OPTIMIZATION OF INTER-STATE FOODGRAIN SUPPLY CHAINS

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Optimization of Inter-State Foodgrain Supply Chains

by

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in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



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Dedicated to

My Family:

Late Smt. Shanti Devi (Grandmother)

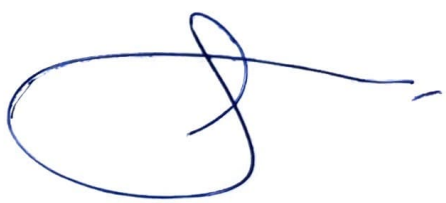
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Smt. Vinay Sharma (Mother)

Certificate

This is to certify that the thesis entitled **"Optimization of Inter-State Foodgrain Supply Chains"** submitted by **Mr. Atul Sharma** to the **Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy**, is a record of the original bonafide research work carried out by him under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations relating to the degree. The results contained in this thesis have not been submitted in part or full to any other university or institute for the award of any degree or diploma.



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2026

Abstract

Ensuring the timely and cost-effective movement of food grains across India is critical for sustaining the Public Distribution System (PDS), one of the world's largest food security programmes. The Food Corporation of India (FCI), responsible for managing national foodgrain logistics, currently relies on fragmented planning processes, informal decision-making, and limited computational tools, leading to inefficiencies, high operational costs, and vulnerability to disruptions. This thesis develops a comprehensive optimization-driven framework to strengthen FCI's interstate foodgrain movement through strategic, tactical, operational and resilience-oriented planning layers.

At the strategic level, an annual planning framework is formulated to minimize transportation expenditure, rationalize warehouse inventories, and evaluate the impact of capacity augmentation. Multiple variants, including multimodal models and integer-rake–based formulations, are developed and tested across realistic allocation and offtake scenarios. The results highlight substantial savings potential and provide insights into optimal inventory distribution, rake utilization, and multimodal routing.

For monthly and daily execution, a novel railhead-centric optimization framework is introduced, capturing operational realities such as rake type restrictions, two-point destinations, Traditional Empty Flow Direction (TEFD) concessions, and unbalanced supply–demand conditions. Dedicated execution methodologies, including a daily optimization algorithm, are designed to ensure minimal deviation from monthly plans. These daily optimization models are implemented through the web-based *Rake Optimization Tool*, a decision support software framework currently under deployment at FCI, enabling digital indent collection, real-time freight integration, and automated movement planning. Field validation with FCI confirms significant monthly and daily cost savings, along with major improvements in transparency, operational

coordination, and planning efficiency.

To address vulnerability in the supply chain, the thesis proposes a bilevel interdiction model that identifies critical railheads whose disruption would maximize system cost. A reformulated solution methodology with relaxed interdiction integrality is developed to ensure tractability on large datasets. Experiments across balanced and unbalanced scenarios reveal cost escalation patterns and resilience insights relevant for policy planning.

Overall, the research delivers an integrated, data-driven, and implementation-oriented framework spanning strategic annual planning, tactical and operational execution, and disruption resilience analysis, offering substantial managerial, financial, and policy benefits for strengthening India's foodgrain supply chain.

Keywords: Foodgrain Logistics, Mathematical Optimization, Multimodal Transportation, Interstate Transportation, Bilevel Programming, Public Distribution System (PDS), Food Corporation of India (FCI), Decision Support System, Mixed Integer Programming, Supply Chain Resilience, and Operations Research.

सारांश

भारत में खाद्यान्नों के समयबद्ध एवं किफायती परिवहन को सुनिश्चित करना सार्वजनिक वितरण प्रणाली की सतत् सफलता के लिए अत्यंत आवश्यक है, जो विश्व के सबसे बड़े खाद्य सुरक्षा कार्यक्रमों में से एक है। भारतीय खाद्य निगम (एफसीआई), जो राष्ट्रीय खाद्यान्न आपूर्ति श्रृंखला के प्रबंधन हेतु उत्तरदायी है, वर्तमान में खंडित योजना प्रक्रियाओं, मैनुअल निर्णय-निर्धारण और सीमित संगणनात्मक उपकरणों पर निर्भर है, जिसके परिणामस्वरूप कार्यकुशलता में कमी, उच्च परिचालन लागत और व्यवधानों के प्रति संवेदनशीलता देखी जाती है। इस शोधकार्य में एक व्यापक अनुकूलन-आधारित रूपरेखा विकसित की गई है, जो रणनीतिक, सामरिक तथा परिचालन स्तरों पर भारतीय खाद्य निगम की अंतरराज्यीय खाद्यान्न आवाजाही को सशक्त बनाती है।

रणनीतिक स्तर पर, एक वार्षिक योजना ढांचा तैयार किया गया है जिसका उद्देश्य परिवहन व्यय को न्यूनतम करना, गोदामों के भंडार को तर्कसंगत बनाना तथा क्षमता-वृद्धि के प्रभाव का मूल्यांकन करना है। इस ढांचे के अंतर्गत बहु-माध्यम और पूर्णांक रेक-आधारित गणितीय मॉडल विकसित किए गए हैं तथा इन्हें यथार्थवादी आवंटन एवं ऑफटेक परिदृश्यों पर परखा गया है। परिणामों से उल्लेखनीय लागत बचत की संभावना तथा भंडार वितरण, रेक उपयोगिता एवं बहु-माध्यम मार्ग-निर्धारण के संबंध में महत्त्वपूर्ण अंतर्दृष्टियाँ प्राप्त हुईं।

मासिक एवं दैनिक निष्पादन के लिए, एक रेलहेड-केंद्रित अनुकूलन ढांचा प्रस्तुत किया गया है, जो परिचालन वास्तविकताओं जैसे रेक प्रकार की सीमाएँ, दो-बिंदु गंतव्य, पारंपरिक रिक्त प्रवाह दिशा रियायतें, तथा असंतुलित आपूर्ति–मांग स्थितियाँ को सम्मिलित करता है। एक समर्पित दैनिक अनुकूलन एल्गोरिथ्म सहित निष्पादन पद्धतियाँ विकसित की गई हैं ताकि मासिक योजना से न्यूनतम विचलन सुनिश्चित हो सके। इन मॉडलों को भारतीय खाद्य निगम में तैनात निर्णय सहयोगी सॉफ़्टवेयर प्रणाली में पूर्णतः लागू किया गया है, जो डिजिटल इंडेंट संग्रह, वास्तविक समय मालभाड़ा एकीकरण, और स्वचालित गति नियोजन को सक्षम बनाता है। भारतीय खाद्य निगम के साथ क्षेत्रीय सत्यापन से मासिक एवं दैनिक लागत में उल्लेखनीय कमी, पारदर्शिता में वृद्धि, और परिचालन दक्षता में सुधार की पुष्टि हुई।

आपूर्ति श्रृंखला की संवेदनशीलता का मूल्यांकन करने हेतु, शोध में एक द्वि-स्तरीय इंटरडिक्शन मॉडल प्रस्तावित किया गया है, जो उन महत्त्वपूर्ण रेलहेडों की पहचान करता है जिनका व्यवधान समग्र प्रणाली लागत को अधिकतम करता है। बड़े डाटासेट्स पर हल निकालने की व्यवहार्यता सुनिश्चित करने हेतु इंटरडिक्शन चर के शिथिलीकरण पर आधारित एक समाधान पद्धति विकसित की गई है। संतुलित एवं असंतुलित परिदृश्यों पर किए गए प्रयोगों से लागत वृद्धि के पैटर्न तथा नीति-निर्धारण के लिए उपयोगी लचीलापन संबंधी अंतर्दृष्टियाँ प्राप्त हुईं।

समग्र रूप से, यह शोध वार्षिक योजना, मासिक निष्पादन, परिचालन अनुकूलन, एवं व्यवधान प्रतिरोध को एकीकृत करते हुए एक एकीकृत, डेटा-संचालित एवं क्रियान्वयन योग्य ढांचा प्रस्तुत करता है, जो भारत की खाद्यान्न आपूर्ति श्रृंखला को सुदृढ़ बनाने हेतु प्रबंधकीय, आर्थिक एवं नीतिगत लाभ प्रदान करता है।

मुख्य शब्द: खाद्यान्न लॉजिस्टिक्स, गणितीय अनुकूलन, बहु-माध्यम परिवहन, अंतर्राज्यीय परिवहन, द्विस्तरीय प्रोग्रामिंग, सार्वजनिक वितरण प्रणाली (पीडीएस), भारतीय खाद्य निगम (एफसीआई), निर्णय सहयोग प्रणाली, मिश्रित पूर्णांक प्रोग्रामिंग, आपूर्ति श्रृंखला लचीलापन, तथा संचालन अनुसंधान।

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List of Symbols

Symbol	Meaning
$\mathbb{R}$	set of real numbers,
$\mathbb{N}$	set of natural numbers,
$\mathbb{Z}$	set of integers,
$\mathbb{Z}^+$	set of positive integers,
$=$	equal to,
$\neq$	not equal to,
$\exists$	there exists,
$\nexists$	there does not exist,
$\forall$	for all,
$\cup$	union,
$\cap$	intersection,
$\in$	belongs to,
$\notin$	does not belong to,
$\emptyset$	empty set,
$A \subseteq X$	A is a subset of X,
$A \not\subseteq X$	A is not a subset of X,
$\lvert V \rvert$	cardinality of the set V,
$\lceil \cdot \rceil$	the smallest integer greater than or equal to $(\cdot)$,
$\lfloor \cdot \rfloor$	the largest integer less than or equal to $(\cdot)$,
W	set of warehouses,
R	set of railheads,
R_s	set of surplus railheads,
R_d	set of deficit railheads,

T	set of time periods,
K	set of commodities,
M	set of transportation modes,
$x\lambda y$	convex combination of x and y,
$O(Z)$	objective function value of problem (Z),

Abbreviations

Abbreviation	Meaning
AP	Andhra Pradesh (FCI Region)
ArP	Arunachal Pradesh (FCI Region)
BCN	Broad Gauge Covered Wagon for General Use
BCNHL	Broad Gauge Covered Wagon High Capacity Light Weight
BIH	Bihar (FCI Region)
CAG	Comptroller and Auditor General
CG	Chattisgarh (FCI Region)
CWC	Central Warehousing Corporation
DFPD	Department of Food and Public Distribution
DO	Divisional Office
DoS	Depot Online System
DSS	Decision Support System
Ex.N	Ex North (FCI Zone)
FCI	Food Corporation of India
FGSC	Food Grains Supply Chain
FIFO	First In First Out
FMOLP	Fuzzy Multi-Objective Linear Programming
FOIS	Freight Operations Information System
FRK BR	Fortified Rice Kernel Boiled Rice
FRK RRA	Fortified Rice Kernel Raw Rice Grade-A
FY	Financial Year
GDP	Gross Domestic Product
GoI	Government of India

GUJ	Gujarat (FCI Region)
HQRS	Headquarters
HTC	Handling and Transportation Charges
INR	Indian Rupees
IR	Indian Railways
IP	Integer Programming
JHK	Jharkhand (FCI Region)
KAR	Karnataka (FCI Region)
KER	Kerala (FCI Region)
LIP	Linear Integer Programming
LMT	Lakh Metric Tonnes
LP	Linear Programming
MAH	Maharashtra (FCI Region)
MCNF	Multicommodity Network Flow
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non Linear Programming
MP	Madhya Pradesh (FCI Region)
MT	Metric Tonnes
NE	North East (FCI Zone)
NFSA	National Food Security Act
OD	Odisha (FCI Region)
PDS	Public Distribution of India
PMGKAY	Pradhan Mantri Gareeb Kalyan Anna Yojana
QKM	Quintals Kilometres
RAJ	Rajasthan (FCI Region)
RH	Railhead
RO	Regional Office
RRA	Raw Rice Grade-A
SDGs	Sustainable Development Goals
SFG	Sponsored Food Grains
SWC	State Warehousing Corporation
TEFD	Traditional Empty Flow Directions
TEL	Telangana (FCI Region)
TN	Tamil Nadu (FCI Region)

UK	United Kingdom
UKD	Uttarakhand (FCI Region)
ULIP	Unified Logistics Interface Platform
UNWFP	United Nations World Food Programme
UP	Uttar Pradesh (FCI Region)
USDA	United States Department of Agriculture
WB	West Bengal (FCI Region)
WFP	World Food Programme

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