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Optimal Capacity addition in Indian States for Food Corporation of India

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Abstract

This paper proposes a three-phase optimization approach aimed at enhancing cost efficiency and infrastructure planning within the Indian Public Distribution System (PDS). The initial phase formulates a transportation cost minimization model that identifies the most economical distribution of foodgrain between surplus and consuming states. The second stage introduces a capacity augmentation model; wherein optimal storage expansion is established without exceeding the baseline transportation cost from initial phase. The third step combines transportation and capacity planning decision in order to minimize the overall system cost, including both grain movement and infrastructure utilization. Moreover, findings reveal that the integrated Model III consistently outperforms the lexicographic Model II, which only tries to minimize additional capacity, achieving lower overall system costs while still satisfying all constraints. Results indicate that while transportation consistently constitutes a major share of system expenditures, capacity expansion contributes a significant and sometimes dominant portion, underscoring its importance in policy and planning. The presented models offer a systematic decision-support mechanism for the Food Corporation of India (FCI) to formulate balanced, cost-efficient policies for national food security.

Keywords
Optimization, Operations Research, Logistics, Transportation and Public Distribution System (PDS).

1. Introduction

India is the world's second-largest producer of food grains, specifically wheat and rice, following China (Mogale et al., 2017b). In recent decades, the production and procurement of food grains in India have consistently increased, however storage capacity hasn't increased proportionately (Mogale et al., 2018). The demand for food grains staples such as wheat and rice, in India is persistently rising, prompting policymakers to enhance food production and improve transportation and storage infrastructures to mitigate post-harvest losses (Singha Mahapatra & Mahanty, 2018). (Singh, 2015) reported a 30–40 percent deficit in warehouse infrastructure within the food sector, resulting in wastage of food products. Owing to insufficient infrastructure and a markedly inefficient supply chain, India's annual food loss approximates 30–35% of total production (Sazzad, 2014). Although numerous studies have contributed to the mathematical modelling of transportation problems, there is a paucity of literature that specifically examines the impact of capacity addition costs on foodgrain distribution systems. Very limited number of studies have presented solution techniques adept at managing extensive datasets encompassing the majority of the Food Corporation of India's (FCI) infrastructure. Furthermore, very few to almost no studies have investigated the synergistic impact of transportation expenses and capacity expansion, underscoring a significant research gap that motivates the present work.

This paper addresses the issue of integrating transportation and capacity development decisions inside the Indian foodgrain distribution system, a subject characterized by its multi-stage nature and significant interdependencies across cost components. A three-stage framework is established to address this complexity: the initial stage reduces transportation expenses, the subsequent stage determines ideal capacity expansions within these cost limitations, and the final stage amalgamates both transportation and capacity utilization costs. Diverse scenarios are formulated and analysed to facilitate informed decision-making concerning capacity expansion, ensuring that policy alternatives are assessed under varying operational conditions. The organization of the paper is outlined as follows: The next subsection details the objectives defined for the study. Section 2 presents insights into the background literature related to the models developed in this area. Section 3 describes the methodology employed in this research. Section 4 outlines the data collection process. Section 5 discusses the results from various scenarios, and finally, Section 6 offers conclusions drawn from the study.

1.1 Objectives

The primary objective of this study is to develop a comprehensive framework for ascertaining the minimum total investment necessary for the annual transportation of foodgrains from excess to consuming regions, while effectively augmenting capacity. The study specifically intends to (i) optimize transportation expenses, (ii) ascertain optimal capacity expansions within cost limitations, and (iii) assess the cumulative effect of transportation and capacity utilization costs. The analysis includes government policy initiatives, such as increasing capacity to four times the allocation in consuming regions, to evaluate their cost-effectiveness and operational viability. Various scenarios are analysed to yield insights for informed policy formulation and effective resource allocation.

2. Literature Review

In recent years, food grain logistics has garnered considerable study interest, with numerous studies documented in the literature (K. P. et al., 2025). This literature survey includes both global and Indian research, analysing distribution systems for food grains and other essential commodities. (Asgari et al., 2013) developed a linear programming model aimed at optimizing the distribution of wheat from production areas to consumption areas in Iran. (Reis & Leal, 2015) explored a soybean supply chain in Brazil, examining the significance of temporal and spatial decisions under deterministic demand conditions. (Hong & An, 2008) modelled a grain supply chain centred in Beijing, examining the factors contributing to inefficiencies in transportation throughout the supply chain. (Masson et al., 2016) designed a two-phase model to handle the annual transportation problem and improve plant assignments for milk routing from farms to processing plants in Canada. A MILP model to minimize overall network costs, encompassing transportation and facility location is developed by (Etemadnia et al., 2015), hence enhancing regional and local food systems as proposed by the USDA. The forest residues supply chain is formulated as a comprehensive MILP model for decision-making about conversion, transportation, and storage to satisfy heating plant demand (Gunnarsson et al., 2004)

In the context of Indian Public Distribution System (PDS), a significant aspect of food grain logistics is the bulk storage and transit of freight, and finding sufficient warehousing facilities for this enormous inventory presents a challenge to stakeholders (Singh, 2015). (Mogale et al., 2017a) formulated a mixed integer non-linear programming (MINLP) model aimed at minimizing total costs, encompassing bulk food grain transportation, storage, and operational expenses. (Maiyar & Thakkar, 2017) develops an operational two-stage food grain transportation model for India using a linear formulation in the first stage and a MINLP in the second stage. A bi-level nodal capacity network flow model for intra-stage optimization, comprising a linear first level and a mixed-integer nonlinear second level, is designed by (Maiyar et al., 2015) to minimize transportation costs. (Mogale et al., 2018) proposes a multi-objective, multi-modal, and multi-period model for the grain silo location-allocation problem, incorporating dwell time, with the simultaneous goal of lowering total supply chain costs and lead times to facilitate GOI decision-making. A mathematical model is developed by (Mogale et al., 2017b) to addresses procurement, transportation, inventory, and location challenges to improve sustainability. The Total Supply Chain Cost of the Indian food grain supply chain is modelled to predict results under various scenarios and to make informed policies aimed at cost reduction (Sachan et al., 2005).

3. Methods

This paper presents a three-stage optimization approach to evaluate the trade-offs between transportation expenses and capacity augmentation in the Public Distribution System (PDS). Initially, a transportation cost minimization model is developed to ascertain the most economical transfer of food grains from surplus to deficit states with the aim of minimum transportation cost expenditure, subject to practical constraints as studied in the FCI system. The optimal transportation cost derived from this model acts as the baseline for the subsequent step, in which a capacity augmentation model is introduced. This model determines the optimal distribution of supplementary storage capacity among states while maintaining compliance with the baseline transportation cost. In the third stage, the framework is expanded to incorporate both transportation and capacity expansion decisions. The model reduces the total costs of transportation and capacity utilization, resulting in the most economical strategy for aligning foodgrain distribution with infrastructure development. The mathematical formulations for all three models are presented below in Table 1.

Table 1. Set of Indices, Parameters and Decision Variables

Index	Description
W	Set of warehouses
W_r	Set of warehouses tagged to railhead r
R	Set of railheads
W_a	Set of warehouses pertaining to state a
A	Set of States
W_{NCS}	Set of warehouses pertaining to Non-Consuming States (NCS)
K	Set of Commodities
Parameter	Description
c_{wr}^k	Cost of transportation (per unit) from w^{th} warehouse to r^{th} railhead for commodity k
c_{rw}^k	Cost of transportation (per unit) from r^{th} railhead to w^{th} warehouse for commodity k
c_{ij}^k	Cost of transportation (per unit) from i^{th} railhead to j^{th} railhead for commodity k
$P_{t,a}^k$	Procurement (in units) of k^{th} commodity in a^{th} state in t^{th} time period
$Q_{t,a}^k$	Allocation (in units) of k^{th} commodity in a^{th} state in t^{th} time period
$TC_{t,w}$	Total Capacity (in units) [Covered Capacity + Covered and Plinth (CAP) capacity] of w^{th} warehouse in t^{th} time period
$b_{t,w}^{k,n}$	Buffer for w^{th} warehouse in t^{th} time period for k^{th} commodity (calculated over n months)
$TC_{t,r}$	Total Capacity (in units) [Covered Capacity + Covered and Plinth (CAP) capacity] of r^{th} railhead in t^{th} time period
C	Baseline Transportation Cost (in units)
C_w	Cost (per unit) of utilizing augmented capacity
Q_a	Monthly allocation (in units) for a^{th} state
Q_c	Monthly allocation (in units) for a^{th} consuming state
Decision Variable	Description
$x_{t,wr}^k$	Quantity of food grains (in units) transported from w^{th} warehouse to r^{th} railhead for commodity k in time period t
$x_{t,rw}^k$	Quantity of food grains (in units) transported from r^{th} railhead to w^{th} warehouse for commodity k in time period t
$x_{t,ij}^k$	Quantity of food grains (in units) transported from i^{th} railhead to j^{th} railhead for commodity k in time period t
$I_{t,w}^k$	Inventory (in units) of w^{th} warehouse for commodity k at the beginning of t^{th} time period

$p_{t,w}^k$	Procurement (in units) of k^{th} commodity in w^{th} warehouse in t^{th} time period
$q_{t,w}^k$	Allocation (in units) of k^{th} commodity in w^{th} warehouse in t^{th} time period
$I_{t,r}^k$	Inventory (in units) of r^{th} railhead for commodity k at the beginning of t^{th} time period
a_{tw}	Augmented Capacity (in units) added to w^{th} warehouse
b_w	Maximum Capacity (in units) of w^{th} warehouse across all months

Model I: Minimum Transportation Cost Model (*Min TraC*)

Objective function:

$$\min \quad \sum_t \sum_k \left(\left(\sum_{r\in R} \sum_{w\in W_r} c_{wr}^k x_{t,wr}^k + c_{rw}^k x_{t,rw}^k \right) + \sum_{i\in R} \sum_{j\in R} c_{ij}^k x_{t,ij}^k \right) \tag{1}$$

Subject to:

$$I_{t+1,w}^k = I_{t,w}^k + p_{t,w}^k - q_{t,w}^k + x_{t,rw}^k - x_{t,wr}^k \tag{2}$$

where $t \in \{0,1,\dots,11\}, w \in W, r \in R, k \in \{\text{rice}, \text{wheat}\}$

$$\sum_{w\in W_a} p_{t,w}^k = P_{t,a}^k \quad \forall t \in \{0,1,\dots,11\}, \forall w \in W, a \in A, k \in K \tag{3}$$

$$\sum_{w\in W_a} q_{t,w}^k = Q_{t,a}^k \quad \forall t \in \{0,1,\dots,12\}, \forall w \in W, a \in A, k \in K \tag{4}$$

where W_a is the set of warehouses in the a^{th} state

$$I_{t,w}^{\text{wheat}} + I_{t,w}^{\text{rice}} \le TC_{t,w} \quad \forall t \in \{0,1,\dots,12\}, w \in W \tag{5}$$

$$I_{t,w}^k \ge b_{t,w}^{k,n} \quad \forall k, t \in \{0,1,\dots,12\}, w \in W \tag{6}$$

where $b_{t,w}^{k,n} = \frac{\beta}{n}\left(Q_{t,w}^k + Q_{t+1,w}^k + \cdots + Q_{t+(n-1),w}^k\right)$, n is number of months over which average demand needs to be found and β is the multiplier for buffer stocks.

$$I_{t+1,r}^k = I_{t,r}^k + \sum_{w\in W_r} x_{t,wr}^k - \sum_{w\in W_r} x_{t,rw}^k + \sum_{i\in R} x_{t,ir}^k - \sum_{j\in R} x_{t,rj}^k \quad \forall k, t \in \{0,1,\dots,11\}, r \in R \tag{7}$$

$$I_{t,r}^{\text{wheat}} + I_{t,r}^{\text{rice}} \le TC_{t,r} \; \forall t \in \{0,1,\dots,12\}, r \in R \tag{8}$$

$$I_{t,r}^{\text{rice}}, I_{t,r}^{\text{wheat}}, x_{t,wr}^k, x_{t,rw}^k, x_{t,ij}^k, q_{t,w}^k, p_{t,w}^k, I_{t,w}^k \ge 0 \;\; \forall \text{t}, \text{r}, \text{w}, \text{k} \tag{9}$$

The objective function (1) focuses on minimizing total costs, which include road costs (i.e., transportation between warehouses and railheads and vice-versa) and rail costs incurred between the railheads across the country. Constraint (2) defines the inventory balance constraint, where inventory levels are determined at the beginning of each month following the completion of procurement, allocation, and distribution activities of the preceding month. Constraints (3) and (4) limit the combined procurement and allocation variables for each state to not exceed the total procurement value designated for that state. Constraint (5) stipulates that at any given time t, the total inventory in a specific warehouse must not surpass its total capacity. Constraint (6) guarantees the maintenance of minimum buffer requirements. As noted for warehouses in constraint (2), constraint (7) outlines the inventory balance constraint applicable to each railhead nationwide, while constraint (8) ensures that the inventory at any railhead does not exceed its total capacity at any time t, concluding with non-negativity restrictions given by (9).

Model IA: Minimum augmented capacity required without any additional cost

$$I_{t,w}^{\text{wheat}} + I_{t,w}^{\text{rice}} \leq TC_{t,w} + a_{tw} \quad \forall t \in \{0,1,\dots,12\}, w \in W \tag{10}$$

The rest of the constraints are (2) – (4) and (6) – (9) as per Model I.

The constraint (5) in Model I is altered by incorporating an augmented capacity variable that incurs no penalty or utilization cost in the objective function, thus allowing for the capacity to be added freely as needed, as given by (10).

Model II: Lexicographic Optimization Model (Minimum additional Capacity required)

Objective function:

$$\min \sum_{w \in W} b_w \tag{11}$$

$$\mathrm{b}_w \geq a_{tw} \qquad \forall t \in \{0,1,\dots,12\}, w \in W \tag{12}$$

$$\sum_t \sum_k \left(\left(\sum_{r \in R} \sum_{w \in W_r} c_{wr}^k x_{t,wr}^k + c_{rw}^k x_{t,rw}^k \right) + \sum_{i \in R} \sum_{j \in R} c_{ij}^k x_{t,ij}^k \right) \leq C \tag{13}$$

$$I_{t,w}^{\text{wheat}} + I_{t,w}^{\text{rice}} \leq TC_{t,w} + a_{tw} \quad \forall t \in \{0,1,\dots,12\}, w \in W \tag{14}$$

$$\mathrm{b}_w , a_{tw} \geq 0 \quad \forall t, \forall w \in W \tag{15}$$

The rest of the constraints are (2) – (4) and (6) – (9) as per Model I.

The objective function of Model II (given by (11)) focuses on minimizing the maximum capacity variable added across all months for each warehouse, as indicated by (12). This approach ensures the necessary capacity augmentation while maintaining the optimal minimum transportation cost outlined in Model I, as indicated by (13). Consequently, this restricts the addition of the capacity variable, unlike the approach taken in Model I.

Model III: Consolidated Cost Minimization Model

Objective function:

$$\min \sum_t \sum_k \left(\left(\sum_{r \in R} \sum_{w \in W_r} c_{wr}^k x_{t,wr}^k + c_{rw}^k x_{t,rw}^k \right) + \sum_{i \in R} \sum_{j \in R} c_{ij}^k x_{t,ij}^k \right) + C_w \sum_w b_w \tag{16}$$

The rest of the constraints are identical as per Model I with addition of constraints (12) and (14).

The objective function (16) aims to minimize total costs, which include transportation expenses based on Model I and the variable costs associated with additional capacity utilization.

In alignment with the aforementioned models, cases have been formulated for models IA, II, and III concerning policy-making decisions related to capacity expansion. To this purpose, Indian states are categorized into two groups:

Consuming States (Deficit States) and Non-Consuming States (Surplus/Procuring States). Consuming States are Indian States where the purchase of food grains for a certain commodity is less than its allocation under the Public Distribution System (PDS) and relies on a continuous supply of food grains from surplus states to fulfill PDS requirements. Surplus states refer to Indian states where the procurement of food grains for a certain product surpasses its allocation under the Public Distribution System (PDS), necessitating the transportation of food grains to deficit regions to accommodate further procurement. According to the government's policy decision-making agencies, the government intends to augment the capacity of consuming states by four times the allocation for that specific state (*Case IA and IB* as described below). To assess this decision, specific cases have been constructed for the discussed model to determine the most effective capacity addition policy in Indian states.

Case IA: *All States scenario* - When augmented capacity is added to all the states (consuming and non-consuming).

$$\sum_{w \in W_a} b_w \geq 4(Q_a) \tag{17}$$

Case IB: *Specific States scenario* - When augmented capacity is added to some specific states (consuming).

$$\sum_{w \in W_c} b_w \geq 4(Q_c) \tag{18}$$

$$\mathrm{a_{tw}} = 0 \quad \forall t,\ w \in W_{NCS} \tag{19}$$

Case IIA: *All States scenario* - When augmented capacity is added to all the states (consuming and non-consuming), it does not exceed four times the allocation for that state.

$$\sum_{w \in W_a} b_w \leq 4(Q_a) \tag{20}$$

Case IIB: *Specific States scenario* - When augmented capacity is added to some specific states (consuming), it does not exceed four times the allocation for that state.

$$\sum_{w \in W_c} b_w \leq 4(Q_c) \tag{21}$$

$$\mathrm{a_{tw}} = 0 \quad \forall t,\ w \in W_{NCS} \tag{22}$$

Constraint (17) in scenario IA stipulates that if capacity is augmented in any state, the maximum capacity for a warehouse across all months, summed over all warehouses in that state, must exceed the allocation figures by a factor of four. Should capacity augmentation be implemented in specific states, as outlined in scenario IB, the augmented capacity variable for non-specific states is pre-processed to zero, as indicated by equation (19) along with the addition of constraint (18). Conversely, if the augmented capacity for a state is intended to remain below four times the allocation value for purposes of comparison and analysis, this is addressed in scenario IIA with constraint (20). Additionally, to align with scenario IB in order to keep the augmented capacity in specific states below four times the allocation, constraint (21) is introduced, and constraint (22) provides the necessary pre-processing.

4. Data Collection

The list of warehouses and railheads, encompassing data on all operational FCI/SWC/CWC warehouses nationwide and their associated railheads, was obtained from the publicly accessible FCI Consignor-Consignee record. The monthly Food Bulletins issued by the Department of Food and Public Distribution (DFPD) were utilized to collect statistics on the procurement, allocation, and offtake of food grains for each state on a monthly basis. The initial inventory values for food grains from each warehouse are established by apportioning the state's monthly closing balance among its warehouses. The statewide Covered and Covered and Plinth (CAP) capacity have been extracted from the bulletins and are allocated uniformly across the state's warehouses. The addresses from the FCI Consignor Consignee document were used to calculate latitude and longitude via the Google Geocoding API, subsequently determining distances as a prerequisite for cost computation. The rail distances between various railheads have been calculated by scraping data from the publicly accessible railway website with advanced programming techniques. The 130A train load of Indian Railways is utilized to calculate rail costs over distances. Certain data assumptions were considered prior to solving the models, particularly regarding road cost calculations. The telescopic rates were assumed to be a flat rate of 13.5 rupees for a 10 km slab, followed by a rate of 13.5 + (x – 10)*0.75 for distances greater than 10 km. These cost rates were derived from the Handling and Transportation Contract (HTC) rates of Uttarakhand State. It was assumed that the initial inventory values at the railheads are zero. Covered railhead capacities for all scenarios were based on the total output railhead inventory values of food grains obtained by running the baseline cost minimization model with infinite railhead capacities. Subsequently, implied capacities were derived and utilized for all other scenarios. Additionally, Covered and Plinth (CAP) railhead capacities were assumed to be 5% of the respective covered capacity values.

5. Results and Discussion

Table 2 presents a consolidated summary of results for various models and their respective cases. The columns labelled "All States" and "Spec States" illustrate scenarios where the augmented capacity variable (a_{tw}) is applied to all states versus only to select states, respectively. The percentage increase in cost compared to the baseline is indicated in brackets next to the cost values within the cells. Based on publicly available data regarding utilization and penalty costs, the parameter (C_w) assumes costs as follows: lower bound (lb) = 8.88 Cr/LMT/year, upper bound (ub) = 11.232 Cr/LMT/year, average (avg) = 10.056 Cr/LMT/year, and Central Warehousing Corporation (CWC) Contract (con) = 12.936 Cr/LMT/year. Additionally, for model II, several scenarios were computed with cost restrictions based on the baseline cost, along with 5% and 10% relaxations of the baseline cost. After determining the optimal additional capacity required, the cost was calculated using all the different parameter (C_w) values, as shown in Table 2. Table 4 presents the detailed results for each state across all scenarios for lexicographic optimization model II.

Table 2. Results Summary

Sno	Model	Scenarios	All States (Cost Cr.)	Spec States (Cost Cr.)
1	Model I	Baseline	4699.28	4699.28
2	Model IA	Augmented variable (Σb_w>=4*Q)	4699.28(0%)	5653.22 (20.30%)
3	Model IA	Augmented variable (Σb_w <=4*Q)	4699.28(0%)	6014.70(27.99%)
4	Model II	Lexicographic Optimization (Baseline Cost)-lb	8023.89(70.75%)	8240.96(45.77%)
5	Model II	Lexicographic Optimization (Baseline Cost)-ub	8904.46(89.49%)	8926.36(57.90%)
6	Model II	Lexicographic Optimization (Baseline Cost)-avg	8464.17(80.12%)	8583.66(51.84%)
7	Model II	Lexicographic Optimization (Baseline Cost)-con	9542.42(103.06%)	9422.93(66.68%)
8	Model II	Lexicographic Optimization (Baseline Cost +5%)-lb	7182.68(52.85%)	7823.08(38.38%)
9	Model II	Lexicographic Optimization (Baseline Cost +5%)-ub	7778.21(65.52%)	8322.93(47.22%)
10	Model II	Lexicographic Optimization (Baseline Cost +5%)-avg	7480.44(59.18%)	8073.01(42.80%)
11	Model II	Lexicographic Optimization (Baseline Cost +5%)-con	8209.67(74.70%)	8685.07(53.63%)
12	Model II	Lexicographic Optimization (Baseline Cost +10%)-lb	7086.76(50.81%)	8066.33(42.69%)
13	Model II	Lexicographic Optimization (Baseline Cost +10%)-ub	7594.65(61.61%)	8555.75(51.34%)
14	Model II	Lexicographic Optimization (Baseline Cost +10%)-avg	7340.71(56.21%)	8311.04(47.01%)
15	Model II	Lexicographic Optimization (Baseline Cost +10%)-con	7962.62(69.44%)	8910.32(57.62%)
16	Model III	Consolidated Cost Min (8.88 Cr) (Σb_w<=4*Q)	6002.29(27.23%)	6917.20(15%)
17	Model III	Consolidated Cost Min (11.232 Cr) (Σb_w<=4*Q)	6216.66(32.29%)	7088.32(17.85%)
18	Model III	Consolidated Cost Min (10.056 Cr) (Σb_w<=4*Q)	6115.03(30.13%)	7004.16(16.45%)
19	Model III	Consolidated Cost Min (12.936 Cr) (Σb_w<=4*Q)	6346.89(35.06%)	7204.66(19.78%)
20	Model III	Consolidated Cost Min (8.88 Cr) (Σb_w>=4*Q)	7060.83(50.25%)	7817.01(38.28%)

21	Model III	Consolidated Cost Min (11.232 Cr) (Σb_w>=4*Q)	7579.17(61.28%)	8306.43(46.93%)
22	Model III	Consolidated Cost Min (10.056 Cr) (Σb_w>=4*Q)	7320.62(55.78%)	8061.72(42.60%)
23	Model III	Consolidated Cost Min (12.936 Cr) (Σb_w>=4*Q)	7952.14(69.22%)	8661(53.20%)

The optimal baseline cost is approximately 4700 crore rupees (see Table 2). This baseline cost remains unchanged for the "All States" scenario, regardless of the policy concerning augmented capacity addition, as there are no penalties or utilization costs for capacity addition in Model I and Model IA. Consequently, capacity can be added freely, and the minimum transportation cost is calculated. In contrast, under the "Spec States" scenario, the corresponding cost increases because the augmented capacity variable is constrained to zero in major procuring states (mainly Punjab and Haryana) (refer to Table 3). This constraint necessitates increased movement of food grains to consuming regions in order to accommodate the upcoming month's food grain procurement. The same rationale applies to the increased transportation expenses in the "Spec States" scenario for Model I and Model IA. In this case, enhancing capacity (at least four times allocation) in specific regions leads to a decrease in the movement of food grains, which ultimately reduces transportation costs. Table 3 provides the detailed results for the Model I and IA with details regarding the existing capacities of these Indian states with augmented/additional capacity required for each state for Baseline and further cases concerning all and specific states.

Table 3. Detailed Results – Model I & IA (Transportation Cost Minimization)

RESULTS			Scenario(0)_Baseline	Scenario(1)_Min_Transportation_cost_(atw_as_free_var)			
				Allstates_Σbw<=4*alloc	Specstates_Σbw<=4*alloc	Allstates_Σbw>=4*alloc	Specstates_Σbw>=4*alloc
			Min_TTC *4699.28 Cr*	Min_TTC *4699.28(0%) Cr*	Min_TTC *6014.70(27.99%) Cr*	Min_TTC *4699.28(0%) Cr*	Min_TTC *5653.22 (20.30%) Cr*
Sno	**State**	**Exist_cap**	**Baseline_addl_cap**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**
1	Andhra Pradesh	41.89	0 (0%)	8.928 (21.3%)	8.929 (21.3%)	17.245 (41.2%)	20.908 (49.9%)
2	Arunachal Pradesh	0.38	0.15 (39.5%)	0.434 (114.2%)	0.269 (70.8%)	0 (0%)	0.269 (70.8%)
3	Assam	4.73	7.57 (159.9%)	9.831 (207.8%)	5.915 (125.1%)	10.024 (211.9%)	12.576 (265.9%)
4	Bihar	17.65	28.54 (161.7%)	32.91 (186.5%)	31.377 (177.8%)	43.814 (248.2%)	41.869 (237.2%)
5	Chhattisgarh	27.75	17.72 (63.8%)	32.615 (117.5%)	0 (0%)	30.198 (108.8%)	0 (0%)
6	Delhi	3.36	0 (0%)	3.442 (102.4%)	0 (0%)	3.607 (107.4%)	0 (0%)
7	Goa	0.25	0.08 (31.6%)	0.24 (96%)	0 (0%)	0.257 (102.8%)	0 (0%)
8	Gujarat	8.29	12.73 (153.6%)	21.775 (262.7%)	0 (0%)	22.831 (275.4%)	0 (0%)
9	Haryana	99.94	68.18 (68.2%)	85.421 (85.5%)	0 (0%)	84.085 (84.1%)	0 (0%)
10	Jharkhand	10.98	7.38 (67.2%)	10.355 (94.3%)	0 (0%)	7.828 (71.3%)	0 (0%)
11	Karnataka	10.61	13.33 (125.6%)	15.395 (145.1%)	9.898 (93.3%)	18.446 (173.9%)	27.436 (258.6%)
12	Kerala	6.95	2.42 (34.9%)	6.726 (96.8%)	0 (0%)	5.493 (79%)	0 (0%)
13	Madhya Pradesh	133.38	119.26 (89.4%)	18.529 (13.9%)	18.529 (13.9%)	120.048 (90%)	134.849 (101.1%)
14	Maharashtra	21.05	24.79 (117.8%)	27.02 (128.4%)	21.366 (101.5%)	37.232 (176.9%)	33.179 (157.6%)
15	Manipur	0.63	0.09 (14.4%)	0.815 (129.4%)	0.815 (129.4%)	0.231 (36.7%)	0.334 (53%)
16	Mizoram	0.32	0 (0%)	0.331 (103.4%)	0.331 (103.4%)	0.018 (5.6%)	0 (0%)
17	Nagaland	0.55	0 (0%)	0.694 (126.2%)	0.694 (126.2%)	0.234 (42.5%)	0.061 (11.1%)
18	Odisha	14.82	13.89 (93.7%)	12.623 (85.2%)	12.623 (85.2%)	26.552 (179.2%)	24.388 (164.6%)
19	Punjab	171.08	214.46 (125.4%)	278.344 (162.7%)	0 (0%)	277.736 (162.3%)	0 (0%)
20	Rajasthan	22.62	26.4 (116.7%)	33.887 (149.8%)	0 (0%)	40.265 (178%)	0 (0%)
21	Tamil Nadu	32.15	11.97 (37.2%)	18.24 (56.7%)	8.296 (25.8%)	29.383 (91.4%)	25.145 (78.2%)
22	Telangana	28.98	5.8 (20%)	20.63 (71.2%)	0 (0%)	15.885 (54.8%)	0 (0%)
23	Tripura	0.51	1.77 (346.9%)	1.32 (258.8%)	0.904 (177.3%)	0.589 (115.5%)	1.624 (318.4%)
24	Uttar Pradesh	57.09	93.21 (163.3%)	51.775 (90.7%)	51.775 (90.7%)	98.898 (173.2%)	191.55 (335.5%)
25	Uttarakhand	2.31	3.98 (172.5%)	5.275 (228.4%)	0 (0%)	4.536 (196.4%)	0 (0%)
26	West Bengal	20.8	10.53 (50.6%)	27 (129.8%)	0 (0%)	33.941 (163.2%)	0 (0%)
	TOTAL	**739.07**	**678.23 (91.8%)**	**724.555 (98%)**	**171.721 (23.2%)**	**929.376 (125.7%)**	**514.188 (69.6%)**

For Model II (lexicographic optimization), the cost figures mentioned in Table 2 represent the computed cost after optimization, utilizing the corresponding cost parameters discussed earlier. When we add additional capacity to all states and relax the baseline cost restriction by 5% and then 10%, the cost decreases. This relaxation permits more movement of food grains, allowing for the addition of less capacity. The costs remain consistently higher for specific states scenarios because more capacity is added in consuming regions, while there is no opportunity for capacity addition in procuring (surplus) regions. This situation leads to increased movement of food grains and, consequently, higher transportation expenses. Table 4 presents the detailed results for Model II, including the total capacity added across India along with sub scenarios related to the baseline cost. The additional capacity for each state is also shown in Table 4, allowing for comparison with existing capacity to aid in policy and decision-making. The optimal cost for various scenarios related to Model III, which aims to minimize total costs by factoring in transportation and capacity utilization, is presented in Table 2. Tables 5 and 6 present comparisons at both the state and national levels. Table 2 clearly indicates that the objective function cost is highest for the sub scenario that includes the greatest augmented capacity cost. Tables 5 and 6 display results for various scenarios based on different values of the augmented cost parameter, with maximum capacity additions equating to four times the allocation and minimum capacity additions equivalent to four times the allocation. Additionally, these tables offer comparisons at both state and national levels for capacity additions relative to existing capacity.

Table 4. Detailed Results – Model II (Lexicographic Optimization)

RESULTS			Scenario(2)_Lexicographic_Optimization_Min∑bw_const(∑bw>=4*alloc)					
			All_states_mincost_approx (4699.29 *crores*)	**All_states**_mincost_+5% (4934.25 *crores*)	**All_states**_mincost_+10% (5169.21 *crores*)	**Spec_states**_mincost_approx (5653.23 *crores*)	**Spec_states**_mincost_+5% (5935.88 *crores*)	**Spec_states**_mincost_+10% (6218.54 *crores*)
			Min ∑b_w : *374.39 LMT* **L**:*8023.89(70.75%)* **U**:*8904.46(89.49%)* **A**: *8464.17(80.12%)* **C**: *9542.42(103.06%)* *all values in Cr.*	**Min ∑b_w** : *253.20 LMT* **L**:*7182.68(52.85%)* **U**:*7778.21(65.52%)* **A**: *7480.44(59.18%)* **C**: *8209.67(74.70%)* *all values in Cr.*	**Min ∑b_w** : *215.93 LMT* **L**:*7086.76(50.81%)* **U**:*7594.65(61.61%)* **A**: *7340.71(56.21%)* **C**: *7962.62(69.44%)* *all values in Cr.*	**Min ∑b_w** : *291.41 LMT* **L**:*8240.96(45.77%)* **U**:*8926.36(57.90%)* **A**: *8583.66(51.84%)* **C**: *9422.93(66.68%)* *all values in Cr.*	**Min ∑b_w** : *212.52 LMT* **L**:*7823.08(38.38%)* **U**:*8322.93(47.22%)* **A**: *8073.01(42.80%)* **C**: *8685.07(53.63%)* *all values in Cr.*	**Min ∑b_w** : *208.08 LMT* **L**:*8066.33(42.69%)* **U**:*8555.75(51.34%)* **A**: *8311.04(47.01%)* **C**: *8910.32(57.62%)* *all values in Cr.*
Sno	**State**	**Exist_cap**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**
1	Andhra Pradesh	41.89	10.709 (25.6%)	10.71 (25.6%)	10.709 (25.6%)	10.711 (25.6%)	10.71 (25.6%)	10.71 (25.6%)
2	Arunachal Pradesh	0.38	0.434 (114.2%)	0.434 (114.2%)	0.434 (114.2%)	0.434 (114.2%)	0.434 (114.2%)	0.434 (114.2%)
3	Assam	4.73	9.839 (208%)	9.838 (208%)	9.838 (208%)	9.839 (208%)	9.838 (208%)	9.839 (208%)
4	Bihar	17.65	32.91 (186.5%)	32.91 (186.5%)	32.91 (186.5%)	32.91 (186.5%)	32.911 (186.5%)	32.909 (186.5%)
5	Chhattisgarh	27.75	9.825 (35.4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
6	Delhi	3.36	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
7	Goa	0.25	0.058 (23.2%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
8	Gujarat	8.29	9.016 (108.8%)	3.003 (36.2%)	1.756 (21.2%)	0 (0%)	0 (0%)	0 (0%)
9	Haryana	99.94	17.676 (17.7%)	2.628 (2.6%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
10	Jharkhand	10.98	3.751 (34.2%)	3.368 (30.7%)	0.717 (6.5%)	0 (0%)	0 (0%)	0 (0%)
11	Karnataka	10.61	15.395 (145.1%)	15.396 (145.1%)	15.396 (145.1%)	15.395 (145.1%)	15.395 (145.1%)	15.395 (145.1%)
12	Kerala	6.95	1.558 (22.4%)	0.486 (7%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
13	Madhya Pradesh	133.38	20.735 (15.5%)	20.735 (15.5%)	20.735 (15.5%)	20.736 (15.5%)	20.734 (15.5%)	20.735 (15.5%)
14	Maharashtra	21.05	27.02 (128.4%)	27.02 (128.4%)	27.021 (128.4%)	27.02 (128.4%)	27.02 (128.4%)	27.02 (128.4%)
15	Manipur	0.63	0.933 (148.1%)	0.933 (148.1%)	0.933 (148.1%)	0.933 (148.1%)	0.933 (148.1%)	0.933 (148.1%)
16	Mizoram	0.32	0.331 (103.4%)	0.331 (103.4%)	0.331 (103.4%)	0.331 (103.4%)	0.331 (103.4%)	0.331 (103.4%)
17	Nagaland	0.55	0.694 (126.2%)	0.694 (126.2%)	0.694 (126.2%)	0.694 (126.2%)	0.694 (126.2%)	0.694 (126.2%)
18	Odisha	14.82	12.728 (85.9%)	12.728 (85.9%)	12.728 (85.9%)	12.728 (85.9%)	12.729 (85.9%)	12.729 (85.9%)
19	Punjab	171.08	108.157 (63.2%)	27.476 (16.1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
20	Rajasthan	22.62	5.359 (23.7%)	2.306 (10.2%)	0.284 (1.3%)	0 (0%)	0 (0%)	0 (0%)
21	Tamil Nadu	32.15	18.239 (56.7%)	18.239 (56.7%)	18.239 (56.7%)	18.239 (56.7%)	18.239 (56.7%)	18.241 (56.7%)
22	Telangana	28.98	1.565 (5.4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
23	Tripura	0.51	1.32 (258.8%)	1.32 (258.8%)	1.321 (259%)	1.32 (258.8%)	1.32 (258.8%)	1.32 (258.8%)
24	Uttar Pradesh	57.09	56.795 (99.5%)	56.795 (99.5%)	56.795 (99.5%)	140.122 (245.4%)	61.235 (107.3%)	56.795 (99.5%)
25	Uttarakhand	2.31	1.071 (46.4%)	0.404 (17.5%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
26	West Bengal	20.8	8.274 (39.8%)	5.448 (26.2%)	5.1 (24.5%)	0 (0%)	0 (0%)	0 (0%)
	TOTAL	**739.07**	**374.392 (50.7%)**	**253.202 (34.3%)**	**215.941 (29.2%)**	**291.412 (39.4%)**	**212.523 (28.8%)**	**208.085 (28.2%)**

The results from the three models highlight specific trade-offs among cost reduction, transportation efficiency, and the extent of capacity augmentation. It is important to note that when there are no restrictions on transportation costs, the capacity addition at the national level is nearly doubling (from 100% to 125%) in Model I, as shown in Table 3. However, when transportation costs are restricted, the capacity addition significantly decreases to approximately 30% to 50%, as illustrated in Table 4 for Model II. For Model III, this reduction is even more pronounced, dropping to about 10% to 30%, as indicated in Tables 5 and 6. Model I, emphasizing the minimization of transportation costs within allocation constraints, results in extensive capacity enhancements, especially in large states like Uttar Pradesh, Bihar, Assam, Karnataka, and Punjab, as well as significant growth in smaller North-Eastern states. In Model II, expansions are still concentrated in high-demand regions like Uttar Pradesh, Bihar, Assam, and Karnataka, although the extent of capacity addition is more equitable compared to Model I. The North-Eastern states exhibit significant relative gains, however the increases in predominantly surplus states like Chhattisgarh and Odisha have markedly diminished, with some states, including Gujarat, Haryana, and Punjab, recording just minimal or insignificant increments. In model III, under the stringent Σbw ≤ 4*alloc restriction, capacity augmentation is negligible throughout the majority of states, with only a few such as Punjab, Bihar, Assam, and Maharashtra exhibiting considerable gains, while the national increment remains below 15%. Conversely, the Σbw ≥ 4*alloc scenario corresponds with the overarching expansion trends of Models I and II, with Uttar Pradesh, Bihar, Assam, and Karnataka reappearing as major benefactors, while the North-Eastern states maintain their elevated relative sensitivity. Nonetheless, capacity expansions in Punjab, Gujarat, and Haryana are still limited in comparison to earlier models.

Table 5. Detailed Results – Model III (Consolidated Cost Minimization)

RESULTS			Scenario(3)_Consolidated_cost_Min_TTC_const(Σbw<=4*alloc)							
			All_states_Lb (*8.88 crores /LMT/year*)	**All_states**_Ub (11.232 *crores /LMT/year*)	**All_states**_Avg (10.056 *crores /LMT/year*)	**All_states**_Con (12.936 *crores /LMT/year*)	**Spec_states**_Lb (*8.88 crores /LMT/year*)	**Spec_states**_Ub (11.232 *crores /LMT/year*)	**Spec_states**_Avg (10.056 *crores /LMT/year*)	**Spec_states**_Con (12.936 *crores /LMT/year*)
			Min TTC 6002.29(27.23%) *Cr* **TC :** *5114.88(85.22%) Cr* **atw**: *887.40(14.78%) Cr* **Max(b_w)** *35.72 LMT*	**Min TTC** 6216.66(32.29%) *Cr* **TC :** *5292.61(85.14%) Cr* **atw**: *924.04(14.86%) Cr* **Max(b_w)** *20.10 LMT*	**Min TTC** 6115.03(30.13%) *Cr* **TC :** *5195.81(84.97%) Cr* **atw**: *919.21(15.03%) Cr* **Max(b_w)** *32.85 LMT*	**Min TTC** 6346.89(35.06%)*Cr* **TC :** *5421.50(85.42%) Cr* **atw**: *925.38(14.58%) Cr* **Max(b_w)** *20.12 LMT*	**Min TTC** 6917.20(15%)*Cr* **TC :** *6254.46(90.42%) Cr* **atw**: *662.73(9.58%) Cr* **Max(b_w)** *51.66 LMT*	**Min TTC** 7088.32(17.85%)*Cr* **TC :** *6298.98(88.86%) Cr* **atw**: *789.33(11.14%) Cr* **Max(b_w)** *51.66 LMT*	**Min TTC** 7004.16(16.45%)*Cr* **TC :** *6271.16(89.53%) Cr* **atw**: *732.99(10.47%) Cr* **Max(b_w)** *51.66 LMT*	**Min TTC** 7204.66(19.78%)*Cr* **TC :** *6393.30(88.74%) Cr* **atw**: *811.35(11.26%) Cr* **Max(b_w)** *46.68 LMT*
Sno	**State**	**Exist_cap**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**
1	Andhra Pradesh	41.89	0.34 (0.8%)	0 (0%)	0.093 (0.2%)	0 (0%)	0.093 (0.2%)	0 (0%)	0.093 (0.2%)	0 (0%)
2	Arunachal Pradesh	0.38	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
3	Assam	4.73	1.84 (38.9%)	1.648 (34.8%)	1.67 (35.3%)	1.644 (34.8%)	1.839 (38.9%)	1.646 (34.8%)	1.678 (35.5%)	1.635 (34.6%)
4	Bihar	17.65	6.394 (36.2%)	6.328 (35.9%)	6.394 (36.2%)	6.306 (35.7%)	7.016 (39.8%)	6.417 (36.4%)	6.73 (38.1%)	6.418 (36.4%)
5	Chhattisgarh	27.75	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
6	Delhi	3.36	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
7	Goa	0.25	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
8	Gujarat	8.29	2.723 (32.8%)	2.651 (32%)	2.712 (32.7%)	2.615 (31.5%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
9	Haryana	99.94	0.719 (0.7%)	0 (0%)	0.167 (0.2%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
10	Jharkhand	10.98	2.599 (23.7%)	1.806 (16.4%)	2.081 (19%)	1.412 (12.9%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
11	Karnataka	10.61	3.065 (28.9%)	2.917 (27.5%)	3.031 (28.6%)	2.608 (24.6%)	3.036 (28.6%)	2.916 (27.5%)	2.962 (27.9%)	2.605 (24.6%)
12	Kerala	6.95	0.136 (2%)	0.061 (0.9%)	0.131 (1.9%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
13	Madhya Pradesh	133.38	1.307 (1%)	0 (0%)	0.309 (0.2%)	0 (0%)	5.267 (3.9%)	2.243 (1.7%)	4.198 (3.1%)	0 (0%)
14	Maharashtra	21.05	5.029 (23.9%)	4.938 (23.5%)	5.201 (24.7%)	5.072 (24.1%)	5.482 (26%)	5.213 (24.8%)	5.379 (25.6%)	5.195 (24.7%)
15	Manipur	0.63	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
16	Mizoram	0.32	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
17	Nagaland	0.55	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
18	Odisha	14.82	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
19	Punjab	171.08	56.296 (32.9%)	41.995 (24.5%)	49.906 (29.2%)	31.632 (18.5%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
20	Rajasthan	22.62	2.618 (11.6%)	2.578 (11.4%)	2.453 (10.8%)	2.801 (12.4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
21	Tamil Nadu	32.15	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
22	Telangana	28.98	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
23	Tripura	0.51	0.102 (20%)	0.098 (19.2%)	0.094 (18.4%)	0.066 (12.9%)	0.125 (24.5%)	0.065 (12.7%)	0.079 (15.5%)	0.065 (12.7%)
24	Uttar Pradesh	57.09	11.545 (20.2%)	11.845 (20.7%)	11.76 (20.6%)	11.968 (21%)	51.775 (90.7%)	51.775 (90.7%)	51.775 (90.7%)	46.803 (82%)
25	Uttarakhand	2.31	0.119 (5.2%)	0.119 (5.2%)	0.119 (5.2%)	0.119 (5.2%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
26	West Bengal	20.8	5.101 (24.5%)	5.291 (25.4%)	5.291 (25.4%)	5.291 (25.4%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	TOTAL	**739.07**	**99.933 (13.5%)**	**82.275 (11.1%)**	**91.412 (12.4%)**	**71.534 (9.7%)**	**74.633 (10.1%)**	**70.275 (9.5%)**	**72.894 (9.9%)**	**62.721 (8.5%)**

Table 6. Detailed Results – Model III (Consolidated Cost Minimization)

RESULTS			Scenario(3)_Consolidated_cost_Min_TTC_const(Σbw>=4*alloc)							
			Allstates_Lb (8.88 *crores /LMT/year*)	**Allstates**_Ub (11.232 *crores /LMT/year*)	**Allstates**_Avg (10.056 *crores /LMT/year*)	**Allstates**_Con (12.936 *crores /LMT/year*)	**Spec_states**_Lb (8.88 *crores /LMT/year*)	**Spec_states**_Ub (11.232 *crores /LMT/year*)	**Spec_states**_Avg (10.056 *crores /LMT/year*)	**Spec_states**_Con (12.936 *crores /LMT/year*)
			Min TTC 7060.83(50.25%)*Cr* **TC :** *5094.09(72.15%) Cr* **atw**:*1966.73(27.85%) Cr* **Max(b_w)** *56.08 LMT*	**Min TTC** 7579.17(61.28%)*Cr* **TC :** *5115.13(67.49%) Cr* **atw**:*2464.03(32.51%) Cr* **Max(b_w)** *56.08 LMT*	**Min TTC** 7320.62(55.78%)*Cr* **TC :** *5104.60(69.73%) Cr* **atw**:*2216.01(30.27%) Cr* **Max(b_w)** *56.08 LMT*	**Min TTC** 7952.14(69.22%)*Cr* **TC :** *5127.47(64.48%) Cr* **atw**:*2824.66(35.52%) Cr* **Max(b_w)** *56.08 LMT*	**Min TTC** 7817.01(38.28%) *Cr* **TC :** *5969.23(76.36%) Cr* **atw**:*1847.77(23.64%) Cr* **Max(b_w)** *56.08 LMT*	**Min TTC** 8306.43(46.93%) *Cr* **TC :** *5969.23(71.86%) Cr* **atw**:*2337.19(28.14%) Cr* **Max(b_w)** *56.08 LMT*	**Min TTC** 8061.72(42.60%) *Cr* **TC :** *5969.23(74.04%) Cr* **atw**:*2092.48(25.96%) Cr* **Max(b_w)** *56.08 LMT*	**Min TTC** 8661(53.20%) *Cr* **TC :** *5969.23(68.92%) Cr* **atw**:*2691.76(31.08%) Cr* **Max(b_w)** *56.08 LMT*
Sno	**State**	**Exist_cap**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**	**Max_atw_LMT_(%inc)**
1	Andhra Pradesh	41.89	10.709 (25.6%)	10.709 (25.6%)	10.708 (25.6%)	10.71 (25.6%)	10.71 (25.6%)	10.71 (25.6%)	10.71 (25.6%)	10.71 (25.6%)
2	Arunachal Pradesh	0.38	0.434 (114.2%)	0.434 (114.2%)	0.434 (114.2%)	0.434 (114.2%)	0.434 (114.2%)	0.434 (114.2%)	0.434 (114.2%)	0.434 (114.2%)
3	Assam	4.73	9.838 (208%)	9.838 (208%)	9.838 (208%)	9.839 (208%)	9.839 (208%)	9.839 (208%)	9.839 (208%)	9.839 (208%)
4	Bihar	17.65	32.909 (186.5%)	32.91 (186.5%)	32.909 (186.5%)	32.911 (186.5%)	32.91 (186.5%)	32.91 (186.5%)	32.911 (186.5%)	32.911 (186.5%)
5	Chhattisgarh	27.75	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
6	Delhi	3.36	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
7	Goa	0.25	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
8	Gujarat	8.29	2.437 (29.4%)	2.256 (27.2%)	2.304 (27.8%)	2.244 (27.1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
9	Haryana	99.94	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
10	Jharkhand	10.98	1.327 (12.1%)	1.115 (10.2%)	1.244 (11.3%)	1.077 (9.8%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
11	Karnataka	10.61	15.397 (145.1%)	15.394 (145.1%)	15.394 (145.1%)	15.395 (145.1%)	15.395 (145.1%)	15.394 (145.1%)	15.394 (145.1%)	15.394 (145.1%)
12	Kerala	6.95	0.163 (2.3%)	0.076 (1.1%)	0.137 (2%)	0.035 (0.5%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
13	Madhya Pradesh	133.38	20.735 (15.5%)	20.735 (15.5%)	20.733 (15.5%)	20.735 (15.5%)	20.735 (15.5%)	20.735 (15.5%)	20.735 (15.5%)	20.734 (15.5%)
14	Maharashtra	21.05	27.02 (128.4%)	27.02 (128.4%)	27.021 (128.4%)	27.02 (128.4%)	27.02 (128.4%)	27.019 (128.4%)	27.02 (128.4%)	27.019 (128.4%)
15	Manipur	0.63	0.933 (148.1%)	0.933 (148.1%)	0.933 (148.1%)	0.933 (148.1%)	0.933 (148.1%)	0.933 (148.1%)	0.933 (148.1%)	0.933 (148.1%)
16	Mizoram	0.32	0.331 (103.4%)	0.331 (103.4%)	0.331 (103.4%)	0.331 (103.4%)	0.331 (103.4%)	0.331 (103.4%)	0.331 (103.4%)	0.331 (103.4%)
17	Nagaland	0.55	0.694 (126.2%)	0.694 (126.2%)	0.694 (126.2%)	0.694 (126.2%)	0.694 (126.2%)	0.694 (126.2%)	0.694 (126.2%)	0.694 (126.2%)
18	Odisha	14.82	12.727 (85.9%)	12.728 (85.9%)	12.728 (85.9%)	12.728 (85.9%)	12.729 (85.9%)	12.728 (85.9%)	12.727 (85.9%)	12.728 (85.9%)
19	Punjab	171.08	1.761 (1%)	0.939 (0.5%)	1.233 (0.7%)	0.351 (0.2%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
20	Rajasthan	22.62	2.342 (10.4%)	1.808 (8%)	2.01 (8.9%)	1.465 (6.5%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
21	Tamil Nadu	32.15	18.239 (56.7%)	18.238 (56.7%)	18.237 (56.7%)	18.24 (56.7%)	18.24 (56.7%)	18.239 (56.7%)	18.24 (56.7%)	18.239 (56.7%)
22	Telangana	28.98	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
23	Tripura	0.51	1.32 (258.8%)	1.32 (258.8%)	1.321 (259%)	1.32 (258.8%)	1.321 (259%)	1.321 (259%)	1.32 (258.8%)	1.32 (258.8%)
24	Uttar Pradesh	57.09	56.795 (99.5%)	56.795 (99.5%)	56.795 (99.5%)	56.795 (99.5%)	56.795 (99.5%)	56.795 (99.5%)	56.795 (99.5%)	56.795 (99.5%)
25	Uttarakhand	2.31	0.075 (3.2%)	0 (0%)	0.075 (3.2%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
26	West Bengal	20.8	5.291 (25.4%)	5.101 (24.5%)	5.282 (25.4%)	5.101 (24.5%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	TOTAL	**739.07**	**221.477 (30%)**	**219.374 (29.7%)**	**220.361 (29.8%)**	**218.358 (29.5%)**	**208.086 (28.2%)**	**208.082 (28.2%)**	**208.083 (28.2%)**	**208.081 (28.2%)**

6. Conclusion

This paper established a three-phase optimization framework to evaluate the trade-offs among minimizing transportation costs, maximizing capacity enhancement, and consolidating integrated costs within the Indian Public Distribution System (PDS). The baseline model determined the minimal transportation cost to be ₹4699.28 crore, serving as the baseline for further analysis. The implementation of lexicographic optimization demonstrated that enforcing transportation costs restrictions substantially affected total system costs and supplementary capacity requirements. Particularly, scenarios where $\sum b_w \geq 4Q$ and $\sum b_w \leq 4Q$ revealed unique distributional patterns among states, with numerous deficit states, including Bihar, Assam, and Uttar Pradesh, demonstrating substantial proportional increases in required capacity, whereas surplus states like Punjab and Madhya Pradesh exhibited relatively stable capacity utilization. The integrated cost framework, which combined transportation expenses and capacity utilization, offered deeper insights into the cost-effectiveness of the capacity expansion policy. The total cost varied between ₹6002 crore and ₹9542 crore for all states, and between ₹6917 crore and ₹9423 crore for specific states, contingent upon the application of lower bound, upper bound, or contract-based cost parameters. Across all scenarios, capacity expansion was found to significantly contribute to the total system cost, accounting for a considerable share ranging from 15% to as much as 50% and even reaching 100% in certain cases. This underscores its critical importance in overall planning and decision-making. The results also demonstrate that Model III outperforms the lexicographic model, which focuses solely on minimizing costs, as the total cost under Model III is consistently lower than that of Model II while still satisfying all imposed constraints. The findings emphasize the necessity for a balanced approach that reduces transportation expenses while optimizing storage expansion across states. Policy implications indicate that concentrated capacity growth in deficit states, especially in the eastern and northeastern regions, can significantly enhance distribution efficiency without excessively increasing system costs. The suggested framework provides a pragmatic decision-support mechanism for the Food Corporation of India (FCI) to devise cost-efficient and equitable Public Distribution System logistics. Future research may investigate the incorporation of the road transport component into the overall transportation cost and thoroughly analyse its implications for capacity enhancement.

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