Optimized Seating Strategies for Safe and Efficient Space Utilization

Sunit Bhagwan Moorjani

Periyar University, Salem, Tamil Nadu, India
moorjani.sunit@gmail.com

Abstract. Ensuring optimal seat allocation while maintaining safety constraints is a critical challenge in public venues and transportation systems. This study presents a data-driven approach to seating optimization, integrating dynamic assignment policies with adaptive constraints. By leveraging stochastic modeling, the framework balances occupancy efficiency with safety regulations, adjusting to fluctuating demand conditions. Simulation-based evaluations highlight the trade-offs between seat utilization and compliance, offering insights into scalable and flexible seat planning strategies for real-world applications.

Keywords: Seating Optimization · Social Distancing · Dynamic Programming · Stochastic Modeling · Integer Programming · Event Planning · Public Safety · Benders Decomposition · Group-Based Allocation · Space Utilization

1 Introduction

The COVID-19 pandemic has drastically altered the way public spaces are utilized, prompting a rethinking of how seating arrangements are managed in venues such as cinemas, trains, and conference halls. Central to these changes is the concept of social distancing, defined by public health organizations like the WHO and CDC as maintaining a physical distance between individuals to minimize the risk of transmission [11,5]. Enforcing such distancing measures, however, introduces logistical and operational challenges, particularly in environments that involve group-based seating.

Social distancing requirements vary globally, ranging from a minimum of one meter in some countries to the enforced limitation of group sizes in others. For instance, during peak pandemic periods in Hong Kong, group sizes were limited to as few as two or four people, with total occupancy often capped at 50% or 75% [7]. These restrictions significantly reduce the number of usable seats in a venue, thereby affecting both the feasibility and profitability of events. Hence, there is a pressing need to develop adaptable, data-driven seating strategies that account for both safety and operational efficiency.

The implementation of distancing measures has economic ramifications. Restaurants, theaters, and other public venues must often redesign their layouts, resulting in lower capacity and, consequently, reduced revenue [12]. Governments

H. J. Hazarika et al. (eds.), *Proceedings of the International Conference on Smart Systems and Social Management (ICSSSM 2025)_Smart Systems Tracks*, Advances in Intelligent Systems Research 201,
https://doi.org/10.2991/978-94-6463-950-6_37

are then faced with the dual challenge of minimizing public health risk while ensuring that such policies do not severely cripple vital sectors. Therefore, understanding how seat allocation strategies interact with distancing mandates is critical for sustainable policy design.

In this paper, we investigate seating optimization under social distancing through three interrelated models: deterministic seat planning, stochastic seat planning, and dynamic seat assignment. Each model addresses a unique operational context—ranging from fully known group reservations to real-time customer arrivals—and together they form a comprehensive framework for safe and efficient space utilization.

In the deterministic model, we consider a fixed set of seating requests, such as for pre-booked events where group compositions are known in advance. This scenario is modeled as an integer programming problem, where the goal is to maximize seated individuals while satisfying spacing constraints. Full and largest pattern strategies are then used to improve seat usage across rows.

The stochastic model addresses uncertainty in group requests using scenario-based optimization. This model is suitable for venues that must commit to a seating layout prior to knowing the exact composition of incoming groups. To solve this efficiently, we apply Benders decomposition, allowing for scalable planning even with a large number of scenarios [4].

In real-time contexts such as ticket sales in cinemas, a dynamic seat assignment model is more appropriate. Here, groups arrive sequentially, and decisions must be made instantly regarding whether to accept the group and where to seat them. This problem is formulated using dynamic programming and complemented by a seat plan generated from the stochastic model.

Our approach also evaluates the macro-level impact of social distancing policies, introducing the concept of a "gap point"—a threshold under which distancing has negligible impact. By quantifying such metrics, we provide actionable insights for both operational managers and policymakers, enabling smarter trade-offs between safety and efficiency.

2 Related Work

Seating optimization under spatial and policy constraints has garnered substantial attention in the literature, especially in contexts affected by public health mandates. Traditional seat management problems have long been studied in operations research, but the inclusion of social distancing constraints introduces a novel class of challenges that require new modeling and computational strategies.

The core of seat planning under distancing requirements can be traced to works on **multiple knapsack problems** (MKPs), where each row is analogous to a knapsack with limited capacity [8]. While classical MKPs aim to maximize value across multiple containers, our problem integrates additional structure—sequential constraints, group-based demands, and spacing buffers—which are not typically addressed in standard formulations.

Another influential stream of work is **Network Revenue Management** (NRM), which explores optimal control of limited resources under stochastic demand. Early works on bid-price and booking-limit control policies [10,6] laid the foundation for dynamic allocation frameworks. However, most of these studies assume unit-sized customers, and few extend to group-based requests with indivisibility constraints. Our setting extends this paradigm by introducing dynamic group acceptance with spatial constraints, where each group must be fully accommodated or rejected.

Seating strategies in pandemic contexts have been recently explored for airlines, classrooms, and theaters. Studies have proposed various models for distancing-aware layout designs, including linear and grid-based distancing formulations [1]. For example, in airline seating, blocking middle seats or redesigning boarding procedures has been analyzed to minimize contact risk [3]. In educational settings, algorithms for distancing-compliant layouts have been proposed using graph coloring and integer programming approaches [2].

Closer to our focus are works that model **group-based social seating**. For instance, seat allocation in trains and cinemas with group separation rules has been studied using dynamic programming and stochastic simulation techniques [9]. However, most of these approaches lack a unifying framework that combines deterministic, stochastic, and real-time assignment, as proposed in our paper.

Lastly, solution methods like **Benders decomposition** have been applied in stochastic programming to manage large-scale scenario-driven planning problems [4]. In our work, this approach is adapted to the seat planning problem with stochastic requests, allowing the decoupling of layout generation from demand realization. This modularity is especially useful when designing scalable systems for varying venue types and event profiles.

In summary, while several lines of research inform aspects of our study—from knapsack optimization to revenue management and distancing-aware layouts—our contribution is unique in its integration of deterministic, stochastic, and dynamic models into a cohesive, application-ready framework for socially compliant seating management.

3 Seating Optimization Models

To manage seating under safety and operational constraints, we develop three optimization models tailored to distinct planning contexts: deterministic seat planning, stochastic seat planning, and dynamic seat assignment. These models account for real-world factors such as group size, row layout, social distancing requirements, and request uncertainty.

3.1 Deterministic Seat Planning

The deterministic model assumes full knowledge of seating requests before the event. Each group request is of a known size, and the goal is to maximize the number of individuals seated while ensuring that social distancing is enforced between groups within the same row. Let M denote the number of group types and N the number of rows. Each group of type i consists of i individuals and occupies $n_i = i + \delta$ seats, where δ represents the minimum spacing (in empty seats) between groups.

Let x_{ij} represent the number of groups of type i placed in row j. The integer programming formulation is:

$$\text{(SPDRP)} \quad \max \sum_{i=1}^{M} \sum_{j=1}^{N} i x_{ij} \tag{1}$$

$$\text{s.t.} \quad \sum_{j=1}^{N} x_{ij} \leq d_i, \quad \forall i \in \{1, \ldots, M\} \tag{2}$$

$$\sum_{i=1}^{M} n_i x_{ij} \leq L_j, \quad \forall j \in \{1, \ldots, N\} \tag{3}$$

$$x_{ij} \in \mathbb{Z}_{\geq 0}, \quad \forall i, j \tag{4}$$

Here, d_i is the demand for group type i, and L_j is the number of usable seats in row j (adjusted for spacing). This model helps plan layouts for events where attendee groups are known in advance, such as office meetings or reserved theater bookings.

3.2 Stochastic Seat Planning

In many applications, exact demand is not known in advance, but probabilistic estimates can be derived from historical data. The stochastic seat planning model seeks to determine a robust seating layout under demand uncertainty. We model this as a **scenario-based stochastic program (SSP)**.

Let Ω denote the set of scenarios, with each scenario ω representing a realization of demand vector $\mathbf{d}^\omega = (d_1^\omega, \ldots, d_M^\omega)$. The objective is to design a seat plan $\{x_{ij}\}$ that performs well in expectation:

$$\max_{x} \ \mathbb{E}_\omega \left[\sum_{i=1}^{M} (i) \cdot \min \left(\sum_{j=1}^{N} x_{ij}, d_i^\omega \right) \right] \tag{5}$$

To handle excess or shortage, auxiliary variables are introduced to allow seats planned for larger groups to be flexibly reassigned to smaller groups. We solve this using **Benders decomposition**, separating layout design from scenario evaluation [4].

3.3 Dynamic Seat Assignment

For real-time applications such as ticketing, requests arrive sequentially, and the system must decide immediately whether to accept or reject each request and, if accepted, where to seat the group. We model this as a finite-horizon **dynamic programming (DP)** problem.

Let $V^t(L)$ denote the expected number of seated individuals from time t onward, given current seat capacities $L = (l_1, \ldots, l_N)$. The Bellman equation is:

$$V^t(L) = \max_{u^t \in \mathcal{U}(L)} \left\{ \sum_{i=1}^{M} p_i \left[i + V^{t+1}(L - n_i e_j) \right] + p_0 V^{t+1}(L) \right\} \tag{6}$$

Here, p_i is the arrival probability for group type i, e_j is a unit vector indicating row assignment, and p_0 is the no-arrival probability. Since solving this exactly is computationally expensive, we develop heuristics based on relaxed DP and a precomputed seat plan.

3.4 From Models to Strategy

Together, these three models form a cohesive decision pipeline: the deterministic model is used for planned events, the stochastic model supports semi-planned seating under demand uncertainty, and the dynamic model enables real-time adaptation. Furthermore, seat plans derived from the deterministic or stochastic models serve as templates for dynamic assignment decisions, enhancing real-time efficiency without sacrificing compliance or utilization.

4 Experimental Evaluation and Discussion

To assess the effectiveness of the proposed seating strategies, we conducted extensive simulations across varying seating layouts, demand distributions, and social distancing constraints. The experiments evaluate both static and dynamic policies in terms of the percentage of seated individuals relative to total seat capacity.

4.1 Simulation Setup

The default venue configuration includes $N = 10$ rows, each with $L_j = 21$ seats. The social distancing parameter is set to $\delta = 1$, requiring one empty seat between adjacent groups. Group types range from size 1 to 4 ($M = 4$), and demand scenarios are generated from four probability distributions D_1 through D_4, based on real cinema attendance data.

We simulate dynamic demand over $T = 60$ to 100 periods. Each simulation is repeated over 100 random runs to ensure statistical robustness. Performance is evaluated by comparing the number of accepted individuals under each policy to the optimal offline solution.

4.2 Policies Compared

We evaluate the following policies:

– **DSA** — Dynamic Seat Assignment with seat plan and group-type control.
– **DPBH** — Dynamic Programming-Based Heuristic without seat plan guidance.
– **BPC** — Bid-Price Control derived from LP relaxation.
– **BLC** — Booking-Limit Control that blocks seats to reserve capacity.

4.3 Results and Analysis

Table 1 summarizes the performance of each policy under different demand distributions and time horizons. The DSA consistently outperforms other strategies, especially in high-demand settings where efficient utilization of available space becomes critical. The BLC performs poorly when group flexibility is needed, while DPBH and BPC lack fine-grained assignment mechanisms.

Table 1. Performance Comparison of Policies (Acceptance Rate in %)

Policy	D1 (T=80)	D2 (T=80)	D3 (T=80)	D4 (T=80)
DSA	99.38	99.54	99.22	99.25
DPBH	98.91	97.89	98.92	98.69
BPC	98.84	97.21	98.40	98.40
BLC	97.06	98.98	96.98	98.22

4.4 Impact of Social Distancing

We examine the effect of distancing constraints on occupancy. The *gap point* is defined as the threshold where distancing starts reducing acceptance significantly. For example, with distribution D_4, the gap point occurs around period $T = 57$, corresponding to a 71.8% threshold occupancy rate. Beyond this, distancing results in an average 10–15% drop in seated individuals, as shown in Figure 1.

The results validate our hypothesis: efficient seat planning and assignment under spacing constraints can retain high occupancy even during strict distancing enforcement.

5 Conclusion and Policy Implications

This study presented a comprehensive framework for optimized seating under social distancing and space constraints, integrating deterministic, stochastic, and dynamic decision models. Each model is tailored to distinct operational

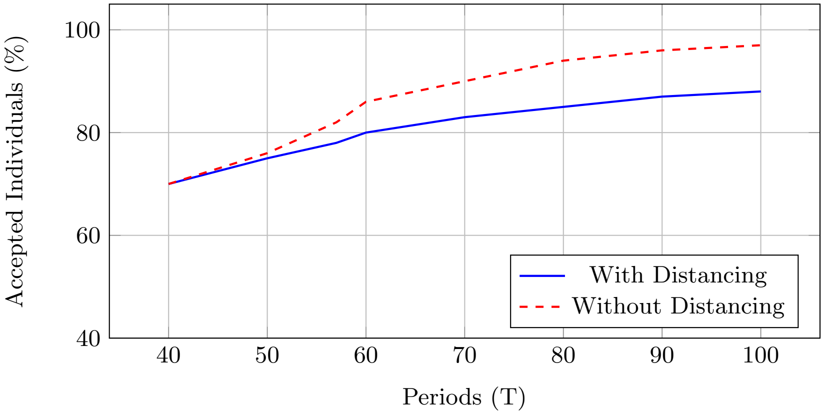

Fig. 1. Impact of Social Distancing on Acceptance Rate

Algorithm 1 Dynamic Seat Assignment (DSA)

Initialize seat plan H, group supplies $X = [X_1, \ldots, X_M]$ each period $t = 1$ to T Observe arriving group of type i $X_i > 0$ **and** available row exists Assign group to best-fit row Update $X_i \leftarrow X_i - 1$ Compute $d_t(i, \hat{i})$ for group-type control $\max d_t(i, \hat{i}) \geq 0$ Reallocate larger group seat to group i Update corresponding X and H Reject request any $X_M = 0$ or pattern broken Regenerate seat plan using deterministic model

settings—pre-planned layouts, uncertain demand environments, and real-time assignment contexts—yet all converge toward a unified goal: maximizing seated individuals while ensuring compliance with safety guidelines.

The deterministic model offers a baseline for high-assurance scenarios such as reserved events or institutional settings where group demand is known in advance. It ensures efficient use of space with guaranteed social distancing, and its pattern-based formulation provides an intuitive yet powerful structure for planning. The stochastic model, on the other hand, adds flexibility by incorporating scenario uncertainty and adapting layout decisions accordingly. This is particularly useful for semi-planned venues like cinemas or public transportation.

For real-time decisions, the dynamic seat assignment model 1 extends the framework into operational practice. By incorporating relaxed dynamic programming, heuristic best-fit assignment, and group-type control, the DSA policy balances computational feasibility with near-optimal seat utilization. Our simulations confirm its superiority across varying demand profiles, time horizons, and distancing rules.

Beyond operational efficiency, the findings have direct implications for public policy. The analysis of the *gap point*—the occupancy threshold beyond which distancing sharply reduces seat acceptance—enables decision-makers to set safe yet economically sustainable guidelines. Venues can plan operations that approach this threshold, optimizing attendance without compromising health standards.

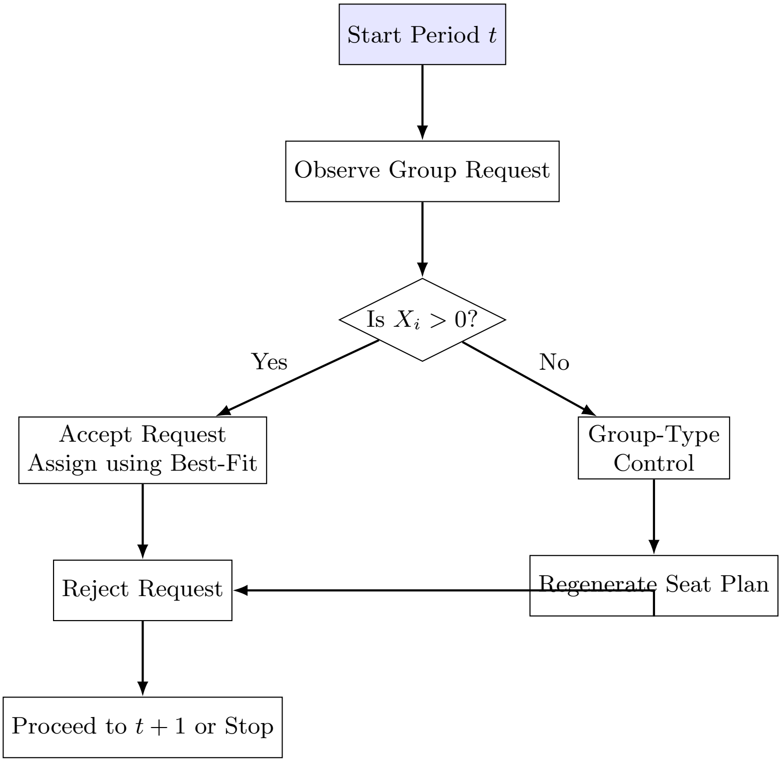

Fig. 2. Compact Flowchart of Dynamic Seat Assignment Strategy

Additionally, the modularity of our framework makes it adaptable to evolving distancing protocols or hybrid environments (e.g., combining vaccinated/unvaccinated zones). It also supports integration with digital ticketing systems for automated enforcement of spatial constraints.

Future work may extend this approach to multi-row 2D seat layouts (e.g., auditoriums), dynamic arrival patterns with cancellations, or integration with agent-based simulations to better model real-world behaviors. Moreover, equity-aware variants could prioritize group types or demographics in access-constrained settings like schools or public health facilities.

In conclusion, our models and algorithms provide practical tools for managing space efficiently and safely in a post-pandemic world. They empower both venue operators and policymakers to make data-driven, context-sensitive seating decisions that uphold safety while preserving economic viability.

References

1. Abueg, M., Hinch, R., Wu, N., et al.: Modeling the effect of social distancing on the spread of COVID-19 in college campuses. medRxiv (2021), https://doi.org/

10.1101/2020.06.25.20140131

2. Alvarez, R., Sorensen, A., et al.: Covid-19 classroom seating plans using graph theory. Discrete Math. Appl. (2021)
3. Barnett, A.: Airplane seating and COVID-19 risk. J. Travel Med. **27**(5) (2020)
4. Birge, J.R., Louveaux, F.: Introduction to Stochastic Programming. Springer (2011)
5. Centers for Disease Control and Prevention: Social distancing. https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/social-distancing.html (2020)
6. Gallego, G., Van Ryzin, G.: Multiproduct revenue management with dynamic prices. Operations Research **45**(1), 24–41 (1997)
7. Hong Kong Government: Government tightens social distancing measures. https://www.info.gov.hk/gia/general/202007/14/P2020071400607.htm (2020)
8. Kellerer, H., Pferschy, U., Pisinger, D.: Knapsack Problems. Springer (2004)
9. Niu, J., Zhang, H.: Social distancing compliant seating arrangements for group requests in theaters. Transp. Res. Part C (2021)
10. Talluri, K.T., Van Ryzin, G.J.: The Theory and Practice of Revenue Management. Springer (2004)
11. World Health Organization: Coronavirus disease (COVID-19): How to protect yourself. https://www.who.int/news-room/q-a-detail/coronavirus-disease-covid-19-how-is-it-transmitted (2020)
12. Xu, T., Zhao, J.: Impact of social distancing on economic activities during the COVID-19 pandemic. J. Policy Model. **43**(2), 344–359 (2021)