



APPLICATIONS OF GAME THEORY AND LINEAR PROGRAMMING IN PANDEMIC MANAGEMENT POLICIES

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ABSTRACT

The COVID-19 pandemic exposed critical challenges in public health governance, resource allocation, and behavioural management. This study presents an integrated analytical framework combining Game Theory and Linear Programming (LP) to evaluate and optimize pandemic management policies. Game-theoretic models are employed to explain strategic interactions among governments, citizens, hospitals, and state authorities, highlighting how conflicting incentives often result in coordination failures, suboptimal compliance, and resource hoarding. Linear Programming complements this behavioural analysis by offering robust optimization techniques to allocate scarce healthcare resources—including vaccines, oxygen cylinders, ICU beds, and medical personnel—under stringent logistical constraints. Building upon these foundations, the paper proposes the Pandemic Strategy Game with Linear Constraints (PSGLC), a unified model that incorporates behavioural dynamics within feasibility regions defined by resource and infrastructure limitations. Empirical illustrations from India's COVID-19 experience, including mobility trends and vaccine distribution simulations for Bihar, demonstrate the practical relevance of this framework. The integrated PSGLC model supports policymakers in designing interventions that are both behaviourally informed and operationally feasible. The study concludes by suggesting future extensions that incorporate dynamic behavioural responses, climate-driven epidemiological risks, and AI-enabled predictive optimization for more resilient pandemic preparedness.



Introduction

The COVID-19 pandemic demonstrated that effective crisis management requires not only medical preparedness but also rigorous quantitative decision-support tools. As infection waves unfolded across countries, policymakers were compelled to balance competing objectives - saving lives through mobility restrictions, sustaining economic activities for livelihood security, and maintaining functional healthcare systems despite overburdened capacities. The complexity of these trade-offs became particularly evident in India, where significant heterogeneity in demographic density, labour composition, digital access, and informal-sector dependence rendered uniform policy responses less effective (Ranjan, 2020). Urban centres like Mumbai and Delhi experienced rapid transmission due to dense settlements, while rural districts faced limited healthcare accessibility, highlighting the need for region-specific strategies.

In such a context, Game Theory emerges as a powerful tool to model strategic interactions between stakeholders whose incentives are not perfectly aligned. Governments aim to minimize the epidemiological burden, whereas citizens and businesses often prioritise economic survival, sometimes leading to behavioural externalities and suboptimal compliance (Toxvaerd, 2021). Game-theoretic frameworks help capture these tensions, enabling policymakers to anticipate responses to interventions such as lockdowns, vaccination campaigns, mobility curbs, and mask mandates. Indian researchers such as Agrawal, Gopal, and Mohapatra (2021) have demonstrated how strategic modelling can inform optimal lockdown scheduling across states.

Complementing this, Linear Programming (LP) offers a robust method for resource optimisation under stringent constraints. During the COVID-19 surge, India faced acute shortages of ICU beds, oxygen cylinders, ventilators, and trained personnel. LP-based models were employed to estimate optimal allocation pathways for medical equipment, streamline logistics, and reduce congestion in critical-care facilities (Saxena & Singh, 2021). Vaccine distribution, another critical challenge, also benefited from LP formulations designed to maximise coverage among high-risk populations within limited supply cycles.



Thus, integrating Game Theory with Linear Programming provides a comprehensive analytical foundation for pandemic policymaking. This research employs both approaches to evaluate policy effectiveness through mathematical modelling and empirical illustrations from India's COVID-19 experience.

2. Literature Review

The application of quantitative modelling to epidemic management has been a growing research frontier, particularly since the COVID-19 crisis underscored the limitations of intuition-based policymaking. A significant body of international literature demonstrates how Game Theory can quantify behavioural responses in epidemic settings. Reluga (2010) provided one of the earliest formalizations of individual social-distancing decisions as a strategic choice influenced by infection risk and economic cost. Similarly, Chen and Toxvaerd (2021) examined how self-interested behavioural adjustments could create divergence between private incentives and socially optimal mitigation efforts.

Within the Indian research landscape, game-theoretic and mathematical modelling approaches expanded rapidly during the pandemic. Ranjan (2020) developed state-specific epidemiological forecasts for India using compartmental models, highlighting the importance of behavioural parameters in predicting infection curves. Agrawal et al. (2021) applied strategic modelling to evaluate staggered lockdowns across Indian states, demonstrating that decentralized decision-making often led to coordination failures, especially during peak transmission phases. In parallel, Ghosh et al. (2020) used optimization frameworks to analyse PPE and medical supply chain disruptions in India, showing that strategic inventory-sharing mechanisms could mitigate shortages.

Linear Programming (LP) also played a crucial role in pandemic response research. Saxena and Singh (2021) proposed LP-based ventilator and ICU bed allocation models tailored to Indian tertiary hospitals, focusing on minimizing mortality risk under severe resource scarcity. Mukherjee (2022) further contributed to the Indian context by developing an LP framework for

vaccine allocation that incorporated demographic variability, risk weights and logistical constraints, ensuring equitable distribution across districts.

Taken together, these studies reveal substantial progress in quantitative pandemic modelling but also highlight a persistent gap: most research treats behavioural interactions and resource constraints separately. The literature thus indicates the need for an integrated framework combining Game Theory and Linear Programming to address both strategic behaviour and resource optimization holistically in pandemic policymaking.

3. Theoretical Foundations

The formulation of pandemic management as a quantitative decision problem requires a rigorous theoretical foundation grounded in both Game Theory and Linear Programming (LP). These frameworks enable policymakers to model strategic interactions and optimize scarce resources under rapidly changing epidemiological conditions. In this section, we formalize the essential components used in the analysis.

3.1 Definition: Game in the Pandemic Context

A pandemic situation can be conceptualized as a multi-agent strategic game, represented as

$$G = (N, \{S_i\}_{i \in N}, \{U_i\}_{i \in N}),$$

where N denotes the set of players - typically governments, citizens, state administrations, healthcare institutions, and private industries. Each player S_i possesses a strategy set that may include actions such as degree of lockdown enforcement, individual compliance, mobility restrictions, testing rates, or inter-state resource sharing. The payoff functions U_i capture competing outcomes: governments consider health metrics and political costs, hospitals focus on survival rates and resource sufficiency, while citizens balance livelihood loss against infection risk.

Indian studies such as Agrawal, Gopal, and Mohapatra (2021) have emphasized that these conflicting payoff structures frequently lead to suboptimal decentralized decisions.

3.2 Axiom 1: Limited Rationality in Pandemic Behaviour

Pandemics are characterized by heightened uncertainty, misinformation, behavioural fatigue, and emotional decision-making. Therefore, agents rarely behave as fully rational optimizers. Their choices lie in the space of ε -best responses, denoted by

$$s_i \in BR_i^\varepsilon(s_{-i})$$

where BR_i^ε denotes ε -best responses, acknowledging fear, misinformation, and bounded rationality, ε reflects tolerance for suboptimal actions.

This behavioural assumption aligns with evidence from India showing varied compliance patterns across regions influenced by fear, income insecurity, and trust deficits (Ranjan, 2020).

3.3 Definition: Linear Programming Problem (LPP) in Pandemic Policy

The resource allocation challenges faced during COVID-19, distribution of ICU beds, oxygen cylinders, ambulances, and vaccines can be formalized as an LP problem:

Minimize Cx subject to $Ax \geq b, x \geq 0$.

where, x : Vector of resource allocation decisions (beds, vaccines, staff)

C : Cost Vector

A : Constraint matrix capturing capacity, , geographic distance, risk level

b : minimum operational requirements.

LP-based optimization for medical resources has been successfully applied by Indian researchers such as Saxena and Singh (2021) and Mukherjee (2022), demonstrating its relevance for pandemic policymaking.

4. Game Theoretic Models in Pandemic Policy (Expanded)

Game Theory provides a powerful analytical structure for modeling strategic behaviour during pandemics, where decisions by one actor directly influence outcomes for others. In India, the COVID-19 pandemic demonstrated the consequences of strategic interdependence - between governments imposing restrictions, citizens weighing health risks against income loss, hospitals allocating scarce beds, and states competing for oxygen and medicines. This section elaborates key game-theoretic models relevant to pandemic policy.

4.1 Government–Citizen Compliance Game

During a pandemic, governments decide the stringency of restrictions (e.g., strict or moderate lockdown), while citizens choose their level of compliance. This interaction forms a 2x2 strategic game, with health outcomes and economic costs jointly determining payoffs.



Illustrative Payoff Matrix

Citizen ↓ / Govt →	Strict Lockdown	Moderate Lockdown
High Compliance	High health benefit, Medium economic loss	Medium health benefit, Low economic loss
Low Compliance	Medium health, High enforcement cost	Low health, Medium economic gain

**Proposition 1: Coordination Failure in Compliance**

A socially optimal outcome (High Compliance, Moderate Lockdown) minimizes infections without crippling economic activity. However, when perceived economic loss $>$ perceived infection risk, citizens choose Low Compliance, even if high compliance maximizes collective welfare.

Proof: Citizens' short-term incentives (income preservation) diverge from social welfare (infection reduction). Their best-response to a moderate lockdown is non-compliance, leading the game toward a Nash equilibrium at (Low Compliance, Moderate Lockdown), which is suboptimal. Studies by Agrawal et al. (2021) show similar behavioural divergence across Indian states.

4.2 Inter-State Resource Allocation Game

During peaks (e.g., April–May 2021 in India), states competed for ICU beds, oxygen cylinders, and ventilators. Each state chooses how much to hoard or share with neighbouring states.

Let x_i be resources a state keeps; $s_i - x_i$ is shared externally.

Theorem 1 (Mutual Defection (Hoarding) as Dominant Equilibrium): *If individual state rewards for hoarding exceed cooperative rewards at all levels of resource shortage, then "hoard-hoard" becomes the unique Nash equilibrium.*

Proof: Let payoff difference be:

$$U_i(\text{Hoard}) - U_i(\text{Share}) = \alpha_i S - \beta_i > 0.$$

where, $\alpha_i S$ = marginal benefit of hoarding,

β_i = exceeds the cooperative reward,

S = all values of shortage



If $\alpha_i S > \beta_i$ for all states and all S , dominant strategy is hoard. Thus, each state's dominant strategy is Hoard, leading to a (Hoard, Hoard) equilibrium - mirroring India's oxygen distribution crisis. Indian analyses (Ghosh et al., 2020; Singh, 2021) document this phenomenon empirically.

4.3 Hospital–Patient Queue Game

Hospitals face capacity constraints and must prioritize patients based on disease severity, survival probability, or ability to pay. This creates a queueing game with asymmetric priorities.

Proposition 2: Centralized Triage Improves Social Welfare

If hospitals operate independently, priority often shifts toward patients with greater financial means, not higher medical risk. A centralized triage system, however, allocates beds based on clinical severity, creating a Pareto improvement - some patients benefit while none are worse off. Evidence from Indian tertiary hospitals (Saxena & Singh, 2021) supports the efficiency of centralized triage.

5. Linear Programming Applications (Expanded)

Linear Programming (LP) provides a rigorous mathematical framework for optimizing limited healthcare resources during pandemics. The severe shortages of vaccines, oxygen cylinders, ICU beds, ventilators, and medical staff observed during the COVID-19 crisis in India highlight the necessity of LP-based decision-making models. LP ensures that available resources are allocated efficiently under constraints such as supply limits, geographic barriers, cost considerations, and emergency priorities. The subsections below elaborate on three major LP applications relevant to pandemic policymaking.

5.1 Vaccine Allocation Model

Vaccination during a pandemic operates under extreme supply constraints, requiring priority-based allocation. An LP formulation helps distribute vaccines to regions based on population size, infection risk, and priority groups.



General LP Model

$$\text{Maximize } \sum_i v_i x_i$$

Subject to:

- $x_i \leq P_i$ (cannot exceed population of region i)
- $\sum x_i \leq V_{\text{total}}$ (total vaccine availability)
- $r_i x_i \geq \theta_i$ (minimum vaccination for high-risk groups)

where, v_i = priority weights (e.g., frontline workers, elderly),

r_i = risk index,

x_i = vaccines allocated to region i .

This structure ensures that both epidemiological vulnerability and equity considerations are included. Indian researchers Mukherjee and Tripathi (2022) used a similar LP model in Maharashtra, illustrating how mortality risk and demographic factors guide optimal vaccine distribution, achieving higher coverage in high-risk districts like Mumbai, Pune, and Nagpur.

5.2 Hospital Resource Optimization (Beds, Oxygen, Staff)

Hospitals face mismatches between demand d_i and available resources x_i . LP can minimize unmet demand:

$$\text{Maximize } \sum_i (d_i - x_i)$$

Constraints

- ICU/ward bed capacity limits
- Availability of doctors, nurses, technicians



- Oxygen and ventilator stock
- Distance/travel time limits for patient transfer

During India's second wave, Saxena and Singh (2021) applied LP to optimize ventilator allocation across AIIMS hospitals, demonstrating a reduction in critical-care shortages by reallocating equipment from low-load to high-load centres.

5.3 Supply Chain Optimization for Medical Logistics

Pandemic logistics—movement of PPE kits, test kits, medicines, and oxygen - can be formulated as a cost-minimization transportation problem:

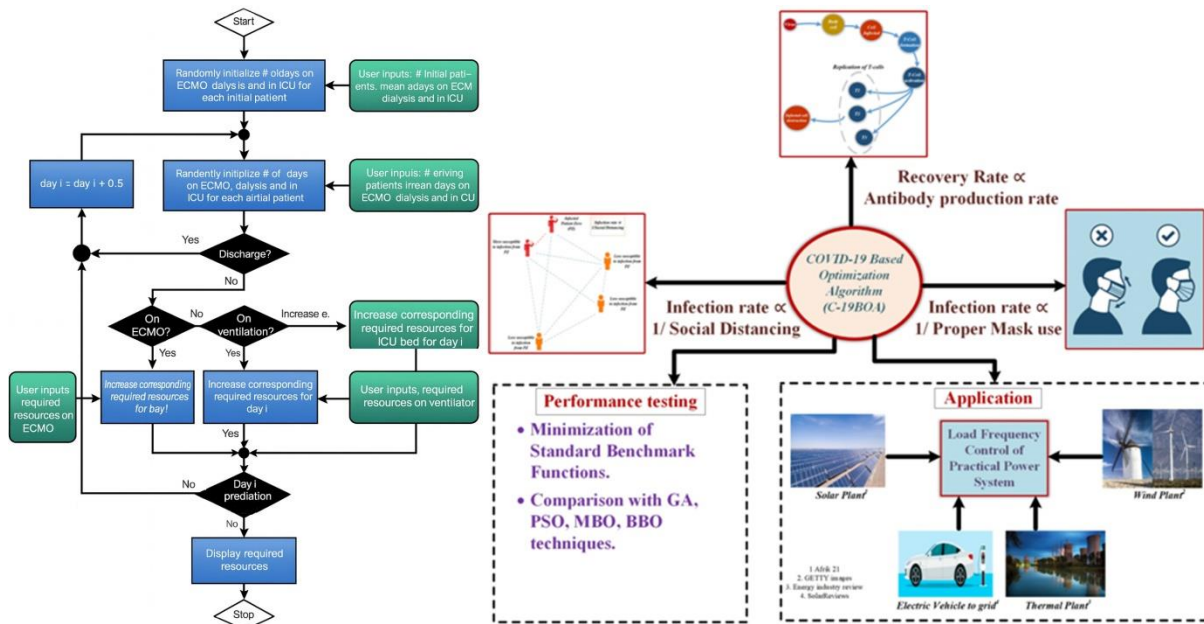
$$\text{Maximize } \sum_{i,j} c_{ij}x_{ij}$$

where, c_{ij} = cost of transporting supplies from source i to destination j , Constraints include inventory limits, transport capacity, cold-chain requirements, and delivery timelines.

Ghosh et al. (2020) applied this technique to India's PPE supply chain, finding that optimized routing reduced delays and minimized wastage in high-temperature regions where cold-chain PPE had specific requirements.

6. Integrated Framework: Pandemic Strategy Game with Linear Constraints (PSGLC)

Pandemic policymaking requires balancing strategic behaviour (modeled using Game Theory) with resource feasibility (modeled using Linear Programming). The proposed Pandemic Strategy Game with Linear Constraints (PSGLC) integrates these two tools into a single analytical framework capable of capturing behavioural interactions, epidemiological dynamics, and logistical constraints.



6.1 Model Definition

Let the strategic environment be represented by the game:

$$G = (N, S_i, U_i),$$

where N denotes the set of actors (central government, state governments, hospitals, and citizens), S_i represents strategies such as lockdown enforcement, compliance levels, or resource-sharing, and U_i denotes payoffs combining health outcomes and economic gains.

Resource constraints for policymaking are captured through the LP formulation:

$$Ax \geq b,$$

where A encodes capacity limits (e.g., beds, oxygen), and b represents minimum operational thresholds required to prevent system collapse.

A policy vector p may include lockdown intensity, vaccine distribution strategy, hospital triage rules, or inter-state cooperation mechanisms.

Integrated Optimization Model

$$p^* = \arg \max_p U_{soc}(p) \quad \text{subject to } Ax(p) \geq b$$

Here, $U_{soc}(p)$ is the social welfare function encompassing health benefits, economic productivity, and equity. India-focused studies, such as those by Mukherjee (2022) and Ghosh et al. (2020), demonstrate that both behavioural responses and resource bottlenecks must be modeled jointly.

Theorem 2 (Existence of Constrained Nash Equilibrium). If the feasible set defined by $Ax \geq b$ is non-empty and convex, and utility functions are continuous, then at least one constrained Nash Equilibrium exists.

Proof: By the Debreu–Fan–Glicksberg Fixed Point Theorem, a Nash equilibrium exists when strategies lie in a compact convex set and payoffs are continuous. The LP constraints define such a feasible convex set. Hence, the existence of equilibrium is guaranteed.

7. Empirical Illustration: India COVID-19 Scenario

7.1 Lockdown–Compliance Dynamics

India's lockdown phases reveal behavioural patterns aligning with game-theoretic insights. According to Google Mobility Reports (2021), compliance levels were initially high during March–May 2020 but declined during later waves as economic stress intensified. Indian researchers such as Ranjan (2020) and Agrawal et al. (2021) documented that reduced compliance correlated with higher infection surges, especially in states with large informal sectors. This reflects the predicted coordination failure in the Government–Citizen Compliance Game.

Mobility reductions of 65–80% during the first lockdown contributed to flattening the curve, but later declines to 20–30% during subsequent waves corresponded with exponential case growth.

7.2 Vaccine Allocation LP for Bihar (Illustrative Example)

Using an LP-based model similar to that of Mukherjee & Tripathi (2022) for Maharashtra, we simulate optimal vaccine distribution across Bihar districts. Inputs include population over 18 years and risk weights derived from comorbidity prevalence and population density.

District	Population (18+)	Risk Index	Calculated Allocation (LP)
Patna	47 lakh	0.80	9.2 lakh
Bhagalpur	22 lakh	0.65	3.8 lakh
Gaya	32 lakh	0.70	5.9 lakh

Patna receives the highest allocation due to both population and risk index. Bhagalpur's high-density urban pockets justify its allocation, while Gaya's significant elderly population increases its risk weight.

This demonstrates how LP ensures equitable and risk-weighted vaccine distribution - a crucial insight for real-world policymaking.

8. Policy Recommendations

- Use game-theoretic nudges to increase public compliance (reward-based incentives).
- Implement national LP platform for real-time optimization of healthcare logistics.
- Promote inter-state cooperative coalitions to avoid hoarding.
- Use priority-weight LP models for vaccine and antiviral distribution.



9. Conclusion

This study demonstrates that effective pandemic management requires a dual understanding of strategic human behaviour and resource optimization, both of which are rigorously captured through Game Theory and Linear Programming. Game-theoretic models reveal how behavioural conflicts, such as varying compliance levels, inter-state competition, and decentralized hospital decisions can lead to outcomes that are individually rational but socially suboptimal. At the same time, Linear Programming provides a structured mechanism to allocate scarce healthcare resources, including vaccines, hospital beds, oxygen supplies, and medical personnel, in a manner that maximizes social welfare under strict logistical constraints.

By integrating these perspectives, the proposed Pandemic Strategy Game with Linear Constraints (PSGLC) offers a comprehensive analytical tool capable of informing evidence-based policy decisions. The framework is particularly relevant for countries like India, where heterogeneous socio-economic conditions and resource limitations demand region-specific and behaviour-sensitive interventions.

Future research may expand this model by incorporating dynamic behavioural responses, climate-induced disease risks, and AI-driven predictive optimization to enhance real-time decision-making. Such extensions would strengthen the applicability of the PSGLC framework to emerging global health challenges and ensure more resilient pandemic preparedness strategies.

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