goldman et al., 2002; Aydin and Birbil, 2018). While these works focus on customer classification and room-type allocation, they do not prioritize real-time assignment. The work of Zhu et al. (2023), which addresses the high-speed train ticket allocation and processes individual seat requests and implicitly accommodates group-like traits through multi-leg journeys (e.g., passengers retaining the same seat across connected segments).

3 The Model

We consider a system with a set $\mathcal{N} = 1, 2, \dots, N$ of knapsacks, where each knapsack j has a capacity $c_j \in \mathbb{Z}^+$. A finite set of item types $\mathcal{M} = 1, 2, \dots, M$ is given, where any item of type i is characterized by a size $w_i \in \mathbb{Z}^+$ and a profit $r_i \in \mathbb{Z}^+$. In the context of online advertising, for instance, size and profit correspond to the impressions required by an ad campaign and the revenue it generates, respectively. The item types are ordered such that their profit-to-weight ratios, r_i/w_i , are monotonically increasing in i .

Requests for these items arrive sequentially. Upon the arrival of a request (which specifies its type), the seller must immediately decide whether to accept or reject it. If accepted, the seller must also assign it to a specific knapsack with sufficient remaining capacity. Each item must be placed whole into a single knapsack; partial assignments or reassignments are not permitted.

To model this problem, we adopt a dynamic programming framework based on discrete time periods $t = 1, 2, \dots, T$. In each period, at most one request arrives. Let λ_i^t denote the probability that a request for an item of type $i \in \mathcal{M}$ arrives at time t . These probabilities satisfy $\sum_{i=1}^M \lambda_i^t \leq 1$ for all t , and we define $\lambda_0^t = 1 - \sum_{i=1}^M \lambda_i^t$ as the probability of no arrival in period t . Arrival events are assumed to be independent across time periods.

The system state is the vector of remaining capacities $\mathbf{C} = (c_1, \dots, c_N)$. When an item of type i arrives, the seller chooses a decision variable $u_{i,j}^t \in \{0, 1\}$ for each knapsack j . The feasible set $U^t(\mathbf{C})$ is defined by:

$$U^t(\mathbf{C}) = \left\{ u_{i,j}^t \in \{0,1\} \left| \begin{array}{ll} \text{(a)} & \sum_{j=1}^N u_{i,j}^t \leq 1 \quad \forall i \in \mathcal{M} \\ \text{(b)} & w_i u_{i,j}^t \leq c_j \quad \forall i \in \mathcal{M}, \forall j \in \mathcal{N} \end{array} \right. \right\}.$$

Constraint (a) ensures the item is assigned to at most one knapsack. Constraint (b) ensures that if the item is assigned to knapsack j ($u_{i,j}^t = 1$), its weight w_i does not exceed c_j . The original vector form of this constraint, $w_i u_{i,j}^t \mathbf{e}_j \leq \mathbf{C}$ (where \mathbf{e}_j is the j -th standard basis vector), is mathematically equivalent to (b).

Let $v^t(\mathbf{C})$ denote the value function, representing the maximum expected revenue obtainable from period t onward, given the current remaining capacity vector \mathbf{C} . The Bellman equation is given by:

$$v^t(\mathbf{C}) = \max_{u_{i,j}^t \in U^t(\mathbf{C})} \left\{ \sum_{i=1}^M \lambda_i^t \left(\sum_{j=1}^N r_i u_{i,j}^t + v^{t+1}(\mathbf{C} - w_i u_{i,j}^t \mathbf{e}_j) \right) + \lambda_0^t v^{t+1}(\mathbf{C}) \right\} \quad (1)$$

The boundary condition is $v^{T+1}(\mathbf{C}) = 0$ for all $\mathbf{C} \geq \mathbf{0}$, indicating that no more revenue can be earned after the final period T .

Let $\mathbf{C}_0 = (C_1, C_2, \dots, C_N)$ be the initial capacity vector. The objective is to compute $v^1(\mathbf{C}_0)$, the maximum total expected revenue over the entire horizon from $t = 1$ to $t = T$, and to find the policy of item assignments that achieves this value.

Solving the dynamic programming problem presented in Equation (1) is computationally intractable for realistic problem sizes due to the curse of dimensionality inherent in the large state space.

To overcome this challenge, we propose a heuristic assignment policy. We first outline a traditional bid-price control policy. We then enhance this approach by introducing a novel bid-price control policy that leverages patterns.

3.1 BPC Policy

Bid-price control is a classical and widely studied methodology in network revenue management. The core idea is to set thresholds, known as bid prices, that represent the opportunity cost of consuming one unit of capacity. An item is accepted only if its revenue exceeds the estimated opportunity cost of the capacity it requires.

Typically, these bid prices are derived from the shadow prices of the capacity constraints in a deterministic approximation of the underlying stochastic problem. In this section, we detail the implementation of a bid-price control policy for our model.

We begin by formulating a deterministic linear programming (LP) approximation, specifically the LP relaxation of a multi-type multiple knapsack problem. This model uses expected demand over the horizon. Let x_{ij} denote the number of type i items assigned to knapsack j , and let $d_i = \sum_{t=1}^T \lambda_i^t$ represent the expected number of requests for type i . The formulation is as follows:

$$\max \quad \sum_{i=1}^M \sum_{j=1}^N r_i x_{ij} \quad (2)$$

$$\text{s.t.} \quad \sum_{j=1}^N x_{ij} \leq d_i, \quad i \in \mathcal{M}, \quad (3)$$

$$\sum_{i=1}^M w_i x_{ij} \leq c_j, \quad j \in \mathcal{N}, \quad (4)$$

$$x_{ij} \geq 0, \quad i \in \mathcal{M}, j \in \mathcal{N}.$$

The objective (2) is to maximize total expected revenue. Constraint (3) ensures the total number of accepted type i items does not exceed its expected demand. Constraint (4) ensures the total weight in each knapsack j does not exceed its initial capacity C_j .

The monotonic increase of the profit-to-weight ratio r_i/w_i with type index i implies that items with a higher index are more profitable per unit of capacity. Consequently, the optimal solution to the LP relaxation exhibits a greedy structure, preferentially utilizing higher-indexed item types. This structural property is formalized in Proposition 1.

Lemma 1. *For the LP relaxation of the MKP problem, there exists an index \tilde{i} such that the optimal solutions satisfy the following conditions: $x_{ij}^* = 0$ for all j , $i = 1, \dots, \tilde{i} - 1$; $\sum_{j=1}^N x_{ij}^* = d_i$ for $i = \tilde{i} + 1, \dots, M$; $\sum_{j=1}^N x_{ij}^* = \frac{L - \sum_{i=\tilde{i}+1}^M d_i w_i}{w_{\tilde{i}}}$ for $i = \tilde{i}$.*

The dual of LP relaxation of the MKP problem is:

$$\begin{aligned} \min \quad & \sum_{i=1}^M d_i z_i + \sum_{j=1}^N c_j \beta_j \\ \text{s.t.} \quad & z_i + \beta_j w_i \geq r_i, \quad i \in \mathcal{M}, j \in \mathcal{N} \\ & z_i \geq 0, i \in \mathcal{M}, \beta_j \geq 0, j \in \mathcal{N}. \end{aligned} \quad (5)$$

In (5), β_j can be interpreted as the bid-price for one size in knapsack j . A request is only accepted if the revenue it generates is no less than the sum of the bid prices of the sizes it uses. Thus, if $r_i - \beta_j w_i \geq 0$, meanwhile, the capacity allows, we will accept the item type i . And choose knapsack $j^* = \arg \max_j \{r_i - \beta_j w_i\}$ to allocate that item.

Proposition 1. *The optimal solution to problem (5) is given by $z_1 = \dots = z_{\tilde{i}} = 0$, $z_i = \frac{r_i w_{\tilde{i}} - r_{\tilde{i}} w_i}{w_{\tilde{i}}}$ for $i = \tilde{i} + 1, \dots, M$ and $\beta_j = \frac{r_{\tilde{i}}}{w_{\tilde{i}}}$ for all j .*

According to Proposition 1, the decision inequality becomes $r_i - \beta_j w_i = r_i - \frac{r_{\tilde{i}}}{w_{\tilde{i}}} w_i \geq 0$. This establishes the threshold policy: reject item type $i, i < \tilde{i}$ and accept item type $i, i \geq \tilde{i}$.

Algorithm 1: Bid-Price Control

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1 for  $t = 1, \dots, T$  do
2   Observe a request of item type  $i$ ;
3   Solve problem (5) with  $\mathbf{d}^{[t,T]}$  and  $\mathbf{C}^t$ ;
4   Obtain  $\tilde{i}$  such that the aggregate optimal solution is  $xe_{\tilde{i}} + \sum_{i=\tilde{i}+1}^M d_i^t e_i$ ;
5   if  $i \geq \tilde{i}$  and  $\max_{j \in \mathcal{N}} c_j^t \geq w_i$  then
6     Set  $k = \arg \min_{j \in \mathcal{N}} \{c_j^t | c_j^t \geq w_i\}$  and break ties;
7     Assign the item to knapsack  $k$ , let  $c_k^{t+1} \leftarrow c_k^t - w_i$ ;
8   else
9     Reject the request;
10  end
11 end

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Let $z(\text{BPC})$, $z(\text{DLP})$ denote the optimal value of (5) and the LP relaxation of the MKP problem with expected demand, respectively. Then we have $z(\text{BPC}) = z(\text{DLP})$.

However, the BPC policy has two drawbacks. First, the capacity feasibility need to be checked when to accept a request. Second, when capacities permit, the policy treats all knapsacks as equally preferable, making no distinction among them.

Example 1. Consider an instance with $M = 3$, $N = 4$, $w_1 = 3, w_2 = 4, w_3 = 5$, $r_1 = 4, r_2 = 6, r_3 = 8$, $\mathbf{C} = [7, 8, 8, 4]$ and $T = 8$. The stationary arrival probability is $\lambda_1 = \lambda_3 = \frac{1}{4}$, $\lambda_2 = \frac{1}{2}$, giving an expected demand vector $\mathbf{d} = (2, 4, 2)$.

Under traditional bid-price control, the bid-price for each knapsack j is $\beta_j^* = \frac{4}{3}$, yielding a total expected reward $z(\text{BPC}) = \frac{124}{3}$. This solution exhibits two major drawbacks:

It fails to differentiate between knapsacks, assigning them a uniform bid-price. It permits potentially infeasible assignments. For instance, even though $r_3 - \beta_4^* * w_3 > 0$, assigning a type 3 item (with weight 5) to knapsack 4 (with capacity 4) is infeasible.

3.2 BPC Policy Based on Patterns (BPP)

In the BPC policy, we treat each size in each knapsack separately. However, a request always occupies a series of consecutive sizes within a knapsack. In order to capture the value of an item, it would be helpful to consider the sizes of an item jointly. In the following, we consider an alternative bid-price formulation based on the idea of pattern and we derive a different set of bid-prices and hence a better-performing control policy. The core idea, as we explain next, is to reformulate the dynamic system with patterns.

Let $\mathbf{h} = [h_1, \dots, h_M]$ denote a pattern for a knapsack, where each h_i denotes the number of type- i items assigned. A pattern \mathbf{h} is feasible for a knapsack with capacity c_j if it satisfies $\sum_{i=1}^M w_i h_i \leq c_j$. For any knapsack j , we construct a set $S(c_j)$ which contains all feasible patterns. For a more general case where \mathbf{h} is subject to additional constraints, the set $S(c_j)$ can be extended to include only those solutions that satisfy them. The following algorithm can also be adjusted accordingly.

A request of type i can be accepted only if there exists at least one knapsack j with sufficient remaining capacity $c_j \geq w_i$. This is equivalent to the existence of a feasible pattern $\mathbf{h} \in S(c_j)$ for that knapsack that includes at least one item of type i (i.e., $h_i \geq 1$).

To formalize this, we define the maximum value obtainable from accepting a type i request. For a given knapsack j and pattern \mathbf{h} that can accommodate the item ($\mathbf{h} \in S(c_j)$, $h_i \geq 1$), the value of placing it in j is the sum of the immediate reward r_i and the future value $v^{t+1}(\mathbf{C} - e_j^T w_i)$ starting from the updated capacity.

We therefore define q_i as the maximum of this value over all feasible placement options:

$$q_i = \begin{cases} \max_{j: \exists \mathbf{h} \in S(c_j), h_i \geq 1} \{v^{t+1}(\mathbf{C} - e_j^T w_i) + r_i\} & \text{if such a knapsack } j \text{ exists,} \\ 0 & \text{otherwise} \end{cases}$$

In this definition, the maximization evaluates the optimal placement of a type- i item by considering all knapsacks j for which there exists at least one feasible pattern $\mathbf{h} \in S(c_j)$ capable of holding it ($h_i \geq 1$).

Now we present the DP formulation from the pattern perspective. Recall that $v^t(\mathbf{C})$ denotes the maximal expected value-to-go at time t , given the remaining capacity \mathbf{C} . The dynamic programming can be reformulated as follows:

$$\begin{aligned} v^t(\mathbf{C}) &\geq \mathbb{E}_{i \sim \lambda^t} \left[\max \{q_i, v^{t+1}(\mathbf{C})\} \right], \forall t, \\ v^{T+1}(\mathbf{C}) &= 0 \end{aligned} \tag{6}$$

The maximization compares the value of accepting i (via the maximization of q_i) and rejecting i (retaining $v^{t+1}(\mathbf{C})$). If no such j exists, the request i is rejected.

We can solve the following program to compute $v^1(\mathbf{C})$ for any given capacity \mathbf{C} :

$$\begin{aligned} \min \quad & v^1(\mathbf{C}) \\ \text{s.t.} \quad & v^t(\mathbf{C}) \geq \mathbb{E}_{i \sim \lambda^t} \left[\max \{q_i, v^{t+1}(\mathbf{C})\} \right], \\ & v^{T+1}(\mathbf{C}) \geq 0. \end{aligned} \tag{7}$$

Solving (7) remains computationally intractable. We therefore adopt an Approximate Dynamic Programming (ADP) approach (Adelman, 2007) to approximate the value function $v^t(\mathbf{C})$. Our proposed approximation is:

$$\hat{v}^t(\mathbf{C}) = \theta^t + \sum_{j=1}^N \max_{\mathbf{h} \in S(c_j)} \left\{ \sum_{i=1}^M \beta_{ij}^\dagger h_i \right\}. \tag{8}$$

The term β_{ij}^\dagger can be regarded as the approximated value for each type i in knapsack j . Unlike traditional linear approximations, our approach retains the linear term θ^t but introduces a nonlinear component for each knapsack j . Specifically, we maximize the linear combination $\sum_{i=1}^M \beta_{ij}^\dagger h_i$ over the feasible set $S(c_j)$.

Substituting (8) into (7), we have:

$$\theta^t - \theta^{t+1} = \hat{v}^t(\mathbf{C}) - \hat{v}^{t+1}(\mathbf{C}) \geq \sum_i \lambda_i^t \max \{q_i - v^{t+1}(\mathbf{C}), 0\} \quad (9)$$

For the case where there exists a knapsack j satisfying both conditions: $\mathbf{h}^* \in \arg \max_{\mathbf{h} \in S(c_j)} \sum_i \beta_{ij}^\dagger h_i$ and $h_i^* \geq 1$, we establish the value difference:

$$\begin{aligned} & v^{t+1}(\mathbf{C} - e_j^T w_i) - v^{t+1}(\mathbf{C}) \\ &= \max_{\mathbf{h} \in S(c_j - w_i)} \left\{ \sum_i \beta_{ij}^\dagger h_i \right\} - \max_{\mathbf{h} \in S(c_j)} \left\{ \sum_i \beta_{ij}^\dagger h_i \right\} \\ &= -\beta_{ij}^\dagger \leq 0 \end{aligned}$$

The acceptance threshold is then defined as:

$$\alpha_i = \max \left\{ \max_j \left\{ r_i - \beta_{ij}^\dagger \right\}, 0 \right\},$$

with $\alpha_i = 0$ when no qualifying knapsack j exists.

Let $\gamma_j = \max_{\mathbf{h} \in S(c_j)} \{\sum_i \beta_{ij}^\dagger h_i\}$. This yields:

$$\begin{aligned} \theta^1 &= \sum_{t=1}^T (\theta^t - \theta^{t+1}) \geq \sum_t \sum_i \alpha_i \lambda_i^t = \sum_i d_i \alpha_i \\ \hat{v}^1(\mathbf{C}) &= \sum_i d_i \alpha_i + \sum_j \gamma_j \end{aligned}$$

Since $\hat{v}^1(\mathbf{C})$ constitutes a feasible solution to (7), we have $\hat{v}^1(\mathbf{C}) \geq v^1(\mathbf{C})$.

If all j exist for $\mathbf{h}^* \in \arg \max_{\mathbf{h} \in S(c_j)} \sum_i \beta_{ij}^\dagger h_i, h_i^* \geq 1$, the corresponding bid-price problem can be expressed as:

$$\begin{aligned} \min \quad & \sum_{i=1}^M \alpha_i d_i + \sum_{j=1}^N \gamma_j \\ \text{s.t.} \quad & \alpha_i + \beta_{ij}^\dagger \geq r_i, \quad \forall i, j, \\ & \sum_{i=1}^M \beta_{ij}^\dagger h_i \leq \gamma_j, \quad \forall j, \mathbf{h} \in S(c_j), \\ & \alpha_i \geq 0, \forall i, \quad \beta_{ij}^\dagger \geq 0, \forall i, j \\ & \gamma_j \geq 0, \quad \forall j. \end{aligned} \quad (10)$$

α_i represents marginal revenue for type i . β_{ij}^\dagger represents the cost for type i assigned in knapsack j . γ_j represents the capacity cost associated with knapsack j .

If for a given item type i , no knapsack j contains an optimal allocation $\mathbf{h}^* \in \arg \max_{\mathbf{h} \in S(c_j)} \sum_i \beta_{ij}^\dagger h_i$

with $h_i^* \geq 1$, then the variable α_i must be zero. This indicates that the constraint associated with item type i and knapsack j is redundant. Although these constraints appear difficult to enforce in advance, the following lemma reveals that in practice we can avoid imposing additional restrictions. Simply solving problem (10) will inherently satisfy all required conditions.

Lemma 2. Define $\mathcal{J}_i = \{j \in \mathcal{N} \mid r_i - \beta_{ij}^{\dagger*} \geq r_i - \beta_{ik}^{\dagger*}, \forall k \in \mathcal{N}, r_i - \beta_{ij}^{\dagger*} > 0\}$. If $\mathcal{J}_i = \emptyset$, the first set of constraints for i is redundant. If $\mathcal{J}_i \neq \emptyset$, then there exists a $j' \in \mathcal{J}_i$ such that:

$$\mathbf{h}^* \in \arg \max_{\mathbf{h} \in S(c_{j'})} \sum_i \beta_{ij'}^{\dagger*} h_i, h_i^* \geq 1.$$

This lemma guarantees that when such a j' exists, the first set of constraints for i becomes active; otherwise, it remains inactive. Consequently, we have $z(\text{BPP}) = \hat{v}^1(\mathbf{C})$.

The control policy is then defined as follows. For the arriving type- i item, if $\alpha_i > 0$, accept the type i . Assign the type i to a knapsack $j \in \mathcal{J}_i$ satisfying:

$$\mathbf{h}^* \in \arg \max_{\mathbf{h} \in S(c_j)} \sum_i \beta_{ij}^{\dagger*} h_i, h_i^* \geq 1.$$

If $\alpha_i = 0$ and there exists a knapsack j such that: $\mathbf{h}^* \in \arg \max_{\mathbf{h} \in S(c_j)} \sum_i \beta_{ij}^{\dagger*} h_i, h_i^* \geq 1$, accept the type i and assign it to knapsack j ; otherwise, reject the type i .

Let $z(\text{BPC})$ and $z(\text{BPP})$ denote the expected optimal value of (5) and (10), respectively.

Proposition 2. We have $z(\text{BPC}) \geq z(\text{BPP})$.

Both bid-price approaches give upper bounds on the value function at any state, meanwhile it follows that BPP provides a tighter approximation to the value function more accurately than BPC does.

Under the approximation (8), the BPP policy operates as follows:

Algorithm 2: Bid-Price Control Based on Patterns

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1 for  $t = 1, \dots, T$  do
2   Observe a request of item type  $i$ ;
3   Solve problem (10) with  $\mathbf{d}^{[t,T]}$  and  $\mathbf{L}^t$ ;
4   if  $\alpha_i > 0$  then
5     Assign the type  $i$  to a knapsack  $j \in \mathcal{J}_i$  satisfying:
        
$$\mathbf{h}^* \in \arg \max_{\mathbf{h} \in S(c_j)} \sum_i \beta_{ij}^\dagger h_i, h_i^* \geq 1.$$

        Let  $c_j^{t+1} \leftarrow c_j^t - w_i$ ;
6   else
7     if There exists  $j$  such that  $\mathbf{h}^* \in \arg \max_{\mathbf{h} \in S(c_j)} \sum_i \beta_{ij}^\dagger h_i, h_i^* \geq 1$  then
8       Assign the item in knapsack  $j$ , let  $c_j^{t+1} \leftarrow c_j^t - w_i$ ;
9     else
10      Reject the request;
11    end
12  end
13 end

```

Unlike the traditional BPC, the BPP does not require explicit feasibility checks on capacity. However, it still needs to verify whether the optimal pattern contains the given request. This introduces a new challenge, as bid-price policies are inherently derived from a dual formulation, which may inherently omit key information preserved in the primal problem.

Example 2. *Continue with the above example:*

For the BPP, the optimal bid prices are $\beta 1^* = [4, 4, 4, 6]$, $\beta 2^* = [6, 6, 6, 6]$, and $\beta 3^* = [10, 8, 8, 8]$. The resulting objective value is $z(\text{BPP}) = 40$, which is less than $z(\text{BPC}) = \frac{124}{3}$. Using type 3 as an example, we see it can only be assigned to knapsack 2 or 3. From the item's perspective, its reduced reward vector $r_3 - \beta 3^* = [-2, 0, 0, 0]$ reveals it is unprofitable for knapsack 1, while from the knapsack's perspective, the optimal solution requires two patterns, $[0, 1, 0]$ and $[1, 0, 0]$ for knapsack 4, indicating that type 3 is also excluded from this knapsack.

While this verification is cumbersome under pure bid-price frameworks, the primal problem offers a more direct way to guarantee the existence of such a request-pattern match. To address this gap, we propose the dynamic primal formulation.

4 Dynamic Primal Based on Patterns

Let $y_{j\mathbf{h}}$ denote the proportion of pattern \mathbf{h} used in knapsack j . The primal problem can be formulated as:

$$\begin{aligned}
& \max \quad \sum_{i=1}^M \sum_{j=1}^N r_i x_{ij} \\
& \text{s.t.} \quad \sum_{j=1}^N x_{ij} \leq d_i, \quad i \in \mathcal{M}, \\
& \quad \quad x_{ij} \leq \sum_{\mathbf{h} \in S(c_j)} h_i y_{j\mathbf{h}}, \quad i \in \mathcal{M}, j \in \mathcal{N}, \\
& \quad \quad \sum_{\mathbf{h} \in S(c_j)} y_{j\mathbf{h}} \leq 1, \quad j \in \mathcal{N}.
\end{aligned} \tag{11}$$

The first set of constraints demonstrate that for each item type i , the sum of assigned items and unassigned items equals the total demand. The second set of constraints shows that the number of items of type i assigned in knapsack j is not larger than the sum of h_i (the count of type i items in pattern \mathbf{h}) weighted by the pattern proportions $y_{j\mathbf{h}}$. The total proportion of patterns used in knapsack j cannot exceed 1.

Proposition 3. *If the optimal solution x_{ij}^* to (11) satisfies $x_{ij}^* > 0$ for a pair (i, j) , then for that knapsack j , we have*

$$\mathbf{h}^* \in \arg \max_{\mathbf{h} \in S(c_j)} \sum_i \beta_{ij}^\dagger h_i, h_i^* \geq 1.$$

In contrast to Lemma 2, this lemma ensures the existence of a knapsack j to accommodate item type i when $x_{ij}^* > 0$. This eliminates the need for explicit existence verification.

4.1 Solve the Dynamic Primal

The pattern \mathbf{h} is efficient for knapsack j if and only if, for some $(\alpha_1, \dots, \alpha_M, \gamma_j)$ (except that $\alpha_i = r_i, \forall i$), \mathbf{h} is the optimal solution to

$$\max_{\mathbf{h}} \sum_{i=1}^M (r_i - \alpha_i) h_i - \gamma_j$$

To generate all efficient patterns, we need to solve the subproblem for each knapsack j :

$$\begin{aligned}
& \max \quad \sum_{i=1}^M (r_i - \alpha_i) h_i - \gamma_j \\
& \text{s.t.} \quad \sum_{i=1}^M w_i h_i \leq c_j, \\
& \quad \quad h_i \in \mathbb{N}, \quad i \in \mathcal{M}.
\end{aligned} \tag{12}$$

If the optimal value of (12) is larger than 0, the primal (11) reaches the optimal. Otherwise, a new pattern can be generated.

One important fact is that only efficient sets are used in the solution to (11). Therefore, if $y_{j\mathbf{h}}^* > 0$ is the optimal solution to (11), then \mathbf{h} is an efficient pattern.

A pattern \mathbf{h} is dominant if there is no distinct pattern \mathbf{h}' where every component of \mathbf{h}' is greater than or equal to the corresponding component of \mathbf{h} . The efficient pattern is a dominating pattern. (If $\alpha_i = r_i$, (11) reaches the optimal and no pattern will be generated.)

The relation between the capacity and the demand shows the different structure of the optimal solution.

Lemma 3. *When $\sum_{i=1}^M d_i w_i < \sum_{j=1}^N c_j$, we have $\gamma_j^* = 0, \forall j$, $\beta_{ij}^{\dagger*} = 0, \forall i, j$ and $\alpha_i^* = r_i, \forall i$. There exists at least one knapsack j such that $\sum_{\mathbf{h} \in S(c_j)} y_{j\mathbf{h}}^* < 1$.*

When $\sum_{i=1}^M d_i w_i \geq \sum_{j=1}^N c_j$, we have $\sum_{\mathbf{h} \in S(c_j)} y_{j\mathbf{h}}^ = 1, \forall j$.*

Algorithm 3: Dynamic Primal

```

1 for  $t = 1, \dots, T$  do
2   Observe a request of type  $i$ ;
3   if  $c_j^t = w_i, \exists j$  then
4     Assign the item to knapsack  $j$ ;
5     continue
6   end
7   Solve problem (11) with  $\mathbf{d}^{[t,T]}$ ;
8   Obtain an optimal solution  $x_{ij}$ ;
9   if  $\max_j \{x_{ij}\} > 0$  then
10    Set  $k = \arg \max_j \{x_{ij}\}$  and break ties;
11    Assign the item to knapsack  $k$ , let  $c_k^{t+1} \leftarrow c_k^t - w_i$ ;
12  else
13    Reject the request;
14  end
15 end

```

Meanwhile, it guarantees feasible placement. Once a request is accepted, the policy ensures it can be assigned to a suitable knapsack without additional feasibility checks.

Example 3. *For the dynamic primal, the optimal solution is given by $\mathbf{x}_1^* = [1, 1, 0, 0]$, $\mathbf{x}_2^* = [1, 0, 2, 1]$, $\mathbf{x}_3^* = [0, 1, 0, 0]$. This indicates that type 1 can be assigned to knapsacks 1 or 2, type 2 cannot be assigned to knapsack 2, type 3 can only be assigned to knapsack 2.*

In the optimal solution, the efficient patterns for each knapsack are $[1, 1, 0]$, $[1, 0, 1]$, $[0, 2, 0]$, $[0, 1, 0]$. For instance, $[1, 1, 0]$ shows that knapsack 1 can hold one item of type 1 and one of type 2.

Using the decision variable x_{ij} to represent these assignments is a straightforward and easily implementable approach.

5 Asymptotic Loss

Given any instance, we define a sequence of problems indexed by $\theta \in \mathbb{N}$ with $C(\theta) = \theta \mathbf{C}$ and $\lambda_i^t(\theta) = \lambda_i^{\lceil t/\theta \rceil}$. We scale the number of capacities and the length of the time horizon proportionally.

θ is the scale parameter.

Proposition 4. *Loss:* $V_\theta^{HO} - V_\theta^{BL} = O(\sqrt{\theta})$.

Proposition 5. *Loss:* $V_\theta^{HO} - V_\theta^P = O(1)$.

5.1 Loss for Static BLC Policy

Booking limit control policy:

$$\begin{aligned} \max \quad & \sum_{i=1}^M \sum_{j=1}^N r_i x_{ij} \\ \text{s.t.} \quad & \sum_{j=1}^N x_{ij} \leq d_i, \quad i \in \mathcal{M}, \\ & \sum_{i=1}^M w_i x_{ij} \leq L_j, j \in \mathcal{N}, \end{aligned} \tag{13}$$

Let $d_i = \sum_t \mathbf{1}_{i_t=i}$ be the realized number of type i over the horizon T . Consider the deterministic linear programming (13), where the right-hand side demands are set to $\sum_t \lambda_i^t$. Let x_{ij}^* be an integral optimal solution to this LP, and define $d_i^* = \sum_j x_{ij}^*$ as the total number of type i assigned in this optimal solution. Finally, let $val(I; \{d_i\})$ denote the optimal objective value of (13) for a given instance I and demand vector $\{d_i\}$.

$$V^{BL}(I) = E_{\{d_i\}}[\sum_i r_i \min\{d_i^*, d_i\}], \quad V^{OPT}(I) = E_{\{d_i\}}[val(I; \{d_i\})] \leq val(I; \{E[d_i]\}).$$

$val(I; \{d_i\})$ is concave in d_i .

$$\begin{aligned} & V^{OPT}(I) - V^{BL}(I) \\ & \leq val(I; \{E[d_i]\}) - V^{BL}(I) \\ & = val(I; \{E[d_i]\}) - val(I; \{\lfloor E[d_i] \rfloor\}) + val(I; \{\lfloor E[d_i] \rfloor\}) - E_{\{d_i\}}[\sum_i r_i \min\{d_i^*, d_i\}] \\ & \leq \sum_i r_i + N \sum_i r_i + E_{\{d_i\}}[\sum_i r_i (d_i^* - \min\{d_i^*, d_i\})] \\ & = (1+N) \sum_i r_i + E_{\{d_i\}}[\sum_i \frac{1}{2} r_i (d_i^* - d_i + |d_i^* - d_i|)] \\ & \stackrel{(a)}{\leq} (1+N) \sum_i r_i + \frac{1}{2} \sum_i r_i (d_i^* - E[d_i] + |d_i^* - E[d_i]| + \sqrt{\text{Var}[d_i]}) \\ & \leq (1+N) \sum_i r_i + \frac{1}{2} \sum_i r_i \sqrt{\text{Var}[d_i]} \\ & \leq (1+N) \sum_i r_i + \frac{1}{2} \sum_i r_i \sqrt{T p_i (1-p_i)} = O(\sqrt{T}) \end{aligned}$$

The revenue loss between the static deterministic heuristic and the optimal is bounded by $C\sqrt{T}$. Thus, $\lim_{T \rightarrow \infty} (V^{OPT}(I) - V^{BL}(I))/T \rightarrow 0$.

$$\text{val}(I; \{E[d_i]\}) - \text{val}(I; \{\lfloor E[d_i] \rfloor\}) \leq \text{val}(I; \{\lceil E[d_i] \rceil\}) - \text{val}(I; \{\lfloor E[d_i] \rfloor\}) \leq \sum_i r_i$$

$$LP - IP \leq \sum_i \sum_j r_i (x_{ij}^* - \lfloor x_{ij}^* \rfloor) < N \sum_i r_i \Rightarrow \text{val}(I; \{\lfloor E[d_i] \rfloor\}) \leq IP + N \sum_i r_i.$$

$$IP = \sum_i \sum_j r_i x_{ij}^* = \sum_i r_i d_i^*$$

(a) results from the following inequalities: $|d_i^* - d_i| = |(d_i^* - E[d_i]) + (E[d_i] - d_i)| \leq |d_i^* - E[d_i]| + |d_i - E[d_i]|$. Take the expectation, we have $E[|d_i^* - d_i|] \leq |d_i^* - E[d_i]| + E[|d_i - E[d_i]|]$. $E[|d_i - E[d_i]|] \leq \sqrt{\text{Var}[d_i]}$ (Since $E[|X|] \leq \sqrt{E[X^2]}$). $d_i^* \leq E[d_i]$.

5.2 Loss for Dynamic Primal Policy

$$E[\text{loss}] = V^{\text{off}} - V_{\pi}^{\text{on}} \geq V^{\text{opt}} - V_{\pi}^{\text{on}}$$

Let $V^{\text{OPT}}(I)$ denote the expected value under offline optimal policy (relaxed) during T periods for instance I (capacity, probability distribution).

Let γ_{ij}, γ_i^0 denote the number of type i accepted in capacity j and rejected by this policy, respectively.

$$\begin{aligned} OPT(\mathbf{C}, d, \gamma) : \quad & \max \quad \sum_{i=1}^M \sum_{j=1}^N r_i x_{ij} \\ \text{s.t.} \quad & \sum_{j=1}^N x_{ij} + x_{i0} = d_i, \quad i \in \mathcal{M}, \\ & x_{ij} \geq \gamma_{ij}, \quad i \in \mathcal{M}, j \in \mathcal{N} \\ & x_{i0} \geq \gamma_i^0, \quad i \in \mathcal{M}, \\ & \sum_{i=1}^M w_i x_{ij} \leq c_j, \quad j \in \mathcal{N}. \end{aligned}$$

$d^{[1,T]}$ is the demand realization during $[1, T]$. $\gamma_{ij}^{[1,t]}$ represents the number of requests i assigned in knapsack j by the policy during $[1, t]$.

$OPT(\mathbf{C}, d^{[1,T]}, \gamma^{[1,t+1]})$ can be interpreted as the total reward obtained under a virtual policy where we first follow the heuristic policy during $[1, t+1]$ and then from time $t+1$ we follow the optimal solution assuming that we know the future demands.

For one sample path of the requests, the revenue loss can be decomposed into T increments.

$$\begin{aligned} & OPT(\mathbf{C}, d^{[1,T]}, 0) - OPT(\mathbf{C}, d^{[1,T]}, \gamma^{[1,T]}) \\ &= \sum_{t=1}^T [OPT(\mathbf{C}, d^{[1,T]}, \gamma^{[1,t]}) - OPT(\mathbf{C}, d^{[1,T]}, \gamma^{[1,t+1]})] \end{aligned}$$

Let $T_i = \sup\{t \leq T : \lambda_i^t > 0\}$.

Then

$$\inf_{\substack{t, i: \\ t \in [\theta T_i]}} \frac{\lambda_i^{(t, \theta T_i]}(\theta)}{\theta T_i - t}$$

is lower bounded by some positive constant

$$\lambda_{\min} \triangleq \inf_i \frac{\lambda_i^{T_i}}{T_i}$$

The expected revenue loss can be upper bounded:

$$\begin{aligned} & E[OPT(\mathbf{C}, d^{[1,T]}, 0) - OPT(\mathbf{C}, d^{[1,T]}, \gamma^{[1,T]})] \\ & \leq l \sum_{t=1}^T P(OPT(\mathbf{C}, d^{[1,T]}, \gamma^{[1,t]}) - OPT(\mathbf{C}, d^{[1,T]}, \gamma^{[1,t+1]}) > 0) \\ & = l \sum_{t=1}^T P(OPT(\mathbf{C}^t, d^{[t,T]}, 0) - OPT(\mathbf{C}^t, d^{[t,T]}, \gamma^{[t,t+1]}) > 0) \\ & \leq l \sum_{t=1}^T P(x_{i^t j^t}^{*,t} < 1) \end{aligned}$$

$OPT(\mathbf{C}, d^{[1,T]}, \gamma^{[1,t]}) - OPT(\mathbf{C}, d^{[1,T]}, \gamma^{[1,t+1]}) \leq l$. l is related to r_M .

Lemma 4. $OPT(\mathbf{C}^1, \hat{d} + d^{[1,t_2]}, \gamma^{[1,t_2]}) = \sum_i r_i \sum_j \gamma_{ij}^{[1,t_1]} + OPT(\mathbf{C}^t, \hat{d} + d^{[t_1,t_2]}, \gamma^{[t_1,t_2]})$

For any optimal solution x^* of $OPT(\mathbf{C}^t, \hat{d} + d^{[t_1,t_2]}, \gamma^{[t_1,t_2]})$, $x^* + \gamma^{[1,t_1]}$ is a feasible solution of $OPT(\mathbf{C}^1, \hat{d} + d^{[1,t_2]}, \gamma^{[1,t_2]})$. For any optimal solution x^* of $OPT(\mathbf{C}^1, \hat{d} + d^{[1,t_2]}, \gamma^{[1,t_2]})$, $x^* - \gamma^{[1,t_1]}$ is a feasible solution of $OPT(\mathbf{C}^t, \hat{d} + d^{[t_1,t_2]}, \gamma^{[t_1,t_2]})$ because $x^* - \gamma^{[1,t_1]} \geq \gamma^{[1,t_2]} - \gamma^{[1,t_1]} = \gamma^{[t_1,t_2]}$.

The first inequality results from $E[A] \leq lE[\mathbf{1}_{A>0}] = lP(A > 0)$.

The first equation follows from Lemma 4. (Let $t_1 = t_2 = t$, $\hat{d} = d^{[t,T]}$; let $t_1 = t$, $t_2 = t + 1$, $\hat{d} = d^{[t+1,T]}$).

The second equation is as follows. If $x_{i^t j^t}^{*,t} \geq 1$, then $x^{*,t}$ is still feasible for $OPT(\mathbf{C}^t, d^{[t,T]}, \gamma^{[t,t+1]})$. (Because the optimal policy)

$x_{i^t j^t}^{*,t}$ is the optimal solution for $OPT(\mathbf{C}^t, d^{[t,T]}, 0)$ at time t .

Now we consider $P(x_{i^t j^t}^{*,t} < 1)$. In time period t , after realization of i^t , based on the maximum choice of j^t in dynamic primal policy, we have

$$\gamma_{i^t j^t}^{P,t} = \max_j \gamma_{i^t j}^{P,t} \geq \frac{\sum_j \gamma_{i^t j}^{P,t}}{\sum_j 1} = \frac{\lambda_{i^t}^{[t,\theta T]}}{N}$$

$$\begin{aligned}
& \mathbb{P} \left(x_{i^t j^t}^{*,t} < 1 \right) \\
& \leq \mathbb{P} \left(x_{i^t j^t}^{*,t} < x_{i^t j^t}^{\text{P},t} + 1 - \frac{\lambda_{i^t}^{[t,\theta T]}}{N} \right) \\
& = \mathbb{P} \left(x_{i^t j^t}^{\text{P},t} - x_{i^t j^t}^{*,t} > \frac{\mathbb{E} \left[d_{i^t}^{[t,\theta T]} \right] - N}{N} \right) \\
& \stackrel{(a)}{\leq} \mathbb{P} \left(\max_{i'} \left| \mathbb{E} \left[d_{i'}^{[t,\theta T]} \right] - d_{i'}^{[t,\theta T]} \right| > \frac{\mathbb{E} \left[d_{i^t}^{[t,\theta T]} \right] - N}{\delta N} \right) \\
& = \mathbb{P} \left(\bigcup_{i'} \left\{ \left| \mathbb{E} \left[d_{i'}^{[t,\theta T]} \right] - d_{i'}^{[t,\theta T]} \right| > \frac{\mathbb{E} \left[d_{i^t}^{[t,\theta T]} \right] - N}{\delta N} \right\} \right) \\
& \leq \sum_{i'} \mathbb{P} \left(\left| \mathbb{E} \left[d_{i'}^{[t,\theta T]} \right] - d_{i'}^{[t,\theta T]} \right| > \frac{\mathbb{E} \left[d_{i^t}^{[t,\theta T]} \right] - N}{\delta N} \right) \\
& \stackrel{(b)}{=} \sum_{i'} \sum_i \mathbb{P} \left(\left| \mathbb{E} \left[d_{i'}^{[t,\theta T]} \right] - d_{i'}^{[t,\theta T]} \right| > \frac{\mathbb{E} \left[d_{i^t}^{[t,\theta T]} \right] - N}{\delta N} \middle| (i^t = i) \right) \mathbb{P}(i^t = i) \\
& \leq \sum_i \sum_{i'} \mathbb{P} \left(\left| \mathbb{E} \left[d_{i'}^{[t,\theta T]} \right] - d_{i'}^{[t,\theta T]} \right| > \frac{\mathbb{E} \left[d_{i^t}^{[t,\theta T]} \right] - N}{\delta N} \middle| (i^t = i) \right) \mathbf{1}_{\{t \leq \theta T_i\}} \\
& \stackrel{(c)}{\leq} \sum_i \sum_{i'} \mathbb{P} \left(\left| \mathbb{E} \left[d_{i'}^{[t,\theta T]} \right] - d_{i'}^{[t,\theta T]} \right| > \frac{\mathbb{E} \left[d_{i^t}^{[t,\theta T]} \right] - N}{\delta N} \middle| (i^t = i) \right) \mathbf{1}_{\{t \leq \theta T_i\}} \\
& \stackrel{(d)}{=} \sum_i \sum_{i'} \mathbb{P} \left(\left| \mathbb{E} \left[d_{i'}^{[t,\theta T]} \right] - d_{i'}^{[t,\theta T]} \right| > \frac{\mathbb{E} \left[d_{i^t}^{[t,\theta T]} \right] - N}{\delta N} \right) \mathbf{1}_{\{t \leq \theta T_i\}}.
\end{aligned}$$

Let $T_0 = \left\lceil \frac{N}{\lambda_{\min}} \right\rceil < \frac{\theta}{2}$. We have

$$\mathbb{E} \left[d_i^{(t,\theta T)} \right] = \lambda_i^{(t,\theta T_i)} \geq \lambda_{\min} (\theta T_i - t).$$

For $t \leq \theta T_i - T_0$,

$$\frac{\mathbb{E} \left[d_i^{(t,\theta T)} \right] - N}{\delta N} \geq \frac{\lambda_{\min} (\theta T_i - t) - \lambda_{\min} T_0 / 2}{\delta N} \geq \frac{\lambda_{\min} (\theta T_i - t)}{\delta N}.$$

Thus,

$$\begin{aligned}
& \leq 2l \sum_{t=1}^{\theta T} \sum_i \sum_{i'} \mathbb{P} \left(\left| \mathbb{E} \left[d_{i'}^{(t,\theta T)} \right] - d_{i'}^{(t,\theta T)} \right| > \frac{\mathbb{E} \left[d_i^{(t,\theta T)} \right] - N}{\delta N} \right) \mathbf{1}_{\{t \leq \theta T_i\}} \\
& \leq 2l \sum_i \sum_{t=1}^{\theta T_i} \sum_{i'} \mathbb{P} \left(\left| \mathbb{E} \left[d_{i'}^{(t,\theta T)} \right] - d_{i'}^{(t,\theta T)} \right| > \frac{\lambda_{\min} (\theta T_i - t)}{\delta N} \right) \\
& \stackrel{(a)}{\leq} 2l \sum_i \sum_{t=1}^{\theta T_i - T_0} \sum_{i'} 2 \exp \left(-2 \frac{(\lambda_{\min} (\theta T_i - t))^2}{(\delta N)^2 (\theta T - t)} \right) + 2l \sum_i \sum_{t=\theta T_i - T_0 + 1}^{\theta T_i} \sum_{i'} 1 \\
& = 2l \sum_i \sum_{t=1}^{\theta T_i - T_0} \sum_{i'} 2 \exp \left(-2 \frac{\lambda_{\min}^2}{\delta^2 N^2} \cdot \frac{(\theta T_i - t)^2}{\theta T - t} \right) + O(1) \\
& \leq 2lN \sum_i \sum_{t=1}^{\theta T_i - T_0} 2 \exp \left(-2 \frac{\lambda_{\min}^2}{\delta^2 N^2} \cdot \frac{(\theta T_i - t)^2}{\theta T - t} \right) + O(1).
\end{aligned}$$

We can further upper bound by

$$\begin{aligned}
& 2lN \sum_i \sum_{t=T_0}^{+\infty} 2 \exp \left(-2 \frac{\lambda_{\min}^2 t^2}{\delta^2 N^2 \theta T} \right) + O(1) \\
& \leq 2lN^2 \sum_{t=T_0}^{+\infty} 2 \exp \left(- \left(2 \frac{\lambda_{\min}^2}{\delta^2 N^2 T} \right) \cdot \frac{t^2}{\theta} \right) + O(1) \\
& = O(\sqrt{\theta})
\end{aligned}$$

NEE (No Early Ending): If $\inf_{\substack{i \geq j: \\ \lambda_{ij}^{[1,T]} > 0}} \lambda_{ij}^T > 0$, then the set of arrival rates satisfies the NEE property.

When the NEE property is satisfied, can be alternatively bounded by

$$\begin{aligned}
& 2lN \sum_i \sum_{t=T_0}^{+\infty} 2 \exp \left(-2 \frac{\lambda_{\min}^2 t^2}{\delta^2 N^2 t} \right) + O(1) \\
& \leq 2lN^2 \sum_{t=T_0}^{+\infty} 2 \exp \left(- \left(2 \frac{\lambda_{\min}^2}{\delta^2 N^2} \right) \cdot t \right) + O(1) \\
& = O(1)
\end{aligned}$$

6 Computational Experiments

$N = 10, L_j = 20\forall j,$
 $D_1 = [0.2, 0.5, 0.3]$
 $w = [3, 4, 5], r = [4, 6, 8], r_i/w_i > 1\forall i$
 $w = [3, 4, 5] = r, r_i/w_i = 1\forall i$
 $w = [8, 6, 4] r = [5, 4, 3], r_i/w_i < 1\forall i$
 $D_2 = [0.25, 0.25, 0.25, 0.25]$
 $w = [3, 5, 7, 9], r = [2, 4, 6, 8].$

Table 1: Performance of Policies

Distribution	T	r_i/w_i	Primal (%)	BPC (%)	BPP (%)
D_1	60	>1	99.15	95.30	97.98
	80	>1	99.37	95.70	98.18
	60	$=1$	99.68	95.66	98.88
	80	$=1$	99.80	96.26	99.44
	60	<1	98.56	95.86	97.66
	80	<1	97.00	95.67	97.31
D_2	60	<1	99.65	94.63	99.84
	80	<1	99.81	96.89	99.91
	100	<1	99.94	99.41	99.97

7 Conclusion

We study the dynamic stochastic multi-type multiple knapsack problem. We consider the bid-price control policy. Then we introduce the dynamic primal policy.

We conduct several numerical experiments to investigate various aspects of our approach. First, we compare different policies. Our proposed policy demonstrates superior and more consistent performance relative to these benchmarks.

References

- Adelman, D., 2007. Dynamic bid prices in revenue management. *Operations Research* 55, 647–661.
- Aydin, N., Birbil, S.I., 2018. Decomposition methods for dynamic room allocation in hotel revenue management. *European Journal of Operational Research* 271, 179–192.
- Bertsimas, D., Popescu, I., 2003. Revenue management in a dynamic network environment. *Transportation Science* 37, 257–277.
- Bienkowski, M., Pacut, M., Piecuch, K., 2020. An optimal algorithm for online multiple knapsack. *arXiv preprint arXiv:2002.04543*.
- Bitran, G.R., Mondschein, S.V., 1995. An application of yield management to the hotel industry considering multiple day stays. *Operations Research* 43, 427–443.

- Chekuri, C., Khanna, S., 2005. A polynomial time approximation scheme for the multiple knapsack problem. *SIAM Journal on Computing* 35, 713–728.
- Dantzig, G.B., 1957. Discrete-variable extremum problems. *Operations Research* 5, 266–288.
- Ferreira, C.E., Martin, A., Weismantel, R., 1996. Solving multiple knapsack problems by cutting planes. *SIAM Journal on Optimization* 6, 858–877.
- Gallego, G., van Ryzin, G., 1997. A multiproduct dynamic pricing problem and its applications to network yield management. *Operations Research* 45, 24–41.
- Goldman, P., Freling, R., Pak, K., Piersma, N., 2002. Models and techniques for hotel revenue management using a rolling horizon. *Journal of Revenue and Pricing Management* 1, 207–219.
- Khuri, S., Bäck, T., Heitkötter, J., 1994. The zero/one multiple knapsack problem and genetic algorithms, in: *Proceedings of the 1994 ACM symposium on Applied computing*, pp. 188–193.
- Kleywegt, A.J., Papastavrou, J.D., 1998. The dynamic and stochastic knapsack problem. *Operations Research* 46, 17–35.
- Kleywegt, A.J., Papastavrou, J.D., 2001. The dynamic and stochastic knapsack problem with random sized items. *Operations Research* 49, 26–41.
- Liu, Q., van Ryzin, G., 2008. On the choice-based linear programming model for network revenue management. *Manufacturing & Service Operations Management* 10, 288–310.
- Martello, S., Toth, P., 1990. *Knapsack problems: algorithms and computer implementations*. John Wiley & Sons, Inc.
- Papastavrou, J.D., Rajagopalan, S., Kleywegt, A.J., 1996. The dynamic and stochastic knapsack problem with deadlines. *Management Science* 42, 1706–1718.
- Pisinger, D., 1999. An exact algorithm for large multiple knapsack problems. *European Journal of Operational Research* 114, 528–541.
- van Ryzin, G.J., Talluri, K.T., 2005. An introduction to revenue management, in: *Emerging Theory, Methods, and Applications*. INFORMS, pp. 142–194.
- Sun, B., Zeynali, A., Li, T., Hajiesmaili, M., Wierman, A., Tsang, D.H., 2020. Competitive algorithms for the online multiple knapsack problem with application to electric vehicle charging. *Proceedings of the ACM on Measurement and Analysis of Computing Systems* 4, 1–32.
- Talluri, K., van Ryzin, G., 1998. An analysis of bid-price controls for network revenue management. *Management Science* 44, 1577–1593.
- Talluri, K.T., van Ryzin, G.J., 2006. *The Theory and Practice of Revenue Management*. Springer Science & Business Media.

- Tönissen, D.D., Van den Akker, J., Hoogeveen, J., 2017. Column generation strategies and decomposition approaches for the two-stage stochastic multiple knapsack problem. *Computers & Operations Research* 83, 125–139.
- Williamson, E.L., 1992. Airline network seat inventory control: Methodologies and revenue impacts. Ph.D. thesis. Massachusetts Institute of Technology.
- Zhu, F., Liu, S., Wang, R., Wang, Z., 2023. Assign-to-seat: Dynamic capacity control for selling high-speed train tickets. *Manufacturing & Service Operations Management* 25, 921–938.

8 Proofs

Proof of Proposition 1

We model the problem as a special case of the multiple knapsack problem, then we consider the LP relaxation of this problem. In the model, groups are categorized into M distinct types. Each type i is characterized by a fixed size w_i , which serves as the weight, and an associated profit equal to r_i . For every type i , there are d_i items. Altogether, the total number of groups is given by $K = \sum_{i=1}^M d_i$. Each individual item k inherits its profit and weight from its type; specifically, if item k belongs to type i , then its profit p_k is r_i , and its weight W_k is w_i . To apply the greedy approach for the LP relaxation of (3), sort these items in non-increasing order of their profit-to-weight ratios: $\frac{p_1}{W_1} \geq \frac{p_2}{W_2} \geq \dots \geq \frac{p_K}{W_K}$. The break item b is the smallest index such that the cumulative weight of item 1 to item b meets or exceeds the total capacity \tilde{c} : $b = \min\{j : \sum_{k=1}^j W_k \geq \tilde{c}\}$, where $\tilde{c} = \sum_{j=1}^N c_j$ is the total size of all knapsacks. For the LP relaxation of (3), the Dantzig upper bound (Dantzig, 1957) is given by $u_{\text{MKP}} = \sum_{j=1}^{b-1} p_j + \left(\tilde{c} - \sum_{j=1}^{b-1} W_j\right) \frac{p_b}{W_b}$. The corresponding optimal solution is to accept the whole groups from 1 to $b-1$ and fractional $(\tilde{c} - \sum_{j=1}^{b-1} W_j)$ item b . Suppose the item b belong to type \tilde{i} , then for $i < \tilde{i}$, $x_{ij}^* = 0$; for $i > \tilde{i}$, $x_{ij}^* = d_i$; for $i = \tilde{i}$, $\sum_{j=1}^N x_{ij}^* = (\tilde{c} - \sum_{i=\tilde{i}+1}^M d_i w_i)/w_{\tilde{i}}$. ■

Proof of Lemma 1

According to the Proposition 1, the aggregate optimal solution to LP relaxation of problem (3) takes the form $x e_{\tilde{i}} + \sum_{i=\tilde{i}+1}^M d_i e_i$, then according to the complementary slackness property, we know that $z_1 = \dots = z_{\tilde{i}} = 0$. This implies that $\beta_j \geq \frac{r_i}{w_i}$ for $i = 1, \dots, \tilde{i}$. Since $\frac{r_i}{w_i}$ increases with i , we have $\beta_j \geq \frac{r_{\tilde{i}}}{w_{\tilde{i}}}$. Consequently, we obtain $z_i \geq r_i - w_i \frac{r_{\tilde{i}}}{w_{\tilde{i}}} = \frac{r_i w_{\tilde{i}} - r_{\tilde{i}} w_i}{w_{\tilde{i}}}$.

Given that \mathbf{d} and \mathbf{L} are both no less than zero, the minimum value will be attained when $\beta_j = \frac{r_{\tilde{i}}}{w_{\tilde{i}}}$ for all j , and $z_i = \frac{r_i w_{\tilde{i}} - r_{\tilde{i}} w_i}{w_{\tilde{i}}}$ for $i = \tilde{i} + 1, \dots, M$. ■

Proof of Lemma 2

We consider two cases based on whether the set \mathcal{J}_i is empty or not.

Case 1: $\mathcal{J}_i = \emptyset$ If $\mathcal{J}_i = \emptyset$, then for all $j \in \mathcal{N}$, we have $r_i - \beta_{ij}^* \leq 0$. This implies that the constraint: $\alpha_i \geq r_i - \beta_{ij}^*$ is automatically satisfied for all $j \in \mathcal{N}$ when $\alpha_i \geq 0$. Therefore, these constraints are redundant and can be removed without affecting the solution.

Case 2: $\mathcal{J}_i \neq \emptyset$ We prove by contradiction that there exists $h_i^* \geq 1$ for some $j' \in \mathcal{J}_i$.

Assumption for contradiction: Suppose that in the optimal solution, for all $j' \in \mathcal{J}_i$, we have $h_i^* = 0$.

Since $\mathcal{J}_i \neq \emptyset$, there exists at least one $j' \in \mathcal{J}_i$ such that $r_i > \beta_{ij'}^*$. From the constraint $\alpha_i \geq r_i - \beta_{ij'}^*$ and the optimality conditions, we must have $\alpha_i = r_i - \beta_{ij'}^* > 0$. Now consider the value:

$$\gamma_{j'} = \max_{\mathbf{h} \in S(c_{j'})} \sum_i \beta_{ij'}^* h_i$$

Under the contradiction assumption ($h_i^* = 0$ for all $j' \in \mathcal{J}_i$), we have: $\gamma_{j'} = \sum_i \beta_{ij'}^* h_i^*$.

Now examine the objective function:

$$\sum_i \alpha_i d_i + \sum_j \gamma_j.$$

Consider perturbing $\beta_{ij'}^{\dagger*}$ by increasing it slightly to $\beta_{ij'}^{\dagger*} + \delta$ (for some small $\delta > 0$ such that $r_i > \beta_{ij'}^{\dagger*} + \delta$ still holds). Then:

- Since α_i is exactly at the boundary ($\alpha_i = r_i - \beta_{ij'}^{\dagger*}$), we can now set $\alpha_i^{\text{new}} = r_i - (\beta_{ij'}^{\dagger*} + \delta) < \alpha_i$.
- The term $\gamma_{j'}$ remains unchanged because $h_i^* = 0$ for $j' \in \mathcal{J}_i$ (by our contradiction assumption), and the perturbation does not affect other terms.
- Since $d_i > 0$ (positive arrival rate for type i), the objective decreases by $\delta \cdot d_i > 0$.

This contradicts the optimality of the current solution. Therefore, our initial assumption must be false, and there must exist some $j' \in \mathcal{J}_i$ such that $h_i^* \geq 1$. ■

Proof of Proposition 2

■

Proof of Proposition 3

If $x_{ij}^* > 0$, then $\sum_{\mathbf{h} \in S(c_j)} h_i y_{j\mathbf{h}} > 0$, then there exists \mathbf{h} such that $y_{j\mathbf{h}} > 0$ and $h_i \geq 1$. Then $\mathbf{h} \in \arg \max(\sum_i (r_i - \alpha_i) h_i - \gamma_j)$.

According to the complementary slackness property, $\alpha_i + \beta_{ij} = r_i$, then $\max \sum_i (r_i - \alpha_i) h_i - \gamma_j$ equals $\max \sum_i \beta_{ij} h_i$. Thus, there exists j such that $\mathbf{h}^* \in \arg \max_{\mathbf{h} \in S(c_j)} \sum_i \beta_{ij}^{\dagger} h_i, h_i^* \geq 1$. ■

Lemma 5. $z(\text{DLP}) \geq V^{\text{HO}}$ results from the concave property.

Proof of Lemma 5

Consider the standard linear program: $\phi(\mathbf{d}) = \{\max \mathbf{c}^T \mathbf{x} : A\mathbf{x} \leq \mathbf{d}, \mathbf{x} \geq \mathbf{0}\}$. Suppose that \mathbf{d}_1 and \mathbf{d}_2 are two demand vectors, the optimal solution is \mathbf{x}_1 and \mathbf{x}_2 . For any $\lambda \in [0, 1]$, $\mathbf{d}_\lambda = \lambda \mathbf{d}_1 + (1 - \lambda) \mathbf{d}_2$. Let $\mathbf{x}_\lambda = \lambda \mathbf{x}_1 + (1 - \lambda) \mathbf{x}_2$, then $A\mathbf{x}_\lambda = A(\lambda \mathbf{x}_1 + (1 - \lambda) \mathbf{x}_2) \leq \lambda \mathbf{d}_1 + (1 - \lambda) \mathbf{d}_2 = \mathbf{d}_\lambda$. Thus, \mathbf{x}_λ is a feasible solution for \mathbf{d}_λ . Then, $\phi(\mathbf{d}_\lambda) \geq \mathbf{c}^T \mathbf{x}_\lambda = \lambda \mathbf{c}^T \mathbf{x}_1 + (1 - \lambda) \mathbf{c}^T \mathbf{x}_2 = \lambda \phi(\mathbf{d}_1) + (1 - \lambda) \phi(\mathbf{d}_2)$, which indicates $\phi(\mathbf{d})$ is concave. Let $\phi(\mathbf{d})$ indicate the optimal value of the linear relaxation of the SPDR problem. Substitute \mathbf{x} with $y_{j\mathbf{h}}$ and view $y_{j\mathbf{h}}$ as the decision variables, then the concave property still holds for (11). $V^{\text{HO}} = E[\phi(\mathbf{d})] \leq \phi(E[\mathbf{d}]) = z(\text{DLP})$. ■