OPTIMIZING CONSTRUCTION AND UTILIZATION OF WHEAT STORAGE FACILITIES TO MINIMIZE POST-HARVEST LOSSES

BY

HATEM IBRAHIM IBRAHIM

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Civil Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2015

Urbana, Illinois

Doctoral Committee:

Professor Khaled A. El-Rayes, Chair
Professor Youssef Hashash, Co-Chair
Associate Professor Liang Y. Liu
Assistant Professor Mani Golparvar-Fard

ABSTRACT

The use of inefficient wheat storage and transportation facilities in developing countries often causes significant quantity and quality losses. These post-harvest losses are estimated to be as much as 20% of harvested wheat and a study by the Government of India puts the total preventable wheat losses at 10% of total production. These post-harvest wheat losses in developing countries can be minimized by (1) optimizing wheat storage and transportation throughout the entire supply chain network of existing facilities in villages, local markets, and regional locations; (2) constructing new public storage facilities that are funded and/or subsidized by government to expand and improve the existing storage facilities; and (3) building new private storage facilities that are funded by farmers to minimize post-harvest losses, maximize profitability of farmers, and improve their food security.

The main goal of this research study is to develop novel models for optimizing the storage and transportation of wheat to minimize post-harvest losses. To accomplish this, the research objectives of this study are to (1) conduct a comprehensive literature review to study local conditions, (2) develop a novel model for optimizing the storage and transportation of wheat using existing facilities in developing countries, (3) develop an innovative model for optimizing the construction of public wheat storage facilities that are funded and/or subsidized by government or other agencies, and (4) develop a novel model for optimizing the construction and utilization of private wheat storage facilities that are cooperatively funded by farmers.

The performance of the developed optimization models is analyzed and verified using case studies. The results of these case studies illustrate the novel and unique capabilities of the developed models in searching for and identifying optimal storage and transportation decisions. These new and unique capabilities are expected to support decision makers such as governments and farmers in identifying (i) optimal wheat storage levels in each existing facility and optimal transportation routes among them to minimize post-harvest losses and minimize storage and transportation costs throughout the entire network; (ii) optimal location, type, and capacity for the construction of new publicly-funded storage facilities to minimize post-harvest losses during storage and transportation throughout the entire network; and (iii) optimal construction decisions for privately-funded storage facilities and optimal wheat sales, purchases and storage quantities to minimize post-harvest losses and maximize the profit of farmers.

The expected impact of the developed optimization models include (a) reduced post-harvest losses during wheat storage and transportation; (b) minimized storage and transportation costs throughout the entire network of existing and new storage facilities; (c) increased annual profits for farmers; (d) enhanced food security for local farmers by increasing the storage capacity in their villages; and (e) expanded storage capacity for grain reserves and for potential increases in wheat production.

ACKNOWLEDGMENTS

Finishing this Ph.D. study was only made possible by a collective effort by everyone involved with me during this time. I would like to take the time to acknowledge the support they have provided me throughout this period.

First and foremost, I would like to thank Prof. Khaled El-Rayes for the guidance and support he has given me throughout my Ph.D. studies. I have learned a great deal from all the time and effort spent working with him from the smallest aspects to the big and challenging feats of my work. I have gained an insight into the function of many things and developed my thought process and therefore feel I have advanced myself, I am most appreciative for all this. Prof. Youssef Hashash, for the help he provided during the early part of the project while we were discovering the challenges of trying to solve PHL problems in India as well as guidance throughout the rest of my studies. Prof. Liang Liu and Prof. Mani Golparvar-Fard, for all the useful and positive feedback they provided for this study as well as all the help they provided throughout my time in Champaign.

I gratefully acknowledge the financial support for this research study from the ADM institute for Prevention of Post-Harvest Loss.

My father, for his lifetime of guidance and wisdom, I would not be where I am today if it were not for him. My dear and loving mother, for her constant and unwavering loving and caring, you will always be in my thoughts. My brother, for always having looked out for me from when we were young till this day.

I would like to also give thanks to my colleagues who have provided a helping hand whenever needed and for their support: Moatassem Abdallah, Aslihan Karatas, Ahmed Abdelmohsen, Ayman Halabya and Tarek El-Ghamrawy.

Last but not least, to my all friends who made my time in Champaign enjoyable and who have impacted my life in their own special way: Mohamed Ali, Abdelrahman Hassaballah, Mohamed Dardiri, Sherif Mahmoud, Rabie Abusaleem, Ashley Alibhai, Ahmed El-Kharbotly, Francesca, Hazem Hossam, Ahmed El-Sherbiny and Mahmoud Lotfy.

TABLE OF CONTENTS

LIST OF FIGURES

Chapter 2

Chapter 3

Chapter 4

Chapter 5

LIST OF TABLES

Chapter 2

Chapter 3

Chapter 4

Chapter 5

1 INTRODUCTION

1.1 Problem Statement

Optimizing the construction and utilization of public and private wheat storage facilities has been recommended by many studies to minimize post-harvest losses (Mc Carthy et al. 2008, Tefera et al. 2011). Post-harvest losses (PHL) can be defined as the degradation in both the quantity and quality of a food product from harvest to consumption (Kader 2004, Kitinoja et al. 2011). Quantity losses refer to those that result in the loss of the amount of a product (Kader 2004). Quality losses include those that affect the nutritive/caloric composition, the acceptability, and the edibility of a given product. In developing countries, the largest amount of PHL usually occurs on or near the farm, where the success of harvesting, consolidation and storage methods are key to keep losses low (Hodges et al., 2011, Kitinoja et al. 2010). For example, the government of India puts total preventable losses at 10% of total production (Basavaraja et al. 2007). These losses are often caused by improper packing, poorly equipped transportation vehicles and inadequate storage facilities (Baqui 2005, Basavaraja et al. 2007, Ofor and Ibeawuchi 2010).

To minimize the aforementioned quantity and quality losses of wheat in developing countries, a number of studies reported the need for (1) optimizing wheat storage and transportation in existing facilities (Ghimiray et al. 2007, Government of India 2011); (2) optimizing the construction of public storage facilities that are funded and/or subsidized by government or other agencies (IFC 2012, SDC 2011, Kiruba et al. 2006); and (3) optimizing the construction of private farm storage facilities that are funded by a number of cooperating farmers (Mc Carthy et al. 2008, Tefera et al. 2011).

1.1.1 Optimizing Wheat Storage and Transportation in Existing Facilities

The need for optimizing wheat storage and transportation in existing facilities has been reported by many studies. For example, Mc Carthy et al. (2008) reported that there is an opportunity to reduce wheat storage losses in India through improved on-farm storage techniques that control storage pests. Other studies also reported that storage and processing facilities are often under-utilized, which leads to waste and unnecessary cost (Ghimiray et al. 2007).

A number of research studies were conducted to investigate the storage and transportation of different types of grains such as wheat and rice in developing countries. These studies focused on: (1) identifying the optimal location and dimension of warehouses for grain storage in Brazil (Bornstein and Villela 1990, Monteroso et al. 1985); (2) analyzing the logistics network layout of agricultural products supply chain in China (Zhongquan et al. 2011); (3) determining the optimal number, size, location and design of grain storage facilities in Bangladesh (Pruzan 1978); and (4) studying the types of storage losses, bulk handling and storage in Pakistan (Food & Feed Grain Institute 1989, Food & Feed Grain Institute 1991). Despite the significant contributions of these studies, there is no or little reported research that focused on optimizing wheat storage and transportation in developing countries in order minimize the overall losses and distribution costs. Accordingly, there is a pressing need for optimization models that are capable of overcoming the limitations of previous models in (1) minimizing the total wheat storage and transportation cost in the entire supply chain network of villages, local markets, and regional locations, and (2) identifying needed upgrades of existing storage facilities and/or transportation routes.

1.1.2 Optimizing the Construction of Public Wheat Storage Facilities

Optimizing the construction of public wheat storage facilities that are funded by government and/or other agencies has been recommended by many recent studies in order to minimize post-harvest losses (IFC 2012, SDC 2011, Kiruba et al. 2006). For example, several studies have reported that wheat storage facilities are often needed to (a) protect harvested wheat from damage and losses during their storage (Kartikeyan et al, 2009); (b) provide extra storage capacity for grain reserves (IFC 2012); and (c) increase wheat production that is often constrained by limited farm-storage capacity (FAO 2009). The need for constructing new storage facilities especially in developing countries was highlighted in a recent report by the Government of India that stated that several Indian states suffer from a lack of covered storage capacity and that an additional 35 million tonnes of warehousing capacity is required in the next five to ten years (Government of India 2011). Another recent report also stated that Africa suffers 20 to 30% post-harvest losses valued at 4 billion dollars annually and there is a need to provide efficient storage facilities in Africa to minimize these post-harvest losses (SDC 2011).

The construction of public wheat storage facilities that are funded and/or subsidized by government or other agencies is a challenging task that requires decision-makers to (a) identify the optimal location, type and capacity for the new facilities; (b) consider the impact of existing storage facilities on the design and construction decisions for the new facilities, and (c) minimize the cost of wheat losses during storage and transportation. A number of existing research studies focused on optimizing: (1) the number, size, and location of soybean processing plants in the US (D'Souza 1988); (2) the location and dimension of warehouses for grain storage in Brazil (Bornstein and Villela 1990, Monteroso et al. 1985); and (3) the number, size, location and design of grain storage facilities in Bangladesh (Pruzan 1978). Despite the significant contributions of these optimization models, they are limited due to their incapability of (a) considering the impact of existing storage facilities, and (b) quantifying and minimizing the cost of wheat losses during storage and transportation. Accordingly, there is a pressing need for new optimization models that are capable of overcoming the aforementioned limitations of existing models for optimizing the construction of new government-funded wheat storage facilities.

1.1.3 Optimizing the Construction of Private Wheat Storage Facilities

Optimizing the construction of privately-owned wheat storage facilities in farms and villages has been recommended by many studies to minimize post-harvest losses, maximize profitability of farmers, and improve their food security (Mc Carthy et al. 2008, Tefera et al. 2011). The lack of adequate farm storage facilities was reported to increase wheat losses due to the high rate of storage losses suffered in existing inefficient facilities (Kader 2004, Kitinoja et al. 2011). Other studies have also reported that the lack of adequate storage facilities on or near farms often force farmers to sell their crops immediately after harvest at low prices and later re-purchase them at higher prices for their family consumption (Global Agri System, Tefera et al. 2011). To overcome these challenges, there is a pressing need for the construction of new efficient wheat storage facilities in farms and villages that are capable of (1) protecting harvested wheat and minimizing storage losses (Kartikeyan et al, 2009); (2) providing food security for farmers

(Tefera et al. 2011); and (3) providing extra storage capacity (IFC 2012). The construction of these wheat storage facilities often requires financial resources that are beyond the capabilities of many individual farmers (Chattha and Lee 2014, Global Agri System, FAO 1994). As a result, Mc Carthy et al. (2008) recommended the development of community savings for the construction of efficient and shared storage facilities that can be used by all participating farmers.

Optimizing the construction and utilization of shared storage facilities in farms and villages is a challenging task that requires decision makers to identify (a) the optimal location, type and capacity of new shared wheat storage facilities from a set of feasible alternatives; and (b) the optimal monthly storage and sale quantities of wheat that maximize farmers' profitability while considering the impact of changing monthly wheat sale prices. A number of studies focused on optimizing the construction of new storage facilities including: (1) optimizing the number, size, and location of soybean processing plants in the US (D'Souza 1988); and (2) optimizing the location and dimension of warehouses for grain storage in Brazil (Bornstein and Villela 1990, Monteroso et al. 1985). Other researchers developed models for optimizing the storage and sales of agricultural products, including (1) Cotty et. al (2014) who developed a model for agricultural crops to identify the optimal storage duration and sales periods of crops to the market in Burkina Faso; (2) Renkow et. al (2004) who developed a model to estimate farmer supply and demand schedules and their impact on the cost of maize in Kenya. Despite the significant contributions of the aforementioned studies, they are not designed to enable a group of farmers to optimize the construction and utilization of shared wheat storage facilities to maximize their annual profits.

1.2 Research Needs

The aforementioned review of the latest research on wheat storage and transportation highlight the pressing need for research and development of new and innovative models that are capable of: (1) optimizing the storage and transportation of wheat using existing facilities in developing countries; (2) optimizing the construction of public wheat storage facilities that are funded and/or subsidized by government or other agencies; and (3) optimizing the construction and utilization of private wheat storage facilities that are cooperatively funded by farmers.

1.3 Research Objectives

The goal of this research study is to investigate and develop new models to minimize post-harvest losses and costs during the storage and transportation phases in developing countries. To accomplish this goal, the specific objectives of this research study along with its research questions are summarized as follows:

Objective one: Conduct a comprehensive literature review and field visits to study wheat storage and transportation practices in selected regions in India as an example of a developing country that produces and consumes a significant percentage of the global wheat production.

Research Questions:

(a) What are the different types of food losses? (b) What are the different stages of food losses? (c) What are the different stages in the supply chain of wheat? (d) Who are the participants? (e) What are the main challenges and problems causing postharvest losses? (f) What are the different storage methods and facilities? (g) What are the various costs of storing and transportation of wheat in India? and (h) What are the different optimization tools and approaches that can be used to optimize post-harvest wheat storage and distribution?

Objective two: Develop a model for optimizing the storage and transportation of wheat using existing facilities in developing countries in order to (a) minimize the total wheat storage and transportation cost in the entire supply chain network of villages, local markets, and regional locations, and (b) identifying needed upgrades of existing storage facilities and/or transportation routes.

Research questions:

(a) How to formulate an optimization model to minimize post-harvest losses in developing countries? (b) What are the main decision variables that need to be optimized? (c) What are the best metrics and criteria to measure and quantify the impact of the identified decision variables on minimizing the total cost of wheat storage and transportation? (d) What are the main constraints and practical factors that should be considered in this problem? and (e) Which optimization algorithm is best suited for this optimization problem?

Objective three: Develop a novel model for optimizing the construction of public wheat storage facilities that is capable of quantifying and minimizing the cost of wheat losses during storage and transportation while considering the impact of existing storage facilities.

Research questions:

(a) How to consider the impact of existing storage facilities on optimizing the construction of public storage facilities that are funded by government and/or other agencies? (b) What are the main construction decision variables that need to be optimized during the construction of new storage facilities in order to minimize wheat storage and transportation costs? (c) What are the different types of public storage facilities that can be constructed and how can they be modeled? (d) What are the best metrics and criteria to measure and quantify the impact of the identified decision variables on minimizing postharvest losses and costs during storage and transportation? (e) What are the practical constraints that should be considered during the construction of new storage facilities? and (f) Which optimization algorithm is best suited for this optimization problem?

Objective four: Develop a model for optimizing the construction and utilization of private wheat storage facilities to maximize the annual profits of farmers.

Research questions:

(a) What are the factors that affect the profit of farmers? (b) How can the profit generated from wheat profit be utilized to construct new storage facilities that are cooperatively owned and utilized by farmers? (d) How can new the sharing of privately-owned storage facilities be modeled? (e) What are the possible types of new facilitates that can be selected for construction? (f) What are the best metrics and criteria to measure and quantify the impact of the identified decision variables on maximizing the annual profits for farmers? (g) What are the practical constraints that should be considered during the construction of new storage facilities? and (h) Which optimization algorithm is best suited for this optimization problem?

1.4 Research Methodology

In order to achieve the aforementioned objectives, the research work is divided into the following four research tasks.

Task 1: Conduct Comprehensive Literature review

Study local conditions in selected regions in a developing country such as India and collect data on post-harvest storage and transportation systems of wheat through field visit and literature review. This task focuses on existing methods and technologies for post-harvest storage and transportation, and explores opportunities for improving and optimizing them. This task will address Objective 1. This research task is divided into the following subtasks:

1.1 Study post-harvest losses (PHL) during storage and transportation in developing countries such as India;

1.2 Identify the different supply chain stages of wheat;

1.3 Study the different storage and transportation techniques used in India;

1.4 Collect local data on post-harvest losses, and wheat storage and transportation systems;

1.5 Investigate feasible optimization tools for wheat storage and transportation.

Task 2: Develop Optimization Model for Existing Storage Facilities

Develop models for studying and optimizing wheat storage and transportation in existing facilities based on the findings of task 1 in order to minimize post-harvest losses and costs. This task will address Objective 2. The research task is divided into the following subtasks:

2.1 Conduct a field study to collect the necessary data to develop objective metrics that enable the quantification and minimization of PHL and costs of storage and transportation decisions;

2.2 Investigate and model all decision variables of wheat storage and transportation that contribute to the optimization objective;

2.3 Formulate model objective function in order to minimize storage and transportation cost and losses

2.4 Identify and model various constraints that affect the overall cost of wheat storage and transportation;

2.5 Implement the model to identify optimal transportation and storage decisions that minimize costs and PHL while complying with all relevant constraints. The model will be designed to distribute the harvested wheat throughout the different storage facilitates in the entire supply chain network of villages, local markets and regional locations;

2.6 Analyze the model results utilizing a case study to identify minimum storage and transportation losses and costs throughout the network.

<u>Task 3: Develop Optimization Model for Construction of Public Wheat Storage Facilities</u>

Develop a model for optimizing the construction of public wheat storage facilities based on the findings of task 1 in order to minimize the total losses and cost of wheat storage and transportation while considering the impact of existing storage facilities. This model will be designed to identify the location, type, and capacity of new storage facilities that need to be constructed to minimize losses and costs. This task will address Objective 3. This research task is divided into the following subtasks:

3.1 Develop objective metrics that enable the quantification and minimization of PHL and costs of storage and transportation decisions;

3.2 Investigate and model all decision variables representing the construction of new storage facilities such as the optimal location, type and capacity of facilities;

3.3 Identify and model various budget constraints that affect the overall cost and operation of the system;

3.4 Implement the formulated optimization model, and perform sensitivity of the model to variations in the construction budget constraint;

3.5 Evaluate the performance of the model by analyzing the new construction facility selections, and study the effects of these selections on the storage and transportation costs.

Task 4: Develop Optimization Model for Construction of Private Wheat Storage Facilities

Develop a model for optimizing the construction and utilization of private wheat storage facilities to maximize the annual profits of farmers based on the findings of task 1 in order to maximize wheat sales profit. The optimization model enables a cooperative approach that allows each farmer to contribute a percentage of their annual wheat sales profit to build a new private shared storage facility that can be shared by all participating farmers. This task will address Objective 4. This research task is divided into the following subtasks:

4.1 Develop objective metrics that enable the quantification and maximization of profit from wheat sales;

4.2 Investigate and model all decision variables representing the farmer wheat sales such as storage duration and wheat sale quantity, as well as the type and capacity of new facilities to be constructed

4.3 Identify and model all storage capacity and wheat storage requirement constraints;

4.4 Implement the model to maximize total farmer profit before and after the construction of private shared wheat facilities;

4.5 Study the effects of the construction of new private shared storage on farmer profit.

1.5 Research Contributions

The proposed research is expected to create novel metrics and innovative optimization models that can be used to minimize postharvest losses in developing countries. The primary contributions of this research to the body of knowledge include the development of: (1) novel optimization model that is capable of optimizing the storage and transportation of wheat using existing facilities in developing countries in order to minimize the total losses and cost of wheat storage and transportation and identify needed upgrades to existing storage facilities and transportation routes; (2) innovative optimization model for the construction of public wheat storage facilities that is capable of quantifying and minimizing the cost of wheat losses during storage and transportation while considering the impact of existing storage facilities on the optimization results; and (3) novel model for optimizing the construction and utilization of private wheat storage facilities in farms and villages that is capable of considering the impact of storage losses on the generated profit. These new and innovative research developments will contribute to improve wheat storage and transportation decisions in developing countries in order to minimize post-harvest losses.

1.6 Thesis Organization

The organization of this report along with its relation to main research tasks is discussed as follow:

Chapter 2 presents a comprehensive literature review of postharvest losses during the storage and transportation phases that includes (1) PHL storage and transportation losses in developing countries such as India; (2) supply chain stages of wheat; (3) different storage and transportation techniques used in India; (3) data on the post-harvest loss and transportation systems; and (4) optimization tools used for wheat storage and transportation.

Chapter 3 presents the development of a novel optimization model, which is capable of optimizing the storage and transportation of wheat in developing countries. This chapter describes the six phases of model development: conducting field data collection; defining the model decision variables; formulating the optimization objective function; modeling the optimization problem constraints; implementing the model using linear programming; and analyzing a case study of wheat storage and transportation in India to illustrate the use of the model and evaluate its performance.

Chapter 4 presents development of an innovative model for optimizing the construction of public wheat storage facilities as well as optimizing wheat storage and transportation in developing countries such as India. This chapter presents the model development in three phases: formulation phase that defines the model decision variables, objective function, and constraints; implementation phase that performs the optimization computations using integer programming and integrates a newly developed storage facilities database that is used to facilitate the input and output of the optimization data; and evaluation phase that analyzes a case study to demonstrate the use of the model and evaluate its performance

Chapter 5 presents the development of a novel model for optimizing the construction and utilization of private wheat storage facilities to maximize the annual profits of farmers. This chapter presents the development of the model including the definition of its decision variables, the formulation of its objective function, the modeling of its constraints, and its implementation using genetic algorithms. Furthermore, the chapter presents an analysis of a case study to evaluate the performance of the developed model.

Chapter 6 presents the conclusions, research contributions, and recommended future research of the present study.

2 LITERATURE REVIEW

2.1 Post-Harvest Losses

Post-harvest loss is an important factor in food production. An estimate by the Government of India puts total preventable losses at 10% of total production or about 20 Metric Ton. With an average per capita consumption at about 15kg, these losses would be enough to feed 70-100 million people, which represents approximately one third of India's total population (Basavaraja et al., 2007). Therefore, post-harvest losses play a significant role and have a huge impact and it is important to study to understand why these losses occur and try to come up with solutions to limit these losses.

2.1.1 Stages of Post-Harvest Losses

Basavaraja et al. (2007) estimated the post-harvest losses at the different stages of rice and wheat production in India. They conducted a survey for the state of Karnaka for the year 2003-04 collecting data from 100 farmers, 20 wholesalers, 20 processors and 20 retailers. The results of this study are summarized in Table 2.1 and they reveal that the largest losses were encountered during farming, which accounted for 73.57% and 75.93% of the total post-harvest losses for rice and wheat, respectively. The two stages that contributed to the highest post-harvest losses for rice were the storage and drying stages that accounted for 23.11% and 15.41% of the total post-harvest losses, respectively. Similarly, the storage and drying stages for wheat accounted for 21.99% and 15.28% of its total post-harvest losses, respectively. These findings indicate that the storage and drying stages for both rice and wheat cause the highest post-harvest losses, which highlights the need for exploring and developing recommendations to minimize losses during these two stages.

Table 2.1 Different Stages of Post-Harvest Losses (Basavaraja et al. 2007)

Stages	**Rice**		**Wheat**	
	Loss (kg/q)	Loss (%)	Loss (kg/q)	Loss (%)
I Farm Level Losses				
Harvesting	0.4	7.7	0.36	8.33
Threshing	0.52	10.02	0.44	10.19
Cleaning/Winnowing	0.2	3.85	0.14	3.24
Drying	0.8	15.41	0.66	15.28
Storage	1.2	23.11	0.95	21.99
Transportation	0.5	9.63	0.51	11.81
Packaging	0.2	3.85	0.22	5.09
Total Losses at farm level	3.82	73.57	3.28	75.93
II Wholesale Level Losses				
Storage	0.12	2.31	0.08	1.85
Transit	0.17	3.27	0.12	2.78
Total Losses at wholesale level	0.29	5.59	0.2	4.63
III Processor level losses				
Storage	0.01	0.17	0.01	0.19
Transit	0.01	0.15	0.01	0.14
Grain scattering	0.01	0.1	0.01	0.14
Total losses at processor level	0.03	0.42	0.03	0.46
IV Retailer Level Losses				
Storage	0.53	10.21	0.41	9.49
Transit	0.32	6.16	0.25	5.79
Handling	0.21	4.04	0.16	3.7
Total losses at retail level	1.06	20.42	0.82	18.98
Total post-harvest losses	5.19	100	4.32	100

2.1.2 Examples of Post-Harvest Losses

Parfitt et al. (2010) studied examples of loss within food supply chains and identified trends that effect supply chain losses. The study defined food waste during post-harvest as either food losses or spoilage and summarized examples of food losses at different stages, as shown in Table 2.2.

Table 2.2 Examples of Food Loss during Different Stages (Parfitt et al. 2010)

Stage	Examples of food waste/loss characteristics
(1) harvesting—handling at harvest	edible crops left in field, ploughed into soil, eaten by birds, rodents, timing of harvest not optimal: loss in food quality crop damaged during harvesting/poor harvesting technique
(2) threshing	loss through poor technique
(3) drying—transport and distribution	poor transport infrastructure, loss owing to spoiling/ bruising
(4) storage	pests, disease, spillage, contamination, natural drying out of food
(5) primary processing—cleaning, classification, de-hulling, pounding, grinding, packaging, soaking, winnowing, drying, sieving, milling	process losses contamination in process causing loss of quality
(6) secondary processing—mixing, cooking, frying moulding, cutting, extrusion	process losses contamination in process causing loss of quality
(7) product evaluation—quality control: standard recipes	product discarded/out-grades in supply chain
(8) packaging—weighing, labelling, sealing	inappropriate packaging damages produce grain spillage from sacks attack by rodents
(9) marketing—publicity, selling, distribution	damage during transport: spoilage poor handling in wet market losses caused by lack of cooling/cold storage
(10) post-consumer—recipes elaboration: traditional dishes, new dishes product evaluation, consumer education, discards	plate scrapings poor storage/stock management in homes: discarded before serving poor food preparation technique: edible food discarded with inedible food discarded in packaging: confusion over 'best before' and 'use by' dates
(11) end of life—disposal of food waste/loss at different stages of supply chain	food waste discarded may be separately treated, fed to livestock/poultry, mixed with other wastes and landfilled

The study also analyzed the characteristics of supply chains in developing, intermediate, and developed systems, as shown in Table 2.3. In developing countries, the majority of the poor rely on short food supply chains with limited post-harvest infrastructure and technologies. In these supply chains, the quality of food is not a concerning factor for farmers and there are many intermediaries between growers and consumers, which limit higher prices for the growers. In addition, farming is mostly small scale, with different degrees of local market involvement. The study reported that any attempt to reduce post-harvest losses in these developing supply chains must take into account cultural implications. In order to account for years with food surpluses, which lead to low food prices, one option would be to store surplus for lean years. However, this may be hindered due to insufficient or suitable storage facilities.

Table 2.3 Characteristics of Post-Harvest Infrastructure in Various Economies (Parfitt et al. 2010)

Technological Development	Level of Development	Supply chain Characteristics	Type of growers	Markets and Quality
Simple technologies labor-intensive traditional storage systems and harvesting techniques	Low-income countries	Poor integration with local markets many intermediaries supplying urban markets	Smallholders including subsistence farmers	Local markets: mostly meeting household/ village food requirements; limited access to international markets
Packing houses refrigeration and storage facilities systems alongside elements of traditional systems	Low and middle Income countries	Requires closer integration of growers, suppliers processors and distribution systems	Small-scale farmers who often have access to limited postharvest Specific infrastructure	Produce of variable quality target both local (including supermarkets) and increasingly export markets in a number of countries
Access to relatively sophisticated technologies e.g. packing-house equipment and cold chains; losses still occur; harvesting highly	Middle- and high-income countries	Use of highly integrated systems between growers and supply chain; more seasonal produce imported; more secondary processing of food	Medium- and large-scale farmers	Meet the quality and safety as well as volume and timeliness demands of local (particularly supermarkets/ convenience

2.1.3 Reasons for Post-Harvest Losses

Basavaraja et al. (2007) analyzed the reasons for losses during the different stages of harvesting and post harvesting in India. During harvesting, the losses were mainly due to the shedding of grains and the amount of losses depends on the crop stage and time of harvesting. During threshing, the losses were mainly in the form of broken grain. The use of traditional methods led to most losses during the drying period. For transportation, carts and tractors are used to transport and the losses occur during the loading and unloading of the crops. During the storing stage, the losses were reported to be caused by the lack of separate godowns for storage, poor storage structures, presence of rodents, insects and dampness, and improper drainage at storage places.

Ofor and Ibeawuchi (2010) reported a number of social and economic reasons for food losses including (a) lack of clear-cut policies to encourage efficient utilization and administration of human, economic and technical resources to prevent deterioration of commodities; (b) shortage of human, economic and technical resources necessary for the prevention of post-harvest losses; (c) lack of knowledge of technical and scientific technologies associated with packaging, transportation and distribution; (d) inefficient commercialization systems for services; and (e) poorly equipped transportation vehicles, which lack proper refrigeration systems.

In another study, Baqui (2005) reported various reasons for food losses in Bangladesh including: (1) inadequate post-harvest activities; (2) inefficient marketing systems; (3) absence of adequate government support for research and extension; (4) absence of adequate processing and preservation facilities all over the country; (5) poor handling during loading and unloading at market points; (6) bruising, puncturing, and crushing due to improper packing; (7) absence of grading especially for fruits and vegetable.

2.2 Supply Chain of Rice and Wheat

2.2.1 Rice and Wheat Processing

Rice: Cleaned paddy yields 72% rice, 22% husk and 6% bran. Paddy is milled into raw or parboiled rice and flaked rice.

Wheat: Wheat consists of 85% flour, 12% bran and 3% embryo. Wheat is harvested, transported and stored in the form of grain. An average weight of 1000-grain of wheat is between 35-45g. Wheat is processed into flour, maida, suji and dalia. Conventional and improved technologies for post harvesting operations in India were analyzed and summarized, as shown in Table 2.4 (Ali 2003).

Table 2.4 Conventional and Improved Post-Harvest Technologies (Ali 2003)

Operation/Activity	Conventional Technology	Improved Technology
Threshing	Manual beating and animal/tractor treading	Mechanical threshing with improved design of threshers.
Winnowing	Manually with ordinary baskets	Mechanical winnowing with manual mechanical power.
Cleaning	Manually operated SUPA simple device but of low capacity.	Manual/power operated cleaner-cum-graders.
Drying	Open yard sun drying	Solar dryers or heated air dryers using mechanical power.
Storage	Earthen pitchers mud bins or bag storage	Metal bins, brick structures and concrete silos of improved designs.
Milling	Hand and foot pounding, rice hullers, stone grinders oil ghanis, etc.	Modern rice, dal and flour mills of different capacities, oil expellers, solvent extraction plants.
Byproduct utilization	Direct feed and fuel uses	Solvent extraction of rice bran and oil cake spelleted animal feed etc.
Marketing	Selling raw materials to middlemen of trade at low prices	Selling of cleaned and graded produces value added products directly to super/cooperative markets for better profitability.
Preparation & Utilization	Open vessel cooking and traditional food preparations	Pressure and microwave cooking. Nutritionally balanced diet/recipes. Use of refrigerators grinders/mixtures
Social responses	Rigidity in food habits and preparations	Flexible & fast changing food habits and varieties, out of home eating, packed foods etc.

2.2.2 Supply Chain in India

Most activities in the supply chain are managed by government agencies. Figure 2.1 shows the supply chain of wheat and the various agencies involved. Central and state governments both play a significant role in the supply chain (Kumar et al. 2007).

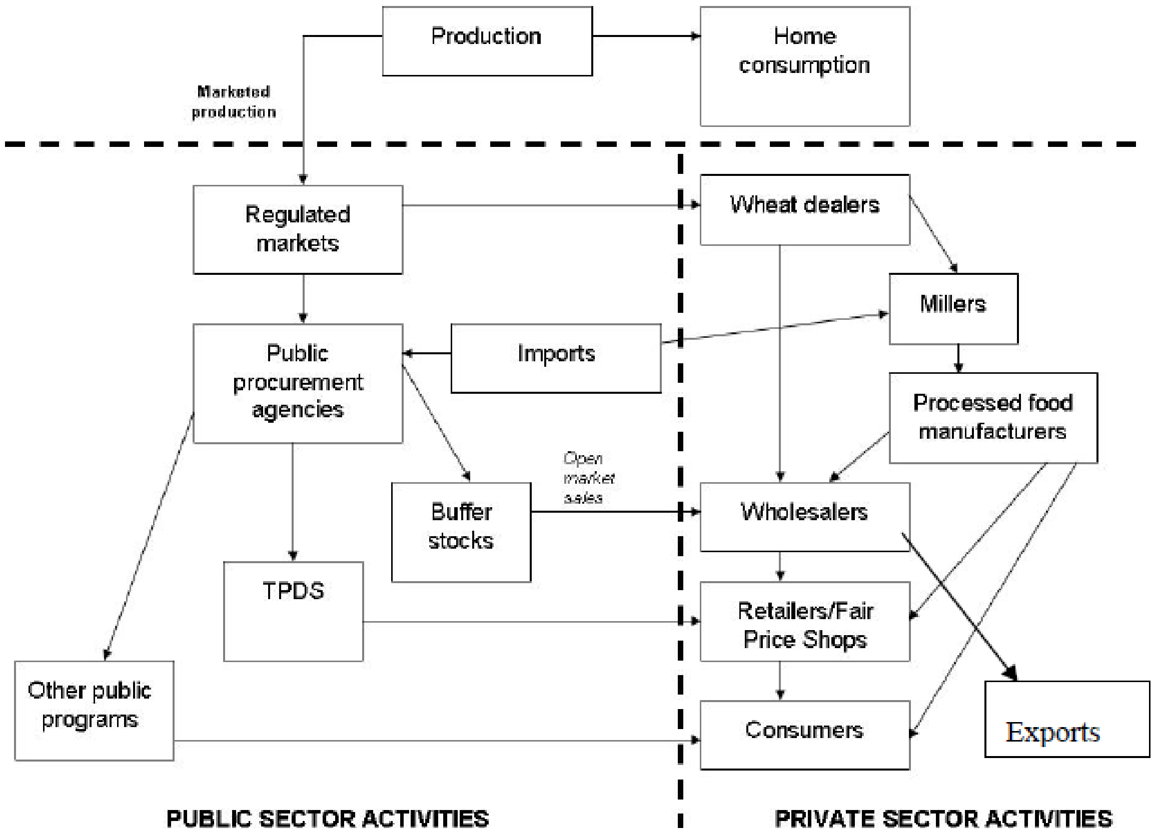


Figure 2.1 Supply Chain of Paddy/Rice (Kumar et al. 2007)

2.2.3 Post-Harvesting Stages in India

Roul (2001) analyzed the different stages in the supply chain of rice and wheat in India. In a more recent study, Dewani et al. (2012) analyzed the different stages in the production and milling of rice in India including harvesting, drying, hulling and milling, which are briefly discussed in the following sections.

<u>Harvesting</u>

For large operations, harvesting and threshing are combined. If rice is harvested manually, beating the stalks by hand or using a mechanized thresher completes threshing.

Drying

Rice grains are dried to have moisture content between 18-22%. Drying can be performed with either artificially heated air or natural sunshine, where the rice grains are left in the fields to dry out.

Figure 2.2 Sun Drying of Produce (www.alisonrutkowski.blogspot.com)

Hulling

Hulling can be performed either by hand or by grinding or rolling rice between stones. If hulling is done through an automated process then this is processed at the mill. The rice is cleaned by passing through a number of sieves, with air blown to remove the top matter. Hulling is done by a machine, and then the shelling machine loosens the hulls from the rice by rolling them between two sheets of metal coated with abrasives. Hulled and unhulled grains are separated at the kernels, which shakes the paddy forcing the heavier unhulled grains to one side of the machine. The unhulled batches are then sent to another batch of shelling machine to complete the hulling process. The hulled grain is known as brown rice.

Milling

The rice mills purchase the paddy from the farmers or from the government, where the processing of the rice takes place. From one quintal of rice, 60% and 75-80% is retained from arrya rice and usna rice, respectively.

The following steps shown in Figure 2.3 are involved in the milling process: (1) pre-cleaning that removes all impurities such as hull and barns; (2) de-stoning that separates stones of bigger size from paddy; (3) husk aspiration that removes the husk from brown rice and unhusked paddy; (4) paddy separation that separates the unhusked paddy from brown rice; (5) whitening that removes all bran layers and germs from brown rice; (6) polishing that improves the appearance of rice by polishing it; (7) grading on the basis of size of rice; (8) blending that mixes head rice with predetermined amount of broken, as required by customer or government. In the USA, the process of grain elevators, flour milling and rice milling are analyzed and summarized in charts by EPA (1995).

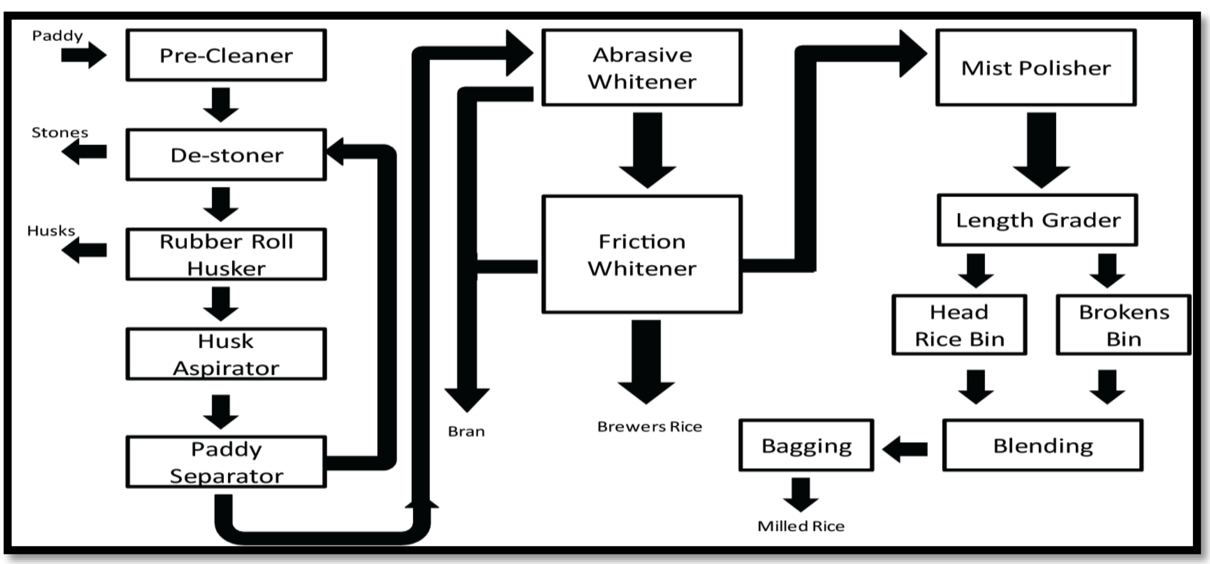


Figure 2.3 Rice Milling Process

Roul (2001) studied the mechanization of different processes in the harvesting and processing stages of rice and wheat in India and discussed post-harvest stages including drying, cleaning, grading, bagging, stitching, weighting, loading/unloading, which are briefly discussed in the following sections.

Drying

Drying takes place in the sun, when there is no drying at the farm level. Tractors then are used to transport the harvest to the mandis.

Cleaning

This operation is performed either mechanically or manually. Mechanical or power cleaners are used in 70% and 50% of wheat and rice harvests, respectively. The electricity expenses of these power cleaners are often paid by the market communities. Manual cleaning is performed using screens and sieves that have an efficiency of one quintal per hour compared to 25-100 quintals per hour for power cleaners.

Grading

Grain inspection is carried out by marketing committees using visual inspection. Mechanical graders with oscillating screens for shape separation are also used. The types of technology available in this mechanization include vibratory boards, air blast for gravity separation and photoelectric for reflection separation.

Bagging, Stitching, Weighting, Loading and Unloading

The laborers manually at the mandis do all these activities. Nearly 80% of wheat bags are stitched using small hand held machines. Weighing of individual bags, loading and unloading bags from the transportation vehicles and stacking of the bags at the market yards and in the warehouses and godowns are done manually.

2.2.4 Participants Involved in Supply chain

Dewani et al. (2012) analyzed the different participants involved in the supply chain of rice in India including farmers, government, rice millers, agents and transporters, which are briefly discussed in the following sections.

Farmers

The farmers grow paddy in the field and they depend on many factors to produce a good product. They use various pesticides to grow good quality and they depend on rainfall for good growth, as paddy is dependent on water. They experience temperatures as high as 50° C in peak summers with an average of 42° C. Farmers are not allowed to grow rice during hot summers due to shortage of water. As soon as rice is harvested, farmers sell it to rice millers or to the government in mandis. The government buys any remaining paddy in order for the millers not to take advantage and exploit the farmers. The price of the paddy is decided by the farmer based on the cost of growing it and the quality of the paddy (Dewani et al., 2012). Small farmers can also sell their grain to local traders, whom in turn sell it to larger farmers. The farmers bring samples of their grain to the market where the quality is inspected and they obtain price quotes from various traders. The farmers sell the majority of their rice during harvest time and keep what they need for home consumption. Ten quintals of wheat is needed for home consumption and cash flow needs (McCarthy et al. 2008).

Government

The government purchases paddy from the farmers in large quantities and then use rice millers to process it. The government pays for all expenses of milling the rice and then sells it to the poor through ration cards (Dewani et al. 2012).

Miller

The rice miller processes the paddy into rice and interacts with the farmer, the government and the market. The rice miller staff often includes purchase experts, drivers, laborers and managers (Dewani et al. 2012).

Agents

The rice miller often hires agents who are responsible for the selling of the produce at the price demanded by the rice miller. They get their commission from both the miller and the buyers (Dewani et al. 2012).

Transporters

The rice miller pays for the transportation charges that include expenses to bring the paddy to the mill and to transport the rice to the buyer. Any increase in transportation prices is reflected in the price of the rice (Dewani et al. 2012).

2.2.5 Problems and Techniques for Improving Post-Harvest Practices

A number of studies analyzed existing post-harvest practices and techniques to improve them. For example, Mc Carthy et al. (2008) analyzed techniques for improving cultivation and post-harvest practices. The study suggested the use of (a) education to improve on-farm storage techniques in order to reduce storage losses; (b) utilizing current technology solutions and correct chemical usage for pests; (c) using Ash and Tumeric powder to improve in-house pit storage. The study suggested that these actions could greatly reduce storage losses and would help farmers overcome price fluctuations. In addition, the study reported that the incorporation of these measures in storing seeds can help farmers reduce farmer input costs. At the milling level, millers can operate at full capacity all year long from the utilization of improved storage. Marketable surplus of crops is managed by farmers using two approaches: some farmers sell all their surplus at harvest time while others store the surplus and try to sell it at a later time to take advantage of price fluctuations. The later approach may involve additional risks due to storage losses.

In another study, Ghimiray et al. (2007) discussed problems encountered by farmers during the post-harvest and processing stage. The study reported that farmers may have to harvest rice much later than its recommended time due to the unavailability of labor at the right time. This leads to pre and post-harvest losses as it results in grain shattering that causes approximately 5% losses. During the transportation stage, another 2% losses are often encountered due to transportation losses from the fields. During the rice milling stage, other losses are often encountered due to the use of crude machinery that causes a lot of grain breakage, which highlights the need for better and newer machines. The study also reported that many individual farmers own rice mills that are under-utilized. In a survey, these mills were reported to have an annual operation 282 hours, which translates to 35 days of operation per year. This inefficient use of mills leads to waste and abrasion and therefore there is a need to improve their efficiency and usage.

Other studies reported the disadvantages of open field drying at the mandis including harvest losses especially during bad weather, long drying time, and congestion at the markets due to the long process of natural drying. Accordingly, moisture content is often ignored in order for mandis to be cleared (Roul 2001). In conventional systems that use drying in the sun and milling by hullers, the total yield of rice rarely exceeds 65% with 20-30% broken when milled as raw and 68% with 15-20% broken as parboiled paddy. This excessive breakage during milling in the conventional system reduces the total recovery of rice. Moreover, the by-products cannot be used economically (Ali 2003).

2.3 Storage & Handling in India

2.3.1 Traditional Storage Methods

In order to improve current storage practices, it is important to study the traditional storage practices that are used on farms. Several storage structures are used in different regions of India such as Thombai, Mankattai, Kululakki, Addukkupaanai, Pathayam Thallpai and Vattappetti that are used by ethnic communities in the Tamil Nadu region (Kiruba, et. al 2006).

The Thombai (Bamboo Bin) is a bamboo skeletal structure with a narrow opening on top. It is placed on a foundation of boulders and covered by clay from all sides. The roof is comprised of Cymbopogan sp. Hackel (Ginger grass) and it is in a form of spire. The Thombai is 3 m high, has a radius of 1 m, and has a capacity of over 500 Kg, as shown in Figure 2.4.

The Mankattai (Mud house) is a variant of the Thombai and is usually kept indoors. It is made of mud bricks and its top is covered with wooden planks once the grains are stored, as shown in Figure 2.5. The size varies and depends on the needs of the farmers.

Figure 2.4 Thombai

Figure 2.5 Mankattai

The *Kulukkai* (Earthen bin) is a structure used for storing smaller quantities of grain (<200kg) and is 2m in height and 0.5m in radius at its broadest point, as shown in Figure 2.6. The base is trenched in soil and is stored inside a protected house. There is a vent used for removing stored grain that is closed by a coconut shell, when stored for longer periods the vent is sealed with clay. The structure can provide storage for about 2 years. It is successful in storing paddy, black gram and millet.

The *Addukkupaanai* (Earthen pot-pile) is a variant of the earthen bin where three pots are arranged one over the other. The pots fit exactly one over another in such a way that there is no gap left, as shown in Figure 2.7.

Figure 2.6 Kululkkai

Figure 2.7 Andukkupaanai

The *Pathayam* (Wooden bin) is a wooden structure with a capacity ranging from 2,000 to 10,000 litres. It is made form wooden planks along all sides with no gaps in between it has a 30x30cm opening at the top, as shown in Figure 2.8.

Figure 2.8 Pathayam

The *Thallpai* (Straw bin) is a structure made up of paddy straw for storing the seed grains. It can hold the seeds for about 2 years. When enough quantities are placed the straw ropes are folded to obtain a rounded structure. The structure is then suspended from roof rafters, as shown in Figure 2.9.

The *Vattappetti* (Palmyra leaf bin) is a short-term storage structure and is used to store the needs of an individual household. It is used mainly for maize storage. Their normal size is 2.5-3 m height, 1 m width, 2 m length and a capacity of >500 Kg. It is made of woven Seasoned Palmyra leaf to form a cylindrical basket, as shown in Figure 2.10.

Figure 2.9 Thallpai

Figure 2.10 Vattappetti

Joshi (2002) discussed other traditional storage structures: (1) *Mud Bin*, which is made of bricks and mud, they are cylindrical and shape and have varying capacity; (2) *Bamboo Reed Bin*, which is made of bamboo splits plastered with a mixture of mud and cow dung; (3) *Thekha* is made of gunny or cotton cloth; (4) *Metal drums*, which are made up of iron sheets in cylindrical and square shapes of various sizes, and (5) *Gunny gabs*, which are made of jute.

Figure 2.11 Mud Bin

Figure 2.12 Metal Drum

Naik and Kaushik discussed grain storage in India and how they play an important role in preventing losses, which are caused due to weevils, beetles, moths, and rodents. Insect pests may destroy 10-15% of the grain and contaminate the rest. It is estimated that 60-70% of food grain produced is stored at home level in native storage structures. Indoor storage includes structures like Kanaja, Kothi, Sanduka and earthern pots, which are briefly described in the following sections.

Kanaia is a container made out of bamboo with a round base and a round opening at the top. In order to prevent spillage it is plastered with mud and cow dung during mixture. The top is covered with paddy straw or gunny bags.

Sanduka is a wooden box used for storing smaller quantities of grains, with a storage capacity of 3-12 quintals. The box can be partitioned to store different kinds of grains and it has a lid on top with an opening to remove the grains. It is kept 12 inches above ground level to protect the grain form moisture.

Kothi is a constructed room used for storing paddy. There is a large door for pouring grains and a small outlet for taking out grains.

Earthen pots are indoor storage containers made using burnt clay into different shapes and sizes.

Naik and Kaushik also discussed some outdoor storage methods, including (a) *Bamboo structures* which are used for storing threshed paddy; (b) *Gummi* which is a structure for storing grains and is made of bamboo strips and placed on a raised platform to prevent rat damage and moisture absorption from the ground; (c) *Kecheri* which is a structure made of paddy or wheat straw and woven as a rope; and (d) *Hogeyu* which is a underground pit lined with straw ropes to prevent moisture damage and it can be constructed as an indoor structure. *Hogeyu* is suitable for dry agro climate zones it does not require fumigation and the grain can be stored for long periods.

2.3.2 Grain Storage Facilities

There are three government agencies that are responsible for large-scale storage of grains in India: (1) Food Corporation of India (FCI); (2) Central Warehousing Corporation (CWC); and (3) 17 State Warehousing Corporations (SWC) (Kumar et al. 2007; Joshi 2002; Naik and Kaushik). The FCI storage capacity is used for food grains, while CWC and SWC are used for food grains and other crops. The storage facilities of these agencies can be classified as (a) covered systems that store grains inside a large storage structure that is called godown or in silos; and (b) cover and plinth (CAP) systems that store grains outdoors in gunny bags that are stacked outdoors and covered by plinth. The total capacity provided by the Food Corporation of India (FCI) is 30.22 million tonnes for covered and 33.6 million tonnes for CAP storage, as shown in Tables 2.5 and 2.6 (FCI 2012). The different costs of rice operations of FCI and traders for the state of Punjab, including procurement, distribution and milling charges are shown in Table 2.7 (Kumar et al. 2007).

Table 2.5 Storage Capacity with FCI (FCI 2012)

Capacity	1st Apr. 2005	1st Apr. 2006	1st Apr. 2007	1st Apr. 2008	1st Apr. 2009	1st Apr. 2010	1st Apr. 2011	1st Apr. 2012
Covered								
Owned	12.91	12.93	12.94	12.95	12.97	12.97	12.99	13.01
Hired	10.46	9.9	9.34	8.71	10.12	12.89	15.46	17.21
Total	23.37	22.83	22.28	21.66	23.09	25.86	28.45	30.22
CAP (Cover and Plinth)								
Owned	2.25	2.21	2.29	2.2	2.17	2.51	2.62	2.63
Hired	0.41	0.51	0.63	0.03	0.02	0.47	0.54	0.75
Total	2.66	2.72	2.92	2.23	2.19	2.98	3.16	3.38
Total	27.03	25.55	25.2	23.89	25.28	28.84	31.61	33.6

Figures in million tonne

Table 2.6 State storage capacity (FCI 2012)

State	Covered							CAP			Grand Total	Utilization (%)	Tot Al Effective Storage Capacity As Per Region	Utilization (%) On Effective Capacity
	FCI Owned	Hired					Total Covered	Owned	Hired	Total				
		State Govt.	CWC	SWC	Private	Tot Al								
Haryana	7.68	4.2	3.22	6.17	2.34	15.93	23.61	3.33	0.16	3.49	27.1	85	27.1	85
Tamil Nadu	5.8	0	2.56	0.52	0.5	3.58	9.38	0.61	0	0.61	9.99	84	10.15	87
Grand Total	130.0	5.85	39.88	107.99	18.41	172.13	302.16	26.37	7.51	33.88	336.04	82	325.86	85

Table 2.7 Cost of Rice Operations in the State of Punjab (Kumar et al. 2007)

Element of Cost	FCI (Rs. per qtl)	Private Trade (Rs. per qtl)	Private costs as % of FCI costs
Procurement Costs	149.59	112.05	74.9
Distribution Costs	191.51	145.00	75.7
Milling Charges (paddy)	13.8	14	
Recovery from sale of bran/husk	0	29.6	
Economic cost of rice (one quintal)	1,086.24	972.79	89.6
Economic cost of rice excluding freight	1,012.58	852.79	84.2

The different types of grain storage facilities in India can be classified as (1) small scale structures; (2) Cover & Plinth (CAP); (3) Silos; (4) Rural Godowns; (5) Mandi Godowns; (6) Central Warehousing Corporations (CWC); and (7) State Warehousing Corporations (SWS) structures are as follows (Kumar et al. 2007; Joshi 2002; Naik and Kaushik).

<u>Small-Scale Storage</u>

Framers usually store their grain in either farm godowns or in house using traditional or improved storage structures where they are stored for short durations (Joshi 2002). Traditional storage structures are reported to have many problems (Naik and Kaushik). Many small-scale storage structures have been developed by different organizations including (a) *PAU bin* that is designed by the Punjab Agriculture University as a structure made of galvanized metal iron and has a capacity ranging from 1.5 to 15 quintals; (b) *Pusa bin* which is a structure made of mud or bricks; (c) *Hapur Tekka* which is a rubber cloth structure supported by bamboo poles on a metal plate and has a small hole in the bottom where grain can be removed; (d) PVC sheets that are used for covering; and (e) jute gunny bags that filled with paddy/rice (Naik and Kaushik; Joshi 2002).

Cover and Plinth (CAP)

Large-scale storage is done in Cover and Plinth (CAP). CAP involves the construction of brick pillars 14” from the ground. Bags of food grain are stacked above it. The stacks are covered with 250-micron LDPE sheets on top and from the four sides. Wheat, paddy, maize are stored in CAP for periods of 6-12 months. The CAP structure can be built in less than 3 weeks and therefore it provides an economical means of storage on a large scale. It is widely used by FCI for bagged grains (Naik and Kaushik).

Kumar et al. (2007) however argues that CAP storage is very inefficient from the stock management point of view. Paddy and wheat are stored in 95kg jute bags, which increases handling and storage losses as opposed to of using synthetic bags or bulk storage. In addition, stocks are regularly fumigated which add to health risks. Moreover, stocks have been kept in storage for long periods, with 50% having been stored for over 2 years.

Figure 2.13 CAP Storage (Joshi 2002)

Silos

Silos are used to a lesser extent in India to store grains and they can be made of metal or concrete with the metal silos being cheaper. The silos are loaded and unloaded using conveyor belts (Naik and Kaushik).

Rural Godowns

Rural storage is important in marketing of agriculture produce. In 2002, 2,373 rural godowns were constructed with a total storage capacity of 36.62 million tonnes (Joshi 2002).

Mandi Godowns

Paddy and rice are moved to the market after harvest, where paddy is kept in bulk and bags while rice is kept in bags. Under the Agriculture Produce Marketing Regulation Acts, storage godowns were constructed in market yards. A receipt is issued when keeping a produce at a godown indicating the kind and weight. CWC and SWS are also allowed to construct godowns in market yards. Traders either posses or hire permanent storage in the form of godowns or warehouses. Paddy/rice is generally kept for a period of one to six months (Joshi 2002).

Figure 2.14 Brick-build Godowns (Joshi 2002)

Warehousing

Food grains are stored in warehouses that are either owned by the public or private sector. The private warehouses are owned by individuals, large businesses or wholesalers. The government owns public warehouses. Storage costs for different bag weights of rice are shown in Table 2.8 (Kumar et al. 2007).

Table 2.8 Grain Storage Tariffs in Andrha Pradesh State Warehouses (Kumar et al. 2007)

Commodity	Type	Weight (kg)	Standard Rate	High Rated-II	High Rated-I
Rice	Bag	50	2.30	2.50	2.60
		51-75	2.50	2.75	2.95
		100	3.00	3.30	3.65
Paddy	Bag	75	2.80	3.00	3.30
Pulses	Bag	100	3.20	3.55	3.80
All Food Grains	Bag	85-101	3.00	3.20	3.30

Central Warehousing Corporation (CWC)

Bulk storage is done in warehouses, which are storage structures constructed for the protection of the quality and quantity of the stored products. The Central warehousing corporation (CWC) was established as a statutory body in 1957 and is the largest warehouse operator in India (Naik and Kaushik; Joshi 2002). CWC provides storage for about 120 agriculture and industrial commodities (Naik and Kaushik). The total storage capacity in all states is 39.88 million tones, while in the states of Tamil Nadu and Haryana they are 2.56 million tones and 3.22 million tones respectively. In addition to storage, CWC provide services in clearing and forwarding, handling and transportation, distribution, disinfestation, fumigation and other ancillary services like safety and security, insurance, standardization and documentation (Naik and Kaushik; Joshi 2002).

State Warehousing Corporation (SWC)

Each state in India has its own warehouses. Each State Warehousing Corporation (SWC) has areas of operation which are district places in the state (Naik and Kaushik; Joshi 2002). The total share capital of SWS is contributed equally by the Central Warehousing Corporation and the State Government (Naik and Kaushik; Joshi 2002). By 2002, SWCs were operating 1,537 warehouses (Joshi 2002). The total SWS storage capacity in 2012 is million 107.99 tons including 6.17 million tons and 0.52 million tons in the states of Haryana and Tamil Nadu, respectively (FCI 2012).

Storage Recommendations

Naik and Kaushik provided a number of recommendations to improve storage, including (a) careful selection of storage site and structure; (b) regular cleaning and fumigation; (c) proper aeration of grains; and (d) regular inspection of grain stock. Pest infestation in grains is affected by moisture content of grains, relative humidity, temperature, storage structure, storage period, processing, hygienic condition and the fumigation frequency followed. The major pests of stored grains include beetles, weevils, moth and rodents. The control measures include two types of treatment – prophylactic and curative.

2.3.3 Metal Silos

Tefera et al. (2011) studied the benefits of using metal silos in developing nations. The study reported that metal silos provide an effective storage technique for reducing post-harvest insect and pathogen losses. With insecticides either too expensive or frequently unavailable, economical storage techniques are needed. Metal silos are constructed from galvanized iron sheets and are sealed. It is effective in protecting harvested grain from insects as well as rodent pests. The silos are air tight and thereby kill any pests due to the lack of oxygen.

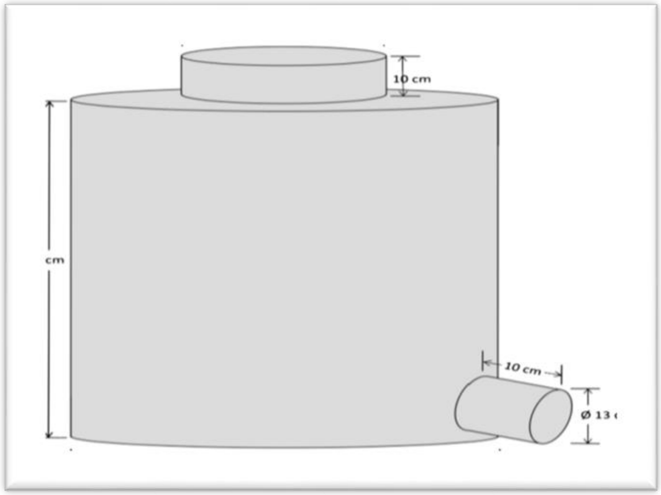


Figure 2.15 A Metal Silo of 100 Kg Maize Grain Holding Capacity

Several steps are taken to insure no pests or pathogens get into the silo for long durations. The silo is cleaned dried, all oxygen is sucked from the silo in order to kill any pests, and finally once all the grain is inside it is air-tight sealed. The costs for producing metal silos include metal sheet, labor and transportation. As the capacity of the silo increases, the cost per kg of grain decreases. Seeds are usually stored in small capacity silos, while grains for consumption in larger metal silos.

Table 2.9 Production Costs in Different Countries (US$)

Metal silo capacity (kg)	Unit Price (Malawian Kwacha)	Unit Price (US Dollar)
1000	50,000	320
1500	55,000	350
2000	65,000	420
3000	75,000	480

Table 2.10 Production Costs in Different Countries (US$)

Country	Metal Silo Capacity				
	120kg	250 kg	500 kg	900 kg	1800 kg
Afghanistan	-	28	70	-	92
Bolivia	20	35	60	-	-
Burkina Faso	26	29	42	56	70
Cambodia	12	20	30	-	50
Chad	-	66	97	128	187
Guinea	-	-	59	-	70
Madagascar	-	40	50	70	100
Malawi	-	22	45	60	-
Mozambique	20	34	54	75	-
Namibia	-	-	22	-	-
Senegal	23	42	60	76	100

Metal silos are reported to provide the following advantages: (i) maintains the quality of the stored product; (ii) air tightness creates effective non-residual fumigation; (iii) avoids the use of insecticides; (iv) requires little space and can be placed inside or near the home; (v) significantly reduces post-harvest losses; (vi) enables smallholder farmers to take advantage of fluctuating grain prices; (vii) prevents rodents and other pests/pathogens that could potentially harm consumer health; and (viii) can be built in-situ with local labor and easily available materials. In addition, metal silos are reported to create the following socioeconomic and environmental benefits Tefera et al. (2011):

Improving food security:

Metal silos are an important part of food security as farmers can feed their families and can choose when to bring surplus grain into the market.

Empowering smallholder farmers:

Famers are able to improve their incomes by storing crops and selling them at premium prices when demand is higher than the supply.

Enhancing income opportunities and job creation:

Metal silo fabrication creates new jobs. It is a new source of income for labor that can produce metal silos when they are not working in the field. This gives them the opportunities for extra seasonal income.

Safeguarding the agro-ecosystems:

The reduction in post-harvest losses contributes to sustainability. The reduction of waste is more sustainable than the increase in production, which leads to more cultivation, which has a negative effect on the environment. Moreover, metal silos are an alternative to the use of pesticides, which have a negative impact on the environment.

2.3.4 Mechanization of Bulk Handling Systems

Roul (2001) studied the mechanization of the bulk handling system. The study reported that many activities during the post harvesting stage are labor intensive that require a lot of manpower and do not yield a very high productivity rate. Activities such as bagging, stitching, weighting, loading and unloading can be completely eliminated by introducing bulk storage facilities such as storage silos. The combination with a mechanical handling system can also negate the problems associated with drying and cleaning as well. This eliminates the need for marketing yards as the silo performs all the actions and the problems associated with peak demands at the yards. Moreover, it eliminates the need to use jute or pollinated bags, which cost around Rs 900. A study was conducted comparing benefits of mechanical and manual handling and reported the results shown in Table 2.11. As shown, the cost and man hours needed utilizing mechanical process are lower than using traditional manual techniques, moreover, the cleaning capacity is considerably higher, highlighting the benefits of the mechanical process over the manual process.

Table 2.11 Cost, Man-hours Needed and Cleaning Capacity of Wheat and Rice

		Wheat	Paddy	Laborers Required
Cost Of Handling One Quintal of Wheat and Rice	Mechanically	RS. 1.30	Rs. 1.71	
	Manually	Rs. 1.34	Rs. 1.82	
Man Hours Needed For Unloading, Cleaning, Bag Filling, Weighing and Stitching 10 Tones.	Mechanically	1.2	1.66	Few workers
	Manually	17.2	24.15	15
Cleaning Capacity per Hour	Mechanically	200	100	
	Manually	80	40	

<u>Bulk storage vs. Bag storage</u>

In India, only a small fraction of storage capacity is bulk. For example, the Food Corporation of India constructed three silos with 20,000 tons of capacity that were not effectively used. The main storage agencies like FCI, CWC and SWC use bag storage due to the following challenges in using bulk storage: (1) cost of bulk storage construction is about Rs 2500 per ton, while the cost of construction godowns was about Rs 700-800 per ton; (2) rail/road system is only suitable for bag handling and the cost of conversion to bulk transportation would be significant; (3) existing bag storage facilities would be obsolete; (4) jute industry would suffer, as it is dependent on the bagging of food grains; and (5) large number of workers would lose their jobs.

<u>Solutions</u>

To overcome the aforementioned challenges, there is a need to analyze and compare (a) the economic cost of bulk storage to its benefits including improved quality and reduced losses; and (b) the aforementioned social cost of bulk storage to the potential benefits including improved worker skills and income. Furthermore, the following solutions can be investigated to overcome the aforementioned challenges of bulk storage: (1) establishing mechanical handling units near the villages or farms to reduce the load on the mandis; (2) construction of silos at marketing yards combined with dryers; (3) constructing silos at production and consumption centers; and (4) conversion of existing godowns from bag to bulk storage.

2.3.5 Grain Handling and Transportation in the US

The following section aims to focus on the grain handling and transportation system in developed countries such as the US to highlight the differences between their practices and those of developing countries. Hough (1994) discussed several alternatives for the transportation of grains throughout the US, including the use of waterways, railways, and highways. The U.S. waterway system includes over 25,000 miles of inland and inter-coastal channels. Barges moved nearly 500 million bushels of wheat in 1992, which equates to 22 percent of wheat shipments. The rail network consists of 113,000 road miles and 191,000 track miles. Railways serviced all of the major wheat producing regions and nearly all grain elevators. Railways moved about two-thirds of all wheat shipments in 1992. The highway system is important to the shipment of wheat and nearly all grain moved from farm gate to elevators was through trucks. Beyond the elevator, trucks moved nearly 8.5 percent of all U.S. wheat.

The key elements of grain handling and transportation system in the US can be summarized as follows (Park and Koo 2001): (1) farmers move 63 million tons of wheat utilizing short truck delivery distances and are paid at delivery; (2) country collection utilize truck or rail transportation; (3) grain handling facilities store over 150 million tons, where grain companies own elevators; (4) long distance transportation is covered by 75% rail and 25% by truck; and (5) terminal handling and port services are found throughout the country including at the West Coast, Gulf and Great Lakes.

2.4 Farm, Village, Market and Regional Data

The Government of India (2002) and the Government of Tamil Nadu provided useful data that can be utilized in the analysis of the PHL losses in particular the optimization of storage facilities. The set of data includes information for both the provinces of Tamil Nadu and Haryana for both grains wheat and rice. A sample of the this data is found in Appendix I and includes: (1) population data which includes average population, average population of cultivator; (2) grain production data that includes the area (hectares) for each grain and the percentage of farms that harvest this grain; (3) total geographic area of farms, including the minimum, maximum and average areas; (4) total cultivated area of farms, including the minimum, maximum and average areas; (5) percentage of cultivated area to geographic area; (6) type of storage available in the different provinces; (7) number of villages that have storage, and the amount of storage capacity for each; (8) number of sample villages that have storage facilities within a radius of 10 km; (9) average storage capacity in the villages as well as storage costs.

In addition, other data was collected and used for the development of the optimization models from several sources including the Government of India, Food Corporation of India, Haryana Food and Supplies Department, Haryana Warehousing Cooperation and Haryana State Agricultural Marketing Board (FCI 2013; Food and Feed Grain Institute 1991; Food and Feed Grain Institute 1989; Gandhi and Koshy 2006; Global Agri System; Government of India 2002; HAFED 2013; HF&SD 2013; HSAMB 2013; HWC 2013; Jha et. al 2007; Joshi 2002; Kiruba et. Al 2006; Mott Macdonald 2013). The data includes (1) storage cost and loss rate data; (2) transportation cost and loss rate data; (3) location type and capacities of wheat storage facilities; (4) harvest rates in different locations and farm consumption rates; and (5) wheat sales and purchase prices.

2.5 Optimization Models and Case Studies

The following sections also discuss previous work performed on network logistic analysis models. They discuss the different types of analysis as well as different applications and case studies that have used these models:

Koo (1987) focuses on several mathematical algorithms used in developing transportation models. One model is deterministic optimization model, which is used to improve the efficiency of the grain distribution system. These models are categorized into intraregional and interregional models. The intraregional model is designed to evaluate efficiency in physical distribution, competition, marketing structure, and capacity of a rural transportation system within a region, while the inter-regional model evaluates carrier capacity, handling and storage capacity, distribution, pricing, and competition among modes of transportation at national and international levels.

MacAulay (1987) discusses different optimization techniques for the Postharvest handling and storage of grains. The four types of models are, network models, transportation-allocation models, location-allocation and spatial equilibrium models. Network models are used for flow analysis and use network method analysis. Transportation-allocation is used for resource allocation and fixed prices and quantities and utilizes linear programming. Location-allocation is used for plant location decision and uses integer programming. The spatial equilibrium is used for price effects and utilizes quadratic programming.

Kar et al. (2001) developed a deterministic inventory model for a single item having two separate storage facilities. The model runs with limited existing capacity with linear time dependent demand increasing over a fixed finite time.

Toquero (1987) aim to study the grain processing industry in the Philippine's. The paper aims to study the efforts to improve and modernize the industry, and why technical, economic, sociocultural and economic reasons have not made this possible. Some issues dealt with the small farm size and the low production of farms. In addition, the quality and standards of grades have been neglected in the region.

Pruzan (1979) aimed to develop a grain model for the country of Bangladesh. The model seeks to determine the optimal number, size, location and design of storage facilities. The model gave several recommendations to the distribution of over 2,000,000 tonnes of grain. It specified where major storage facilities should be located, in addition, it gave preference to existing storage units as opposed to new facilities. Moreover, it gave preference to more primitive manual technology over bulk handling and storage. The model aimed more towards a filter approach whereby the model outputs provide good starting points for future manual evaluations rather than an optimal solution.

Monterosso et al. (1985) developed a model dealing with the grain storage in developing areas with regard to the location and size of the facilities. They aimed to answer several questions such as: (a) How efficient is the present storage system? (b) What additional units need to be built? (c) What would be the least cost location and size of units? (d) What type of roads should the facilities be located on? Findings of the research reveal facilities built from scratch to minimize transfer costs are obtained by a larger number of units of smaller average capacity spread more evenly throughout each micro region. Results also reveal that storage units don’t necessarily have to be located on good roads.

Goetschalckxa et al. (2002) presented work to demonstrate the savings potential generated by the integration of the design of strategic global supply chain networks. Two models were presented in their work. The first model aims to maximize the after tax profit deals by setting a transfer price in a global supply chain. The second developed model studies the production and distribution allocation in country, based on changing seasonal demands.

D’Souza (1988) developed a transshipment model to identify existing and optimal structure of the soybean processing industry in the US. The model seeks to minimize the combined transshipment cots throughout the network.

3 OPTIMIZING WHEAT STORAGE AND TRANSPORTATION IN EXISTING FACILITIES

3.1 Introduction

This chapter presents the formulation of a novel model for optimizing the storage and transportation of wheat in existing facilities. The model is designed to (a) minimize the total wheat storage and transportation cost in the entire supply chain network of villages, local markets, and regional locations; and (b) identify needed upgrades of existing storage facilities and/or transportation routes. The model was developed in six main phases that focus on: (1) conducting field data collection; (2) defining the model decision variables; (3) formulating the optimization objective function; (4) modeling the optimization problem constraints; (5) implementing the model using linear programming; and (6) analyzing a case study of wheat storage and transportation in India to illustrate the use of the model and evaluate its performance. The following sections in this Chapter describe these six development phases.

3.2 Field Data Collection

To ensure the formulation of a practical model for developing countries, wheat storage and transportation practices were investigated during site visits to India. The field data collected during these site visits were then used to formulate a practical model that represents (1) the different types of storage facilities at the village, local market, and regional location levels, as shown in Figure 3.1; and (2) the transportation links among these facilities, as shown in Figure 3.2.

Figure 3.1 Storage Facilities in Villages, Local Markets and Regional Locations

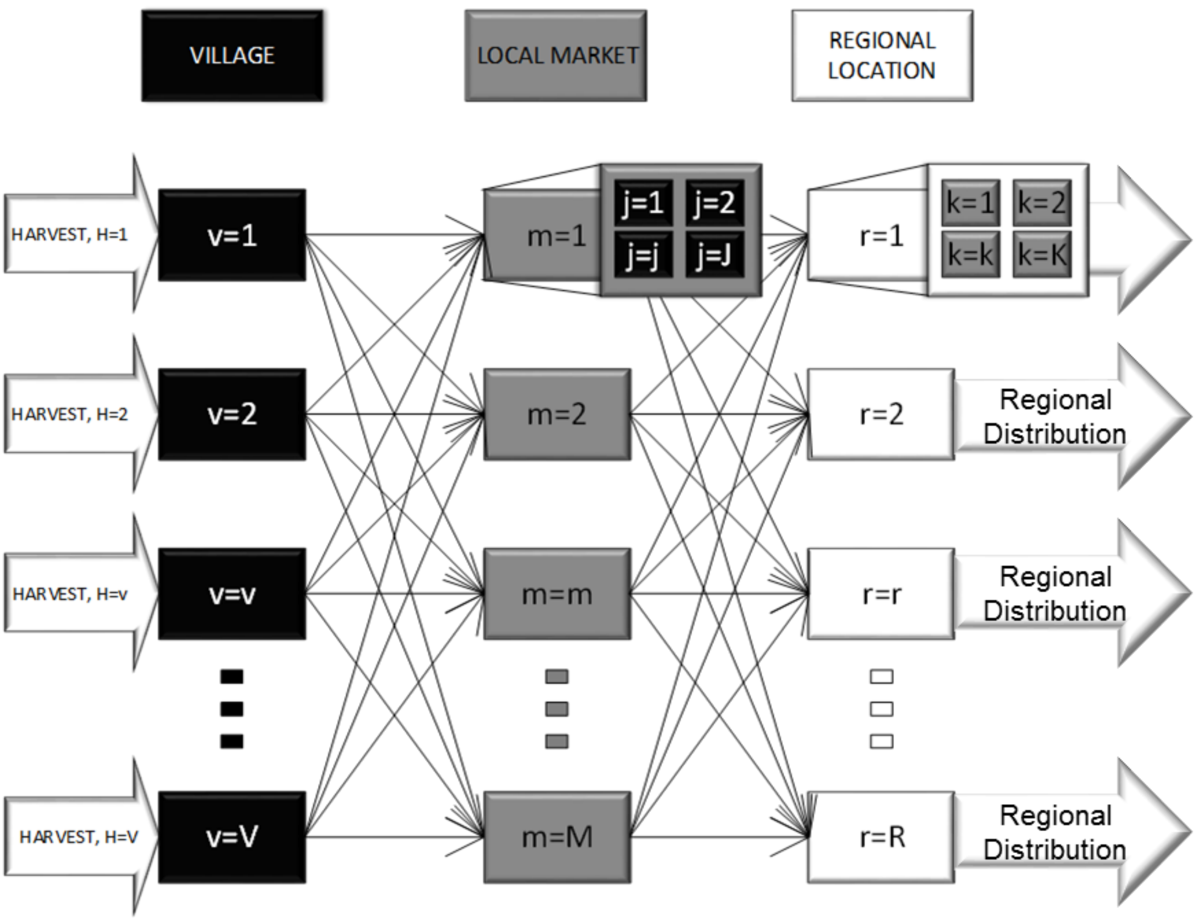


Figure 3.2 Wheat Storage in Villages, Local Markets, and Regional Location

3.3 Decision Variables

The model is designed to optimize the storage and transportation of harvested wheat throughout its supply chain. Accordingly, the model is designed to consider and optimize all relevant storage and transportation decision variables, including: (1) the quantity of stored wheat (Sv) in tonnes per month in each village v; (2) the percent of wheat ($Dr_{v,m,i}$) transported from each village v to each storage facility i in local market m; (3) the quantity of stored wheat (Sm,i) in tonnes per month in each storage facility i in local market/mandi m; (4) the percent of wheat ($Dr_{m,r,k}$) transported from the local market/mandi m to storage facility k in regional location r; and (5) the quantity of stored wheat (Sr,k) in tonnes per month in each storage facility k in regional location r, as shown in Figure 3.1.

These decision variables are designed to determine the optimum storage quantities and distribution rates of harvested wheat among the various storage facilities at the village, local market and regional levels. The optimum storage quantities are affected by the cost of storage in different facilities and their storage losses. In addition, the optimum distribution rates and transported quantities among the various storage facilities are influenced by the transportation costs and the losses.

3.4 Objective Function

The model is designed to minimize the overall cost of storage and transportation of wheat in the entire supply chain network. Accordingly, the objective function of this model seeks to minimize the overall cost that can be expressed as the sum of: (1) the total storage cost (SC) in villages, local markets and regions during the estimated storage durations; (2) the total storage losses costs (SLC) caused by quantity and quality losses in all storage facilities in villages, local markets and regions that can be calculated as the product of estimated quantity of losses and the sales price per unit volume, the quantity and quality losses consider all pest, moisture, weather factors; (3) the total transportation cost (TC) throughout the entire supply chain; and (4) the total transportation losses costs

(TLC) due to losses caused by wheat transportation throughout the entire supply chain, as shown in Equation (3-1). The calculation of each of these four main types of costs is shown in Equations (3-2) through (3-5), respectively.

$$Minimize\ overall\ cost = SC + SLC + TC + TLC \tag{3-1}$$

$$SC = \sum_{v=1}^{V} [S_v * CS_v * Sd_v] + \sum_{m=1}^{M} \sum_{i=1}^{I(m)} [S_{m,i} * CS_{m,i} * Sd_{m,i}] + \sum_{r=1}^{R} \sum_{k=1}^{K(r)} [S_{r,k} * CS_{r,k} * Sd_{r,k}] \tag{3-2}$$

Where,

SC = total storage cost in villages, local markets and regions during the estimated storage durations;

SLC = total storage losses costs caused by quantity and quality losses in all storage facilities in villages, local markets and regions that can be calculated as the product of estimated quantity of losses and the sales price per unit volume, the quantity and quality losses consider all pest, moisture, weather factors;

TC = total transportation cost throughout the entire supply chain;

TLC = total transportation losses costs due to losses caused by wheat transportation throughout the entire supply chain;

S_v = quantity of stored wheat in each village v in tonnes per month;

CS_v = storage cost in village v of 1 tonne of wheat per month;

Sd_v = wheat storage duration in village v in months;

$S_{m.i}$ = quantity of stored wheat in each storage facility i in local market m in tonnes per month;

$CS_{m,i}$ = storage cost in facility i in local market m of 1 tonne of wheat per month;

$Sd_{m,i}$ = wheat storage duration in storage facility i in the market m in months;

$S_{r,k}$ = quantity of stored wheat in each storage facility k in regional facility r in tonnes per month;

$CS_{r,k}$ = storage cost in storage facility k in regional facility r of 1 tonne of wheat per month;

$Sd_{r,k}$ = wheat storage duration in facility k in the region r in months;

$$SLC = \sum_{v=1}^{V} [S_v * LS_v * Sd_v * SV] + \sum_{m=1}^{M} \sum_{i=1}^{I(m)} [S_{m,i} * LS_{m,i} * Sd_{m,i} * SV] + \sum_{r=1}^{R} \sum_{k=1}^{K(r)} [S_{r,k} * LS_{r,k} * Sd_{r,k} * SV] \quad (3\text{-}3)$$

Where,

S_v = quantity of stored wheat in each village v in tonnes per month;

LS_v = wheat unit sales price per tonne;

Sd_v = wheat storage duration in village v in months;

SV = the wheat unit sales price per tonne.

$S_{m.i}$ = quantity of stored wheat in each storage facility i in local market m in tonnes per month;

$Sd_{m,i}$ = wheat storage duration in storage facility i in the market m in months;

$LS_{m,i}$ = percentage of quantity and quality losses in storage facility i in local market m per month;

$S_{r,k}$ = quantity of stored wheat in each storage facility k in regional facility r in tonnes per month;

$Sd_{r,k}$ = wheat storage duration in facility k in the region r in months; and

$LS_{r,k}$ = percentage of quantity and quality losses in storage facility k in regional facility r per month;

$$TC = \left\{\sum_{v=1}^{V} T_v * [\sum_{v=1}^{V} \sum_{m=1}^{M} \sum_{i=1}^{I(m)} Dr_{v,m,i} * CT_{v,m} * Ds_{v,m}]\right\}$$

$$+ \left\{\sum_{m=1}^{M} T_m * [\sum_{m=1}^{M} \sum_{r=1}^{R} \sum_{k=1}^{K(r)} Dr_{m,r,k} * CT_{m,r} * Ds_{m,r}]\right\} \tag{3-4}$$

$$TLC = \left\{\sum_{v=1}^{V} T_v * [\sum_{v=1}^{V} \sum_{m=1}^{M} \sum_{i=1}^{I(m)} Dr_{v,m,i} * LT_{v,m} * Ds_{v,m} * SV]\right\}$$

$$+ \left\{\sum_{m=1}^{M} T_m * [\sum_{m=1}^{M} \sum_{r=1}^{R} \sum_{k=1}^{K(r)} Dr_{m,r,k} * LT_{m,r} * Ds_{m,r} * SV]\right\} \tag{3-5}$$

Where,

T_v = amount of wheat transported from each village in tonnes;

$Dr_{v,m,i}$ = distribution ratios of wheat volumes transported from village v to the storage facility i in the local market m;

$CT_{v,m}$ = transportation cost from village v to the storage facility i in the local market m of 1 tonne of wheat per kilometer;

$Ds_{v,m}$ = distance from village v to the storage facility i in the local market m in kilometers;

T_m = amount of wheat transported from each local market in tonnes;

$Dr_{m,r,k}$ = distribution ratios of wheat volumes transported from local markets m to regional storage facility k in regional facility r;

$CT_{m,r}$ = transportation cost from local markets m to regional storage facility k in regional facility r of 1 tonne of wheat per kilometer;

$Ds_{m,r}$ = distance from local markets m to regional storage facility k in regional facility r in kilometers;

$LT_{v,m}$ = transportation loss of wheat from village v to the storage facility i in the local market m of 1 tonne;

SV = the wheat unit sales price per tonne; and

$LT_{m,r}$ = transportation loss of wheat from local markets m to regional storage facility k in regional facility r of 1 tonne.

3.5 Constraints

The model is designed to consider all relevant practical constraints, including (1) storage capacity constraints; (2) distribution of harvested wheat constraint; and (3) distribution of transported wheat constraints.

Storage Capacity Constraints: These constraints are imposed to ensure that the volume of stored wheat in each facility does not exceed its available storage capacity and meet any minimum storage requirements in each facility, as shown in Equations (3-6), (3-7), and (3-8).

$$N_v \leq S_v \leq C_v \quad (3\text{-}6)$$

$$N_{m.i} \leq S_{m.i} \leq C_{m.i} \quad (3\text{-}7)$$

$$N_{r,k} \leq S_{r,k} \leq C_{r,k} \quad (3\text{-}8)$$

Where,

N_v = the minimum storage requirement in village *v;*

C_v = the maximum storage capacity in village *v*;

$N_{m.i}$ = the minimum storage requirement of facility *i* in local market m;

$C_{m.i}$ = the maximum storage capacity of market facility *i* in market, m;

$N_{r,k}$ = the minimum storage requirement of facility *k* in regional location r; and

$C_{r,k}$ = the maximum storage capacity of regional facility *k* in region r.

In addition, the sum of the minimum storage requirements in all villages *v*, facility *i* in local markets *m* and facility *k* in regional location *r,* should not exceed the total harvest as shown in Equation (3-9).

$$\sum_{v=1}^{V} M_v + \sum_{m=1}^{M} M_{m,i} + \sum_{r=1}^{R} M_{r,k} \leq \sum_{v=1}^{V} H_v \quad (3\text{-}9)$$

Distribution of Harvested Wheat Constraint: These two constraints are formulated to ensure that (1) the harvested wheat in each village H_v will be distributed over the amount stored in each village S_v and the amount of wheat transported from each village T_v, as shown in Equation (3-10); and (2) the harvested wheat from all villages, at any given time, will be distributed over the storage facilities at the village, local market and regional location levels while considering the suffered losses during the transportation of the wheat among these network nodes, as shown in Equation (3-11).

$$H_v = S_v + T_v \tag{3-10}$$

$$\sum_{v=1}^{V} H_v = \sum_{v=1}^{V} S_v + \sum_{m=1}^{M} \sum_{i=1}^{I(m)} S_{m,i} + \sum_{r=1}^{R} \sum_{k=1}^{K(r)} S_{r,k}$$
$$+[\sum_{v=1}^{V} T_v * [\sum_{m=1}^{M} LT_{v,m}]] + [\sum_{m=1}^{M} T_m * [\sum_{m=1}^{M} \sum_{r=1}^{R} LT_{m,r}]] \tag{3-11}$$

Distribution of Transported Wheat Constraints: These four constraints are formulated to ensure that (1) the transported wheat from each village will be distributed over the local market facilities based on their distribution ratios and the summation of these ratios is equal to one, as shown in Equation (3-12); (2) the transported wheat from each local market will be distributed over the regional facilities based on their distribution ratios and the summation of these ratios is equal to one, as shown in Equation (3-13); and (3) the total transported wheat from each local market $\mathrm{T_m}$ is equal to the amount of wheat transported to that market from all villages minus the amount of wheat lost in transportation from the villages to the local market as well as the amount of wheat stored in the local market, as shown in Equation (3-14).

$$\sum_{m=1}^{M} \sum_{i=1}^{I(m)} [\, Dr_{v,m,i}] = 1 \tag{3-12}$$

$$\sum_{r=1}^{R} \sum_{k=1}^{K(r)} [\, Dr_{m,r,k}] = 1 \tag{3-13}$$

$$T_m = [\sum_{v=1}^{V} [T_v \;\; * \sum_{i=1}^{I(m)} Dr_{v,m,i}]] - [\sum_{v=1}^{V} [\, T_v \;\; * \sum_{i=1}^{I(m)} Dr_{v,m,i}] * [\, \sum_{v=1}^{V} LT_{v,m}]] - \sum_{i=1}^{I(m)} S_{m,i} \tag{3-14}$$

3.6 Optimization Method

The optimization model was implemented using linear programming due to the linearity of the problem. The model is implemented in three main stages: (1) input stage that facilitates the input of all required data; (2) an optimization stage that executes the linear programming optimization; and (3) output stage that generates and displays the optimization results, as shown in Figure 3.3.

Input Stage

The model enables the user to input the relevant data for performing the optimization procedure. As shown in Figure 3.3, there are three sets of data (1) storage data; (2) transportation data; and (3) harvest data. A sample of the data is presented to the user, as shown in Figure 3.4.

Optimization Stage

The optimization computations of the model use the aforementioned input data to optimize the optimizing wheat storage and transportation throughout the entire network The optimization computations are performed in the present model using linear programming due to the linearity of the problem and the reported efficiency of linear programming in solving these types of problems (Luenberger and Ye 2008).

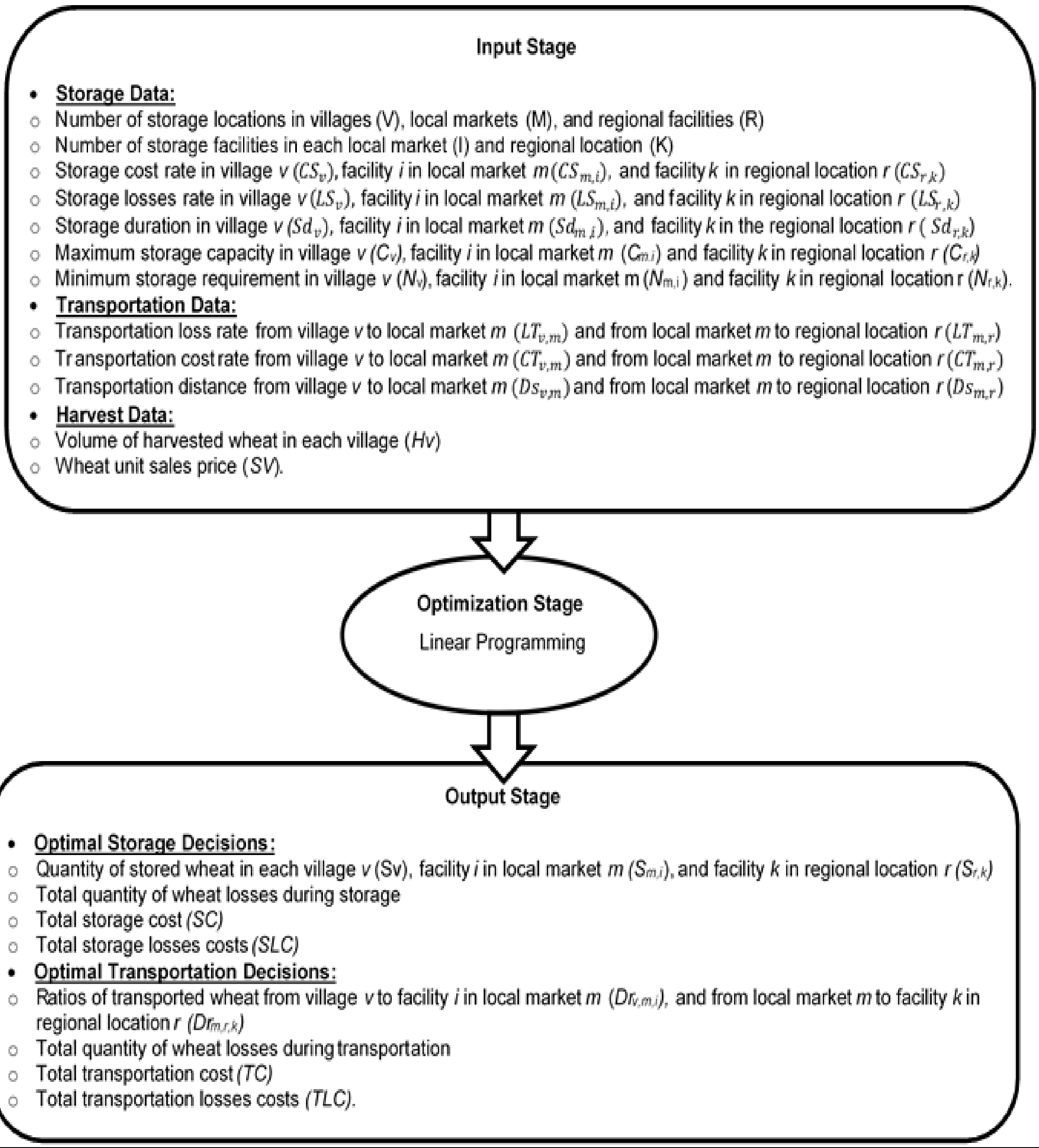


Figure 3.3 Model Implementation for Existing Facilities Model

TRANSPORTATION - VILLAGES TO MARKETS

D(f,m)		DISTRIBUTION %	COST	DISTANCE (MILES)	Transportation Losses	ISTRIBUTION	COST	DISTANCE (MILES)
M(1)	i (1,1)	1E-300	8	7.03	0.0013	0.10453768	8	7.68
	i (1,2)	1E-300	8	7.03	0.0013	1E-300	8	7.68
	i (1,3)	1E-300	8	7.03	0.0013	1E-300	8	7.68
M(2)	i (2,1)	1E-300	10	17.68	0.0010	0.633851778	10	19.91
	i (2,2)	1E-300	10	17.68	0.0010	1E-300	10	19.91
M(3)	i (3,1)	1E-300	8	17.07	0.0013	1E-300	8	23.20
	i (3,2)	1E-300	8	17.07	0.0013	1E-300	8	23.20
	i (3,3)	0.005529291	8	17.07	0.0013	1E-300	8	23.20
M(4)	i (4,1)	1E-300	8	9.88	0.0013	1E-300	8	11.51
	i (4,2)	1E-300	8	9.88	0.0013	1E-300	8	11.51
	i (4,3)	0.994470709	8	9.88	0.0013	1E-300	8	11.51
M(5)	i (5,1)	1E-300	10	25.46	0.0010	1E-300	10	31.48
	i (5,2)	1E-300	10	25.46	0.0010	1E-300	10	31.48
M(6)	i (6,1)	1E-300	8	20.68	0.0013	0.261610542	8	24.55
	i (6,2)	1E-300	8	20.68	0.0013	1E-300	8	24.55
	i (6,3)	1E-300	8	20.68	0.0013	1E-300	8	24.55
CONSTRAINT SUM OF DISTIBUTION RATIOS =1		1.00	TRUE			1.00	FALSE	

STORAGE IN MARKETS

M / i	MARKET LEVEL	m(1) i(1,1)	m(1) i(1,2)	m(1) i(1,3)
CS(m,i)	COST OF STORAGE/ 1 TON/ MONTH	50	50	50
LS(m,i)	STORAGE LOSSES/ 1 TON/ MONTH	0.015	0.015	0.015
Sd(m,i)	ESTIMATED STORAGE DURATION, MONTH (BEFORE SALES TAKING PLACE	3	3	3
C(m,i)	MARKETS' STORAGE CAPACITIES	C(1,1) 10,000.00	C(1,2) 10,000.00	C(1,3) 10,000.00
Sm(m,i)	DESIGN VARIABLE MARKETS' STORED VOLUMES	Sm(1,1) 4,531.00	Sm(1,2) 10,000.00	Sm(1,3) 3,878.00
% of MARKET CAPACITY OCCUPIED		45.31%	100.00%	38.78%
CONSTRAINT S ≤ C		TRUE	FALSE	TRUE
INPUT CONSTRAINT		1.09	0.14	0.87

TRANSPORTATION - MARKETS TO REGIONS

D(m,r)		DISTRIBUTION %	Cost of Transportation (Rs/ tonne / Mile)		DISTANCE (MILES)		Transportation Losses (%loss/ tonne/ Mile)	
R(1)	k (1,1)	0.000	ct(1,1,1)	20	Dmr(1,1,1)	20.69333978	Lt(1,1,1)	0.0030
	k (1,2)	0.000	ct(1,1,2)	20	Dmr(1,1,2)	20.69333978	Lt(1,1,2)	0.0030
	k (1,3)	0.000	ct(1,1,3)	20	Dmr(1,1,3)	20.69333978	Lt(1,1,3)	0.0030
R(2)	k (2,1)	0.000	ct(1,2,1)	30	Dmr(1,2,1)	16.65539975	Lt(1,2,1)	0.0020
	k (2,2)	0.000	ct(1,2,2)	30	Dfm(1,2,2)	16.65539975	Lt(1,2,2)	0.0020
R(3)	k (3,1)	0.886	ct(1,3,1)	20	Dmr(1,3,1)	27.18799315	Lt(1,3,1)	0.0030
	k (3,2)	0.114	ct(1,3,2)	20	Dmr(1,3,2)	27.18799315	Lt(1,3,2)	0.0030
	k (3,3)	0.000	ct(1,3,3)	20	Dmr(1,3,3)	27.18799315	Lt(1,3,3)	0.0030
	CONSTRAINT SUM OF DISTIBUTION RATIOS =1	1.00	TRUE					

Figure 3.4 Data Input and User Interface

<u>Output Stage</u>

Upon the completion of the aforementioned optimization computations, the model generates an optimal solution for wheat storage and transportation throughout the entire network. The optimization results generated by the present model includes: (1) optimal storage decisions; and (2) optimal wheat transportation decisions, as shown in Figure 3.3.

3.7 Model assumptions

The model assumes that storage cost rates, storage losses rates, transportation cost rates, and transportation losses rates can be estimated and provided by the user as input data, as shown in Figure 3.3. Storage cost rates in village v (CS_v), facility i in local market m $(CS_{m,i})$, and facility k in regional location r $(CS_{r,k})$ are assumed to cover storage cost, overhead cost and utility usage. Storage losses rates in village v (LS_v), facility i in local market m $(LS_{m,i})$, and facility k in regional location r $(LS_{r,k})$ are assumed to account for losses due to weather conditions, moisture content, quantity losses and other related factors. Transportation cost rates from village v to local market m $(CT_{v,m})$ and from local market m to regional location r $(CT_{m,r})$ are assumed to include transportation cost and overhead cost. Transportation losses rates from village v to local market m $(LT_{v,m})$ and from local market m to regional location r $(LT_{m,r})$ are assumed to cover quantity losses suffered during transportation.

3.8 Case Study

A case study is analyzed to illustrate the use of the developed model and demonstrate its unique capabilities in optimizing the storage and transportation of wheat in developing countries. The case study involves optimizing the storage and transportation of wheat in the district of Hissar in the state of Haryana, India.

A total of 30 villages are modeled, along with 6 local markets and 3 regional facilities. Each location includes various storage facilities, with a total of 47 facilities across the network. The geographical locations of the villages (blue markings) local market (red markings) and regional location (green markings) are shown in Figure 3.5. The total harvested volume in this example was 180,000 tonnes of wheat, while the total available storage capacity in the network was 316,900 tonnes.

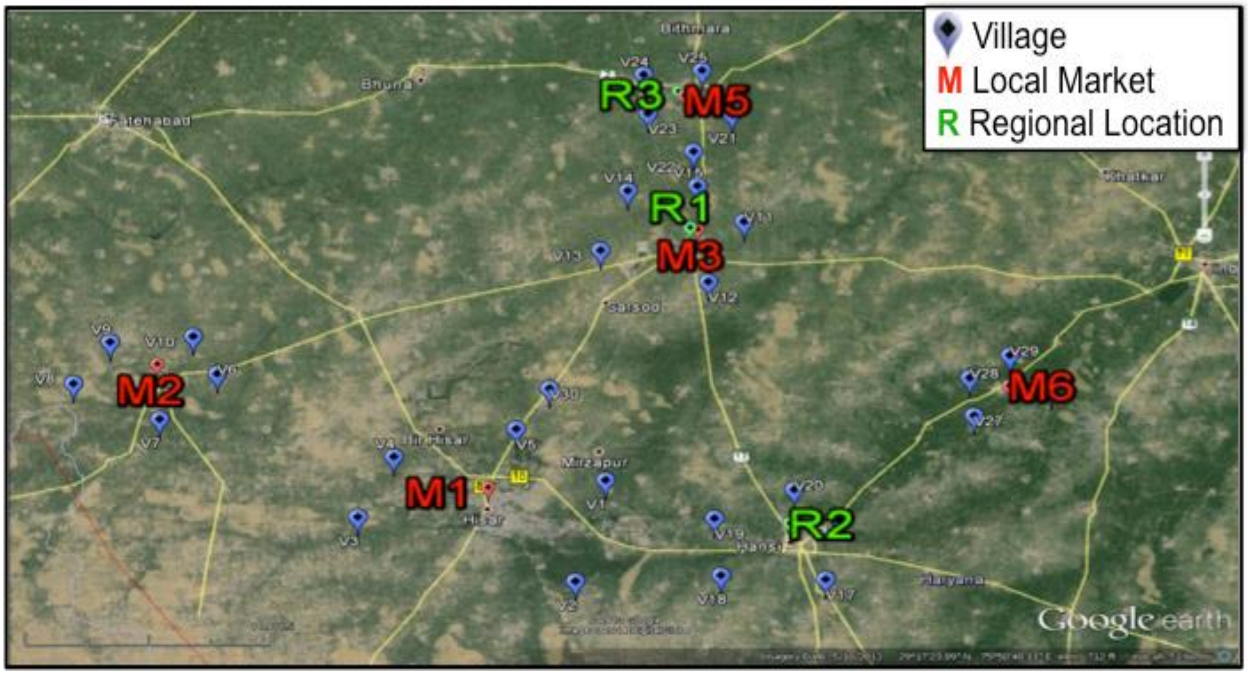


Figure 3.5 Location of the Villages (Blue), Local Market (Red) and Regional Facilities (Green) In the District Of Hissar

The input data for this application example was gathered from several sources including the Government of India, Food Corporation of India, Haryana Food and Supplies Department, Haryana Warehousing Cooperation and Haryana State Agricultural Marketing Board (FCI 2013; Food and Feed Grain Institute 1991; Food and Feed Grain Institute 1989; Government of India 2002; HAFED 2013; HF&SD 2013; HSAMB 2013; HWC 2013; Kiruba et. Al 2006; and Joshi 2002). As shown in Figure 3.3, the gathered input data are classified as storage, transportation and harvest data. First, the storage input data includes (1) number of storage locations in villages (V), local markets (M), and regional location (R); (2) number of storage facilities in each local market (I) and each regional location (K); (3) storage cost rate in each village (CS_v), local market facility ($CS_{m,i}$), and regional location ($CS_{r,k}$); (4) storage losses rate in each village (LS_v), local market facility ($LS_{m,i}$), and regional location ($LS_{r,k}$); (5) storage capacity in each village (C_v), local market facility ($C_{m.i}$) and regional location ($C_{r,k}$); and (6) storage duration in each village (Sd_v), local market facility ($Sd_{m,i}$), and regional location ($Sd_{r,k}$) that is assumed to be 3 months in all facilities. Each of these storage facilities has its unique cost rate, loss rate and capacities as shown in the sample input data in Table 3.1. The ranges of these cost rates, loss rates and capacities among the various facilities in the current network are summarized in Table 3.2. The reason for different cost & loss rates among different locations is due to the different type of storage structures that can be (a) covered indoor storage structures such as warehouses, or (b) open outdoor storage structures such as cover and plinth. Open outdoor structures suffer higher losses rates compared to covered indoor structures.

It should be noted that this case study includes (a) 180 possible transportation routes between the 30 analyzed villages and 6 local markets, and (b) 18 possible routes between the 6 local markets and the 3 regional facilities shown in Figure 3.5. Each of these transportation routes has its unique transportation cost rate, losses rate, and distance as shown in the sample input data in Table 3.2. The ranges of these transportation cost rates, losses rates and distances are summarized in Table 4. The harvest input data includes (1) harvested quantities (Hv) which is assumed to be 6,000 tonnes in each village; and (2) wheat sales value (SV), which is assumed to be 5,000 Rs/t.

Second, the transportation input data includes (1) transportation cost rates from each village to each local market ($CT_{v,m}$) and from each local market to each regional location ($CT_{m,r}$); (2) wheat loss rates during the transportation from each village to each local market ($LT_{v,m}$) and from each local market to each regional location ($LT_{m,r}$); and (3) transportation distance from each village to each local market ($Ds_{v,m}$) and from each local market to each regional location ($Ds_{m,r}$). It should be noted that this case study includes (a) 180 possible transportation routes between the 30 analyzed villages and 6 local markets, and (b) 18 possible routes between the 6 local markets and the 3 regional facilities shown in Figure 3.6. Each of these transportation routes has its unique transportation cost rate, losses rate, and distance as shown in the sample input data in Table 3.3. The ranges of these transportation cost rates, losses rates and distances are summarized in Table 3.4. Third, the harvest input data includes (1) harvested quantities (H_v) which is assumed to be 6,000 tonnes in each village; and (2) wheat sales value (*SV),* which is assumed to be 5,000 Rs/t.

Table 3.1 Sample Input and Output Data for Local Market M2 and Regional Location R3

Input Data					Output Data	
Location	Storage Facility	Storage Cost Rate (Rs/t*month)	Storage Loss Rate (% Loss/t*month)	Storage Capacity (t)	Optimal Storage Volume (t)	% of Capacity
Local Market M2 (m = 2)	i	$CS_{m,i}$	$LS_{m,i}$	$C_{m,i}$	$S_{m,i}$	
	1	60	1	10,000	10,000	100%
	2	60	1	10,000	10,000	100%
Regional Location R3 (r = 3)	k	$CS_{r,k}$	$LS_{r,k}$	$C_{r,k}$	$S_{r,k}$	
	1	70	1	23000	9823.8	42%
	2	40	2.5	1000	0.0	0%
	3	40	2.5	23000	0.0	0%

Table 3.2 Ranges of Storage Data for all Villages, Local Markets and Regional Location Facilities

Location	Number of Locations	Number of Storage Facilities	Range of Storage Cost Rates (Rs/t*month)		Range of Storage Loss Rates (% Loss/t*month)		Range of Capacities (t)	
			Min	Max	Min	Max	Min	Max
			CS_v		LS_v		C_v	
Village	V=30	30	8	11	2.0	3.0	2000	2000
			$CS_{m,i}$		$LS_{m,i}$		$C_{m,i}$	
Local Market	M=6	I=12	40	60	1.0	2.0	2500	10000
			$CS_{r,k}$		$LS_{r,k}$		$C_{r,k}$	
Regional Location	R=3	K=5	40	70	1.0	2.5	1000	56000

Table 3.3 Sample Transportation Data between Local Markets and all Regional Locations

Local Market Origin	Regional Location Destination: Transportation Cost Rate (Rs/ t*km) CTm,r			Transportation Loss Rate (% of Loss/ t*km) LTm,r			Transportation Distance (km) Dsm,r		
	R1	R2	R3	R1	R2	R3	R1	R2	R3
M1	12	18	12	0.18	0.12	0.18	33.30	26.80	43.75
M2	12	18	12	0.18	0.12	0.18	35.96	44.17	38.93
M3	12	18	12	0.18	0.12	0.18	0.00	31.50	16.00
M4	12	18	12	0.18	0.12	0.18	31.50	0.00	47.33
M5	12	18	12	0.18	0.12	0.18	16.00	47.33	0.00
M6	12	18	12	0.18	0.12	0.18	28.52	21.99	42.90

Table 3.4 Ranges of Transportation Data between Villages, Local Markets and Regional Locations

Transportation Route	Range of Transportation Cost Rates (Rs/ t*km)		Range of Transportation Loss Rates (% of Loss/ t*km)		Range of Distances (km)	
	Min	Max	Min	Max	Min	Max
Village to Local Market (v,m)	CTv,m		LTv,m		Dsv,m	
	5	12	0.06	0.08	0.0	72.9
Local Market to Regional Location (m,r)	CTm,r		LTm,r		Dsm,r	
	12	18	0.12	0.18	0.0	47.3

The aforementioned input data was analyzed by the developed optimization model in order to minimize the losses and cost of wheat storage and transportation throughout the entire network. The model was able to identify the optimal storage levels in each village (Sv), in each storage facility i in local market m (Sm,i), and in each storage facility k in regional location r (Sr,k), as shown in the sample optimal results in Table 3.1 for regional location 3. The difference in the storage levels in these three facilities in regional location 3 is due to their varying storage cost and loss rates, as shown in Table 3.1. In order to minimize the overall cost of wheat storage and transportation in the entire network, the model identified an optimal wheat storage of 42% in facility 1 due to its lower storage cost and loss rates, and zero storage in facilities 2 and 3 due to their higher rates. The total volumes of identified optimal wheat storage in all villages, local markets and regional locations as well as their estimated losses are summarized in Table 3.5. The results in Table 3.5 illustrate that wheat storage volumes in regional locations were higher than those of local markets and villages due to their lower storage cost and loss rates as well as storage constraints.

Table 3.5 Optimal Wheat Storage in all Villages, Local Markets and Regional Locations

	Storage Quantity Before Losses (thousand t)	Storage Losses (thousand t)	Storage Losses (%)
All Villages	48.24	3.49	7.25%
All Local Markets	48.59	1.81	3.73%
All Regional Locations	79.75	2.39	3.00%
Total	176.6	7.70	4.28%

In addition, the model identified the optimal distribution ratios of wheat to be transported from each village v to each storage facility i in local market m (Drv,m,i), and from each local market m to each regional storage facility k in regional location r (Drm,r,k), as shown in sample optimal transportation results in Table 3.6. These optimal transportation routes were identified by the model to minimize the overall transportation costs that consider transportation cost rates, loss rates, and distance. A ratio of 1 between an origin and destination in Table 3.6 indicates that all the transported wheat from that origin will be transported to a single destination, while a ratio of zero indicates that the listed route was not utilized for transporting wheat. The total volumes of identified optimal wheat transported between villages to local markets and local markets to regional locations as well as their estimated losses are summarized in Table 3.7.

Table 3.6 Optimal Transportation Ratios and Quantities between Local Markets and Regional Locations

Village Origin	Local Market Destination											
	Total $Dr_{v.m.i}$						Quantity Transported (t)					
	M1	M2	M3	M4	M5	M6	M1	M2	M3	M4	M5	M6
V1	0.0	0.0	0.0	1.0	0.0	0.0	0	0	0	4,000	0	0
V2	0.02	0.74	0.0	0.0	0.0	0.23	103	2,956	0	0	0	938
V3	0.1	0.0	0.60	0.0	0.0	0.29	477	0	2,977	0	0	1,445
V4	0.0	0.0	0.53	0.3	0.0	0.17	0	0	2,135	1,199	0	664
V5	0.0	0.0	0.69	0.0	0.31	0.0	0	0	2,759	0	1,240	0
V6	0.33	0.0	0.0	0.0	0.0	0.67	1,563	0	0	0	0	3,289
V7	0.0	0.0	0.32	0.68	0.0	0.0	0	0	1,265	2,734	0	0
V8	0.0	0.0	0.02	0.0	0.0	0.98	0	0	88	0	0	4,000

Table 3.7 Optimal Transportation Results

	Total Transported Quantities Before Losses (t)	Transportation Losses (t)	Transportation Losses (%)
Total Villages to Local Markets	131,752.0	3,145.7	2.39%
Total Local Markets to Regional Locations	80,012.3	254.2	0.32%
Total	211,764.3	3,399.9	1.61%

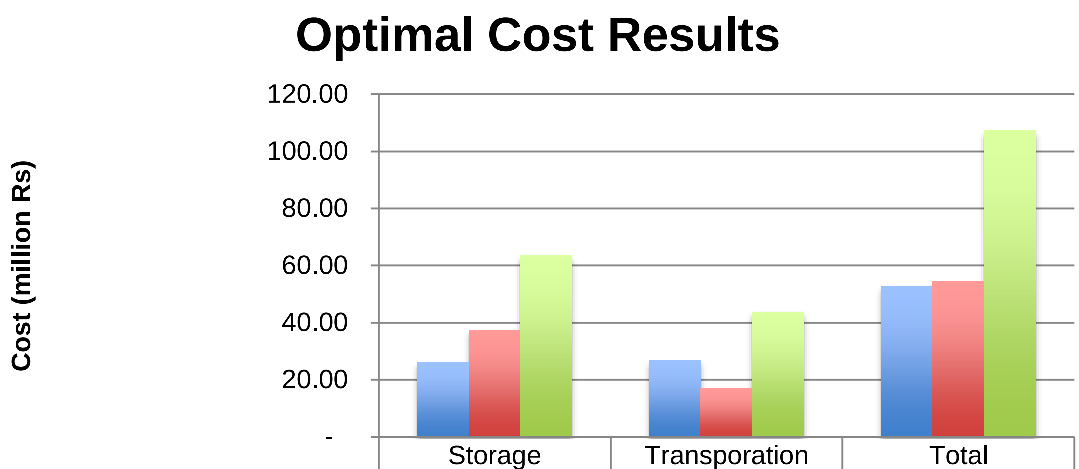
The minimum total cost of wheat storage and transportation that was identified for this case study was 107.26 million Rs. As shown in Figure 3.6, this minimum total cost can be broken down to (1) total storage direct cost throughout the entire network of villages, local markets, and regional locations during the specified storage period of 3 months; (2) total storage losses costs caused by quantity and quality losses in all storage facilities; (3) total transportation cost throughout the entire network; and (4) total transportation losses costs suffered during wheat transportation throughout the network.

The average storage and transportation cost rates, loss rates and capacities filled in the local markets and regional locations are summarized in Figure 3.7. A closer examination of the generated optimal results reveals that local markets M2, M5, and M6 were filled to their capacity due to their collective lower average storage and transportation cost rates and loss rates and distance compared to local markets M1, M3 and M4, as shown in Figure 3.7. Similarly, comparing regional locations R1 and R2 reveals that R1 was filled at 47% of its full capacity while R2 was 78% due to the lower average transportation cost rate and transportation distances to R2 compared to R1, as shown in Figure 3.7. In addition, R3 was the least filled of the regional locations mainly due to its average storage loss rate (2%) that was double the rate of the other two locations (1%) and due to its longer average transportation distance. Detailed results of the case study are presented in Appendix II. These results highlight the need to upgrade storage facilities that are under-utilized due to their high storage cost and loss rates to improve their storage efficiency. In addition, facilities filled to capacity may be expanded and/or upgraded to meet higher storage demands and provide further improvements in their cost and loss rates. Accordingly the model provides decision makers with the capabilities of (1) minimizing the total wheat storage and transportation cost in the entire supply chain network of villages, local markets, and regional locations, and (2) identifying needed upgrades of existing storage facilities and/or transportation routes

A sensitivity analysis was conducted to analyze the sensitivity of the model results to uncertainties and variations in its input data such as variations in the storage loss rates at the regional locations, as shown in Table 3.8. The results of this analysis illustrate that an increase in the storage loss rate at the regional locations causes a decrease in the volume of wheat stored in all regional locations. This reduction in the storage volumes at the regional locations was caused by reallocating these storage volumes from regional locations to local markets that have lower storage loss rates. The results also show that a decrease in storage loss rates did not cause an increase in the volume of wheat stored in the regional locations. The reason for this is due to the regional locations original low storage loss rates. Even though the volume of wheat at the regional location did not increase with a decrease in the storage loss rates, the type of facilities where the wheat was stored within the regional locations changed. For example, a reduction in the storage loss rates (see last row in Table 3.8) caused the storage of 9,820 tons of wheat to be reallocated from the first facility (k=1) to the third facility (k=3) in regional location R3 to minimize the overall wheat storage cost that depends on the storage cost rate and storage loss rate, as shown in Equations 3-1 to 3-3. This storage reallocation from k=1 to k=3 was due to (a) the lower storage cost rate of the third facility (k=3) compared to the first facility (k=1) as shown in Table 3.1, and (b) lowering the cost of storage losses in both facilities to the point that it did not have a significant impact on the overall storage cost. The sensitivity analysis shows the optimization results were sensitive to these variations in the analyzed storage losses.

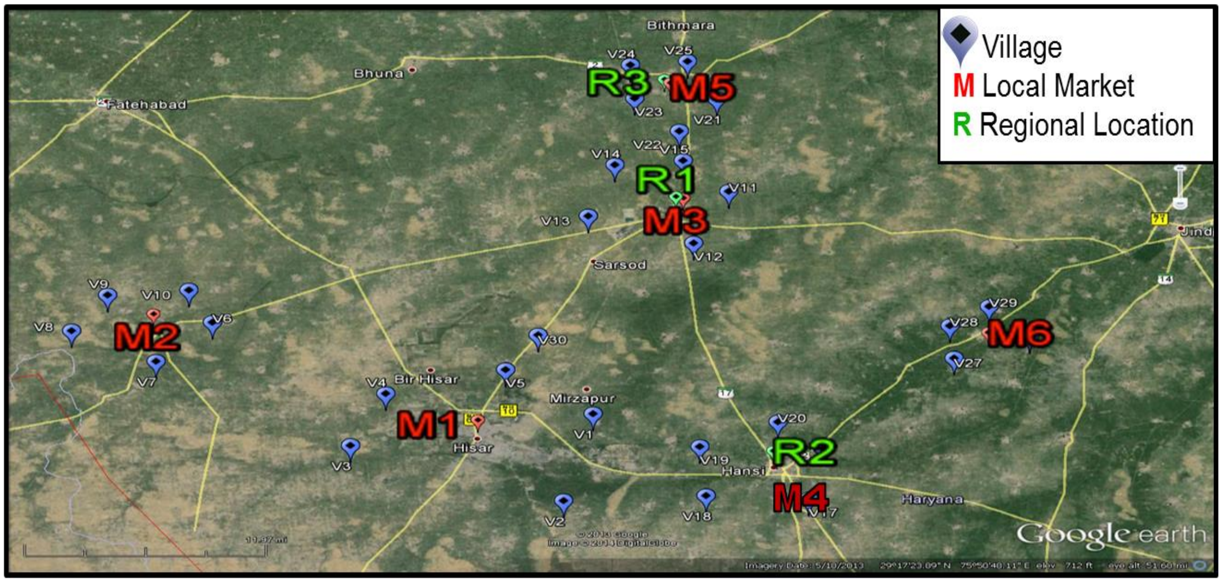
Table 3.8 Sensitivity Analysis of Optimal Storage to Variation in Storage Losses at Regional Locations

Variation from Case Study Storage Loss Rates in Regional Locations	Storage Loss Rate (%)		Storage Volume before Losses (thousand t)					
	Min	Max	R1	R2	R3			All Regional Locations
					K=1	K=2	K=3	
+75%	1.75	4.37	12.92	15.77	9.82	0.00	0.00	38.61
+50%	1.5	3.75	16.96	15.77	9.82	0.00	0.00	42.56
+25%	1.25	3.12	16.96	43.21	9.82	0.00	0.00	69.99
0%	1.0	2.5	26.49	43.55	9.82	0.00	0.00	79.87
-25%	0.75	1.87	26.49	43.55	9.82	0.00	0.00	79.87
-50%	0.5	1.25	26.49	43.55	9.82	0.00	0.00	79.87
-75%	0.25	0.62	26.49	43.55	0.00	0.00	9.82	79.87



	Storage	Transporation	Total
Direct Costs	26.12	26.75	52.87
Losses Costs	37.39	17.00	54.39
Overall Costs (Direct+Loss)	63.51	43.75	107.26

Figure 3.6 Optimal Cost Results for Existing Facilities Model



Local Market Storage						
Local Markets	M1	M2	M3	M4	M5	M6
Average Storage Cost (Rs/t*month)	50	60	50	40	50	60
Average Storage Losses (% Loss/t*month)	1.5%	1.0%	1.5%	2.0%	1.5%	1.0%
Average Transportation Cost to Local Markets (Rs/ t*km)	8	10	8	8	10	8
Average Transportation Losses to Local Markets (%/ t*km)	0.13%	0.10%	0.13%	0.13%	0.10%	0.13%
Average Transportation Distance to Local Markets (km)	18	21	16	18	21	22
Storage Capacity (thousand t)	30	20	7.5	30	5	5
Wheat Stored (thousand t)	18.4	20	0	0	5	5
% of Capacity Filled	62%	100%	0%	0%	100%	100%
% of Wheat Stored in Network	10.27%	11.11%	0.00%	0.00%	2.78%	2.78%

Regional Location Storage			
Regional Locations	R1	R2	R3
Average Storage Cost (Rs/t*month)	70	70	50
Average Storage Losses (% Loss/t*month)	1.00%	1.00%	2.00%
Average Transportation Cost to Regional Locations (Rs/ t*km)	20	30	20
Average Transportation Losses to Regional Locations (%/ t*km)	0.30%	0.20%	0.30%
Average Transportation Distance to Regional Locations (km)	15	18	20
Storage Capacity (thousand t)	56.1	56.1	47
Wheat Stored (thousand t)	26.3	43.5	9.8
% of Capacity Filled	47%	78%	21%
% of Wheat Stored in Network	14.65%	24.20%	5.46%

Figure 3.7 Optimal Wheat Storage for Existing Facilities Model

3.9 Summary

This chapter presented the development of a model for optimizing the storage and transportation of wheat in developing countries. The model provides the capability of minimizing the costs and losses of wheat storage and transportation among the storage facilities in the villages, local markets and regional locations. The model was developed in six main steps that included field collection, defining its model decision variables, formulating its objective function, modeling its constraints, implementing it using linear programming and analyzing it though a case study. The case study was analyzed to illustrate the use of the developed model and demonstrate its effectiveness in optimizing the storage and transportation of wheat in developing countries. The results of this analysis illustrates the capabilities of the developed model in minimizing the total wheat storage and transportation cost including the total storage cost throughout the entire network of villages, local markets, and regional locations; the total storage losses costs caused by quantity and quality losses in all storage facilities; the total transportation cost throughout the entire network; and the total transportation losses costs suffered during wheat transportation throughout the network. These capabilities contribute to (1) minimizing the total wheat storage and transportation cost in the entire supply chain network of villages, local markets, and regional locations, and (2) identifying needed upgrades of existing storage facilities and/or transportation routes.

4 OPTIMIZING THE CONSTRUCTION OF PUBLIC WHEAT STORAGE FACILITIES

4.1 Introduction

This chapter presents the development of a novel model for optimizing the construction of public wheat storage facilities as well as optimizing wheat storage and transportation in developing countries. The model is designed to minimize the losses and cost of wheat storage and transportation while considering the impact of existing storage facilities. The optimization model is developed in three main phases: (1) formulation phase that defines the model decision variables, objective function, and constraints; (2) implementation phase that performs the optimization computations using integer programming and integrates a newly developed storage facilities database to facilitate the input and output of the optimization data; and (3) evaluation phase that analyzes a case study to demonstrate the use of the model and evaluate its performance, as shown in Figure 4.1.

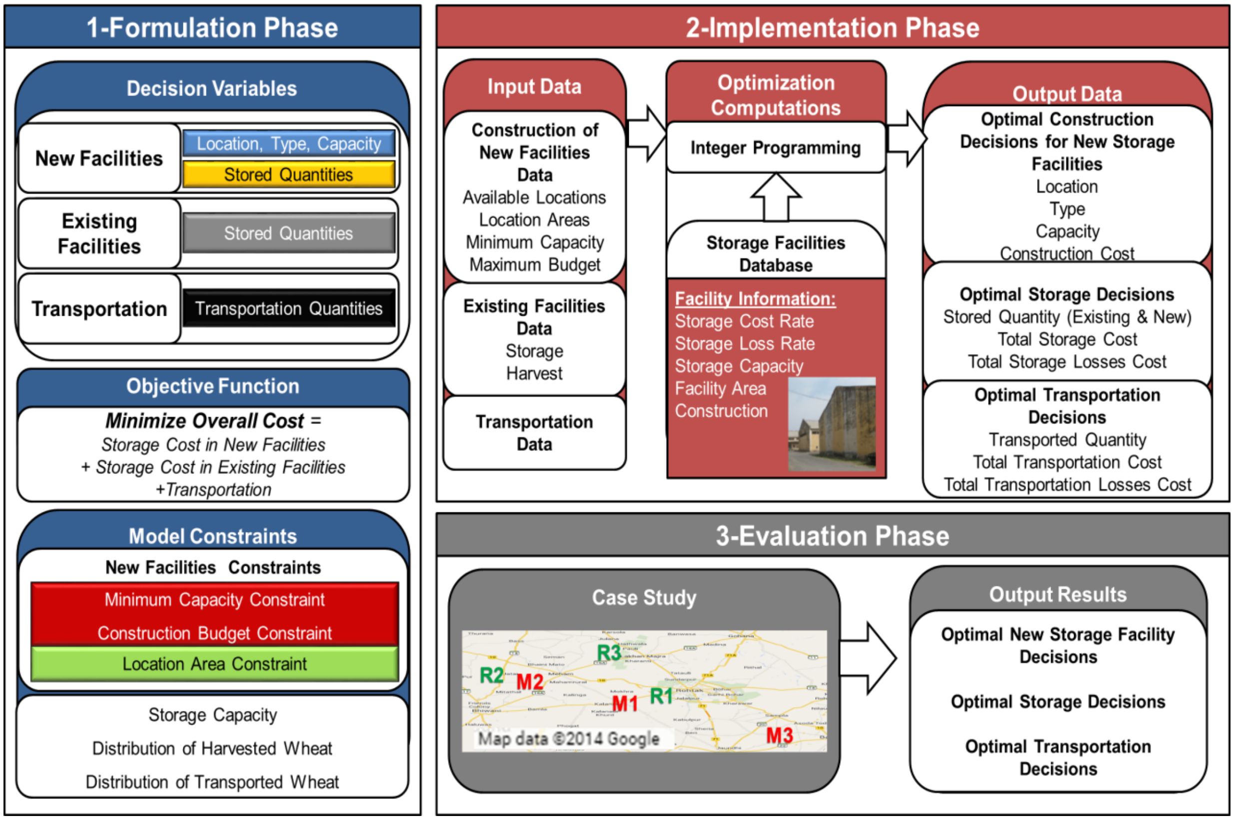


Figure 4.1 New Construction Optimization Model Development Phases

4.2 Formulation Phase

To ensure the formulation of a practical model for optimizing the construction of new wheat storage facilities in developing countries, wheat storage and transportation practices were investigated during a field study of wheat storage in India. The findings of this field study were used to define the optimization model decision variables, objective function, and constraints, which are described in the following sections.

4.2.1 Decision Variables

The model is formulated to identify all relevant decision variables and define the optimization objective function in all villages, local markets, and regional locations. The decision variables of the model can be grouped into three main categories (1) new storage facilities as shown in Figure 4.2, (2) existing storage facilities, and (3) transportation routes among all storage facilities, as shown in Figure 4.3.

The first set of decision variables in the present model is designed to optimize the construction decisions of new public wheat storage facilities. Accordingly, these decision variables are designed to identify the optimal location, type, and capacity of new public wheat storage facilities at the village, local market and regional location levels (see Table 4-1). A simplified example of the set of decision variables at the local market level is shown in Figure 4.2. In this example, a decision-maker is required to select the optimal locations for the construction of new public wheat storage facilities at the local market level from a set of feasible alternatives that includes locations M1, M2, M3 and M4, as shown in Figure 4.2. In addition to the optimal location, the decision-maker in this example needs to identify for each location: (a) the optimal type from a set of feasible alternatives that includes silos and warehouse; and (b) capacity from a set of feasible alternatives that includes 1000, 2000, 3000, and 5000 tonnes, as shown in Figure 4.2.

New Construction Facility Selection $X_{m,i}^{t,c}$			
Location	Storage Facility	Type	Capacity
m	i	t	c

Location m=2			
Decision Variable $X_{m,i}^{t,c}$	Storage Facility i	Type t	Capacity c
1	1	Silo	1000
0	2	Silo	2000
0	3	Silo	3000
1	4	Silo	5000
0	5	Warehouse	1000
0	6	Warehouse	2000
1	7	Warehouse	3000
0	8	Warehouse	5000

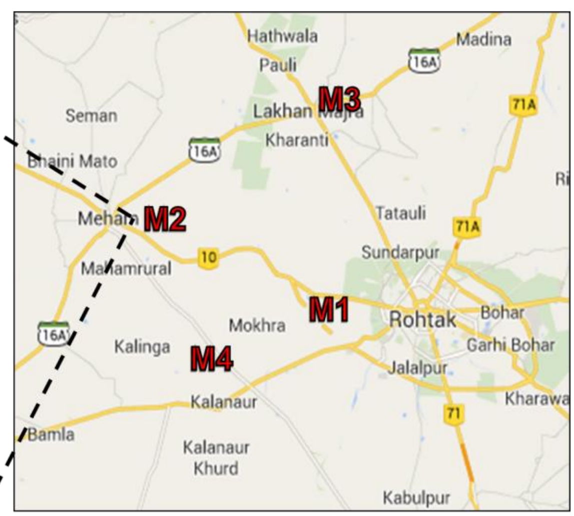


Figure 4.2 Decision Variable for Construction of New Storage Facilities for Local Market Example

The second set of decision variables is used to determine the optimal storage quantities of wheat in existing facilities at the village, local market and regional location levels (see Figure 4.3 and Table 4.1). The third set of decision variables is used to optimize the transportation of harvested wheat among all existing and new storage facilities throughout the supply chain. These decision variables are designed to determine the optimal distribution rates of harvested wheat among all storage facilities at the village, local market and regional location levels. The optimal distribution rates and transported quantities among the various existing and new storage facilities are influenced by the transportation costs and the losses.

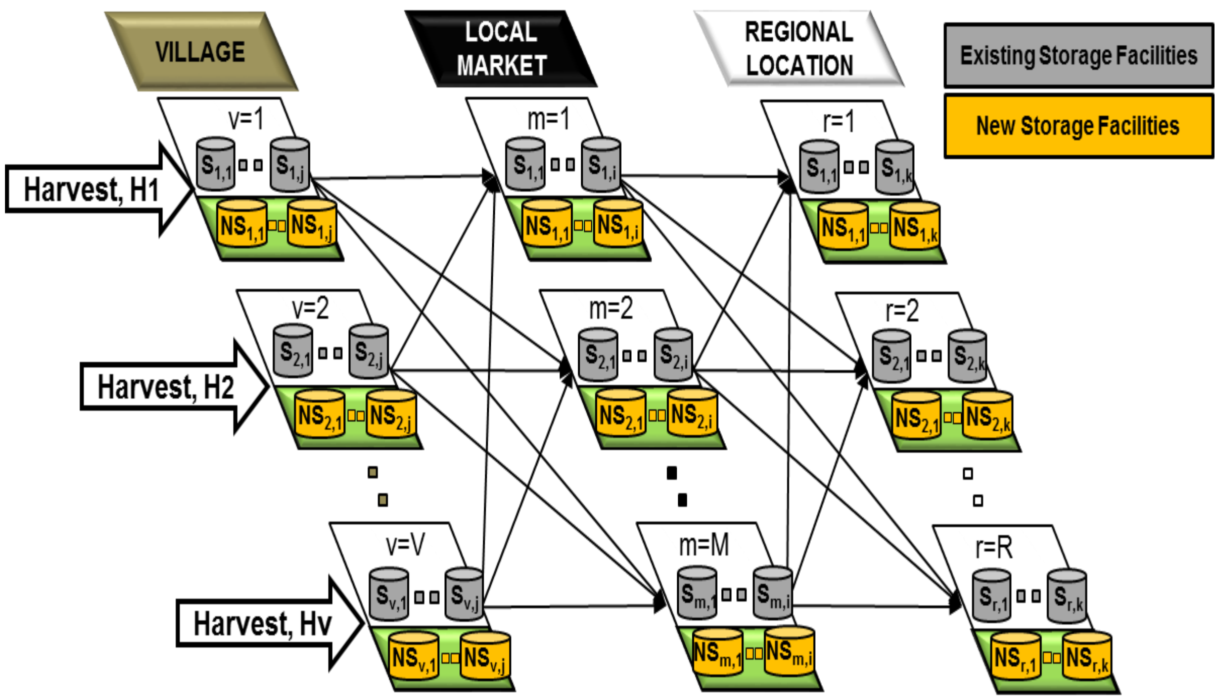


Figure 4.3 Wheat Storage for Existing and New Public Storage Facilities in Villages, Local Markets, and Regional Locations

Table 4.1 Decision Variables for New Public Facilities Model

	Description	Notation
New Facilities	Binary function of whether new facility *j* is to be constructed of type *t* and capacity *c* in location village *v*	$X_{v,j}^{t,c}$
	Binary function of whether new facility *i* is to be constructed of type *t* and capacity *c* in location local market *m*	$X_{m,i}^{t,c}$
	Binary function of whether new facility *k* is to be constructed of type *t* and capacity *c* in location regional facility *r*	$X_{r,k}^{t,c}$
	Quantity of stored wheat per month of facility type *t* and capacity *c* in each storage facility *j* in each *village v* in tonnes	$NS_{v,j}^{t,c}$
	Quantity of stored wheat per month of facility type *t* and capacity *c* in each storage facility *i* in local market *m* in tonnes	$NS_{m,i}^{t,c}$
	Quantity of stored wheat per month of facility type *t* and capacity *c* in each storage facility *k* in regional location *r* in tonnes	$NS_{r,k}^{t,c}$
Existing Facilities	Quantity of stored wheat per month in each storage facility *j* in *village v* in tonnes	$S_{v,j}$
	Quantity of stored wheat per month in each storage facility *i* in local market *m* in tonnes	$S_{m,i}$
	Quantity of stored wheat per month in each storage facility *k* in regional location *r* in tonnes	$S_{r,k}$
Transportation	Percent of wheat transported from each village *v* to each storage facility *i* in local market *m*	$Dr_{v,m,i}$
	Percent of wheat transported from each local market *m* to storage facility *k* in regional location *r*	$Dr_{m,r,k}$

4.2.2 Objective Function

The model is designed to minimize the overall cost of storage and transportation of wheat in the entire supply chain network of existing and new public storage facilities. Accordingly, the objective function of this model seeks to minimize the overall cost of wheat storage and transportation that consists of: (1) storage cost in new facilities; (2) storage cost in existing facilities; and (3) the total transportation costs throughout the entire supply chain, as shown in Equation (4.1). These three types of cost are explained in the following sections.

$$\begin{aligned} &\textit{Minimize Overall Cost} = \textit{Storage Cost in New Facilities} \\ &+ \textit{Storage Cost in Existing Facilities} + \textit{Transportation Cost} \\ &= (SCN+SLCN) + (SCE+SLCE) + (TC+TCL) \end{aligned} \quad (4\text{-}1)$$

Storage Cost in New Facilities

The overall cost of wheat storage in new storage facilities that are to be constructed can be expressed as the sum of: (1) the total storage cost (SCN) at the new storage facilities in villages, local markets and regional locations during the estimated storage durations; (2) the total storage losses costs (SLCN) caused by quantity and quality losses in all new storage facilities in villages, local markets and regional locations that can be calculated as the product of estimated quantity of losses and the sales price per unit volume, as shown in Equations (4-2) and (4-3).

$$SCN = \sum_{v=1}^{V} \sum_{j=1}^{J(v)} \sum_{t=1}^{T} \sum_{c=1}^{C} \left[X_{v,j}^{t,c} * (NS_{v,j}^{t,c} * CS_{v,j}^{t,c} * Sd_{v,j}^{t,c})\right]$$

$$+\sum_{m=1}^{M} \sum_{i=1}^{I(m)} \sum_{t=1}^{T} \sum_{c=1}^{C} \left[X_{m,i}^{t,c} * (NS_{m,i}^{t,c} * CS_{m,i}^{t,c} * Sd_{m,i}^{t,c})\right] \qquad (4\text{-}2)$$

$$+\sum_{r=1}^{R} \sum_{k=1}^{K(r)} \sum_{t=1}^{T} \sum_{c=1}^{C} \left[X_{r,k}^{t,c} * (NS_{r,k}^{t,c} * CS_{r,k}^{t,c} * Sd_{r,k}^{t,c})\right]$$

Where,

$X_{v,j}^{t,c}$ = the binary variable that represents whether or not new facility *j* of type *t* and capacity *c* will be constructed in village location *v;*

$NS_{v,j}^{t,c}$ = the quantity of stored wheat per month of facility type *t* and capacity *c* in each storage facility *j* in each *village v* in tonnes*;*

$CS_{v,j}^{t,c}$ = the storage cost of 1 tonne of wheat per month in storage facility *j* of type *t* and capacity *c* in village *v* in $;

$Sd_{v,j}$ = the storage duration of 1 tonne of wheat in storage facility *j* in village *v* in months;

$X_{m,i}^{t,c}$ = the binary variable that represents whether or not new facility *i* of type *t* and capacity *c* will be constructed in location local market *m;*

$NS_{m,i}^{t,c}$ = the quantity of stored wheat per month of facility type *t* and capacity *c* in each storage facility *i* in local market *m* in tonnes*;*

$CS_{m,i}^{t,c}$ = the storage cost of 1 tonne of wheat per month in storage facility *i* of type *t* and capacity *c* in local market *m* in $;

$Sd_{m,i}$ = the storage duration of 1 tonne of wheat in storage facility *i* in the market *m* in months*;*

$X_{r,k}^{t,c}$ = the binary variable that represents whether or not new facility *k* of type *t* and capacity *c* will be constructed in location regional facility *r;*

$NS_{r,k}^{t,c}$ = the quantity of stored wheat per month of facility type *t* and capacity *c* in each storage facility *k* in regional location *r* in tonnes*;*

$CS_{r,k}^{t,c}$ = the storage cost of 1 tonne of wheat per month in storage facility *k* of type *t* and capacity *c* in regional location *r* in $; *and*

$Sd_{r,k}$ = the storage duration of 1 tonne of wheat storage facility *k* in the regional location, *r* in months.

This storage cost rate $CS_{v,j}^{t,c}, CS_{m,i}^{t,c}\ and\ CS_{r,k}^{t,c}$ should be estimated using a life-cycle cost analysis that considers all related parameters including initial cost of construction, annual operating and maintenance costs, demolition and disposal cost, savage value, service life, and interest rate.

$$SLCN = \sum_{v=1}^{V} \sum_{j=1}^{J(v)} \sum_{t=1}^{T} \sum_{c=1}^{C} \left[X_{v,j}^{t,c} * (NS_{v,j}^{t,c} * LS_{v,j}^{t,c} * Sd_{v,j}^{t,c} * SV)\right]$$

$$+ \sum_{m=1}^{M} \sum_{i=1}^{I(m)} \sum_{t=1}^{T} \sum_{c=1}^{C} \left[X_{m,i}^{t,c} * (NS_{m,i}^{t,c} * LS_{m,i}^{t,c} * Sd_{m,i}^{t,c} * SV)\right] \qquad (4\text{-}3)$$

$$+ \sum_{r=1}^{R} \sum_{k=1}^{K(r)} \sum_{t=1}^{T} \sum_{c=1}^{C} \left[X_{r,k}^{t,c} * (NS_{r,k}^{t,c} * LS_{r,k}^{t,c} * Sd_{r,k}^{t,c} * SV)\right]$$

Where,

$LS_{v,j}^{t,c}$ = the percentage of quantity and quality losses per month in storage facility *j* of type *t* and capacity *c* in village *v;*

SV = the wheat unit sales price per tonne in $;

$LS_{m,i}^{t,c}$ = the percentage of quantity and quality losses per month in storage facility *i* of type *t* and capacity *c* in local market *m; and*

$LS_{r,k}^{t,c}$ = the percentage of quantity and quality losses per month in storage facility *k* of type *t* and capacity *c* in regional location *r.*

Storage Cost in Existing Facilities

The overall cost of wheat storage in existing facilities is calculated in the presented model as the sum of: (1) the total storage cost (SCE) of wheat in existing facilities in all villages, local markets and regional locations during the estimated storage durations; (2) the total wheat storage losses costs (SLCE) that are suffered because of both quantity and quality losses during wheat storage in existing facilities in all villages, local markets and regional locations that can be calculated as the product of the estimated quantity of wheat losses during storage and the sales price per unit volume, as shown in Equations (4-4) and (4-5).

$$SCE = \sum_{v=1}^{V} \sum_{j=1}^{J(v)} [S_{v,j} * CS_{v,j} * Sd_{v,j}] + \sum_{m=1}^{M} \sum_{i=1}^{I(m)} [S_{m,i} * CS_{m,i} * Sd_{m,i}] + \sum_{r=1}^{R} \sum_{k=1}^{K(r)} [S_{r,k} * CS_{r,k} * Sd_{r,k}] \quad (4\text{-}4)$$

Where,

$S_{v,j}$ = the quantity of stored wheat per month in each storage facility *j* in village *v* in tonnes;

$CS_{v,j}$ = the storage cost of 1 tonne of wheat per month in storage facility *j* in village *v* in $;

$Sd_{v,j}$ = the storage duration of 1 tonne of wheat in storage facility *j* in village *v* in months;

$S_{m,i}$ = the quantity of stored wheat per month in each storage facility *i* in local market *m* in tonnes;

$CS_{m,i}$ = the storage cost of 1 tonne of wheat per month in storage facility *i* in local market *m* in $;

$Sd_{m,i}$ = the storage duration of 1 tonne of wheat in storage facility *i* in the market *m* in months;

$S_{r,k}$ = the quantity of stored wheat per month in each storage facility *k* in regional location *r* in tonnes;

$CS_{r,k}$ = the storage cost of 1 tonne of wheat per month in storage facility *k* in regional location *r* in $*; and*

$Sd_{r,k}$ = the storage duration of 1 tonne of wheat storage facility *k* in the regional location, *r* in months*.*

$$SLCE = \sum_{v=1}^{V} \sum_{j=1}^{J(v)} [S_{v,j} * LS_{v,j} * Sd_{v,j} * SV] + \sum_{m=1}^{M} \sum_{i=1}^{I(m)} [S_{m,i} * LS_{m,i} * Sd_{m,i} * SV] + \sum_{r=1}^{R} \sum_{k=1}^{K(r)} [S_{r,k} * LS_{r,k} * Sd_{r,k} * SV] \quad (4\text{-}5)$$

Where,

$LS_{v,j}$ = the percentage of quantity and quality losses per month in storage facility *j* in village *v;*

$LS_{m,i}$ = the percentage of quantity and quality losses per month in storage facility *i* in local market *m; and*

$LS_{r,k}$ = the percentage of quantity and quality losses per month in storage facility *k* in regional location *r.*

Transportation Cost

The overall cost of wheat transportation in the entire network consists of: (1) the total transportation cost (TC) of wheat among new and existing storage facilities throughout the entire supply chain; and (2) the total cost of wheat losses (TCL) suffered during transportation throughout the entire supply chain, as shown in Equations (4-6) and (4-7).

$$TC = \left\{\sum_{v=1}^{V} T_v * [\sum_{v=1}^{V} \sum_{m=1}^{M} \sum_{i=1}^{I(m)} Dr_{v,m,i} * CT_{v,m} * Ds_{v,m}]\right\}$$

$$+ \left\{\sum_{r=1}^{R} T_m * [\sum_{m=1}^{M} \sum_{r=1}^{R} \sum_{k=1}^{K(r)} Dr_{m,r,k} * CT_{m,r} * Ds_{m,r}]\right\} \tag{4-6}$$

$$TCL = \left\{\sum_{v=1}^{V} T_v * [\sum_{v=1}^{V} \sum_{m=1}^{M} \sum_{i=1}^{I(m)} Dr_{v,m,i} * LT_{v,m} * Ds_{v,m} * SV]\right\}$$

$$+ \left\{\sum_{r=1}^{R} T_m * [\sum_{m=1}^{M} \sum_{r=1}^{R} \sum_{k=1}^{K(r)} Dr_{m,r,k} * LT_{m,r} * Ds_{m,r} * SV]\right\} \tag{4-7}$$

Where,

T_v = the amount of wheat transported from each village in tonnes;

$Dr_{v,m,i}$ = the percent of wheat transported from each village *v* to each storage facility *i* in local market *m*

$CT_{v,m}$ = the transportation cost of 1 tonne of wheat per mile from village *v* to the storage facility *i* in the local market *m* in $;

$DS_{v,m}$ = the distance from village *v* to the storage facility *i* in the local market *m* in miles;

T_m = the amount of wheat transported from each local market in tonnes;

$Dr_{m,r,k}$ = the percent of wheat transported from the local market *m* to storage facility *k* in regional location *r*

$CT_{m,r}$ = the transportation cost of 1 tonne of wheat per mile from local markets *m* to regional storage facility *k* in regional location *r* in $;

$DS_{m,r}$ = the distance from local markets *m* to regional storage facility *k* in regional location *r* in miles*;*

$Lt_{v,m}$ = the transportation loss of 1 tonne of wheat from village *v* to the storage facility *i* in the local market *m;*

SV = the wheat unit sales price per tonne in $; *and*

$Lt_{m,r}$ = the transportation loss of 1 tonne of wheat from local markets *m* to regional storage facility *k* in regional location *r.*

4.2.3 Model Constraints

The model is designed to consider all relevant practical constraints, including (1) construction budget constraint; (2) minimum construction capacity constraint; (3) area constraint; (4) storage capacity constraints; (5) distribution of harvested wheat constraint; and (6) distribution of transported wheat constraints.

Total Construction Budget Constraint: This constraint is formulated to insure that total construction cost of all new wheat storage facilities in all villages *v*, local markets *m*, and regional locations *r* do not exceed the total allocated budget *B* for the construction of these new facilities, as shown in Equation (4-8). This construction budget should account for the available budget for construction in the public agency and any additional long-term loans, if any, that can be obtained from other local agencies and/or international organizations such as the World Bank or the International Monetary Fund.

$$\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{v=1}^{V}\sum_{j=1}^{J(v)} CC_{v,j}^{t,c} + \sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{i=1}^{I(m)} CC_{m,i}^{t,c} + \sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{r=1}^{R}\sum_{k=1}^{K(r)} CC_{r,k}^{t,c} \leq B \quad (4\text{-}8)$$

Where,

$CC_{v,j}^{t,c}$ = the construction cost of new facility at facility *j* of type *t* and capacity *c* in village *v;*

$CC_{m,i}^{t,c}$ = the construction cost of new facility at facility *i* of type *t* and capacity *c* in local market *m;*

$CC_{r,k}^{t,c}$ = the construction cost of new facility at facility *k* of type *t* and capacity *c* in regional location *r; and*

B = the allocated budget for the construction of all new storage facilities;

Minimum Construction Capacity Constraints: The model incorporates three constraints to insure that the capacities of the newly constructed storage facilities and existing facilities exceed the minimum required capacity in all villages, local markets and regional locations, respectively, as shown in Equations (4-9) through (4-11).

$$\boldsymbol{Cv} \leq \sum_{v=1}^{V}\sum_{j=1}^{J(v)} \boldsymbol{C_{v,j}} + \sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{v=1}^{V}\sum_{j=1}^{J(v)} \boldsymbol{C_{v,j}^{t,c}} \quad (4\text{-}9)$$

$$\boldsymbol{Cm} \leq \sum_{m=1}^{M}\sum_{i=1}^{I(m)} \boldsymbol{C_{m,i}} + \sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m=1}^{M}\sum_{i=1}^{I(m)} \boldsymbol{C_{m,i}^{t,c}} \quad (4\text{-}10)$$

$$\boldsymbol{Cr} \leq \sum_{r=1}^{R} \sum_{k=1}^{K(r)} \boldsymbol{C}_{\boldsymbol{r},\boldsymbol{k}} + \sum_{t=1}^{T} \sum_{c=1}^{C} \sum_{r=1}^{R} \sum_{k=1}^{K(r)} \boldsymbol{C}_{\boldsymbol{r},\boldsymbol{k}}^{\boldsymbol{t},\boldsymbol{c}} \tag{4-11}$$

Where,

Cv = the minimum capacity required throughout all villages in tonnes;

$C_{v,j}$ = the maximum storage capacity of storage facility *j* in village *v* in tonnes;

$C_{v,j}^{t,c}$ = the maximum storage capacity of storage facility *j* of type *t* and capacity *c* in village *v* in tonnes;

Cm = the minimum capacity required throughout all local markets in tonnes;

$C_{m.i}$ = the maximum storage capacity of market facility *i* in local market, *m* in tonnes;

$C_{m,i}^{t,c}$ = the maximum storage capacity of market facility *i* of type *t* and capacity *c* in local market, *m* in tonnes;

Cr = the minimum capacity required throughout all regional locations in tonnes;

$C_{r,k}$ = the maximum storage capacity of regional facility *k* in regional location *r* in tonnes; *and*

$C_{r,k}^{t,c}$ = the maximum storage capacity of regional facility *k* of type *t* and capacity *c* in regional location *r* in tonnes.

Area Constraint: These constraints are formulated to insure that the required area for all new construction facilities at each village *v*, local market *m* and regional location *r*, does not exceed the available land areas as shown in Equations (4-12) through (4-14), respectively.

$$0 \leq \sum_{j=1}^{J} AS_{v,j}^{t,c} \leq A_v \tag{4-12}$$

$$0 \leq \sum_{i=1}^{I} AS_{m,i}^{t,c} \leq A_m \tag{4-13}$$

$$0 \leq \sum_{k=1}^{K} AS_{r,k}^{t,c} \leq A_r \tag{4-14}$$

Where,

$AS_{v,j}^{t,c}$ = the area required for the construction of a new storage type *t* and capacity *c* at facility *j* in village *v* in square feet;

A_v = the available area for the construction of a new storage facilities at village *v* in square feet;

$AS_{m,i}^{t,c}$ = the area required for the construction of a new storage type *t* and capacity *c* at facility *i* in local market *m* in square feet;

A_m = the available area for the construction of a new storage facilities at local market *m* in square feet;

$AS_{r,k}^{t,c}$ = the area required for the construction of a new storage type *t* and capacity *c* at facility *k* in regional location *r* in square feet; *and*

A_r = the available area for the construction of a new storage facilities at regional location *r* in square feet.

Storage Capacity Constraints: These constraints are imposed to ensure that the volume of stored wheat in each facility does not exceed its available storage capacity and meet any minimum storage requirements in each facility, as shown in equations (4-15) 4-15) through (4-20), respectively.

$$N_{v,j} \leq S_{v,j} \leq C_{v,j} \quad (4\text{-}15)$$

$$N_{m.i} \leq S_{m.i} \leq C_{m.i} \quad (4\text{-}16)$$

$$N_{r,k} \leq S_{r,k} \leq C_{r,k} \quad (4\text{-}17)$$

$$N_{v,j} \leq NS_{v,i}^{t,c} \leq C_{v,j}^{t,c} \quad (4\text{-}18)$$

$$N_{m.i} \leq NS_{m,i}^{t,c} \leq C_{m,i}^{t,c} \quad (4\text{-}19)$$

$$N_{r,k} \leq NS_{r,k}^{t,c} \leq C_{r,k}^{t,c} \quad (4\text{-}20)$$

Where,

$N_{v,j}$ = the minimum storage requirement of facility *j* in village *v* in tonnes*;*

$N_{m.i}$ = the minimum storage requirement of facility *i* in local market m in tonnes; and

$N_{r,k}$ = the minimum storage requirement of facility *k* in regional location r in tonnes.

Distribution of Harvested Wheat Constraint: These two constraints are formulated to ensure that (1) the harvested wheat in each village $\mathrm{H_v}$ will be distributed over the amount stored in each village storage $S_{v,j}$ and $NS_{v,j}$ and the amount of wheat transported from each village $\mathrm{T_v}$, as shown in Equation (4-21); and (2) the harvested wheat from all villages, at any given time, will be distributed over the storage facilities throughout the network while also considering the losses suffered during the transportation between the facilities, as shown in Equation (4-22).

$$H_v = (S_{v,j} + NS_{v,i}^{t,c}) + T_v \quad (4\text{-}21)$$

$$\sum_{v=1}^{V} H_v = \sum_{v=1}^{V}\sum_{j=1}^{J(v)} (S_{v,j} + NS_{v,i}^{t,c}) + \sum_{m=1}^{M}\sum_{i=1}^{I(m)} (S_{m,i} + NS_{m,i}^{t,c}) + \sum_{r=1}^{R}\sum_{k=1}^{K(r)} (S_{r,k} + NS_{r,k}^{t,c}) + [\sum_{v=1}^{V} T_v * [\sum_{m=1}^{M} LT_{v,m}]] + [\sum_{m=1}^{M} T_m * [\sum_{m=1}^{M}\sum_{r=1}^{R} LT_{m,r}]] \quad (4\text{-}22)$$

Distribution of Transported Wheat Constraints: These three constraints are formulated to ensure that (1) the transported wheat from each village will be distributed over the local market facilities based on their distribution ratios and the summation of these ratios is equal to one, as shown in Equation(4-23); (2) the transported wheat from each local market will be distributed over the regional facilities based on their distribution ratios and the summation of these ratios is equal to one, as shown in Equation (4-24); (3) the total transported wheat from each local market $\mathrm{T_m}$ is equal to the amount of wheat transported to that market from all villages minus the amount of wheat lost in transportation from the villages to the local market as well as the amount of wheat stored in the local market, as shown in Equation (4-25); and (4) the total transported wheat to each regional location is equal to the amount of wheat transported to that regional location from all local markets minus the amount of wheat lost in transportation from the local markets to the regional location, as shown in Equation (4-26).

$$\sum_{m=1}^{M} \sum_{i=1}^{I(m)} [\, Dr_{v,m,i}] = 1 \tag{4-23}$$

$$\sum_{r=1}^{R} \sum_{k=1}^{K(r)} [\, Dr_{m,r,k}] = 1 \tag{4-24}$$

$$T_m = [\sum_{v=1}^{V} (T_v * \sum_{i=1}^{I(m)} Dr_{v,m,i})] * [1 - \sum_{v=1}^{V} LT_{v,m}] - \sum_{i=1}^{I(m)} (S_{m,i} + NS_{m,i}^{t,c}) \tag{4-25}$$

$$\sum_{i=1}^{I(m)} (S_{r,k} + NS_{r,k}^{t,c}) = [\sum_{m=1}^{M} (T_m * \sum_{i=1}^{I(m)} Dr_{m,r,k})] * [1 - \sum_{m=1}^{M} LT_{m,r}] \tag{4-26}$$

4.3 Implementation Phase

To enable the model to optimize the construction of new public storage facilities and to identify the minimal cost and losses, integer programming was used to perform the optimization computations of the aforementioned formulated model. The implementation of the model is accomplished in three main stages: (1) the input of all relevant data and the initialization of the integer programming process; (2) the optimization computations that identifies the optimal location, type and capacity of new storage facilities and generates minimal total cost of wheat storage and transportation utilizing a newly developed wheat storage facilities database; and (3) the output of the optimization results.

4.3.1 Input Data

The required input data in the present model consists of (a) new storage facilities data, (b) existing storage facilities data, and (c) wheat transportation data. First, the new storage facilities input data includes (1) available locations for constructing the new storage facilities in villages (V), local markets (M), and regional location (R), as shown in Figure 4.3; (2) the available land area for the construction of a new storage facility, if any, in each village (A_v), local market (A_m) and regional location (A_r); and (3) the minimum capacity required by the construction of new storage facilities in each village *(Cv)*, local market *(Cm)* and regional location*(Cr)*; and (4) the maximum budget (*B*) allocated to the construction of these new storage facilities, as shown in Tables 4.2, 4.3, and 4.4.

Second, the input data for existing storage facilities includes (1) harvested quantities (H_v) in each village; and (2) wheat sales value (*SV)*; (3) number of exiting storage locations in villages (V), local markets (M), and regional locations (R); (4) number of storage facilities in each village (J), local market (I), and each regional location (K), as shown in Figure

4.3; (5) storage cost rate in each village ($CS_{v,j}$), local market facility ($CS_{m,i}$), and regional location ($CS_{r,k}$); (6) storage losses rate in each village ($LS_{v.j}$), local market facility ($LS_{m,i}$), and regional location ($LS_{r,k}$); (7) storage capacity in each village (C_v), local market facility ($C_{m.i}$) and regional location ($C_{r,k}$); and (8) storage duration in each village (Sd_v), local market facility ($Sd_{m,i}$), regional location ($Sd_{r,k}$), as shown in Tables 4.2 to 4.4.

Third, the wheat transportation input data includes (1) transportation cost rates from each village to each local market ($CT_{v,m}$) and from each local market to each regional location ($CT_{m,r}$); (2) wheat loss rates during the transportation from each village to each local market ($LT_{v,m}$) and from each local market to each regional location ($LT_{m,r}$); and (3) transportation distance from each village to each local market ($Ds_{v,m}$) and from each local market to each regional location ($Ds_{m,r}$), as shown in Table 4.5.

4.3.2 Optimization Computations and Storage Database

The optimization computations of the model use the aforementioned input data to optimize the construction of new public wheat storage facilities as well as optimizing wheat storage and transportation throughout the entire network of existing and new storage facilities. The optimization computations also utilize a newly developed database that contains required storage facilities data in villages, local markets, and regional locations including: (1) facility type (t); (2) capacity of each facility (C); (3) cost of constructing each facility ($CC^{t,c}$); (4) required facility area ($AS^{t,c}$); (5) storage cost rate($CS^{t,c}$); and (6) storage loss rate ($LS^{t,c}$), as shown in the sample data in Table 4.6.

4.3.3 Output Data

Upon the completion of the aforementioned optimization computations, the model generates an optimal solution for the construction of new public wheat storage facilities as well as an optimal solution for wheat storage and transportation throughout the entire network. As shown in Figure 4.1, the optimization results generated by the present model includes: (1) optimal construction decisions for new wheat storage facilities, including their location in each village (*v*), local market *(m)* and regional location *(r)*, as well as their type (*t*) and capacity (*c*); (2) optimal storage decisions for new and existing facilities in each storage facility *j* in village *v* ($NS_{v,j}^{t,c}$, $S_{v,j}$), in each storage facility *i* in local market *m* ($NS_{m,i}^{t,c}$, $S_{m,i}$) and in each storage facility *k* in regional location *r* ($NS_{r,k}^{t,c}$, $S_{r,k}$); and (3) optimal wheat transportation decisions from each village *v* to each storage facility *i* in local market *m* ($Dr_{v,m,i}$), and from each local market *m* to each regional storage facility *k* in regional location *r* ($Dr_{m,r,k}$). Moreover, the model identifies minimum total cost of wheat storage and transportation cost throughout the network that consists of: (a) total storage cost throughout the entire network in all new and existing facilities; (b) total storage losses costs in all new and existing storage facilities; (c) total transportation cost; and (d) total transportation losses costs, as shown in Figures 4.4 and 4.5.

4.4 Evaluation Phase

A case study is analyzed to illustrate the use of the developed model and demonstrate its unique capabilities in optimizing the construction of new public wheat storage facilities as well as optimizing wheat storage and transportation throughout the entire network of new and existing storage facilities. The case study involves optimizing the construction of new storage facilities in the district of Rohtak in the state of Haryana, India. The case study focuses on optimizing the construction decisions for new storage facilities in 15 villages, 5 local markets and 5 regional locations, as shown in Figure 4.4. This example covers a geographical area that includes 15 existing villages, 3 existing local markets and 3 existing regional locations that can be expanded to include 2 additional local markets and 2 additional regional locations, as shown in Figure 4.4 that represents the geographical locations of the villages in blue, local markets in red, and regional locations in green. The total harvested volume in this example is assumed to be 105,000 tonnes of wheat, while the total available existing storage capacity in the network was assumed to be 76,500 tonnes. The maximum available budget for the construction of new storage facilities is assumed to be $4 million, while the minimum capacity requirements is assumed to be 30,000 tonnes for all villages (Cv), 30,000 tonnes for all local markets (Cm), and 39,000 tonnes for all regional locations (Cr).

The input data for this application example was gathered from several sources including the Government of India, Food Corporation of India, Haryana Food and Supplies Department, Haryana Warehousing Cooperation and Haryana State Agricultural Marketing Board (FCI 2013; Food and Feed Grain Institute 1991; Food and Feed Grain Institute 1989; Government of India 2002; HAFED 2013; HF&SD 2013; HSAMB 2013; HWC 2013; Kiruba et. Al 2006; and Joshi 2002; Mott Macdonald 2013). The input data includes (1) new facilities data; (2) existing facilities data; and (3) transportation data. The new facilities data includes the available locations for the construction new storage facilities in villages, local market, and regional locations (*V, M, R*) and their areas(A_v,A_m, A_r), as shown in Tables 4.2 to 4.4. The new facilities data also includes the type (t) of each new storage facility alternative, as well as its capacity (c), construction cost ($CC^{t,c}$), required area($AS^{t,c}$), storage cost rate ($CS^{t,c}$), and storage loss rate ($LS^{t,c}$), as shown in the sample database in Table 4.6.

The existing facilities data includes the harvested quantities (H_v), which is assumed to be 7,000 tonnes in each village and wheat sales value (*SV),* which is assumed to be 100 $/t. The existing facilities data also includes the storage cost rate in each exiting storage facility ($CS_{v,j}$, $CS_{m,i}, CS_{r,k}$), as well as its storage loss rate ($LS_{v.j}, LS_{m,i}, LS_{r,k}$) and capacity ($C_v$, $C_{m.i}$, $C_{r,k}$) , as shown in Tables 4.2 to 4.4. The transportation data includes the ranges of the transportation cost rates ($CT_{v,m}, CT_{m,r}$), losses rates ($LT_{v,m}, LT_{m,r}$), and distances ($Ds_{v,m}, Ds_{m,r}$) which are summarized in Table 4.5.

Table 4.2 Input Data for New and Existing Storage Facilities in Villages

Location	New Storage Facilities		Existing Storage Facilities		
	Available Site for New Construction (Yes/No)	Available Area For New Construction (SF)	Storage Cost Rates ($/t*month)	Storage Loss Rates (% Loss/t*month)	Capacity (t)
		A_v	$CS_{v,j}$	$LS_{v,j}$	$C_{v,j}$
V1	Yes	25,000	0.20	2.0	1,000
V2	Yes	10,000	0.18	3.0	1,000
V3	Yes	14,000	0.22	2.0	1,000
V4	Yes	25,000	0.16	3.0	1,000
V5	Yes	14,000	0.20	2.0	1,000
V6	Yes	10,000	0.16	3.0	1,000
V7	Yes	25,000	0.20	2.0	1,000
V8	Yes	14,000	0.20	2.0	1,000
V9	Yes	8,000	0.16	3.0	1,000
V10	Yes	20,000	0.20	2.0	1,000
V11	Yes	14,000	0.16	3.0	1,000
V12	Yes	5,000	0.20	2.0	1,000
V13	Yes	25,000	0.16	3.0	1,000
V14	Yes	5,000	0.20	2.0	1,000
V15	Yes	25,000	0.16	3.0	1,000
Total		239,000			15,000

Table 4.3 Input Data for New and Existing Storage Facilities in Local Markets

Location	New Storage Facilities		Existing Storage Facilities		
	Available Site for New Construction	Available Area For New Construction	Storage Cost Rates	Storage Loss Rates	Capacity
	(Yes/No)	(SF)	($/t*month)	(% Loss/t*month)	(t)
		A_m	$CS_{m,i}$	$LS_{m,i}$	$C_{m,i}$
M1	Yes	25,000	1.00	1.5	12,500
M2	Yes	25,000	0.80	2.0	5,000
M3	Yes	25,000	1.00	1.5	5,000
M4	Yes	60,000	-	-	-
M5	Yes	60,000	-	-	-
Total		175,000			22,500

Table 4.4 Input Data for New and Existing Storage Facilities in Regional Locations

Location	New Storage Facilities		Existing Storage Facilities		
	Available Site for New Construction	Available Area For New Construction	Storage Cost Rates	Storage Loss Rates	Capacity
	(Yes/No)	(SF)	($/t*month)	(% Loss/t*month)	(t)
		A_r	$CS_{r,k}$	$LS_{r,k}$	$C_{r,k}$
R1	Yes	45,000	1.20	1.5	16,000
R2	Yes	45,000	1.20	1.5	9,000
R3	Yes	45,000	1.10	1.2	14,000
R4	Yes	70,000	-	-	-
R5	Yes	70,000	-	-	-
Total		275,000			39,000

Table 4.5 Transportation Data between Existing Villages, Local Markets and Regional Locations

Transportation Route	Range of Transportation Cost Rates ($/ t*mile)		Range of Transportation Loss Rates (% of Loss/ t*mile)		Range of Distances (miles)	
	Min	Max	Min	Max	Min	Max
Village to Local Market (v,m)	$CT_{v,m}$		$LT_{v,m}$		$Ds_{v,m}$	
	0.16	0.20	0.10	0.13	0.0	45.3
Local Market to Regional Location (m,r)	$CT_{m,r}$		$LT_{m,r}$		$Ds_{m,r}$	
	0.40	0.60	0.20	0.30	0.0	37.0

Table 4.6 Sample of the Storage Facilities Database for Local Markets

Number	Facility Type	Capacity (t)	Construction Cost ($)	Required Area (SF)	Storage Cost Rate ($/ t*month)	Storage Loss Rate (% Loss/t*month)
f_m	t	c	$CC^{t,c}$	$AS^{t,c}$	$CS^{t,c}$	$LS^{t,c}$
1	Godown Warehouse	1,000	80,000	6,000	1.2	1
2	Godown Warehouse	2,000	150,000	12,000	1.2	1
3	Godown Warehouse	3,000	200,000	16,000	1.2	1
4	Godown Warehouse	5,000	360,000	30,000	1.2	1
5	Godown Warehouse	10,000	700,000	60,000	1.2	1
6	CAP	300	4,800	1,800	0.8	2.5
7	CAP	500	8,000	3,000	0.8	2.5
8	CAP	1,000	16,000	6,000	0.8	2.5
9	CAP	3,000	48,000	18,000	0.8	2.5
10	CAP	5,000	80,000	30,000	0.8	2.5
11	CAP	10,000	260,000	60,000	0.8	2.5
12	Steel Silo	1,000	120,000	3,000	1.15	0.5
13	Steel Silo	3,000	360,000	9,000	1.15	0.5
14	Steel Silo	5,000	600,000	15,000	1.15	0.5
15	Steel Silo	10,000	1,200,000	30,000	1.15	0.5

The aforementioned input data along with the storage facilities database were analyzed by the developed model to optimize the construction of new storage facilities in order to minimize the losses and cost of wheat storage and transportation throughout the entire network. The generated optimal decisions for this case study include: (1) optimal construction decisions for new wheat storage facilities that specify their optimal location in each village, local market and regional location, as well as their optimal type and capacity; (2) optimal storage decisions for new and existing facilities in each village, local market and regional location; and (3) optimal wheat transportation decisions, as shown in the sample optimal results in Figure 4.4. These generated optimal decisions produced a minimum total wheat storage and transportation cost of $941,000 throughout the entire network, as shown in Figure 4.4. This generated minimum total cost consists of: (a) total storage cost in all new and existing facilities; (b) total storage losses costs in all new and existing storage facilities; (c) total transportation cost; and (d) total transportation losses costs throughout the network, as shown in Figures 4.4 and 4.5.

A sample of the generated optimal location, type and capacity for new storage facilities is shown in Figure 4.4. For example, a new steel silo storage facility with a capacity of 3,000 tonnes was identified as the optimal selection for village V6 with a total construction cost of $360,000. Similarly, the optimal decision for local market location M5 recommended the construction of a CAP facility with a capacity of 10,000 tonnes at a cost of $160,000, while the optimal decision for regional location R3 recommended no new construction. The generated optimal results provide an additional 47,000 tonnes of new wheat capacity over the existing 76,500 tonnes in order to provide adequate storage for all the harvested wheat while keeping total wheat storage and transportation cost to a minimum. This increase in capacity supports the minimum capacity requirements at the village, local market and regional locations. Moreover, the increase in capacity provides extra storage capacity for possible future production increases and grain reserves.

The generated optimal solution also produced a reduction in wheat storage losses and cost throughout the entire network because of the lower storage losses rate of $3.3/t in the new storage facilities compared to the $5.1/t in existing facilities. This produced an overall rate of wheat storage losses of $4.3/t in the entire network of new and existing facilities, as shown in Figure 4.4. The optimal results also show that the construction of new facilities increased the storage cost rate from $2.5/t in existing facilities to $2.8/t in the entire network of new and existing facilities, as shown in Figure 4.4. Despite this increase in the storage cost rate, the optimal construction of new storage facilities was able to reduce the total storage and losses cost rates from $7.6/t in existing facilities to

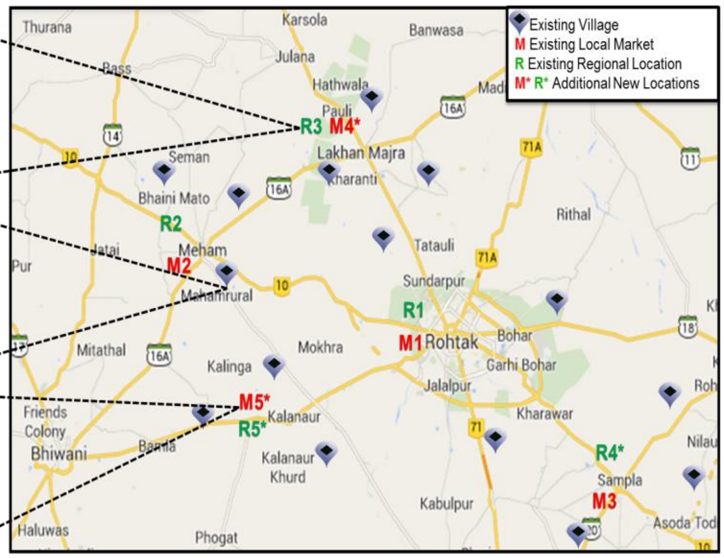
$7.1/t in the entire network of new and existing facilities, as shown in Figure 4.4. Accordingly, the construction of the new storage facilities was able to 870 tonnes of wheat from storage losses throughout the entire network with an average savings rate of 1% of the total stored wheat. The total optimal transportation results were also minimized to identify the least transportation cost and loss routes, as shown in Figure 4.4. A detailed summary of the results are presented in Appendix III-1 and III-2.

Sample Optimal Construction Decisions for New Storage Facilities

Location: R3	
Facility Type	-
Capacity (t)	-
Construction Cost ($)	-
Existing Capacity (t)	14,000

Location: V6	
Facility Type	1 Steel Silo
Capacity (t)	3,000
Construction Cost ($)	360,000
Existing Capacity (t)	1,000

Location: M5	
Facility Type	1 CAP
Capacity (t)	10,000
Construction Cost ($)	160,000
Existing Capacity (t)	-



Optimal New & Existing Storage Facility Decisions

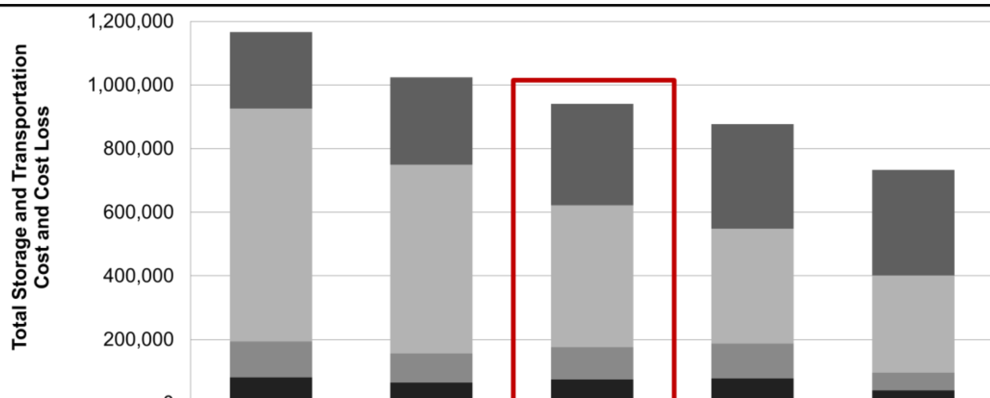
Location	Capacity		Wheat Stored		Construction Cost	Storage Cost Rate			Storage Loss Rate			Total Storage Cost & Loss Rate		
	Existing Facilities	New Facilities	Existing Facilities	New Facilities		Existing Facilities	New Facilities	Existing & New Facilities	Existing Facilities	New Facilities	Existing & New Facilities	Existing Facilities	New Facilities	Existing & New Facilities
	(t)	(t)	(t)	(t)	($)	($/t)	($/t)	($/t)	($/t)	($/t)	($/t)	($/t)	($/t)	($/t)
M1	12,500	3,000	7,936	2,984	200,000	3	3.6	3.2	4.5	3.0	4.1	7.5	6.6	7.2
M2	5,000	3,000	2,844	3,000	200,000	2.4	3.6	3.0	6	3.0	4.5	8.4	6.6	7.4
M3	5,000	6,000	5,000	5,950	560,000	3	3.5	3.3	4.5	2.2	3.3	7.5	5.7	6.5
M4	-	0	-	0	0	-	-	-	-	-	-	-	-	-
M5	-	10,000	-	10,000	160,000	-	2.4	-	-	7.5	-	-	9.9	-
R1	16,000	0	3,632	0	0	3.6	-	3.6	4.5	-	4.5	-	-	-
R2	9,000	0	8,984	0	0	3.6	-	3.6	4.5	-	4.5	-	-	-
R3	14,000	0	13,875	0	0	3.3	-	3.3	3.6	-	3.6	-	-	-
R4	-	0	-	0	0	-	-	-	-	-	-	-	-	-
R5	-	0	-	0	0	-	-	-	-	-	-	-	-	-
Total Village	**15,000**	**25,000**	**15,000**	**25,000**	**2,880,000**	**0.5**	**3.3**	**2.28**	**7.4**	**1.9**	**3.9**	**8.0**	**5.2**	**6.2**
Total Local Market	**22,500**	**22,000**	**15,780**	**21,934**	**1,120,000**	**2.9**	**3.0**	**2.97**	**4.8**	**4.8**	**4.8**	**7.7**	**7.9**	**7.8**
Total Regional Location	**39,000**	**0**	**26,491**	**0**	**0**	**3.4**	**-**	**3.44**	**4.0**	**-**	**4.0**	**7.5**	**-**	**7.5**
Total	**76,500**	**47,000**	**57,271**	**46,934**	**4,000,000**	**2.5**	**3.2**	**2.83**	**5.1**	**3.3**	**4.3**	**7.6**	**6.4**	**7.1**

Optimal Transportation Decisions

	Total Transported Volumes Before Losses (t)	Transportation Losses (t)	Transportation Losses (%)
Total Villages to Local Markets	65,000	570	0.88%
Total Local Markets to Regional Locations	26,666	174	0.65%
Total	91,666	744	0.81%

Figure 4.4 Optimal Solution for $4 million Construction Budget

In order to evaluate the sensitivity of the optimization results to variation in the construction budget constraint, the case study was analyzed under varying construction budgets including 1, 2, 4, 6, and 8 million dollars, as shown in Figure 4.5. The results of this sensitivity analysis show that increasing the construction budget leads to a decrease in wheat storage losses cost, as shown in Figure 4.5. The reason for this is that lower construction budgets limits the selection of new storage facilities to the less expensive and less effective storage types (e.g., CAP) that typically have higher wheat storage losses rates. On the other hand, the availability of higher construction budgets enables the selection of more effective and more expensive storage types (e.g. Godown, Steel Silo) that have lower storage losses rates. A detailed summary of the sensitivity analysis results are presented in Appendix III-3.



Budget	1,000,000	2,000,000	4,000,000	6,000,000	8,000,000
Total Exisitng and New Storage Cost	240,863	274,849	318,733	327,393	332,055
Total Exisitng and New Sorage Loss Cost	731,737	593,341	445,802	362,471	305,685
Total Transportation Cost	111,697	91,006	102,281	108,169	55,043
Total Transportation Loss Cost	81,799	64,765	74,457	78,610	40,447

Figure 4.5 Optimal New Public Facility Optimization Result

The aforementioned optimization results illustrate the novel and unique capabilities of the developed model in (1) identifying optimal construction decisions for new public wheat storage facilities; (2) considering and minimizing all wheat storage and transportation costs throughout the network; and (3) considering and minimizing wheat quantity and quality losses that can be suffered during storage and transportation. The results of the case study also illustrate the benefits that can be gained from optimizing the construction of new public storage facilities including (a) improved protection of the stored crops by reducing their storage losses; (b) enhanced food security for local farmers by increasing the storage capacity available in their villages; (c) expanded storage capacity for grain reserves and for potential increases in wheat production.

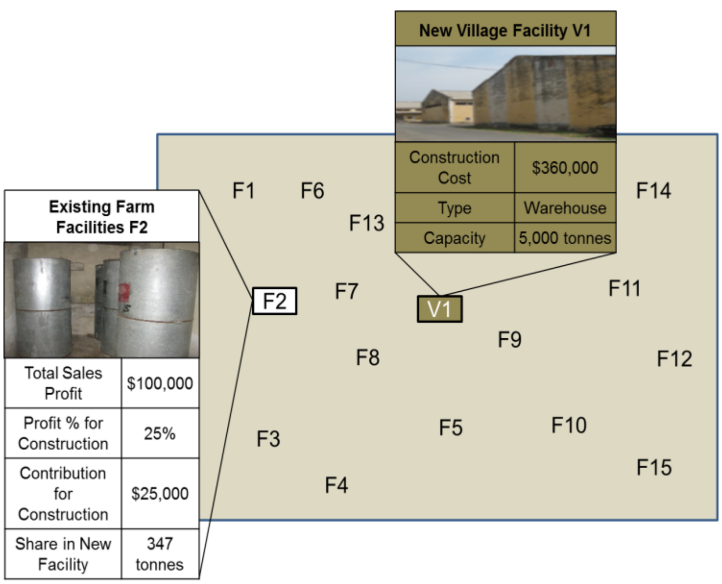
4.5 Summary

This chapter presented the development of a novel optimization model that provides the capability of optimizing the construction of public wheat storage facilities as well as optimizing wheat storage and transportation throughout the entire network of new and existing storage facilities. The model is designed to minimize the losses and cost of wheat storage and transportation. The optimization model is developed in three main phases: formulation phase that defines the model decision variables, objective function, and constraints; implementation phase that executes the optimization computations using integer programming; and an evaluation phase that analyzes the model performance using a case study. The analysis results of the case study illustrated the novel and unique capabilities of the developed model in optimizing the construction decisions of new storage facilities. These new and innovative research developments will enable government planners to identify the optimal location, type, and capacity of new wheat storage facilities that minimize wheat storage and transportation losses and costs throughout the entire supply chain. The primary contribution of this research include the development of a novel optimization model for the construction of new wheat storage facilities that is uniquely capable of (1) considering the impact of existing storage facilities on the optimization results, and (2) quantifying and minimizing the cost of wheat losses during storage and transportation.

5 OPTIMIZING THE CONSTRUCTION OF PRIVATE WHEAT STORAGE FACILITIES

5.1 Introduction

The objective of this chapter is to present the development of a novel model for optimizing (a) the construction of private wheat storage facilities to provide additional storage capacity for all participating farms, and (b) the utilization of existing and new wheat storage in order to maximize the profitability of farmers, as shown in Figure 5.1. The optimization model enables a cooperative approach that allows each farmer to contribute a percentage of the annual wheat sales profit to build a new village storage facility that can be shared by all participating farmers. The share of each farmer in this new storage facility depends on his/her contribution to the overall cost of the new facility, as shown in Figure 5.1.



Farms	Total Sales Profit ($)	Profit Percentage for Construction (%)	Contribution for Construction ($)	Share of Storage Capacity in New Facility (t)
1	200,000	20	40,000	555
2	100,000	25	25,000	347
3	150,000	30	45,000	625
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
15	50,000	30	15,000	208
Total	1,000,000		360,000	5000

Figure 5.1 New Private Village Facility Construction

The optimization model can be applied at the beginning of the first year to optimize the monthly wheat sales and storage quantities in existing farm storage facilities in order to maximize the profit generated from wheat sales. The generated profits from wheat sales in the first year can then be used to build shared private facilities during the second year. This assumes that the construction duration of this type of private village storage facilities is up to a year (Mott Macdonald 2013). Accordingly, these new private village storage facilities can start to be utilized and provide additional storage capacity after the next harvest time at the beginning of the third year. The same cycle can also be repeated for future years to expand storage capacity for all participating farmers. For example, the profit generated from the second year can be used to build new private village facilities during the third year that can then be used at the beginning of the fourth year, as shown in Figure 5.2. The repetition of this cycle can continue to provide additional village storage capacity for all participating farmers until they reach their desired storage capacity, as shown in Figure 5.2.

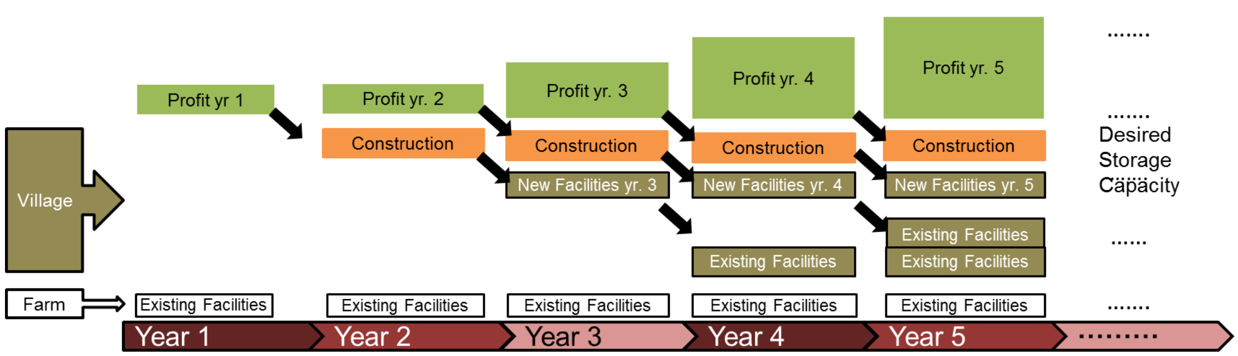


Figure 5.2 New Private Facility Construction Timeline

To enable the optimization of wheat storage decisions before and after the construction of new private village storage facilities, the optimization model is designed to cover two phases: pre-construction phase, and post-construction phase. The pre-construction phase model seeks to optimize the monthly storage and sale of wheat in existing farm facilities during the first year, as shown in Figure 5.3. The post-construction phase model utilizes the profits generated from the sales of wheat during the pre-construction phase for the construction of new private village storage facilities to provide additional storage capacity for all participating farms. Moreover, the post-construction model seeks to optimize the monthly wheat sales and storage quantities in existing farm facilities and new village facilities after the completion of their construction during the third and subsequent years, as shown in Figure 5.3.

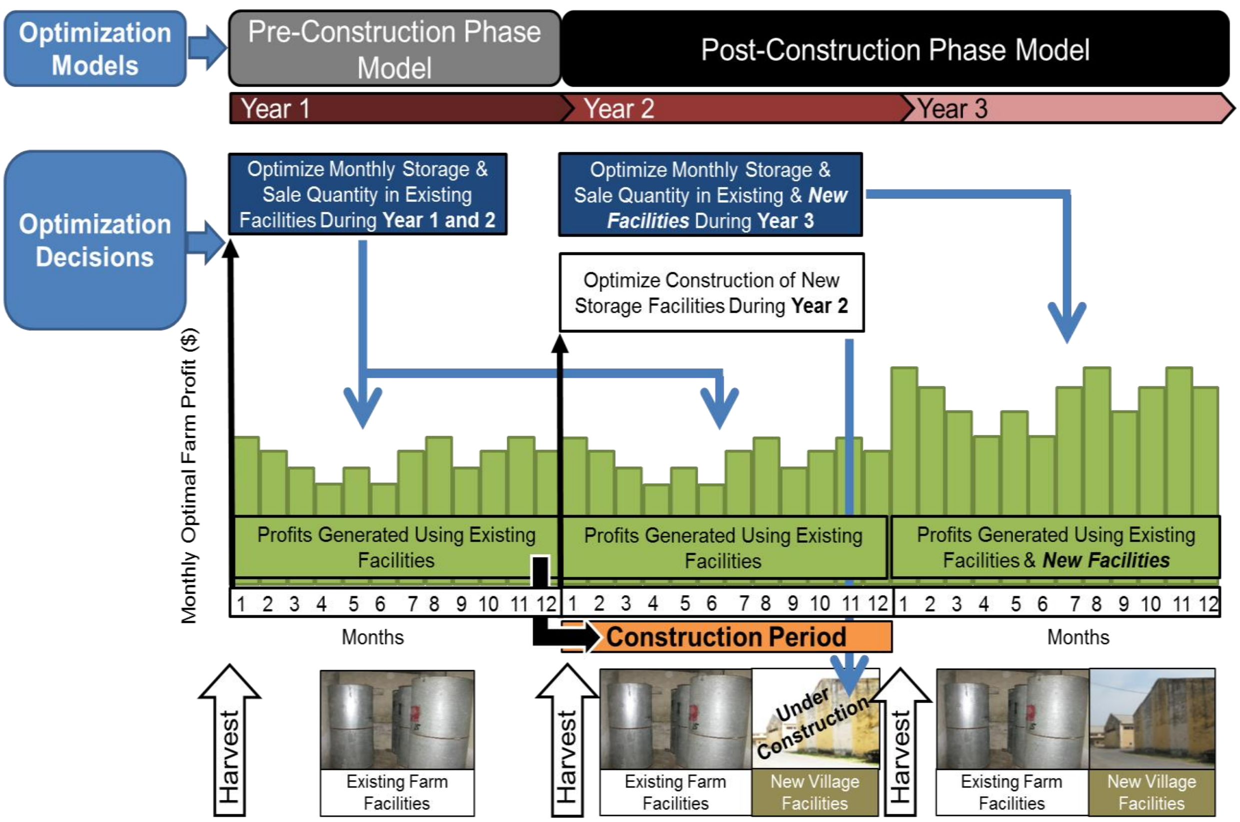


Figure 5.3 Optimization Models

Each of the pre-construction and post-construction phase models is developed in four main steps that focus on: defining the model decision variables, formulating the optimization objective function, modeling the optimization problem constraints, and implementing the model using genetic algorithms. The following sections provide a brief description of (1) development of the pre-construction phase model, (2) development of the post-construction phase model, and (3) a case study to illustrate the use of the two models and evaluate their performance, as shown in Figure 5.4.

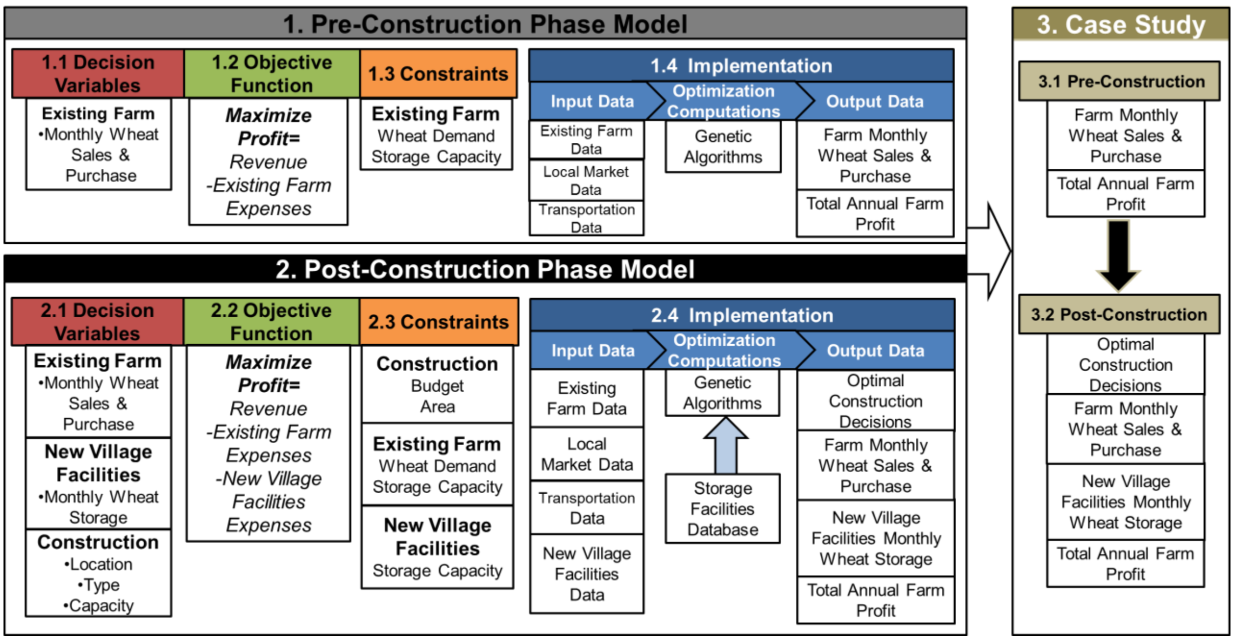


Figure 5.4 Optimization Model Development Phases

5.2 Pre-Construction Phase Model

5.2.1 Decision Variables

The pre-construction phase model is designed to identify all relevant decision variables. The identified set of decision variables are designed to optimize monthly wheat sales from each farm and/or monthly wheat purchases from each local market. Accordingly, the decision variables in this model consist of (a) quantity of monthly wheat sales at the beginning of each month *d* from farm *f* to local market *m* in tonnes, ($S_{f,m}^{d}$), and (b) quantity of monthly wheat purchases at the beginning of each month *d* from local market *m* to farm *f* in tonnes ($B^{d}_{f,m}$), as shown in Figure 5.5.

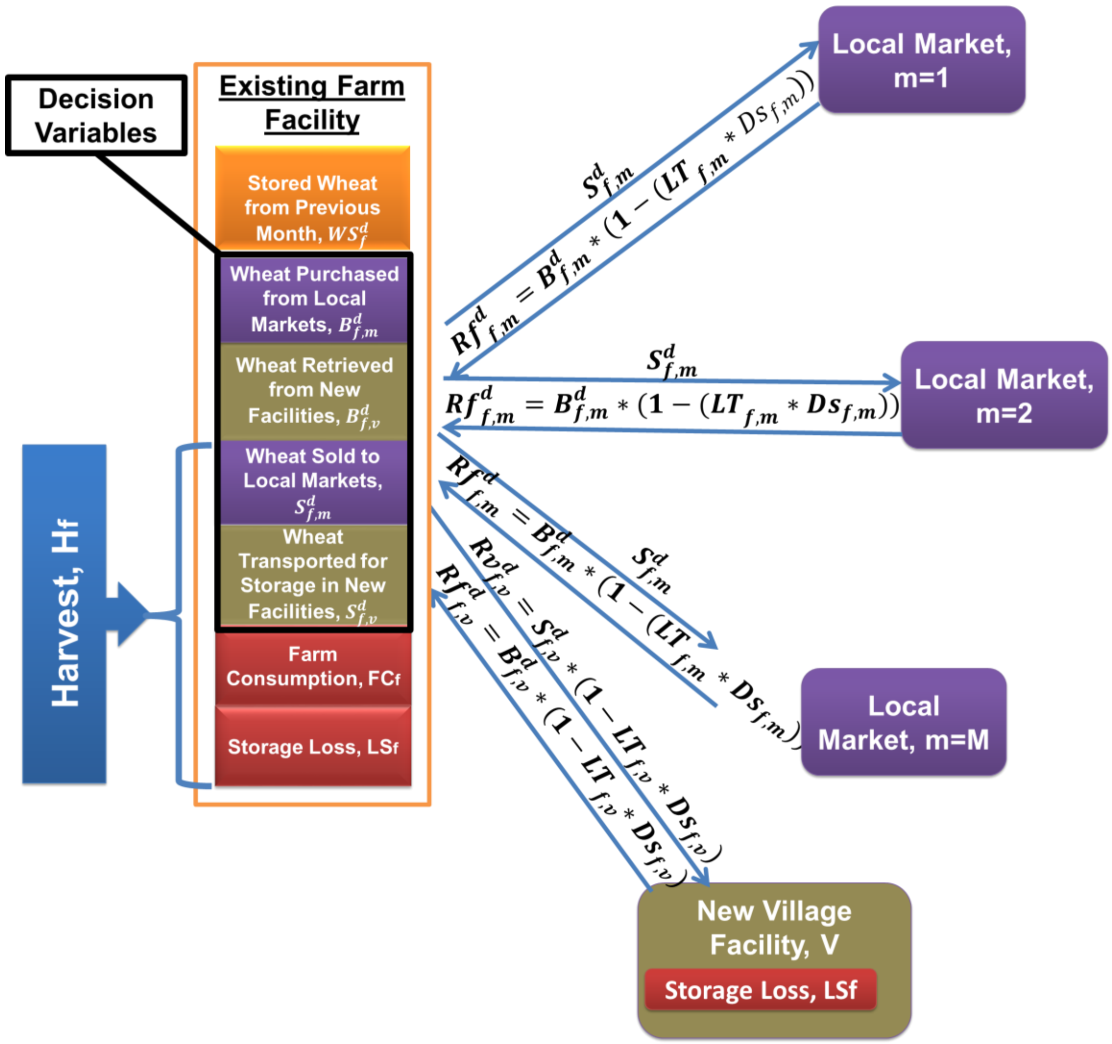


Figure 5.5 Decision Variables

5.2.2 Objective Function

The pre-construction phase model is designed to maximize the total profit of each farmer from the sale wheat from farm *f* to all local markets (*m=1, M*). Accordingly, the objective function of this model seeks to maximize the pre-construction annual profit (PeP_f) using Equation (5-1) that calculates the difference between: (a) the annual revenues generated by each farmer $(Revenue_f)$ from the monthly sales of wheat to all local markets as shown in Equation (5-2); and (b) the annual expenses ($Farm\ Expenses_f$) incurred from the monthly storage cost of wheat at farm *f*; the monthly purchase cost of wheat from local markets, if any, to cover potential wheat shortages; and the transportation costs from local markets (*m=1, M),* as shown in Equation (5-3).

$$Maximize\ Profit\ (PeP_f) = Revenue_f - Farm\ Expenses_f \tag{5-1}$$

$$Revenue_f = \sum_{d=1}^{12} \sum_{m=1}^{M} S_{f,m}^{d} * SV_m^d \tag{5-2}$$

$$\begin{aligned} Farm\ Expenses_f = \sum_{d=1}^{D} \sum_{m=1}^{M} \left[CS_f * (WS_f^d + Rf_{f,m}^d - S_{f,m}^d)\right] \\ + \left[B_{f,m}^d * BV_m^d\right] + \left[(B_{f,m}^d + S_{f,m}^d) * (CT_{f,m} * Ds_{f,m})\right] \end{aligned} \tag{5-3}$$

$$WS_f^d = (1 - LS_f) * (WS_f^{d-1} + \sum_{m=1}^{M} Rf_{f,m}^{d-1} - \sum_{m=1}^{M} S_{f,m}^{d-1}) - FC_f \tag{5-4}$$

$$Rf_{f,m}^d = B_{f,m}^d * (1 - (LT_{f,m} * Ds_{f,m})) \tag{5-5}$$

Where,

$S_{f,m}^d$ = quantity of wheat sales at the beginning of month d from farm f to local market m in tonnes;

SV_m^d = sales price of wheat at month d at local market m in $;

CS_f = storage cost of 1 tonne of wheat per month at farm f in $ per tonnes;

WS_f^d = quantity of wheat stored at the start of month *d* at farm *f* in tonnes, as shown in Equation (5-4);

CS_f =storage cost of 1 tonne of wheat per month at farm *f*;

WS_f^d =quantity of wheat stored in tonnes at the start of month *d* at farm *f*, as shown in Equation (5-4);

$Rf_{f,m}^d$ = quantity of wheat received in farm f in month d from the local market m after considering transportation losses in tonnes, as shown in Equation (5-5);

$B_{f,m}^d$ = quantity of wheat purchases at the beginning of month d from local market m to farm f in tonnes;

BV_m^d = purchase price of wheat in month d at local market m in $;

$CT_{f,m}$ = transportation cost of 1 tonne of wheat per mile between farm f and local market m in $/tonne per mile;

$Ds_{f,m}$ =distance between farm f and local market m in miles;

LS_f =percentage of wheat storage losses per month in farm f in % per tonnes; and

FC_f =monthly consumption of wheat at farm *f* in tonnes.

5.2.3 Constraints

The pre-construction phase model is designed to consider relevant practical constraints, including farm wheat demand constraint and farm capacity constraint.

Farm Wheat Demand Constraint: This constraint is imposed to insure that at the end of each month d at farm f, the stored wheat exceeds the minimum storage requirement as shown in Equation (5-6). In this constraint, the calculation of the quantity of stored wheat at the end of each month d at farm f considers the percentage of monthly storage losses, the stored quantity at the beginning of the month, the monthly purchased quantity, the monthly sold quantity, and monthly farm consumption (see Equation 5-6).

$$(1 - LS_f) * (WS_f^d + \sum_{m=1}^{M} B_{f,m}^d - \sum_{m=1}^{M} S_{f,m}^d) - FC_f \geq MC_f \qquad (5\text{-}6)$$

Where, MC_f is the minimum storage requirement of wheat at farm *f* in tonnes.

Farm Storage Capacity Constraint: This constraint is imposed to insure that at the start of each month d at farm f after all wheat sales and purchases, the stored wheat does not exceed the storage capacity, as shown in Equation (5-7).

$$C_f \geq WS_f^d + \sum_{m=1}^{M} Rf_{f,m}^d - \sum_{m=1}^{M} S_{f,m}^d \qquad (5\text{-}7)$$

Where, C_f is the available storage capacity of farm *f* in tonnes.

5.2.4 Implementation

The pre-construction phase model was implemented using genetic algorithms (GA) due to its capability of modeling non-linearity in the objective function and constraints that exist in the present model, and identifying near optimal solutions in a reasonable computational time (Goldberg 1989; Greenhalgh and Marshall 2000; Pendharkar and Koehler 2007).

The model implementation is accomplished in three main stages: (1) the input of all relevant data and the initialization of the genetic algorithm process, (2) the optimization computations that are executed using genetic algorithms, and (3) the output of the optimization results that identifies the optimal monthly storage quantities and sales that maximize the profit of each farmer. The required input data in the present model consists of farm data, local market data and transportation data, as shown in Table 5.1. The optimization computations of the model use this input data to optimize monthly storage and sale quantity in existing farm facilities to maximize farmer profitability. Upon the completion of the optimization computations, the model generates an optimal solution that is summarized in Table 5.1.

Table 5.1 Pre-Construction Phase Model Input and Output Data

	Description	Notation
Input Data	**Existing Farms Data**	
	Number of farms	F
	Harvest quantity in each farm *f* in tonnes	H_f
	Storage capacity in each farm *f* in tonnes	C_f
	Monthly consumption rate in each farm *f* in tonnes	FC_f
	Monthly storage cost rate in each farm *f* in $/tonnes	CS_f
	Monthly storage losses rate in each farm *f* in %/tonnes	LS_f
	Minimum monthly storage requirement in each farm *f* in tonnes	MC_f
	Local Markets Data	
	Number of local markets	M
	Monthly sales price of wheat at each local market in $/tonne	SV_m^d
	Monthly purchase price of wheat at each local market in $/tonne	BV_m^d
	Transportation Data	
	Transportation cost rates from each farm *f* to each local market *m* in $/tonne/mile	$CT_{f,m}$
	Wheat loss rates during transportation from each farm *f* to each local market *m* in %	$LT_{f,m}$
	Transportation distance from each farm *f* to each local market *m* in miles	$Ds_{f,m}$
Output Data	Optimal sales *S* in each month *d* from each farm *f* to each local market *m* in tonnes	$S_{f,m}^d$
	Optimal purchases *B* in each month *d* from each farm *f* to local market *m* in tonnes	$B_{f,m}^d$
	Optimal profit generated at each farm *f* in $	PeP_f

5.3 Post-Construction Phase Model

5.3.1 Decision Variables

The post-construction phase model is designed to identify all relevant decision variables that are required to optimize (1) sales and storage decisions in existing farm facilities; (2) construction decisions for new private village storage facilities; and (3) storage decisions in new private village facilities, as shown in Table 5.2 and Figure 5.6.

The first category of decision variables focuses on identifying the optimal monthly storage and sales quantities to local markets, and they are identical to those described earlier in the pre-construction phase model. The second category of decision variables is used to optimize the construction decisions of new private storage facilities as shown in Table 5.2. These decision variables are designed to select the location, type and capacity of storage facility to be constructed. The third category of decision variables is designed to optimize the monthly storage and transported wheat quantities to and from the newly constructed village facilities, as shown in Figure 5.6 and Table 5.2.

A simple example of these three categories of decision variables is shown in Figure 6 between an example farm (F4), local market (M1), and new village storage facility (V2). For this example, a decision maker is required to identify (1) the optimal monthly storage and sales quantities of wheat to a local market, (2) the type and capacity of the new storage facility to be constructed, which was selected to be a 1,000 tonne silo, and (3) the optimal monthly quantities of wheat that will be transported from the farm for temporary storage in the new village facility $S_{4,2}^{d}$, and from the new village storage facility for consumption in the farm $B_{4,2}^{d}$.

Table 5.2 Decision Variables of Post-Construction Phase Model

Category	Description	Notation
Existing Farm Sales	Quantity of wheat sales at the beginning of month *d* in tonnes from farm *f* to local market *m*	$S_{f,m}^{d}$
	Quantity of wheat purchases at the beginning of month *d* in tonnes from local market *m* to farm *f*	$B_{f,m}^{d}$
New Construction	Integer variable that represents the selection of new facility of type *t* and capacity *c* in location *v*	$X_{v}^{t,c}$
New Village Storage Facilities	Quantity of wheat in tonnes to be transported in month *d* from farm *f* for storage in new village storage facility *v*	$S_{f,v}^{d}$
	Quantity of wheat in tonnes to be transported in month *d* to farm *f* from stored wheat in new village storage facility *v*	$B_{f,v}^{d}$

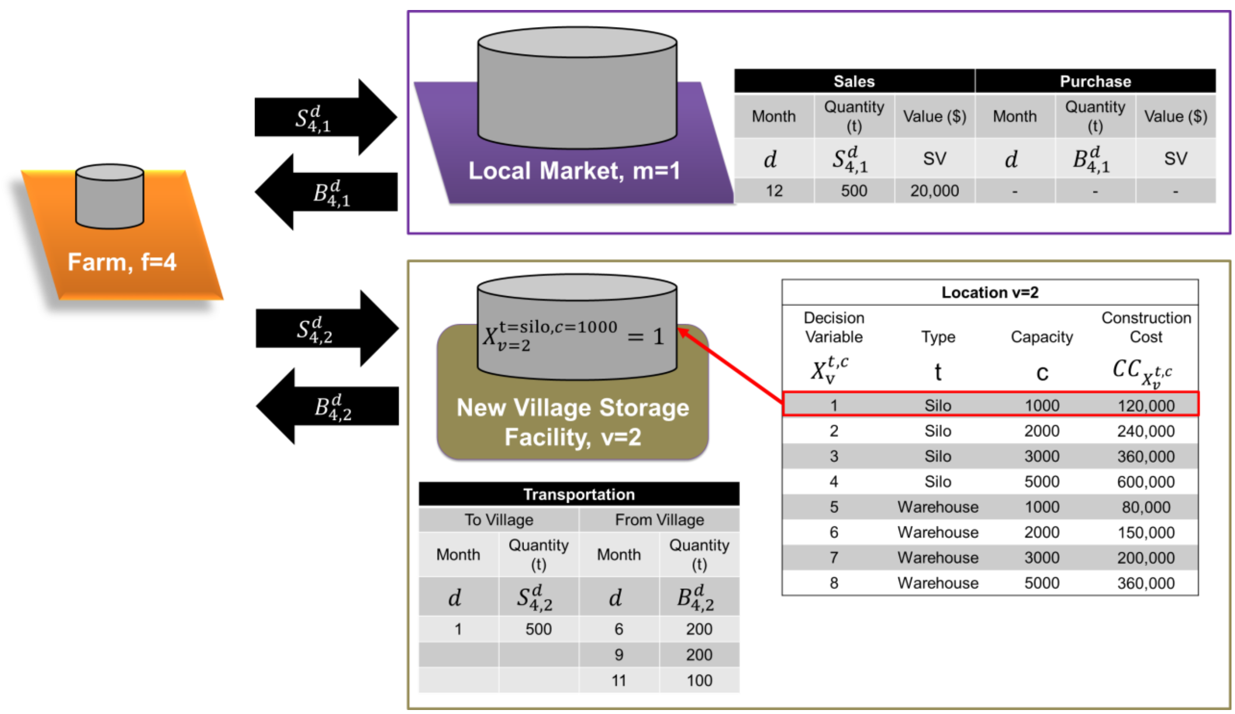


Figure 5.6 Example Decision Variables of Post-Construction Phase Model

5.3.2 Objective Function

The post-construction phase model is designed to maximize the total profit of each farmer generated from wheat sales from farm *f* to all local markets (*m=1 to M*). Accordingly, the objective function of this model seeks to maximize the post construction profit (PoP_f) using Equation (5-8) that calculates the difference between: (a) the annual revenues generated $\left(Revenue_f\right)$ from the sale of wheat from farm *f* to all local markets (*m = 1 to M*) that is calculated in Equation (5-9); (b) the annual total expenses of existing farms $(Existing\ Farm\ Expenses_f)$; and (c) the annual operating cost of new village storage facilities $(New\ Village\ Facilities\ Expenses_f)$. These annual expenses of existing farms include: (i) storage cost of wheat at farm *f*, (ii) purchase cost of wheat from the local markets to cover wheat consumption in the farm, (iii) transportation costs and losses of purchased and/or sold wheat from and to all local markets (*m = 1 to M*), as shown in Equation (5-10). The annual operating cost of new village storage facilities $(New\ Village\ Facilities\ Expenses_f)$ includes: (i) storage cost of wheat in new village storage facilities (*v = 1 to V*); and (ii) transportation costs and losses to and from new village storage facilities, as shown in Equation (5-11).

$$Maximize\ Profit\ (PoP_f) = Revenue_f - Existing\ Farm\ Expenses_f - New\ Village\ Facilities\ Expenses_f \tag{5-8}$$

$$Revenue_f = \sum_{d=1}^{12} \sum_{m=1}^{M} S_{f,m}^{d} * SV_{m}^{d} \tag{5-9}$$

$$Existing\ Farm\ Expenses_f = \sum_{d=1}^{12} \sum_{m=1}^{M} \sum_{v=1}^{V} [\left(CS_f * (WS_f^d + Rf_{f,m}^d - S_{f,m}^d + Rf_{f,v}^d - S_{f,v}^d)\right) + (B_{f,m}^d * BV_m^d) + ((B_{f,m}^d + S_{f,m}^d) * (CT_{f,m} * Ds_{f,m}))] \tag{5-10}$$

$$New\ Village\ Facilities\ Expenses_f = \sum_{d=1}^{12} \sum_{v=1}^{V} [CS_{X_v^{t,c}} * (WS_v^d + Rv_{f,v}^d - B_{f,v}^d)$$

$$+(S_{f,v}^d + B_{f,v}^d) * (CT_{f,v} * Ds_{f,v})] \tag{5-11}$$

$$WS_f^d = \left(1 - LS_f\right) * [WS_f^{d-1} + \sum_{m=1}^{M} (Rf_{f,m}^{d-1} - S_{f,m}^{d-1}) + \sum_{v=1}^{V}(Rf_{f,v}^{d-1}$$

$$- S_{f,v}^{d-1})] - FC_f \tag{5-12}$$

$$Rf_{f,v}^d = B_{f,v}^d * (1 - LT_{f,v} * Ds_{f,v}) \tag{5-13}$$

$$Rv_{f,v}^d = S_{f,v}^d * (1 - LT_{f,v} * Ds_{f,v}) \tag{5-14}$$

Where,

$S_{f,v}^d$ =quantity of wheat to be transported at the beginning of month *d* from farm *f* for storage in new village storage facility *v* in tonnes*;*

$B_{f,v}^d$ =quantity of wheat to be transported at the beginning of month *d* to farm *f* from stored wheat in new village storage facility *v* in tonnes;

$Rf_{f,v}^d$ =quantity of wheat received at farm *f* in month *d* from the stored wheat in new village storage facility *v* after considering transportation losses in tonnes, as shown in Equation (5-13);

$Rv_{f,v}^d$ =quantity of wheat received at new village storage facility *v* in month *d* in from farm *f* after considering transportation losses in tonnes, as shown in Equation (5-14);

$X_v^{t,c}$ =integer variable that represents the selection of new facility of type *t* and capacity *c* in location *v;*

$CS_{X_v^{t,c}}$ =storage cost of 1 tonne of wheat per month at new facility *x* of type *t* and capacity *c* in location *v*;

$CT_{f,v}$ =the transportation cost of 1 tonne of wheat per mile between farm *f* and new facility *v*; and

$Ds_{f,v}$ =distance between farm *f* and new facility *v* in miles.

It should be noted that variables $S_{f,m}^d$, $B_{f,m}^d$, SV_m^d, BV_m^d, CS_f , WS_f^d , $CT_{f,m}$, $Ds_{f,m}$, LS_f , $Rf_{f,m}^d$ and FC_f are identical to those defined earlier in the pre-construction phase model. It should be noted also that the storage cost rate of wheat at the new facility $CS_{X_v^{t,c}}$ is part of the input data provided by the decision maker. This storage cost rate $CS_{X_v^{t,c}}$ should be estimated using a life-cycle cost analysis that considers all related parameters including initial cost of construction, annual operating and maintenance costs, demolition and disposal cost, savage value, service life, and interest rate.

5.3.3 Constraints

The post-construction phase model is designed to consider all relevant practical constraints, including (1) construction budget constraint; (2) area constraint; (3) farm wheat demand constraint; (4) farm storage capacity constraint; and (4) new village facility storage capacity constraint.

Total Construction Budget Constraint: This constraint is formulated to insure that the total construction cost of all new village storage facilities v does not exceed the total allocated budget for the construction of these new facilities, which is the sum of the profit generated during the pre-construction model multiplied by the allocated percentage for new construction, as shown in Equation (5-15).

$$\sum_{v=1}^{V}\sum_{x=1}^{X} Y_{X_v^{t,c}} * CC_{X_v^{t,c}} \leq \sum_{f=1}^{F} PeP_f \; * w_f \qquad (5\text{-}15)$$

Where, $Y_{X_v^{t,c}}$ is a binary variable that indicates whether feasible alternative $X_v^{t,c}$ was selected for construction or not; $CC_{X_v^{t,c}}$ the construction cost of new village facility *x* of type *t* and capacity *c* in location *v* in $; and w_f is the percentage of profit generated from each farm *f* for the construction of new facilities.

Area Constraint: These constraints are formulated to insure that the required area for all new construction facilities at each village v does not exceed the available land area, as shown in Equations (5-16).

$$\sum_{x=1}^{X} Y_{X_v^{t,c}} * AS_{X_v^{t,c}} \;\; \leq A_v \qquad (5\text{-}16)$$

Where, $AS_{X_v^{t,c}}$ is the area required for the construction of new village facility *x* of type *t* and capacity *c* in location *v* in sf; A_v is the available land area for the construction of a new storage facilities in village *v* in square feet.

Farm Wheat Demand Constraint: This constraint insures that at the end of each month *d,* the stored wheat at farm *f* does not fall below its minimum wheat demand, as shown in Equation (5-17).

$$\left(1 - \; LS_f\right) * [WS_f^d + \sum_{m=1}^{M}(\; Rf_{f,m}^d - S_{f,m}^d) + \sum_{v=1}^{V}(\; Rf_{f,v}^d - S_{f,v}^d)] - FC_f \geq MC_f \qquad (5\text{-}17)$$

Farm Storage Capacity Constraint: This constraint insures that at the start of each month *d,* all wheat sales and purchases to and from all local markets and after all transported and received wheat from new village storage facilities, the stored wheat at farm *f* does not exceed its storage capacity, as shown in Equation (5-18).

$$C_f \geq WS_f^d + \sum_{m=1}^{M} (Rf_{f,m}^d - S_{f,m}^d) + \sum_{v=1}^{V} (Rf_{f,v}^d - S_{f,v}^d) \qquad (5\text{-}18)$$

New Village Facility Storage Capacity Constraint: This constraint insures that for each farm *f,* the quantity of wheat stored at the start of month *d* at new shared village storage facility *v* after all transported and received wheat from the farm does not exceed the farmer's share of storage capacity in the new facility, as shown in Equation (5-19).

$$WS_v^d + Rv_{f,v}^d - B_{f,v}^d \ \leq C_{X_v^{t,c}} * \frac{PeP_f \ * w_f}{\sum_{f=1}^{F} \ PeP_f \ * w_f} \qquad (5\text{-}19)$$

Where, $LS_{X_v^{t,c}}$ is the percentage of wheat storage losses per month in new village facility *x* of type *t* and capacity *c* in location *v;* $LT_{f,v}$ is the rate of wheat losses suffered during the transportation of 1 tonne per mile between farm *f* and new facility v; and $C_{X_v^{t,c}}$ is the storage capacity of new village facility *x* of type *t* and capacity *c* in location *v* in tonnes*.*

5.3.4 Implementation

The post-construction phase model was implemented using genetic algorithms due to its capability of modeling non-linearity in the objective function and constraints that exist in the present model as discussed earlier in the previous model. The required input data by the model and its generated output data are summarized in Tables 5.1 and 5.3. To facilitate the use of the model by decision-makers, a newly developed database was integrated to provide a comprehensive list of feasible alternatives for the construction of new village storage facilities. The database includes data on: (1) cost of constructing each facility ($CC_{X_v^{t,c}}$); (2) required area for construction($AS_{X_v^{t,c}}$); (3) type of each facility *(t*); (3)

capacity of each facility (c); (4) storage cost rate ($CS_{X_v^{t,c}}$); and (5) storage loss rate ($LS_{X_v^{t,c}}$), as shown in Table 5.7.

Table 5.3 Additional Input and Output Data of the Post-Construction Phase Model

	Description	Notation
	New Village Facilities Data	
Input Data	Number of villages with available locations for constructing new storage facilities	V
	Available land area for constructing new storage facilities in village *v* in square feet	A_v
	Transportation Data	
	Transportation cost rates from each farm *f* to each new facility *v* in $/tonne/mile	$CT_{f,v}$
	Wheat loss rates during the transportation from each farm *f* to each new facility *v* in %	$LT_{f,v}$
	Transportation distance from each farm *f* to each new facility *v* in miles	$Ds_{f,v}$
	Profit Data Generated by Pre-Construction Model	
	Optimal profit generated from each farm *f* in $	PeP_f
	Percentage of profit contribution from each farm *f*	w_f
Output Data	Optimal sales in each month *d* from each farm *f* to each local market *m* in tonnes	$S_{f,m}^d$
	Optimal purchases in each month *d* from each farm *f* to local market *m* in tonnes	$B_{f,m}^d$
	Optimal location *v*, type *t*, and capacity *c* for constructing new storage facilities	$X_v^{t,c}$
	Optimal sales in each month *d* from each farm *f* to new village facility *v* in tonnes	$S_{f,v}^d$
	Optimal purchases in each month *d* from each farm *f* to new village facility *v* in tonnes	$B_{f,v}^d$
	Optimal profit generated in each farm *f* in $	PoP_f

5.4 Case Study

A case study is analyzed to illustrate the use of the developed models and demonstrate their unique capabilities. The case study focuses on optimizing monthly wheat storage and sales in thirty existing farms and two local markets. The case study is optimized using the aforementioned pre-construction and post-construction models. The pre-construction model is used to identify the optimal monthly wheat sales and storage quantities in existing farm facilities during the first and second years to maximize profit for each farm *f* independently, as shown in Figure 5.3. The post-construction model utilizes the profits generated from the sales of wheat during the pre-construction phase for the construction of new village storage facilities to provide additional storage capacity for all participating farms. The post-construction model is applied to optimize the construction decisions for new private village storage facilities and the monthly wheat sales and storage quantities in existing farm facilities and new village facilities after the completion of their construction during the third and subsequent years, as shown in Figure 5.3.

The required input data for this case study are summarized in Tables 5.1 and 5.3, and they include existing farms data, local markets data, transportation data, and new village facilities data. A sample of the input data for existing farms and their existing storage facilities is shown in Table 5.4. The local markets input data including their monthly wheat sales and purchases prices are shown in Table 5.5. The transportation input data including the ranges and averages of transportation cost rates, loss rates, and distances between farms, local markets, and new village facilities are summarized in Table 5.6. The new village storage facilities data includes two available locations V1 and V2 for the construction of new facilities, where the available area for construction is 45,000 sf for V1 and 60,000 sf for V2. In addition, the model integrates a database that includes data on the cost of constructing each new facility, its required area for construction, its type and capacity, its storage cost rate, and its storage loss rate, as shown in Table 5.7. This input data was gathered from several sources including the Government of India, Haryana Food and Supplies Department, Haryana Warehousing Cooperation and Haryana State Agricultural Marketing Board (Food and Feed Grain Institute 1991; Food and Feed Grain Institute 1989; Gandhi and Koshy 2006; Global Agri System; Government of India 2002; HAFED 2014; HF&SD 2014; HSAMB 2014; Jha et. al 2007; Joshi 2002; Kiruba et. al 2006; Mott Macdonald 2013). In addition, the GA parameters that were specified in analyzing this case study are summarized in Table 5.8.

Table 5.4 Sample Input Data for Existing Farms

Farm	Harvest (t)	Storage Capacity (t)	Farm Monthly Consumption (t/month)	Storage Cost Rate ($/t*month)	Storage Loss Rate (%/t*month)	Profit Contribution %
f	H_f	C_f	FC_f	CS_f	LS_f	w_f
1	4000	2000	42	0.13	2.5	4
4	600	200	30	0.15	2.3	18
6	2600	1000	36	0.15	2.3	6
13	800	400	30	0.15	2.5	12
24	620	150	18	0.15	2.5	11

Table 5.5 Local Markets Data for Wheat Sales and Purchase Prices

Duration	Sales Price		Purchase Price	
	M1	M2	M1	M2
(month)	($)	($)	($)	($)
d	SV_1^d	SV_2^d	BV_1^d	BV_2^d
1	90	91	95	96
2	92	93	97	98
3	94	94	99	99
4	96	96	101	101
5	98	97	103	102
6	100	98	105	103
7	102	100	107	105
8	104	101	109	106
9	106	103	111	108
10	107	105	112	110
11	109	107	114	112
12	110	108	116	113

Table 5.6 Transportation Input Data between Farms, Local Markets and New Village Facilities

Transportation Route	Range of Transportation Cost Rates ($/ t*mile)			Range of Transportation Loss Rates (% of Loss/ t*mile)			Range of Distances (miles)		
	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
		$CT_{f,m}$			$LT_{f,m}$			$Ds_{f,m}$	
Farms to Local Market 1 (f,1)	0.13	0.14	0.15	0.10	0.10	0.10	1	4.9	11
Farms to Local Market 2 (f,2)	0.12	0.12	0.14	0.12	0.127	0.13	1	4.5	10
		$CT_{f,m}$			$LT_{f,m}$			$Ds_{f,m}$	
Farms to New Village Facility 1 (f,1)	0.14	0.15	0.16	0.13	0.137	0.14	1	1.8	3
Farms to New Village Facility 2 (f,2)	0.13	0.14	0.15	0.14	0.14	0.14	1	1.5	4

Table 5.7 Storage Facilities Database

Number	Facility Type	Capacity (t)	Construction Cost ($)	Required Area (SF)	Storage Cost Rate ($/ t*month)	Storage Loss Rate (% Loss/t*month)
$X_v^{t,c}$	t	c	$CC_{X_v^{t,c}}$	$AS_{X_v^{t,c}}$	$CS_{X_v^{t,c}}$	$LS_{X_v^{t,c}}$
1	Godown Warehouse	500	30,000	3,000	0.25	0.7
2	Godown Warehouse	1,000	60,000	6,000	0.25	0.7
3	Godown Warehouse	2,000	112,500	12,000	0.25	0.7
4	Godown Warehouse	3,000	150,000	16,000	0.25	0.7
5	Godown Warehouse	5,000	270,000	30,000	0.25	0.7
6	Godown Warehouse	10,000	525,000	60,000	0.25	0.7
7	Cover and Plinth (CAP)	300	3,600	1,800	0.2	1
8	Cover and Plinth (CAP)	500	6,000	3,000	0.2	1
9	Cover and Plinth (CAP)	1,000	12,000	6,000	0.2	1
10	Cover and Plinth (CAP)	2,000	24,000	12,000	0.2	1
11	Cover and Plinth (CAP)	3,000	36,000	18,000	0.2	1
12	Cover and Plinth (CAP)	5,000	60,000	30,000	0.2	1
13	Cover and Plinth (CAP)	10,000	120,000	60,000	0.2	1
14	Steel Silo	500	45,000	3,000	0.35	0.5
15	Steel Silo	1,000	90,000	3,000	0.35	0.5
16	Steel Silo	2,000	180,000	6,000	0.35	0.5
17	Steel Silo	3,000	270,000	9,000	0.35	0.5
18	Steel Silo	5,000	450,000	15,000	0.35	0.5
19	Steel Silo	10,000	900,000	30,000	0.35	0.5

Table 5.8 Genetic Algorithm Parameters

GA Operators	Pre-Construction Model	Post-Construction Model
Population Size	3000	6000
Mutation Rate	0.15	0.15
Cross-Over Rate	0.5	0.5

5.4.1 Pre-Construction Model Results

The aforementioned input data was analyzed by the developed pre-construction model to maximize the profitability of each farm during the first and second years utilizing Genetic Algorithms, as shown in Figure 5.3. The generated optimal decisions for the analyzed case study include: (1) optimal monthly wheat sales and purchases; and (2) total annual sales profit generated at each farm. A sample of the optimal monthly sale and purchase quantities in farm 4 to and from local markets M1 and M2 is presented in Table 5.9. A closer examination of these sample results reveal that (a) farm 4 had to sell 400 tonnes during the first month from the total quantity of harvested wheat of 600 tonnes due to its limited storage capacity of 200 tonnes; (b) the monthly wheat purchases of farm 4 ranged from 26 to 32 tonnes during months 7 to 12 to cover the required monthly storage requirements needed for farm consumption; and (c) all farm sales and purchases were exchanged with the local market that provides the best overall framer’s profit. The results also show that the model recommended selling the minimum wheat quantity during first month due to the low sales prices during the first months, and purchasing the required wheat quantities during later months to cover the monthly shortfalls in wheat storage levels. The optimal profits generated by all farms are summarized in Table 5.10 that illustrates that the total sales profit for all farms was $1,973,319 and the total profit allocated for the construction of new private facilities was a total of $159,758. A detailed summary of the Pre-Construction Model results are presented in Appendix IV-1.

Table 5.9 Sample Optimal Pre-Construction Sale and Purchase Quantities from Farm 4 to Local Markets

		Sale to Local Markets		Purchase from Local Markets	
Farm	Month	Sold Quantity M1 (t)	Sold Quantity M2 (t)	Purchased Quantity M1 (t)	Purchased Quantity M2 (t)
	d	$S_{4,1}^{d}$	$S_{4,2}^{d}$	$B_{4,1}^{d}$	$B_{4,2}^{d}$
4	1	-	400	-	-
	.	.	.	.	.
	.	.	.	.	.
	7	-	-	-	31
	8	-	-	-	32
	9	-	-	-	31
	10	-	-	-	31
	11	-	-	-	31
	12	-	-	-	26

Table 5.10 Optimal Pre-Construction Annual Profits in all Farms

Farm	Total Annual Sales Profit ($)	Profit % for Construction	Contribution for Construction ($)	Farm	Total Annual Sales Profit ($)	Profit % for Construction	Contribution for Construction ($)
f	PeP_f	w_f	$PeP_f * w_f$		PeP_f	w_f	$PeP_f * w_f$
1	309,222	4	12,369	16	17,220	18	3,100
2	179,786	6	10,787	17	30,539	12	3,665
3	34,634	10	3,463	18	204,220	8	16,338
4	16,305	18	2,935	19	61,801	7	4,326
5	31,323	10	3,132	20	29,568	13	3,844
6	190,094	6	11,406	21	180,955	6	10,857
7	35,001	11	3,850	22	32,135	11	3,535
8	16,429	18	2,957	23	17,082	17	2,904
9	30,325	13	3,942	24	33,219	11	3,654
10	36,223	10	3,622	25	221,884	7	15,532
11	19,115	15	2,867	26	36,317	13	4,721
12	35,764	11	3,934	27	17,430	14	2,440
13	34,493	12	4,139	28	31,180	10	3,118
14	16,920	18	3,046	29	32,085	12	3,850
15	28,497	10	2,850	30	13,554	19	2,575
				Total	1,973,319	8%	159,758

5.4.2 Post-Construction Model Results

Upon the completion of the aforementioned analysis, the post-construction model was used to optimize the construction decisions for new private shared village storage facilities and the monthly wheat sales and storage quantities in existing farm facilities and new village facilities in the post-construction phase during the third and subsequent years, as shown in Figure 5.3. The post-construction model utilized the generated results from the pre-construction model and the aforementioned input data of the case study to maximize the profitability of each farm.

The generated optimal decisions by the post-construction model include: (1) optimal construction decisions for new private shared wheat storage facilities, including their location, type, and capacity; (2) optimal monthly farm wheat sales and purchases to and from local markets; (3) optimal monthly wheat storage at new shared village facilities that depends on the optimal quantity of transported wheat from and to these facilities; and (4) optimal annual profits in each farm.

First, the identified optimal construction decisions for this case study recommended the construction of (a) new CAP facility with a capacity of 3,000 tonnes in village location V1 at a cost of $36,000, and (b) new CAP facility with a capacity of 10,000 tonnes in village location V2 at a cost of $120,000. Second, the model identified the optimal monthly farm wheat sales and purchases based on the newly expanded farm storage capacities that include both existing farm facilities and newly constructed village facilities. Third, the optimal monthly wheat storage at new village facilities was identified. Table 5.11 shows a sample of the generated optimal results for Farm 4, including monthly (i) wheat sales and purchases to and from local markets M1 and M2, and (ii) transported wheat for temporary storage to and from the new shared village facilities V1 and V2. It should be noted that the share of Farm 4 in the new village facilities V1 and V2 is 55 tonnes and 183 tonnes, respectively. This added storage capacity enabled Farm 4 to (a) fully utilize its share of storage capacity in the new village facilities V1 and V2 during the first month because of their lower storage loss rates; (b) decrease its sale quantities to the local markets in month 1 from 400 to 162 tonnes due to the low sales prices in the first months after the harvest; (c) increase its sale quantities to the local markets in month 12 from 0 to 35 tonnes due to the high sales prices in the later months of the harvest year; and (d) use the stored wheat in the new village facilities V1 and V2 to cover its monthly wheat demand in months 7 to 12 instead of purchasing wheat from local markets due to their high purchase prices, as shown in Tables 5.9 and 5.11.

Table 5.11 Optimal Sale Quantities from Farm 4 to Local Markets and New Facilities during Post-Construction

Farm	Month	Sold Quantity to Local Markets		Purchased Quantity from Local Markets		Transported Quantity to New Facilities		Transported Quantity from New Facilities	
		M1 (t)	M2 (t)	M1 (t)	M2 (t)	V1 (t)	V2 (t)	V1 (t)	V2 (t)
	d	$S_{4,1}^d$	$S_{4,2}^d$	$B_{4,1}^d$	$B_{4,2}^d$	$S_{4,1}^d$	$S_{4,2}^d$	$B_{4,1}^d$	$B_{4,2}^d$
4	1	-	162	-	-	55	183	-	-
	.	.	.	.	.	.	.	.	.
	.	.	.	.	.	.	.	.	.
	7	-	-	-	-	-	-	27	-
	8	-	-	-	-	-	-	24	7
	9	-	-	-	-	-	-	-	31
	10	-	-	-	-	-	-	-	31
	11	-	-	-	-	-	-	-	30
	12	35	-	-	-	-	-	-	66

Fourth, the identified optimal annual profits for each of the thirty farms after the construction of the new private village facilities are summarized in Table 5.12. The results in Table 5.12 also show the percentage of annual increased profits for each farm that was realized from the added storage capacity provided by the new construction. The results show that the annual profit increase for the 30 farms ranged from 6.91% for smaller farms to 2.86% for bigger farms. These results illustrate that farmers in this case study can increase their annual profits by an average of 3.91% in the third and each subsequent year if they can invest an average of 8% of their optimal profits in the first year, as shown in Figure 5.3. The results in Table 5.12 also show that the payback period ranged between 1.4 to 2.5 years for the initial investment made by each framer in the construction of new village construction, which highlights the significant benefits that can be realized from this investment. In addition to these financial benefits, the construction of these farmers-funded facilities more than doubled the average storage capacity of the farmers from a ratio of 0.37 to 0.76 of storage capacity to annual harvest, as shown in Table 5.12. A detailed summary of the Post-Construction Model results are presented in Appendix IV-2.

The optimization results illustrate the novel and unique capabilities of the developed model in maximizing the profitability of farmers by optimizing (a) the storage of wheat in existing farm facilities in the first and second years, and (b) the construction of new village storage facilities in the second year to maximize the profit of farmers and expand their storage capacity in the third and subsequent years, as shown in Figure 5.3. The same cycle can also be repeated for future years to expand storage capacity for all participating farmers. The repetition of this cycle can continue to provide additional village storage capacity for all participating farmers until they reach their desired storage capacity, as shown in Figure 5.2. The results of the case study also illustrate the benefits that can be gained from the construction of new village storage facilities including (a) increased annual profits for farmers; (b) improved protection of the stored crops by reducing their storage losses; (c) enhanced food security for local farmers by increasing the storage capacity in their villages; and (d) expanded storage capacity for grain reserves and for potential increases in wheat production.

Table 5.12 Optimal Profit Generated at all Farms during Post-Construction

Farm	Allocated % of Pre-Construction Profit for New Facilities	Post-Construction Annual Profit	Post-Construction Increase in Annual Profit	Payback Period	Existing Capacity /Harvest	New Capacity /Harvest
	(%)	($)	(%)	(yrs)		
f	w_f	PoP_f				
1	4	314,465	1.70%	2.4	0.50	0.75
2	6	184,072	2.38%	2.5	0.40	0.75
3	10	36,221	4.58%	2.2	0.50	0.85
4	18	17,975	10.24%	1.8	0.33	0.73
5	10	32,948	5.19%	1.9	0.22	0.64
6	6	195,433	2.81%	2.1	0.38	0.74
7	11	36,586	4.53%	2.4	0.50	0.89
8	18	17,941	9.21%	2.0	0.33	0.73
9	13	32,154	6.03%	2.2	0.25	0.78
10	10	38,030	4.99%	2.0	0.50	0.87
11	15	20,702	8.30%	1.8	0.33	0.72
12	11	37,464	4.75%	2.3	0.22	0.71
13	12	36,511	5.85%	2.1	0.50	0.92
14	18	18,724	10.66%	1.7	0.33	0.75
15	10	29,795	4.55%	2.2	0.21	0.61
16	18	18,945	10.02%	1.8	0.35	0.77
17	12	32,159	5.30%	2.3	0.24	0.74
18	8	210,970	3.30%	2.4	0.20	0.73
19	7	63,649	2.99%	2.3	0.53	0.90
20	13	31,238	5.65%	2.3	0.24	0.78
21	6	186,396	3.01%	2.0	0.38	0.73
22	11	34,534	7.47%	1.5	0.50	0.86
23	17	18,616	8.98%	1.9	0.37	0.76
24	11	34,790	4.73%	2.3	0.24	0.72
25	7	230,338	3.81%	1.8	0.30	0.72
26	13	38,744	6.68%	1.9	0.41	0.86
27	14	18,574	6.56%	2.1	0.42	0.75
28	10	32,637	4.67%	2.1	0.25	0.66
29	12	34,827	8.54%	1.4	0.50	0.89
30	19	15,103	11.43%	1.7	0.37	0.72
Total	8%	2,050,539	3.91%		0.37	0.76

5.5 Summary

This chapter presented the development of a novel model for optimizing the construction and utilization of private shared wheat storage facilities to maximize the annual profits of farmers. The optimization model was developed in two phases: pre-construction and post-construction phase. The pre-construction model was designed to optimize the monthly storage and sale quantities of wheat in existing facilities. The post-construction model utilizes the profits generated from the sale of wheat during the pre-construction phase for the construction of new private wheat storage facilities, as well as optimizing the monthly storage and sale quantities of wheat in new and existing facilities after the construction of the new facilities. A case study was analyzed to illustrate the use of the developed model and demonstrate its effectiveness in optimizing the storage of wheat in farms and the construction of new and shared storage facilities. The results of this analysis illustrate the new and unique capabilities provided by the model that enable decision makers to maximize the annual profit of each farm by identifying its optimal (a) monthly wheat sales, purchases and storage quantities in existing facilities in the first and second years; (b) construction decisions for new private shared village storage facilities including their location, type, and capacity; and (c) storage decisions in new village facilities in the third and subsequent years. These unique capabilities enable farmers to maximize their annual profits, expand their wheat storage capacities, and minimize wheat losses during the storage and transportation of wheat.

6 CONCLUSIONS

6.1 Summary

The present research study focused on optimizing the storage and transportation of wheat to minimize post-harvest loss and cost. The primary contributions of this research to the body of knowledge include the development of (1) novel optimization model that is capable of optimizing the storage and transportation of wheat using existing facilities in developing countries, (2) innovative optimization model for optimizing the construction of public wheat storage facilities that are funded and/or subsidized by government or other agencies, and (3) novel model for optimizing the construction and utilization of shared wheat storage facilities that are cooperatively funded by farmers. These new and innovative research developments will contribute to improve the storage and transportation decisions of harvested wheat in order to minimizing the post-harvest losses.

First, a novel optimization model is developed for optimizing the storage and transportation of wheat in developing countries. The model provides the capability of minimizing the costs and losses of wheat storage and transportation among the storage facilities in the villages, local markets and regional locations. The model was developed in six main steps that focused on conducting field data collection, defining the model decision variables, formulating the optimization objective function, modeling the optimization problem constraints, implementing the model using linear programming, and analyzing the model performance using a case study to illustrate the use of the developed model and demonstrate its effectiveness in optimizing the storage and transportation of wheat in developing countries. The results of this analysis illustrates the capabilities of the developed model in minimizing the total wheat storage and transportation cost including the total storage cost throughout the entire network of villages, local markets, and regional locations; the total storage losses costs caused by quantity and quality losses in all storage facilities; the total transportation cost throughout the entire network; and the total transportation losses costs suffered during wheat transportation throughout the network. These new capabilities contribute to (1) minimizing the total wheat storage and transportation cost in the entire supply chain network of villages, local markets, and regional locations, and (2) identifying needed upgrades of existing storage facilities and/or transportation routes.

Second, a novel optimization model was developed to optimize the construction of public wheat storage facilities while considering the impact of existing storage facilities. The model is designed to minimize the losses and cost of wheat storage and transportation. The optimization model is developed in three main phases: formulation phase that defines the model decision variables, objective function, and constraints; implementation phase that executes the optimization computations using integer programming; and an evaluation phase that analyzes the model performance using a case study. The analysis results of the case study illustrated the novel and unique capabilities of the model in optimizing the construction decisions of new public storage facilities. These new and innovative research developments will enable government planners to identify the optimal location, type, and capacity of new wheat storage facilities that minimize wheat storage and transportation losses and costs throughout the entire supply chain.

Third, an optimization model that provides the capability of optimizing the construction and utilization of private wheat storage facilities to maximize the annual profits of farmers.

The optimization model was developed in two phases: pre-construction and post-construction phase. The pre-construction model was designed to optimize the monthly storage and sale quantities of wheat in existing facilities. The post-construction model utilizes the profits generated from the sale of wheat during the pre-construction phase for the construction of new wheat storage facilities, as well as optimizing the monthly storage and sale quantities of wheat in new and existing facilities after the construction of the new facilities. A case study was analyzed to illustrate the use of the developed model and demonstrate its effectiveness in optimizing the storage of wheat in farms and the construction of new and shared storage facilities. The results of this analysis illustrate the new and unique capabilities provided by the model that enable decision makers to maximize the annual profit of each farm by identifying its optimal (a) monthly wheat sales, purchases and storage quantities in existing facilities in the first and second years; (b) construction decisions for new shared village storage facilities including their location, type, and capacity; and (c) storage decisions in new village facilities in the third and subsequent years. These unique capabilities enable farmers to maximize their annual profits, expand their wheat storage capacities, and minimize wheat losses during the storage and transportation of wheat.

6.2 Research Contributions

The proposed research is expected to create novel metrics and innovative optimization models that can be used to minimize postharvest losses in developing countries. The main research contributions can be summarized as follows:

1. Developing a novel optimization model to optimize the storage and transportation of wheat using existing facilities in developing countries in order to (a) minimize

the total wheat storage and transportation cost in the entire supply chain network of villages, local markets, and regional locations, and (b) identifying needed upgrades of existing storage facilities and/or transportation routes.

2. Developing an innovative model for optimizing the construction of public wheat storage facilities that is uniquely capable of (a) considering the impact of existing storage facilities on the optimization results, and quantifying and (b) minimizing the cost of wheat losses during storage and transportation.
3. Developing a novel model for optimizing the construction and utilization of private storage facilities to maximize the annual profits of farmers that is capable of identifying the optimal (a) monthly wheat sales, purchases and storage quantities in existing facilities; (b) construction decisions for new private storage facilities including their location, type, and capacity; and (c) storage decisions in the newly constructed private facilities.

Furthermore, the application of the aforementioned models is expected to lead to broad and profound impacts including: (a) reduced post-harvest losses during wheat storage and transportation; (b) minimized storage and transportation costs throughout the entire network of existing and new storage facilities; (c) increased annual profits for farmers; (d) enhanced food security for local farmers by increasing the storage capacity in their villages; and (e) expanded storage capacity for grain reserves and for potential increases in wheat production.

6.3 Future Research Work

Although the present study was able to fully accomplish its research objectives, a number of additional research areas have been identified to expand and build on the completed research work in this study. These future research areas include: (1) performing a longitudinal field study to evaluate and refine the performance of the developed optimization models; (2) modeling uncertainties in model input data; (3) considering the social and economic impacts of constructing new modern storage facilities; and (4) developing an automated multi-cycle profit model utilizing the construction of new private storage facilities.

6.3.1 Longitudinal Field Study

The three developed optimization models can be applied to optimize the storage and transportation decisions of harvested wheat in order to minimize post-harvest losses and to maximize the profits of farmers. In addition, case studies were conducted for each of the developed model to evaluate the performance of these models. The performance of these models can be further analyzed and refined by conducting a longitudinal field study to calibrate actual field data to the developed optimization models. The findings of this field study can be used to evaluate and calibrate the performance of the models and to refine their performance.

6.3.2 Modeling Uncertainties in Model Input Data

Despite the significant contributions of the developed models they do not consider the uncertainties involved in estimating various input data of the model such as annual wheat production, annual wheat consumption of farmers, and wheat sales price. The developed models can be expanded in future studies to consider and model these uncertainties and their impact on the generated optimization results.

6.3.3 Social and Economic Impacts of New Storage Construction

The introduction of new modern storage facilities can produce many benefits including reduced cost and losses during wheat storage. Despite these economic benefits, the introduction of these new facilities may have an indirect effect on labor force required to operate these facilities. Modern facilities such as wheat silos store wheat in bulk and these facilities require less labor than the traditional bag storage techniques which require an abundant labor force. Therefore, there is a need to study these social and economic effects and develop expanded models to consider and optimize these socio-economic impacts.

6.3.4 Automated Multi-Cycle Profit Model Utilizing the Construction of Private Storage Facilities

The developed optimization model for optimizing the construction of new private storage facilities is performed for the first cycle covering an initial three years. During the first year the optimization is performed on existing facilities, the profits generated during the first year are utilized for the construction of new storage facilities during the second year and for the optimization of stored wheat during the second and third year. The same cycle can also be repeated for future years to expand storage capacity for all participating farmers. The repetition of this cycle can continue to provide additional village storage capacity for all participating farmers until they reach their desired storage capacity. There is a need to develop an automated multi-cycle profit model utilizing the construction of new storage facilities to consider automated profit contribution from each individual farmer as well as possible harvest increase.

REFERENCES

Ali, N. (2003). “Post-Harvest Technology for Employment Generation in Rural Sector of India.” *Regional Seminar on Post-Harvest Technology for Major Crops 3-5 November 2003* Kunming, Yunnan Province, China, 62-105.

Basavaraja, H. ,Mahajanashetti, S.B. and Udagatti, N. C. (2007). “Economic Analysis of Post-harvest Losses in Food Grains in India: A Case Study of Karnataka.” *Agricultural Economics Research Review*, 20, January-June 2007, 117-126.

Baqui, M. (2005). “Post-harvest Processing, Handling, and Preservation of Agricultural Products: Its present Status and Future Challenges in Bangladesh.” *FMPHT Division Bangladesh Rice Research Institute (BRRI)*, pp. 10.

Bornstein, C., and Villela, P. (1990). “Warehouse Location in a Developing Country: Problems in Formulating the Problem.” *European Journal of Operational Research*, 49, 222-229.

Chattha, S. and Lee, T. (2014). “Storage Methods and Problems of Wheat Grain at Sindh, Pakistan.” *International Journal of Biosciences*, 5(7), 260-274.

Cotty, T., Maître d’Hôtel, E., Soubeyran, R. and Subervie, J. (2014). “Wait and Sell: Farmers’ Individual Preferences and Crop Storage in Burkina Faso.” *Centre de Recherche en Économie et Management*, <http://crem.univ-rennes1.fr/> (Dec. 22, 2014).

D’Souza, G. (1988). “Structure of the U.S. Soybean Processing Industry in the 1990s.” *Agribusiness*, 4, 11–23.

Dewani, D., Jain, S., and Gupta, S. (2012). “Supply Chains of Commodity Products in India: The Case of Rice. In M. Garg, & S. Gupta (Eds.).” *Cases on Supply Chain and Distribution Management: Issues and Principles*. Hershey, PA: Business Science Reference, 97-115.

EPA (1995). “AP 42, *Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources”* Fifth Edition.

Evolver (2013). “The Genetic Algorithm Solver for Microsoft Excel”, Version 6, January, 2013.

FAO (1994). *Grain Storage Techniques: Evolution and Trends in Developing Countries*, Issue 109, Rome.

FAO (2009). “Agribusiness Handbook, Wheat, Flour.” <http://www.fao.org/ > (Sep. 1, 2014).

FAO (2013). *FAOStat* <faostat.org> (Oct. 30, 2013).

FCI (2012). “Storage and Contract.” *Food Corporation of India*, <fciweb.nic.in/storages> (Sept. 30, 2012).

FCI (2013). “Storage and Contract.” *Food Corporation of India*, <fciweb.nic.in/storages> (Oct. 30, 2013).

Food & Feed Grain Institute (1989). “Impact of Fair Average Quality Procurement Procedures and No Loss Policy on Public Sector Storage of Wheat.” *Storage Technology Development and Transfer-Pakistan, Report 3,* Manhattan, Kansas.

Food & Feed Grain Institute (1991). “Proceedings, Bulk Wheat Handling and Storage Conference, Lahore, Pakistan, 1991.” *Storage Technology Development and Transfer-Pakistan, Report 8,* Manhattan, Kansas.

Gandhi, V. & Koshy, A. (2006). “Wheat Marketing and its Efficiency in India.” *Indian Institute of Management*, Ahmedabad, India.

Ghimiray, M., Wangdi, K., Chhetri, G., Bockel, L. and Punjabi, M. (2008). “Rice Commodity Chain Analysis: A Working Document.” *Ministry of Agriculture, Royal Government of Bhutan and Food and Agriculture Organization*, pp. 4.

Global Agri System. “Evaluation and Impact Assessment for the Central Sector Scheme of Grameen Bhandaran Yojna.” <http://www.agmarknet.nic.in/> (Dec. 22, 2014).

Goetschalckxa, M., Vidalb, C., and Doganc, K. (2002). “Modeling and Design of Global Logistics Systems: A Review of Integrated Strategic and Tactical Models and Design Algorithms.” *European Journal of Operational Research,* 143(1), 1-18.

Goldberg, D. (1989). *Genetic Algorithms in Search Optimization and Machine Learning,* 1st ed Addison-Wesley Longman Publishing Co., Inc. Boston, MA, USA.

Government of India (2002). “Estimation of Marketable Surplus & Post-Harvest Losses of Food Grains in India: Methodology and Profile of Sample Villages.” *Government of India, Ministry of Agriculture,* Nagpur.

Government of India (2011). “Report of Working Group on Warehousing Development and Regulation for the Twelfth Plan Period (2012-17).” *Government of India Planning Commission,* New Delhi.

Government of Tamil Nadu (2006). “Season and Crop Report of Tamil Nadu 2005-06.” <http://www.tn.gov.in/crop/>

Greenhalgh, D., and Marshall, S. (2000). “Convergence Criteria for Genetic Algorithms.” *Journal Comput*, 30, 269-82.

Gustavsson, J., Cederberg, C., Sonesson, U., Otterdijk, R. & Meybeck, A. (2011). *Global Food Losses and Food Waste, Extent Causes and Prevention,* FAO, Rome. <http://www.fao.org/ > (Jan. 1, 2015).

HAFED (2013). *The Haryana State Cooperative Supply and Marketing Federation Limited*, <http://hafed.gov.in/> (Oct. 30, 2013).

HF&SD (2013). "Procurement." *Haryana Food and Supplies Department*, <http://haryanafood.gov.in/> (Oct. 30, 2013).

Hodges, R. J., Buzby, J. C., & Bennett, B. (2011). "Postharvest Losses and Waste in Developed and Less Developed Countries: Opportunities to Improve Resource Use." *Journal of Agricultural Science,* 149, 37-45.

Hough, J. (1994). "Logistics Of The U.S. Wheat Industry." *National Association of Wheat Growers Foundation.*

HSAMB (2013). "Infrastructure." *Haryana State Agricultural Marketing Board,* <http://hsamb.gov.in/> (Oct. 30, 2013).

HWC (2013). "Storage Capacities." *Haryana Warehousing Cooperation* <hwc.nic.in> (Oct. 30, 2013).

IFC (2012). "Public-Private Partnerships in Agricultural Storage." <http://www.ppiaf.org> (Sep. 1, 2014).

Jha, S., Srinivasan, P., & Landes, M. (2007). "Indian Wheat and Rice Sector Policies and the Implications of Reform." *United States Department of Agriculture*, Economic Research Report 41.

Joshi, B. K. (2002). "Post-Harvest Profile of Paddy/Rice." *Government of India*, <agmarknet.nic.in/> (Oct. 30, 2013).

Kader, A. A. (2004). "Increasing Food Availability by Reducing Postharvest Losses of Fresh Produce." *Proceedings of the 5th International Post-Harvest Symposium*, Ed. F Mencarelli, and P.Tonutti. Verona: International Society for Horticultural Science (ISHS).

Kar, S., Bhunia, A.K., and Maiti, M. (2001). "Deterministic Inventory Model with Two Levels of Storage, a Linear Trend in Demand and a Fixed Time Horizon." *Computers & Operations Research*, 28(13), 1315–1331.

Kartikeyan, C., Veeraraghavantham, D., Karpagam, D. and Firdouse, S.A. (2009). "Traditional Storage Practices." *Indian Journal of Traditional Knowledge*, 8(4), 564-568.

Kiruba, S., Manohar Das, S. S. and Papadopoulou, S. (2006). "Prospects of Traditional Seed Storage Strategies against Insect Infestation Adopted by Two Ethnic Communities of Tamil Nadu, Southern Peninsular India." *Bulletin of Insectology* 59 (2), 129-134.

Kitinoja, L., Saran, S., Roy, S.K., and Kader, A. (2011). "Postharvest Technology for Developing Countries: Challenges Opportunities in Research, Outreach and Advocacy." *Journal of the Science of Food and Agriculture*, 91, 597-603.

Koo, W. (1987). "A Overview of Handling and Transportation of Grain." *Proceedings, International Seminar on Postharvest Handling and Transportation of Grain*, Australian Center for International Agricultural Research, 46-52.

Kumar, A., Gulati, A. and Cummings Jr., R. (2007). "Food Grains Policy and Management in India, Responding to Today's Challenges and Opportunities." Indira Gandhi Institute of Development Research, Mumbai. International Food Policy Research Institute (IFPRI), New Delhi.

Luenberger, D. and Ye, Y. (2008). Linear and Nonlinear Programming, 3rd Ed., Springer, New York.

MacAulay, T.G. (1987). “Optimization Techniques for the Economic Analysis of the Postharvest Handling and Storage of Grains.” *Proceedings, International Seminar on Postharvest Handling and Transportation of Grain*, Australian Center for International Agricultural Research, 53-67.

McCarthy, S., Singh, D. D. and Schiff, H. (2008). “Value Chain Analysis of Wheat and Rice in Uttar Pradesh, India: Partnership for Innovation and Knowledge in Agriculture.” *ACDI/VOCA for World Vision.*

Monterosso, C., Wright, C., Lacerda, M. and Ofugi, N. (1985). “Grain Storage in Developing Areas: Location and Size of Facilities.” *American Journal of Agricultural Economics*, 67(1), 101-111.

Mott Macdonald. (2013). “Setting Up of Steel Grain Silo in Sehore, Madhya Pradesh.” MPWarehousing, <http://mpwarehousing.com > (Sep. 1, 2014).

Naik, S. N. and Kaushik, G. “Grain Storage in India: An Overview” <http://www.vigyanprasar.gov.in/> Centre for Rural Development & Technology, IIT Delhi.

Ofor, M. O. and Ibeawuchi, I. I. (2010). “Sun-drying – A low cost Technology for Reducing Postharvest losses.” Academic Arena.

Parfitt, J., Barthel, M. and Macnaughton, S. (2010). “Food Waste within Food Supply Chains: Quantification and Potential for Change to 2050” Phil. Trans. R. Soc. B 365, 3065–3081.

Park, J. and Koo, W. (2001). “U.S./Canada Grain Handling and Transportation Systems.” *Agribusiness & Applied Economics,* Report No. 451.

Pendharkar, P. and Koehler, G. (2007). “A General Steady State Distribution Based Stopping Criteria for Finite Length Genetic Algorithms.” *Eur Journal Operation res,* 176, 1436-51.

Pruzan, P. (1978). “The Bangladesh grain model.” *European Journal of Operational Research,* 3 (2), 110–121.

Renkow, M., Hallstroma, D. and Karanjab, D. (2004). “Rural Infrastructure, Transactions Costs and Market Participation in Kenya.” *Journal of Development Economics*, 73, 349– 367.

Roul, C. (2001). *Bitter to Better Harvest: Post-green Revolution: Agricultural and Marketing Strategy for India*, Northern Book Centre, New Delhi.

Rutkowski, A. (2009). “India.” <www.alisonrutkowski.blogspot.com> (Feb. 1, 2013).

SDC (2011). “Effective Grain Storage for Better Livelihoods of African Farmers Project.” <www.sdc-foodsecurity.ch> (Sep. 1, 2014).

Tefera T., Kanampiu F., Groote H., Hellin J., Mugo S., Kimenju S., Beyene Y., Boddupalli P., Shiferaw B. and Banziger M. (2011). “The Metal Silo: An Effective Grain Storage Technology for Reducing Post-Harvest Insect and Pathogen Losses in Maize While Improving Smallholder Farmers’ Food Security in Developing Countries.” *Crop Protection*, Elsevier, 30, pp 140-245.

Toquero, Z. (1987). “Issues Determining the Capitalization of the Rice Processing Industry in the Philippines.” *Proceedings, International Seminar on Postharvest Handling and Transportation of Grain*, Australian Center for International Agricultural Research, 77-86.

Zhongquan, Q., Fuhua, L., Yusong,Y. & Zuoan, H. (2011). "Logistics Network Layout of Green Agricultural Products Closed Supply Chain Based On Logistics Loss." *3rd International Conference on Transportation Engineering*, ASCE, Chengdu, China, 2400-2405.

APPENDIX

Appendix I: Supply Chain, Storage and Transportation Data

Appendix I: Sample Data on Population, Grain Production, Area and Storage for Villages in Tamil Nadu and Haryana for Rice and Wheat (Source: Government of India, 2002)

Table I.1: Population and Grain Production

State	Average Population	Total No. of Sample Villages	Avg. Population of Cultivator Household	Avg. no. of family members	Paddy		Wheat	
					Area (Hectares)	%	Area (Hectares)	%
Tamil Nadu	5,735	75	241	5.51-6	218.84	67.64	0.04	0.01
Haryana	2,876	45	240	7.51 and above	246.19	29.27	527.4	62.7

Table I.2: Farm Area

State	Total Farm Geographic Area (Hectares)					Geographic Area in hectares		
	Below 500	500-1500	1500-3000	3000-5000	above 5000	min	max	avg
Tamil Nadu	20	38	12	5	0	71.27	4,343	1,118.65
Haryana	18	20	3	4	0	90	4,555	992.14
	Total Cultivated Area (Hectares)					Cultivated area in hectares		
Tamil Nadu	38	35	1	1	0	51.34	3143	601.03
Haryana	23	15	4	5	0	72	4189	877.49
	Total Cultivated Area as % of Total Geographic Area					% share cultivated area to geographic area		
	<30%	30-50%	50-70%	70-90%	>90%	min	max	avg
Tamil Nadu	7	13	30	22	3	20.55	93.06	60.62
Haryana	0	0	2	25	18	63.36	94.26	86.92

Table I.3: Storage

State	Average Institutional Storage Capacity In Quintals			Average Cost Of Storage (Rs/Qtl/Month)		Institutional Storage Available		Avg Institutional Storage Capacity Available Within 10km (Qtls)
	In The Village	Outside The Village	Co-Operative	State Warehousing Corporation	Outside The Village	Co-Operative	State Warehousing Corporation	
Tamil Nadu	1,131	486	1,617	0.7	1.5-3.5	X	X	9,617
Haryana	578	106,886	107,464	1.7	1.7	X	X	107,464

(1Qtl= 100 tonne, assume currency conversion $1=50Rs)

Appendix II: Optimization Wheat Storage and Transportation in Existing Facilities Case Study

Appendix II-1: Village Storage Data

Table II.1: Optimal Village Storage Data

Village Level	V	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13	V14	V15
Total Annual Harvest In All Villages (Tonnes)	H_v	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000
Cost Of Storage/ I Tonne/ Month	CS_v	10	9	11	8	10	8	10	10	8	10	8	10	8	10	8
Storage Losses/ 1 Tonne/ Month	LS_v	2.0	3.0	2.0	3.0	2.0	3.0	2.0	2.0	3.0	2.0	3.0	2.0	3.0	2.0	3.0
Estimated Storage Duration , (Month)	Sd_v	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Villages Storage Capacities (Tonnes)	C_v	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Design Variables Villages' Stored Volumes (Tonnes)	S_v	2,000	2,000	1,100	2,000	2,000	1,147	2,000	2,000	2,000	1,300	2,000	1,800	2,000	2,000	1,254
% Of Village Capacity Occupied		0%	100%	100%	55%	100%	100%	57%	100%	100%	100%	65%	100%	90%	100%	100%

Village Level	V	V16	V17	V18	V19	V20	V21	V22	V23	V24	V25	V26	V27	V28	V29	V30
Total Annual Harvest In All Villages (Tonnes)	H_v	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000
Cost Of Storage/ I Tonne/ Month	CS_v	10	8	10	8	10	8	10	10	8	10	10	8	10	8	10
Storage Losses/ 1 Tonne/ Month	LS_v	2.0	3.0	2.0	3.0	2.0	3.0	2.0	2.0	3.0	2.0	2.0	3.0	2.0	3.0	2.0
Estimated Storage Duration , (Month)	Sd_v	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Villages Storage Capacities (Tonnes)	C_v	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Design Variables Villages' Stored Volumes (Tonnes)	S_v	2,000	2,000	1,000	840	2,000	1,114	2,000	2,000	947	768	1,293	2,000	2,000	798	887
% Of Village Capacity Occupied		100%	100%	50%	42%	100%	56%	100%	100%	47%	38%	65%	100%	100%	40%	44%

Appendix II-2: Local Market Storage Data

Table II.2: Optimal Local Market Storage Data

Market Level	M i	M1 i(1,1)	 i (1,2)	 i (1,3)	M2 i (2,1)	 i (2,2)	M3 i (3,1)	 i (3,2)	M4 i(4,1)	 i (4,2)	 i (4,3)	M5 i (5,1)	M6 i(6,1)
Cost Of Storage/ I Tonne/ Month	$CS_{m,i}$	50	50	50	60	60	50	50	40	40	40	50	60
Storage Losses/ 1 Tonne/ Month	$LS_{m,i}$	1.5	1.5	1.5	1.0	1.0	1.5	1.5	2.0	2.0	2.0	1.5	1.0
Estimated Storage Duration , (Month)	$Sd_{m,i}$	3	3	3	3	3	3	3	3	3	3	3	3
Markets' Storage Capacities (Tonnes)	$C_{m,i}$	C(1,1) 10,000	C(1,2) 10,000	C(1,3) 10,000	C(2,1) 10,000	C(2,2) 10,000	C(3,1) 5,000	C(3,2) 2,500	C(4,1) 10,000	C(4,2) 10,000	C(4,3) 10,000	C(5,1) 5,000	C(6,1) 5,000
Decision Variable Markets' Stored Volumes (Tonnes)	$S_{m,i}$	S(1,1) 4,531	S(1,2) 10,000	S(1,3) 3,878	S(2,1) 10,000	S(2,2) 10,000	S(3,1) 5,000	S(3,2) 2,500	S (4,1) 8,308	S (4,2) 10,000	S(4,3) -	S(5,1) 5,000	S(6,1) 5,000
% Of Market Capacity Occupied		45.31%	100%	38.78%	100%	100%	100%	100%	83.08%	100%	0.00%	100.00 %	100.00 %

Appendix II-3: Regional Location Storage Data

Table II.3: Optimal Regional Location Storage Data

Regional Locations	R K	R 1 K (1,1)	R 2 K (2,1)	R 3 K (3,1)	 K (3,2)	 K (3,3)
Cost Of Storage/ I Ton/ Month	$Cs_{r,k}$	70	70	70	40	40
Storage Losses/ 1 Ton/ Month	$Ls_{r,k}$	1	1	1	2.5	2.5
Estimated Storage Duration, (Month)	$Sd_{r,k}$	3	3	3	3	3
Regions' Storage Capacities (Tonnes)	$C_{r,k}$	C(1,1) 56000	C(2,1) 56000	C(3,1) 23000	C(3,2) 1000	C(3,3) 23000
Decision Variable Regional Location Stored Volumes (Tonnes)	$S_{r,k}$	S(1,1) 26,376.6	S(2,1) 43,556.22	S(3,1) 9,823.51	S(3,2) -	S(3,3) -
% Of Region Capacity Occupied		47.10%	77.78%	42.71%	0%	0%
Constraint $S \leq C$		True	True	True	True	True

Appendix II-4: Optimal Transportation Ratios

Table II.4: Optimal Transportation Data between Villages and Local Markets

Village Origin	$Dr_{v.m.i}$ Local Market Destination											
	M1			M2		M3		M4			M5	M6
	M (1,1)	M (1,2)	M (1,3)	M (2,1)	M (2,2)	M (3,1)	M (3,2)	M (4,1)	M (4,2)	M (4,3)	M (5,1)	M (6,1)
V1	-	-	-	-	-	-	-	-	-	1.00	-	-
V2	0.03	-	-	0.71	0.03	-	-	-	-	-	-	0.23
V3	0.10	-	-	-	-	-	0.60	-	-	-	-	0.30
V4	-	-	0.00	-	-	0.53	-	-	-	0.30	-	0.17
V5	-	-	-	-	-	-	0.69	-	-	-	0.31	-
V6	0.32	-	0.00	-	-	-	-	-	-	-	-	0.68
V7	-	-	-	-	-	0.04	0.28	0.68	-	-	-	-
V8	-	-	-	-	-	-	0.02	0.00	-	-	-	0.98
V9	-	-	0.03	-	-	-	0.33	-	0.64	-	-	-
V10	0.01	0.00	-	-	-	-	0.24	-	-	-	-	0.74
V11	-	-	-	-	0.02	-	0.00	-	0.73	-	0.25	-
V12	-	0.25	-	-	0.74	-	-	-	-	-	-	-
V13	-	-	-	-	-	-	0.06	0.00	-	0.31	0.64	-
V14	-	0.36	-	0.63	-	0.00	-	-	-	-	-	-
V15	0.12	0.01	-	-	-	-	0.86	-	-	-	-	-
V16	-	-	-	-	-	-	0.01	0.74	-	0.24	-	-
V17	-	-	-	-	-	-	-	-	0.69	-	-	0.31
V18	0.00	-	-	-	0.50	0.17	-	0.03	-	-	0.30	-
V19	-	-	0.70	-	-	0.01	-	-	-	-	0.29	-
V20	0.12	-	-	-	-	-	-	-	0.69	-	0.18	-
V21	-	-	-	-	0.73	-	-	-	-	-	0.27	-
V22	-	-	-	-	0.00	-	-	-	0.25	-	0.75	-
V23	-	-	-	0.76	-	-	0.01	-	-	-	0.23	-
V24	-	0.75	-	-	-	-	0.01	0.00	-	-	0.24	-
V25	-	0.24	-	-	-	-	-	-	0.76	-	-	-
V26	-	-	-	0.00	-	1.00	-	-	-	-	-	-
V27	-	-	-	0.45	-	0.00	-	0.54	-	-	-	-
V28	-	-	-	-	-	-	-	-	0.39	0.59	-	0.02
V29	-	-	-	-	-	-	1.00	-	-	-	-	-
V30	0.31	0.52	-	-	0.17	-	-	-	-	-	-	-

Table II.5: Optimal Transportation Data between Local Markets and Regional Locations

Local Market Origin	$Dr_{m,r,k}$ **Regional Location Destination**				
	R1	R2	R3		
	R (1,1)	R (2,1)	R (3,1)	R (3,2)	R (3,3)
M1	0.0	0.0	1.0	0.0	0.0
M2	1.0	0.0	0.0	0.0	0.0
M3	1.0	0.0	0.0	0.0	0.0
M4	0.0	1.0	0.0	0.0	0.0
M5	0.0	0.0	1.0	0.0	0.0
M6	0.0	1.0	0.0	0.0	0.0

Appendix III: Optimizing the Construction of Public Wheat Storage Facilities Case Study

Appendix III-1: Optimal Existing Facilities Storage Data

Table III.1: Optimal Existing Facilities Data

Location	Storage Cost Rate ($/t/month)	Storage Loss Rate (%/t/month)	Existing Capacity (t)	Wheat Stored in Existing Facilities (t)
	$CS_{v,j}$	$LS_{v,j}$	$C_{v,j}$	$S_{v,j}$
V1	0.2	2	1,000	1,000
V2	0.18	3	1,000	1,000
V3	0.22	2	1,000	1,000
V4	0.16	3	1,000	1,000
V5	0.2	2	1,000	1,000
V6	0.16	3	1,000	1,000
V7	0.2	2	1,000	1,000
V8	0.2	2	1,000	1,000
V9	0.16	3	1,000	1,000
V10	0.2	2	1,000	1,000
V11	0.16	3	1,000	1,000
V12	0.2	2	1,000	1,000
V13	0.16	3	1,000	1,000
V14	0.2	2	1,000	1,000
V15	0.16	3	1,000	1,000
Total Village			15,000	15,000
	$CS_{m,i}$	$LS_{m,i}$	$C_{m,i}$	$S_{m,i}$
M1	1	1.5	12,500	7,936
M2	0.8	2	5,000	2,844
M3	1	1.5	5,000	5,000
M4	-	-	-	-
M5	-	-	-	-
Total Local Market			22,500	15,780
	$CS_{r,k}$	$LS_{r,k}$	$C_{r,k}$	$S_{r,k}$
R1	1.2	1.5	16,000	3,632
R2	1.2	1.5	9,000	8,984
R3	1.1	1.2	14,000	13,875
R4	-	-	-	-
R5	-	-	-	-
Total Regional Location			39,000	26,491
Total			76,500	57,271

Appendix III-2: Optimal New Constructed Facilities Storage Data

Table III.2: Optimal New Constructed Facilities Storage Data

Location	Available Site for New Construction	Available Area For New Construction	Site Selected	Type of New Facility Constructed	Capacity of New Facility Constructed	Construction Cost of New Facility	Wheat Stored in New Facilities
	(Yes/No)	(SF)			(t)	($)	(t)
		A_v		t	c	$CC^{t,c}$	$NS_{v,j}^{t,c}$
V1	yes	25,000	yes	Silo	3,000	360,000	3,000
V2	yes	10,000	yes	Silo	1,000	120,000	1,000
V3	yes	14,000	yes	Silo	3,000	360,000	3,000
V4	yes	25,000	yes	Silo	3,000	360,000	3,000
V5	yes	14,000	-	-	-	-	-
V6	yes	10,000	yes	Silo	3,000	360,000	3,000
V7	yes	25,000	yes	Silo	3,000	360,000	3,000
V8	yes	14,000	yes	Silo	3,000	360,000	3,000
V9	yes	8,000	-	-	-	-	-
V10	yes	20,000	yes	Godown	1,000	80,000	1,000
V11	yes	14,000	yes	Godown	1,000	80,000	1,000
V12	yes	5,000	-	-	-	-	-
V13	yes	25,000	yes	Godown	1,000	80,000	1,000
V14	yes	5,000	-	-	-	-	-
V15	yes	25,000	yes	Silo	3,000	360,000	3,000
Total Village		239,000			25,000	2,880,000	25,000
		A_m		t	c	$CC^{t,c}$	$NS_{m,i}^{t,c}$
M1	yes	25,000	yes	Godown	3,000	200,000	2,984
M2	yes	25,000	yes	Godown	3,000	200,000	3,000
M3	yes	25,000	yes	Godown+Silo	6,000	560,000	5,950
M4	yes	60,000	-	-	-	-	-
M5	yes	60,000	yes	CAP	10,000	160,000	10,000
Total Local Market		195,000			22,000	1,120,000	21,934
		A_r		t	c	$CC^{t,c}$	$NS_{r,k}^{t,c}$
R1	yes	45,000	-	-	-	-	-
R2	yes	45,000	-	-	-	-	-
R3	yes	45,000	-	-	-	-	-
R4	yes	70,000	-	-	-	-	-
R5	yes	70,000	-	-	-	-	-
Total Regional Location		275,000			-	-	-
Total		709,000			47,000	4,000,000	46,934

Appendix III-3: Sensitivity Analysis to Variation to the Construction Budget Constraint

Table III.3: Sensitivity Analysis to Construction Budget ($1 Million and $2 Million)

	$1 Million Budget			**$2 Million Budget**		
Location	Type	Capacity	Construction Cost	Type	Capacity	Construction Cost
		(t)	($)		(t)	($)
	t	c	$CC^{t,c}$	t	c	$CC^{t,c}$
V1	CAP	3,000	48,000	Godown	3,000	200,000
V2	CAP	1,000	16,000	Godown	1,000	80,000
V3	CAP	1,000	16,000	Godown	2,000	150,000
V4	CAP	3,000	48,000	Godown	3,000	200,000
V5	CAP	1,000	16,000	Godown	2,000	150,000
V6	CAP	1,000	16,000	Godown	1,000	80,000
V7	CAP	3,000	48,000	Godown	3,000	200,000
V8	CAP	1,000	16,000	Godown	1,000	80,000
V9	CAP	1,000	16,000	Godown	1,000	80,000
V10	CAP	3,000	48,000	CAP	3,000	48,000
V11	CAP	1,000	16,000	Godown	1,000	80,000
V12	-	-	-	CAP	500	8,000
V13	CAP	3,000	48,000	Godown	1,000	80,000
V14	-	-	-	CAP	500	8,000
V15	CAP	3,000	48,000	CAP	3,000	48,000
Total Village		26,000	416,000		26,000	1,492,000
	t	c	$CC^{t,c}$	t	c	$CC^{t,c}$
M1	CAP	4,000	64,000	CAP	3,000	48,000
M2	CAP	3,000	48,000	CAP	3,000	48,000
M3	CAP	3,300	52,800	CAP	3,000	48,000
M4	CAP	10,000	160,000	CAP	10,000	160,000
M5	CAP	10,000	160,000	CAP	10,000	160,000
Total Local Market		30,300	484,400		29,000	464,000
	t	c	$CC^{t,c}$	t	c	$CC^{t,c}$
R1	CAP	3,000	48,000	-	-	-
R2	-	-	-	-	-	-
R3	CAP	3,000	48,000	-	-	-
R4	-	-	-	-	-	-
R5	-	-	-	-	-	-
Total Regional Location		6,000	96,000		-	-
Total		62,300	996,800		55,000	1,956,000

Table III.4: Sensitivity Analysis to Construction Budget ($4 Million, $6 Million and $8 Million)

	$4 Million Budget			**$6 Million Budget**			**$8 Million Budget**		
Location	Type	Capacity	Construction Cost	Type	Capacity	Construction Cost	Type	Capacity	Construction Cost
		(t)	($)		(t)	($)		(t)	($)
	t	c	$CC^{t,c}$	t	c	$CC^{t,c}$	t	c	$CC^{t,c}$
V1	Silo	3,000	360,000	Silo	6,000	720,000	Silo	5,000	600,000
V2	Silo	1,000	120,000	Silo	3,000	360,000	Silo	3,000	360,000
V3	Silo	3,000	360,000	Silo	3,000	360,000	Silo	3,000	360,000
V4	Silo	3,000	360,000	-	-	-	Silo	6,000	720,000
V5	-	-	-	-	-	-	Silo	3,000	360,000
V6	Silo	3,000	360,000	-	-	-	Silo	3,000	360,000
V7	Silo	3,000	360,000	Silo	3,000	360,000	Silo	5,000	600,000
V8	Silo	3,000	360,000	Silo	3,000	360,000	Silo	3,000	360,000
V9	-	-	-	Silo	1,000	120,000	Silo	1,000	120,000
V10	Godown	1,000	80,000	Silo	5,000	600,000	Silo	5,000	600,000
V11	Godown	1,000	80,000	Godown+Silo	2,000	200,000	Godown	1,000	80,000
V12	-	-	-	-	-	-	-	-	-
V13	Godown	1,000	80,000	Silo	3,000	360,000	Silo	3,000	360,000
V14	-	-	-	Silo	1,000	120,000	Silo	1,000	120,000
V15	Silo	3,000	360,000	Silo	5,000	600,000	Silo	5,000	600,000
Total Village		25,000	2,880,000		35,000	4,160,000		47,000	5,600,000
	t	c	$CC^{t,c}$	t	c	$CC^{t,c}$	t	c	$CC^{t,c}$
M1	Godown	3,000	200,000	Godown+Silo	2,000	200,000	Silo	3,000	360,000
M2	Godown	3,000	200,000	Silo	3,000	360,000	Silo	6,000	720,000
M3	Godown+Silo	6,000	560,000	Silo	5,000	600,000	Silo	5,000	600,000
M4	-	-	-	-	-	-	-	-	-
M5	CAP	10,000	160,000	Godown+Silo	6,000	680,000	Silo	6,000	720,000
Total Local Market		22,000	1,120,000		16,000	1,840,000		20,000	2,400,000
	t	c	$CC^{t,c}$	t	c	$CC^{t,c}$	t	c	$CC^{t,c}$
R1	-	-	-	-	-	-	-	-	-
R2	-	-	-	-	-	-	-	-	-
R3	-	-	-	-	-	-	-	-	-
R4	-	-	-	-	-	-	-	-	-
R5	-	-	-	-	-	-	-	-	-
Total Regional Location		-	-		-	-		-	-
Total		47,000	4,000,000		51,000	6,000,000		67,000	8,000,000

Appendix IV: Optimizing the Utilization and Construction of Private Wheat Storage Facilities Case Study

Appendix IV-1: Pre-Construction Model Results

Table IV.1: Model Input Data and Annual Sales Profit & Contribution for Construction

	Input Data					
Farm	Harvest (t)	Existing Capacity (t)	Farm Monthly Consumption (t/month)	Storage Cost Rate ($/t*month)	Storage Loss Rate (%/t*month)	Capacity/Harvest
f	H_f	C_f	FC_f	CS_f	LS_f	
1	4000	2000	42	0.13	2.5%	0.500
2	2500	1000	36	0.16	2.7%	0.400
3	800	400	30	0.15	2.3%	0.500
4	600	200	30	0.15	2.3%	0.333
5	600	130	18	0.17	2.5%	0.217
6	2600	1000	36	0.15	2.3%	0.385
7	800	400	30	0.16	2.0%	0.500
8	600	200	30	0.16	2.0%	0.333
9	600	150	19	0.12	2.5%	0.250
10	800	400	29	0.15	2.0%	0.500
11	600	200	28	0.15	2.0%	0.333
12	650	140	18	0.18	2.7%	0.215
13	800	400	30	0.15	2.5%	0.500
14	600	200	29	0.20	2.8%	0.333
15	580	120	19	0.15	2.5%	0.207
16	600	210	29	0.13	2.7%	0.350
17	590	140	18	0.15	2.5%	0.237
18	2500	500	18	0.20	2.3%	0.200
19	950	500	19	0.13	2.7%	0.526
20	580	140	18	0.15	2.5%	0.241
21	2500	950	36	0.20	2.3%	0.380
22	800	400	31	0.13	2.7%	0.500
23	600	220	29	0.20	2.8%	0.367
24	620	150	18	0.15	2.5%	0.242
25	3000	900	38	0.14	2.9%	0.300
26	850	350	32	0.20	2.3%	0.412
27	600	250	29	0.15	2.5%	0.417
28	610	150	19	0.20	2.3%	0.246
29	800	400	31	0.13	2.7%	0.500
30	600	220	32	0.20	2.3%	0.367
Total	33,330	12,420				0.373

Table IV.2: Annual Sales Profit & Contribution for Construction

	Output Data		
Farm	Annual Sales Profit ($)	Profit Contribution (%)	Contribution for Construction ($)
f	PeP_f	w_f	$PeP_f * w_f$
1	309,222	4	12,369
2	179,786	6	10,787
3	34,634	10	3,463
4	16,305	18	2,935
5	31,323	10	3,132
6	190,094	6	11,406
7	35,001	11	3,850
8	16,429	18	2,957
9	30,325	13	3,942
10	36,223	10	3,622
11	19,115	15	2,867
12	35,764	11	3,934
13	34,493	12	4,139
14	16,920	18	3,046
15	28,497	10	2,850
16	17,220	18	3,100
17	30,539	12	3,665
18	204,220	8	16,338
19	61,801	7	4,326
20	29,568	13	3,844
21	180,955	6	10,857
22	32,135	11	3,535
23	17,082	17	2,904
24	33,219	11	3,654
25	221,884	7	15,532
26	36,317	13	4,721
27	17,430	14	2,440
28	31,180	10	3,118
29	32,085	12	3,850
30	13,554	19	2,575
Total	1,973,319	8%	159,758

Table IV.3: Optimal Pre-Construction Sale Quantities from Farms to Local Markets

Farms	Local Markets	Quantities Sold to Local Markets (t) $S^{d}_{f,m}$											
		Months											
		1	2	3	4	5	6	7	8	9	10	11	12
1	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	3394	-	6	3	-	-	-	-	-	-	-	-
2	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	1972	-	7	2	-	-	-	-	-	-	-	-
3	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	569	-	-	-	-	-	-	-	-	-	-	-
4	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	400	-	-	-	-	-	-	-	-	-	-	-
5	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	470	-	-	-	-	-	-	-	-	-	-	-
6	M1	-	-	-	-	-	3	1	-	-	-	-	-
	M2	1600	480	-	-	-	-	-	-	-	-	-	-
7	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	547	-	-	-	-	-	-	-	-	-	-	-
8	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	400	-	-	-	-	-	-	-	-	-	-	-
9	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	450	-	-	-	-	-	-	-	-	-	-	-
10	M1	-	-	-	-	-	-	-	-	-	1	-	-
	M2	401	-	-	-	-	-	-	-	-	-	-	-
11	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	400	-	-	-	-	-	-	-	-	-	-	-
12	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	510	-	-	-	-	-	-	-	-	-	-	-
13	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	602	-	-	-	-	-	-	-	-	-	-	-
14	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	400	-	-	-	-	-	-	-	-	-	-	-
15	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	460	-	-	-	-	-	-	-	-	-	-	-
16	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	390	-	-	-	-	-	-	-	-	-	-	-
17	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	450	-	-	-	-	-	-	-	-	-	-	-
18	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	2220	16	11	-	-	-	-	-	-	-	-	-
19	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	930	-	-	-	-	-	-	-	-	-	-	-
20	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	440	-	-	-	-	-	-	-	-	-	-	-
21	M1	-	-	-	-	-	-	-	6	-	-	-	-
	M2	1955	33	-	-	-	-	-	-	-	-	-	-
22	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	400	-	-	-	-	-	-	-	-	-	-	-
23	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	380	-	-	-	-	-	-	-	-	-	-	-
24	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	470	-	-	-	-	-	-	-	-	-	-	-
25	M1	-	-	-	-	-	-	-	-	-	-	4	4
	M2	2431	-	-	-	-	-	-	-	-	-	-	-
26	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	500	-	-	-	-	-	-	-	-	-	-	-
27	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	350	-	-	-	-	-	-	-	-	-	-	-
28	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	460	-	-	-	-	-	-	-	-	-	-	-
29	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	400	-	-	-	-	-	-	-	-	-	-	-
30	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	380	-	-	-	-	-	-	-	-	-	-	-

Table IV.4: Optimal Pre-Construction Purchase Quantities from Farms to Local Markets

Farms	Local Markets	Quantities Purchased from Local Markets (t) $B_{f,m}^{d}$											
		Months											
		1	2	3	4	5	6	7	8	9	10	11	12
1	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	-	-	-	-	-
2	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	-	-	-	-	-
3	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	36	36	38	45	-
4	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	31	32	31	31	31	26
5	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	17	20	18	19	18	11
6	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	-	-	-	-	-
7	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	16	31	31	30	24
8	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	32	30	30	30	31	27
9	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	23	20	21	19	13
10	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	-	-	-	-	-
11	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	20	29	29	30	28	20
12	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	6	18	19	18	19	15
13	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	33	37	32	32	31	20
14	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	29	29	30	30	30	27
15	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	11	19	18	19	19	18	18
16	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	19	30	30	30	31	25
17	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	25	24	25	20	-
18	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	-	-	-	-	-
19	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	20	20	20	20	20	20	20	20	19	19	18
20	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	-	-	-	-	-
21	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	-	-	-	-	-
22	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	-	-	-	19	16
23	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	8	30	31	30	36	22
24	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	11	20	20	28	6
25	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	-	-	-	-	-
26	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	-	-	19	30	29
27	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	23	27	27	26	26
28	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	-	27	24	23	22	-
29	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	4	-	-	-	-	10	10	12
30	M1	-	-	-	-	-	-	-	-	-	-	-	-
	M2	-	-	-	-	-	-	32	33	31	31	31	31

Appendix IV-2: Post-Construction Model Results

Table IV.5: Optimal Output Data

Farm f	Village 1 Capacity (t)	Village 2 Capacity (t)	Total New Capacity (t)	New Capacity /Existing Capacity	Total New and Existing Capacity (t)	Total Capacit y/Harve st
1	232	774	1,006	50%	3,006	0.75
2	203	675	878	88%	1,878	0.75
3	65	217	282	70%	682	0.85
4	55	184	239	119%	439	0.73
5	59	196	255	196%	385	0.64
6	214	714	928	93%	1,928	0.74
7	72	241	313	78%	713	0.89
8	56	185	241	120%	441	0.73
9	74	247	321	214%	471	0.78
10	68	227	295	74%	695	0.87
11	54	179	233	117%	433	0.72
12	74	246	320	229%	460	0.71
13	78	259	337	84%	737	0.92
14	57	191	248	124%	448	0.75
15	54	178	232	193%	352	0.61
16	58	194	252	120%	462	0.77
17	69	229	298	213%	438	0.74
18	307	1,023	1,329	266%	1,829	0.73
19	81	271	352	70%	852	0.90
20	72	241	313	223%	453	0.78
21	204	680	883	93%	1,833	0.73
22	66	221	288	72%	688	0.86
23	55	182	236	107%	456	0.76
24	69	229	297	198%	447	0.72
25	292	972	1,264	140%	2,164	0.72
26	89	296	384	110%	734	0.86
27	46	153	199	79%	449	0.75
28	59	195	254	169%	404	0.66
29	72	241	313	78%	713	0.89
30	48	161	210	95%	430	0.72
Total	3,000	10,000	13,000	105%	25,420	0.76

Table IV.6: Optimal Output Data Including Profit Generated at all Farms during Post-Construction

Farm f	Annual Sales Profit ($) PoP_f	Profit Increase (%)	Payback Period (yrs)
1	309,222	1.70%	2.4
2	179,786	2.38%	2.5
3	34,634	4.58%	2.2
4	16,305	10.24%	1.8
5	31,323	5.19%	1.9
6	190,094	2.81%	2.1
7	35,001	4.53%	2.4
8	16,429	9.21%	2.0
9	30,325	6.03%	2.2
10	36,223	4.99%	2.0
11	19,115	8.30%	1.8
12	35,764	4.75%	2.3
13	34,493	5.85%	2.1
14	16,920	10.66%	1.7
15	28,497	4.55%	2.2
16	17,220	10.02%	1.8
17	30,539	5.30%	2.3
18	204,220	3.30%	2.4
19	61,801	2.99%	2.3
20	29,568	5.65%	2.3
21	180,955	3.01%	2.0
22	32,135	7.47%	1.5
23	17,082	8.98%	1.9
24	33,219	4.73%	2.3
25	221,884	3.81%	1.8
26	36,317	6.68%	1.9
27	17,430	6.56%	2.1
28	31,180	4.67%	2.1
29	32,085	8.54%	1.4
30	13,554	11.43%	1.7
Total	1,973,319	3.91%	

Table IV.7: Optimal Post-Construction Sale and Purchase Quantities from Farms to Local Markets

Farms	Local Markets	Quantities Sold to Local Markets (t) $S^d_{f,m}$												Quantities Purchased from Local Markets (t) $B^d_{f,m}$											
		Months												Months											
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1	M1	-	-	-	-	-	-	-	-	-	-	4	844	-	-	-	-	-	-	-	-	-	-	-	-
	M2	2462	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	M1	-	-	-	-	-	-	-	-	1	1	-	751	-	-	-	-	-	-	-	-	-	-	-	-
	M2	1142	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	M1	-	-	-	-	-	-	-	-	-	-	-	130	-	-	-	-	-	-	-	-	-	-	-	-
	M2	250	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	M1	-	-	-	-	-	-	-	-	-	-	-	35	-	-	-	-	-	-	-	-	-	-	-	-
	M2	162	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	M1	-	-	-	-	-	-	-	-	-	-	-	128	-	-	-	-	-	-	-	-	-	-	-	-
	M2	216	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-
6	M1	-	-	-	-	-	-	-	-	-	-	-	611	-	-	-	-	-	-	-	-	-	-	-	-
	M2	1436	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	M1	-	-	-	-	-	-	-	-	-	-	-	217	-	-	-	-	-	-	-	-	-	-	-	-
	M2	124	-	9	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	M1	-	-	-	-	-	-	-	-	-	-	-	39	-	-	-	-	-	-	-	-	-	-	-	-
	M2	159	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	M1	-	-	-	-	-	-	-	-	-	-	-	193	-	-	-	-	-	-	-	-	-	-	-	-
	M2	130	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
10	M1	-	-	-	-	-	-	-	-	-	-	-	118	-	-	-	-	-	-	-	-	-	-	-	-
	M2	284	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	M1	-	-	-	-	-	-	-	-	-	-	-	55	-	-	-	-	-	-	-	-	-	-	-	-
	M2	168	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	M1	-	-	-	-	-	-	-	-	-	-	-	192	-	-	-	-	-	-	-	-	-	-	-	-
	M2	190	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	M1	-	-	-	-	-	-	-	-	-	-	-	122	-	-	-	-	-	-	-	-	-	-	-	-
	M2	263	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	M1	-	-	-	-	-	-	-	-	-	-	-	50	-	-	-	-	-	-	-	-	-	-	-	-
	M2	153	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	M1	-	-	-	-	-	-	-	-	-	-	-	87	-	-	-	-	-	-	-	-	-	-	-	-
	M2	229	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	M1	-	-	-	-	-	-	-	-	-	-	-	64	-	-	-	-	-	-	-	-	-	-	-	-
	M2	138	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	M1	-	-	-	-	-	-	-	-	-	-	-	174	-	-	-	-	-	-	-	-	-	-	-	-
	M2	152	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	M1	-	-	-	-	-	2	5	-	-	-	-	1115	-	-	-	-	-	-	-	-	-	-	-	-
	M2	1000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	M1	-	-	-	-	-	-	-	-	-	-	-	218	-	-	-	-	-	-	-	-	-	-	-	-
	M2	447	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	M1	-	-	-	-	-	-	-	-	-	-	-	187	-	-	-	-	-	-	-	-	-	-	-	-
	M2	127	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
21	M1	-	-	-	-	-	-	1	-	-	-	-	610	-	-	-	-	-	-	-	-	-	-	-	-
	M2	1335	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22	M1	-	-	-	-	-	-	-	-	-	-	1	132	-	-	-	-	-	-	-	-	-	-	-	-
	M2	228	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	M1	-	-	-	-	-	-	-	-	-	-	-	57	-	-	-	-	-	-	-	-	-	-	-	-
	M2	144	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
24	M1	-	-	-	-	-	-	-	-	-	-	-	181	-	-	-	-	-	-	-	-	-	-	-	-
	M2	173	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
25	M1	-	-	-	-	-	-	-	-	-	-	-	938	-	-	-	-	-	-	-	-	-	-	-	-
	M2	1432	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26	M1	-	-	-	-	-	-	-	-	-	-	-	214	-	-	-	-	-	-	-	-	-	-	-	-
	M2	180	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
27	M1	-	-	-	-	-	-	-	-	-	-	-	49	-	-	-	-	-	-	-	-	-	-	-	-
	M2	152	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
28	M1	-	-	-	-	-	-	-	-	-	-	-	132	-	-	-	-	-	-	-	-	-	-	-	-
	M2	207	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
29	M1	-	-	-	-	-	-	-	-	-	-	-	124	-	-	-	-	-	-	-	-	-	-	-	-
	M2	242	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	M1	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-
	M2	171	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table IV.8: Optimal Post-Construction Transported Quantities from Farms to New Village Facilities

Farms	New Facility	Quantities Transported to New Facility (t) $S^d_{f,v}$											
		Months											
		1	2	3	4	5	6	7	8	9	10	11	12
1	V1	232	-	-	-	-	-	-	-	-	-	-	-
	V2	775	-	-	-	-	-	-	-	-	-	-	-
2	V1	202	-	-	-	-	-	-	-	-	-	-	-
	V2	677	-	-	-	-	-	-	-	-	-	-	-
3	V1	65	-	-	-	-	-	-	-	-	-	-	-
	V2	217	-	-	-	-	-	-	-	-	-	-	-
4	V1	55	-	-	-	-	-	-	-	-	-	-	-
	V2	183	-	-	-	-	-	-	-	-	-	-	-
5	V1	59	-	-	-	-	-	-	-	-	-	-	-
	V2	196	-	-	-	-	-	-	-	-	-	-	-
6	V1	214	-	-	-	-	-	-	-	-	-	-	-
	V2	715	-	-	-	-	-	-	-	-	-	-	-
7	V1	72	-	-	-	-	-	-	-	-	-	-	-
	V2	241	-	-	-	-	-	-	-	-	-	-	-
8	V1	55	-	-	-	-	-	-	-	-	-	-	-
	V2	186	-	-	-	-	-	-	-	-	-	-	-
9	V1	74	-	-	-	-	-	-	-	-	-	-	-
	V2	247	-	-	-	-	-	-	-	-	-	-	-
10	V1	68	-	-	-	-	-	-	-	-	-	-	-
	V2	227	-	-	-	-	-	-	-	-	-	-	-
11	V1	53	-	-	-	-	-	-	-	-	-	-	-
	V2	179	-	-	-	-	-	-	-	-	-	-	-
12	V1	73	-	-	-	-	-	-	-	-	-	-	-
	V2	247	-	-	-	-	-	-	-	-	-	-	-
13	V1	77	-	-	-	-	-	-	-	-	-	-	-
	V2	259	-	-	-	-	-	-	-	-	-	-	-
14	V1	57	-	-	-	-	-	-	-	-	-	-	-
	V2	190	-	-	-	-	-	-	-	-	-	-	-
15	V1	53	-	-	-	-	-	-	-	-	-	-	-
	V2	178	-	-	-	-	-	-	-	-	-	-	-
16	V1	58	-	-	-	-	-	-	-	-	-	-	-
	V2	194	-	-	-	-	-	-	-	-	-	-	-
17	V1	68	-	-	-	-	-	-	-	-	-	-	-
	V2	230	-	-	-	-	-	-	-	-	-	-	-
18	V1	307	-	-	-	-	-	-	-	-	-	-	-
	V2	1024	-	-	-	-	-	-	-	-	-	-	-
19	V1	81	-	-	-	-	-	-	-	-	-	-	-
	V2	271	-	-	-	-	-	-	-	-	-	-	-
20	V1	72	-	-	-	-	-	-	-	-	-	-	-
	V2	241	-	-	-	-	-	-	-	-	-	-	-
21	V1	204	-	-	-	-	-	-	-	-	-	-	-
	V2	680	-	-	-	-	-	-	-	-	-	-	-
22	V1	66	-	-	-	-	-	-	-	-	-	-	-
	V2	221	-	-	-	-	-	-	-	-	-	-	-
23	V1	54	-	-	-	-	-	-	-	-	-	-	-
	V2	182	-	-	-	-	-	-	-	-	-	-	-
24	V1	68	-	-	-	-	-	-	-	-	-	-	-
	V2	229	-	-	-	-	-	-	-	-	-	-	-
25	V1	292	-	-	-	-	-	-	-	-	-	-	-
	V2	973	-	-	-	-	-	-	-	-	-	-	-
26	V1	88	-	-	-	-	-	-	-	-	-	-	-
	V2	295	-	-	-	-	-	-	-	-	-	-	-
27	V1	45	-	-	-	-	-	-	-	-	-	-	-
	V2	153	-	-	-	-	-	-	-	-	-	-	-
28	V1	58	-	-	-	-	-	-	-	-	-	-	-
	V2	195	-	-	-	-	-	-	-	-	-	-	-
29	V1	72	-	-	-	-	-	-	-	-	-	-	-
	V2	241	-	-	-	-	-	-	-	-	-	-	-
30	V1	48	-	-	-	-	-	-	-	-	-	-	-
	V2	161	-	-	-	-	-	-	-	-	-	-	-

Table IV.9: Optimal Post-Construction Transported Quantities to Farms from New Village Facilities

Farms	New Facility	Quantities Transported from New Facility (t) $B^{d}_{f,v}$											
		Months											
		1	2	3	4	5	6	7	8	9	10	11	12
1	V1	-	-	-	-	-	-	-	-	-	-	-	207
	V2	-	-	-	-	-	-	-	-	-	-	11	682
2	V1	-	-	-	-	-	-	-	-	-	-	-	180
	V2	-	-	-	-	-	-	-	-	-	-	-	604
3	V1	-	-	-	-	-	-	-	-	30	29	-	-
	V2	-	-	-	-	-	-	-	-	-	2	31	161
4	V1	-	-	-	-	-	-	27	24	-	-	-	-
	V2	-	-	-	-	-	-	-	7	31	31	30	66
5	V1	-	-	-	-	-	-	9	18	19	8	-	-
	V2	-	-	-	-	-	-	-	-	-	10	19	146
6	V1	-	-	-	-	-	-	37	37	37	37	37	11
	V2	-	-	-	-	-	-	-	-	-	-	-	638
7	V1	-	-	-	-	-	-	-	-	-	6	25	33
	V2	-	-	-	-	-	-	-	-	-	-	-	215
8	V1	-	-	-	-	-	-	17	34	-	-	-	-
	V2	-	-	-	-	-	-	8	-	28	31	31	69
9	V1	-	-	-	-	-	-	-	18	20	24	6	-
	V2	-	-	-	-	-	-	-	-	-	-	17	204
10	V1	-	-	-	-	1	-	-	31	31	-	-	-
	V2	-	-	-	-	-	-	-	-	-	27	30	146
11	V1	-	-	-	-	-	-	12	28	9	-	-	-
	V2	-	-	-	-	-	-	-	-	20	29	29	83
12	V1	-	-	-	-	-	-	1	19	19	19	9	-
	V2	-	-	-	-	-	-	-	-	-	-	8	212
13	V1	-	-	-	-	-	-	31	31	9	-	-	-
	V2	-	-	-	-	-	-	-	-	22	31	31	149
14	V1	-	-	-	-	-	-	24	29	-	-	-	-
	V2	-	-	-	-	-	-	-	2	30	31	33	75
15	V1	-	-	-	-	-	5	19	20	5	-	-	-
	V2	-	-	-	-	-	-	-	-	17	20	19	104
16	V1	-	-	-	-	-	-	19	30	5	-	-	-
	V2	-	-	-	-	-	-	-	-	24	30	30	91
17	V1	-	-	-	-	-	-	-	19	20	21	2	-
	V2	-	-	-	-	-	-	-	-	-	-	12	193
18	V1	-	-	-	-	-	-	-	-	18	19	18	220
	V2	-	-	-	-	-	-	-	-	-	-	-	915
19	V1	-	-	-	-	-	-	-	20	19	20	15	-
	V2	-	-	-	-	-	-	-	-	-	-	4	237
20	V1	-	-	-	-	-	-	-	19	19	20	7	-
	V2	-	-	-	-	-	-	-	-	-	-	9	206
21	V1	-	-	-	-	-	-	-	36	37	37	25	50
	V2	-	-	-	-	-	-	-	-	-	-	12	596
22	V1	-	-	-	-	-	-	-	-	32	28	-	-
	V2	-	-	-	-	-	-	-	-	-	5	32	161
23	V1	-	-	-	-	-	-	7	30	13	-	-	-
	V2	-	-	-	-	-	-	-	-	23	30	30	81
24	V1	-	-	-	-	-	-	-	10	19	18	15	-
	V2	-	-	-	-	-	-	-	-	-	-	4	200
25	V1	-	-	-	-	-	-	-	40	40	39	33	112
	V2	-	-	-	-	-	-	-	-	-	-	25	845
26	V1	-	-	-	-	-	-	-	-	33	33	14	-
	V2	-	-	-	-	-	-	-	-	-	-	25	239
27	V1	-	-	-	-	-	-	-	9	30	2	-	-
	V2	-	-	-	-	-	-	-	-	-	28	40	69
28	V1	-	-	-	-	-	-	-	17	19	17	-	-
	V2	-	-	-	-	-	-	-	-	-	3	19	152
29	V1	-	-	-	-	-	-	-	32	34	-	-	-
	V2	-	-	-	-	-	-	-	-	-	30	32	154
30	V1	-	-	-	-	-	-	23	21	-	-	-	-